ASME PTC 18-2011
(Revision of ASME PTC 18-2002)

Hydraulic Turbines and Pump-Turbines

Performance Test Codes

AN INTERNATIONAL CODE

The American Society of Mechanical Engineers

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The American Society of Mechanical Engineers
Three Park Avenue • New York, NY • 10016 USA

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The next edition of this Code is scheduled for publication in 2016. There will be no addenda issued to this edition.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this Code. Interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org as they are issued.

The American Society of Mechanical Engineers
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NOTICE

All Performance Test Codes **MUST** adhere to the requirements of **PTC 1, GENERAL INSTRUCTIONS**. The following information is based on that document and is included here for emphasis and for the convenience of the user of this Code. It is expected that the Code user is fully cognizant of Parts I and III of PTC 1 and has read them prior to applying this Code.

ASME Performance Test Codes provide test procedures which yield results of the highest level of accuracy consistent with the best engineering knowledge and practice currently available. They were developed by balanced committees representing all concerned interests. They specify procedures, instrumentation, equipment operating requirements, calculation methods, and uncertainty analysis.

When tests are run in accordance with a Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do not specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree before starting the test and preferably before signing the contract on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any Code to determine or interpret how such comparisons shall be made.

FOREWORD

The "Rules for Conducting Tests of Waterwheels" was one of a group of ten test codes published by the ASME in 1915. The Pelton Water Wheel Company published a testing code for hydraulic turbines, which was approved by the Machinery Builders' Society on October 11, 1917. This code included the brine velocity method of measuring flow wherein the time of passage of an injection of brine was detected by electrical resistance. Also in October 1917, the Council of the ASME authorized the appointment of a joint committee to undertake the task of revising the "Rules for Conducting Tests of Waterwheels." The joint committee consisted of thirteen members, four from the ASME and three each from ASCE, AIEE, and NELA (National Electric Light Association). The code was printed in the April 1922 issue of *Mechanical Engineering* in preliminary form. It was approved in the final revised form at the June 1923 meeting of the Main Committee and was later approved and adopted by the ASME Council as a standard practice of the Society.

Within three years the 1923 revised edition was out of print and a second revision was ordered by the Main Committee. In November 1925, the ASME Council appointed a new committee, the Power Test Codes Individual Committee No. 18 on Hydraulic Power Plants. This committee organized itself quickly and completed a redraft of the code in time for a discussion with the advisory on Prime Movers of the IEC at the New York meeting later in April 1926. The code was redrafted in line with this discussion and was approved by the Main Committee in March 1927. It was approved and adopted by the ASME Council as the standard practice of the Society on April 14, 1927.

In October 1931 the ASME Council approved personnel for a newly organized committee, Power Test Codes Individual Committee No. 18 on Hydraulic Prime Movers, to undertake revision of the 1927 test code. The committee completed the drafting of the revised code in 1937. The Main Committee approved the revised code on April 4, 1938. The code was then approved and adopted by the Council as standard practice of the Society on June 6, 1938. The term "Hydraulic Prime Movers" is defined as reaction and impulse turbines, both of which are included in the term "hydraulic turbines." A revision of this Code was approved by the Power Test Codes Committee and by the Council of ASME in August 1942. Additional revisions were authorized by Performance Test Code Committee No. 18 (PTC 18) in December 1947. Another revision was adopted in December 1948. It was also voted to recommend the reissue of the 1938 Code to incorporate all of the approved revisions as a 1949 edition. A complete rewriting of the Code was not considered necessary, because the 1938 edition had been successful and was in general use. A supplement was prepared to cover index testing. The revised Code including index testing was approved on April 8, 1949, by the Power Test Codes Committee and was approved and adopted by the Council of ASME by action of the Board on Codes and Standards on May 6, 1949.

The members of the 1938 to 1949 committees included C. M. Allen, who further developed the Salt Velocity Method of flow rate measurement; N. R. Gibson, who devised the Pressure-Time Method of flow rate measurement; L. F. Moody, who developed a method for estimating prototype efficiency from model tests; S. Logan Kerr, successful consultant on pressure rise and surge; T. H. Hogg, who developed a graphical solution for pressure rise; G. R. Rich, who wrote a book on pressure rise; as well as other well known hydro engineers.

In 1963, Hydraulic Prime Movers Test Code Committee, PTC 18, was charged with the preparation of a Test Code for the Pumping Mode/Pump Turbines. The Code for the pumping mode was approved by the Performance Test Codes Supervisory Committee on January 23, 1978, and was then approved as an American National Standard by the ANSI Board of Standards Review on July 17, 1978.

The PTC 18 Committee then proceeded to review and revise the 1949 Hydraulic Prime Movers Code as a Test Code for Hydraulic Turbines. The result of that effort was the publication of PTC 18-1992 Hydraulic Turbines.

Since two separate but similar Codes now existed, the PTC 18 Committee proceeded to consolidate them into a single Code encompassing both the turbine and pump modes of Pump/Turbines. The consolidation also provided the opportunity to improve upon the clarity of the preceeding Codes, as well as to introduce newer technologies such as automated data-acquisition and computation techniques, and the dye-dilution method. Concurrently, the flow methods of salt velocity, pitot tubes and weirs, which had become rarely used, were removed from the 2002 Edition. However, detailed descriptions of these methods remain in previous versions of PTC 18 and PTC 18.1

Following the publication of the 2002 Revision of PTC 18, the PTC 18 Committee began work on the next Revision to further modernize and increase the accuracy of measuring techniques and to improve clarity. The 2011 Revision is characterized by the following features: increased harmonization of text with other ASME Performance Test Codes according to PTC 1 General Instructions; improvement of text and illustrations; modernization of techniques with increased guidance on electronic data acquisition systems and — in the case of the Ultrasonic Method — increasing ultrasonic flow-measurement accuracy with additional paths; deletion from this Code of the seldom used Venturi, volumetric and pressure-time Gibson flow-measurement methods; deletion from this Code of the seldom practical direct method of power measurement; and removal of the Relative Flow Measurement–Index Test from the main text of the Code to a nonmandatory Appendix.

The methods of measuring flow rate included in this Code meet the criteria of the PTC 18 Committee for soundness of principle, have acceptable limits of accuracy, and have demonstrated application under laboratory and field conditions. There are other methods of measuring flow rate under consideration for inclusion in the Code at a later date.

This Code was approved by the Board on Standardization and Testing on March 3, 2011, and approved as an American National Standard by the ANSI Board of Standards Review on April 25, 2011.

ASME PTC COMMITTEE
Performance Test Codes

(The following is the roster of the Committee at the time of approval of this Code.)

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DEDICATION

This Revision of PTC 18, Hydraulic Prime Movers, is dedicated to the memory of Norman Latimer, who passed away while this revision was in progress: Mr. Latimer was an outstanding engineer who significantly promoted the importance of hydro power-plant performance activities, a faithful Member of the Committee, and a major contributor to the content of this Code.

CORRESPONDENCE WITH THE PTC 18 COMMITTEE

General. ASME Codes are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Code may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to:

Secretary, PTC 18 Committee
The American Society of Mechanical Engineers
Three Park Avenue
New York, NY 10016-5990 USA

Proposing Revisions. Revisions are made periodically to the Code to incorporate changes which appear necessary or desirable, as demonstrated by the experience gained from the application of the Code. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Code. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal including any pertinent documentation.

Interpretations. Upon request, the PTC 18 Committee will render an interpretation of any requirement of the Code. Interpretations can only be rendered in response to a written request sent to the Secretary of the PTC 18 Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his request in the following format:

Subject: Cite the applicable paragraph number(s) and a concise description.

Edition: Cite the applicable edition of the Code for which the interpretation is being requested.

Question: Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings, which are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format will be rewritten in this format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee. ASME does not “approve,” “certify,” “rate,” or “endorse” any item, construction, proprietary device, or activity.

Attending Committee Meetings. The PTC 18 Committee holds meetings or telephone conferences, which are open to the public. Persons wishing to attend any meeting or telephone conference should contact the Secretary of the PTC 18 Committee or check our Web site http://www.asme.org/codes/.

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HYDRAULIC TURBINES AND PUMP-TURBINES

Section 1
Object and Scope

1-1 OBJECT

This Code defines procedures for field performance and acceptance testing of hydraulic turbines and pump-turbines operating with water in either the turbine or pump mode.

1-2 SCOPE

This Code applies to all sizes and types of hydraulic turbines or pump-turbines. It defines methods for ascertaining performance by measuring flow rate (discharge), head, and power, from which efficiency may be determined. Requirements are included for pretest arrangements, types of instrumentation, methods of measurement, testing procedures, methods of calculation, and contents of test reports. This Code also contains recommended procedures for index testing and describes the purposes for which index tests may be used.

1-3 UNCERTAINTIES

The test procedures specified herein and the limitations placed on measurement methods and instrumentation are capable of providing uncertainties, calculated in accordance with the procedures of PTC 19.1 and this Code of not more than the following:

(a) *Head:* ±0.40%
(b) *Power:* ±0.90%
(c) *Flow rate:* ±1.75%
(d) *Efficiency:* ±2.00%

Where favorable measurement conditions exist and the best methods can be used, smaller uncertainties should result. Any test with an efficiency uncertainty greater than the above value does not meet the requirements of this Code.

Section 2
Definitions and Descriptions of Terms

2-1 DEFINITIONS

The Code on Definitions and Values, ASME PTC 2, and referenced portions of Supplements on Instruments and Apparatus, ASME PTC 19, shall be considered as part of this Code. Their provisions shall apply unless otherwise specified. Common terms, definitions, symbols, and units used throughout this Code are listed in this Section. Specialized terms are explained where they appear. The following definitions apply to this Code:

acceptance test: the field performance test to determine if a new or modified machine satisfactorily meets its performance criteria.

calibration: the process of comparing the response of an instrument to a standard over some measurement range and recording the difference.

instrument: a tool or device used to measure the value of a variable.

machine: any type of hydraulic turbine or pump turbine.

parties to the test: for acceptance tests, those individuals designated in writing by the purchaser and machine suppliers to make the decisions required in this Code. Other agents, advisors, engineers, etc., hired by the parties to the test to act on their behalf or otherwise, are not considered by this Code to be parties to the test.

point: established by one or more consecutive runs at the same operating conditions and unchanged wicket-gate, blade, or needle openings.

primary variables: those variables used in calculations of test results.

pump: a machine operating in the pumping mode.

pump-turbine: machine that is capable of operating as a pump and as a turbine.

random errors: statistical fluctuations (in either direction) in the measured data due to the precision limitations of the measurement device. Also called *precision errors*.

reading: one recording of all required test instruments.

run: comprises the readings and/or recordings sufficient to calculate performance at one operating condition.

runner: turbine runner or pump impeller.

secondary variables: variables that are measured but are not entered into the performance calculation.

sensitivity: ratio of the change in a result to a unit change in a parameter.

systematic errors: reproducible inaccuracies that are consistently in the same direction. Systematic errors are often due to a problem that persists throughout the entire experiment. Also called *bias errors.*

test: a series of points and results adequate to establish the performance over the specified range of operating conditions.

total error: the true, unknown difference between the measured value and the true value. The total error consists of two components: *systematic error* and *random error*.

turbine: a machine operating in the turbine mode.

uncertainty: the interval about the measurement or result that contains the true value for a given confidence level (usually 95%).

2-2 INTERNATIONAL SYSTEM OF UNITS (SI)

The International System of Units (SI) is used throughout this Code with U.S. Customary Units shown in parentheses (see Table 2-2-1). ASME PTC 2 provides conversion factors for use with ASME performance tests.

2-3 TABLES AND FIGURES

The symbols, terms, definitions, and units in this Code are listed in Tables 2-3-1 through 2-3-8. See Figs. 2-3-1 through 2-3-5 for a graphical definition of certain terms.

2-4 REFERENCE ELEVATION, Z_C

By agreement between the parties to the test, the runner reference elevation, Z_C, for determining the plant cavitation factor may be selected at the location where the development of cavitation has a predominant influence on the performance of the machine. In the absence of such agreement, the reference elevation, Z_C, shall be as shown in Fig. 2-4-1.

2-5 CENTRIFUGAL PUMPS

Some definitions in this Code may differ from those customarily associated with centrifugal pumps.

Table 2-2-1 Conversion Factors Between SI Units and U.S. Customary Units of Measure

Quantity	SI Units to U.S. Customary Units	U.S. Customary Units to SI Units
Force	1 N = 0.224809 lbf	1 lbf = 4.44822 N
Mass	1 000 kg = 68.5218 slugs 1 kg = 2.20462 lbm	1 slug = 14.5939 kg = 32.1740 lbm 1 lbm = 0.453592 kg
Length	1 m = 3.28084 ft	1 ft = 0.3048 m
Temperature	T °C = (T°F − 32)/1.8	T °F = 1.8 T°C + 32
Pressure	1 kPa = 0.145038 lbf/in.^{2}	1 lbf/in.^{2} = 6.89476 kPa
Flow rate	1 m^3/s = 35.3147 ft^3 /sec	1,000 ft^3 /sec = 28.3168 m^3/s
Density	1 000 kg/m^3 = 1.94032 slugs/ft^3 = 62.4280 lbm/ft^3	1 slug/ft^3 = 515.379 kg/m^3
Power	1 kW = 1.34102 hp	1 hp = 0.745706 kW
Standard gravity acceleration	g_o = 9.80665 m/s^2	g_o = 32.1740 ft/sec^2

GENERAL NOTES:

(a) The above conversion factors were derived from the following primary relationships:

π = 3.14159265359
g_o = 9.80665 m/s^2
1 ft = 0.3048 m
1 lbm = 0.45359237 kg

(b) More details on unit conversion can be found in ASME PTC 2, Section 5, Common Conversion Factors.

2-6 SUBSCRIPTS USED THROUGHOUT THE CODE

The following subscripts are used throughout the Code to give the symbols a specific meaning:

(a) "0" indicates static or zero-flow conditions
(b) "1" refers to the high-pressure side of the machine, or as otherwise defined
(c) "2" refers to the low-pressure side of the machine, or as otherwise defined
(d) "g" refers to a gage
(e) "p" refers to a pump or to a pool
(f) "spec" refers to specified conditions stated in purchase specification
(g) "T" indicates measured value during test, or as otherwise defined
(h) "t" refers to a turbine

Density of a liquid used in a manometer for the pressure measurement is related to the mid-height of the liquid column.

Table 2-3-1 Letter Symbols and Definitions

Symbol	Term	Definition/Formula/ Reference/Remark	Units SI	Units U.S. Customary
A	Flow section area	Area of water passage cross section normal to general direction of flow	m^2	ft^2
		Area of current metering section	m^2	ft^2
A_1	Area of high-pressure section	Area of agreed flow section in machine high-pressure passage between machine and any valve	m^2	ft^2
A_2	Area of low-pressure section	Area of agreed flow section in machine low-pressure passage between machine and any valve	m^2	ft^2
B	Width of rectangular conduit section	Ultrasonic	m	ft
	Height of distributor	Power measurement	m	ft
	Width of impulse turbine bucket	Power measurement	m	ft
B_h	Blade height at hub of propeller-type runner	Power measurement	m	ft
B_t	Blade height at peripheral of propeller-type runner	Power measurement	m	ft
C_1	Concentration of injected dye	Dye dilution	...	...
C_2	Dye concentration after complete mixing with flow	Dye dilution	...	...
C_o	Background dye concentration	Dye dilution	...	...
c	Speed of sound in water	Ultrasonic	m/s	ft/sec
D	Machine reference diameter	Pelton: Pitch diameter Kaplan: Discharge ring diameter at center line of runner blades Francis: Runner throat or discharge diameter	m	ft
	Average diameter in the pressure–time measuring section	Pressure–time	m	ft
	Height of rectangular conduit section	Ultrasonic	m	ft
D_i	i^{th} diameter measured in a plane in the ultrasonic flow section	Ultrasonic	m	ft
D_s	Dilution factor of standard	Dye dilution	...	...
D_t	Dilution factor of test water	Dye dilution	...	...
d	Inside diameter of pressure tap	Pressure taps	m	ft
d_i	Tip diameter of the i^{th} current meter	Current meters	m	ft
	Distance of the i^{th} chordal path from conduit centerline	Ultrasonic	m	ft
E	Sign factor for direction of acoustic pulse	Ultrasonic	...	...
F	Force	...	N	lbf
	Pipe factor	Pressure–time	m^{-1}	ft^{-1}
F_c	Fluorescence corrected to reference temperature	Dye dilution	...	...
F_m	Measured fluorescence at sample temperature	Dye dilution	...	...

Table 2-3-1 Letter Symbols and Definitions (Cont'd)

Symbol	Term	Definition/Formula/Reference/Remark	Units SI	Units U.S. Customary
F_s	Fluorescence of standard	Dye dilution	...	...
F_t	Fluorescence of test sample	Dye dilution	...	...
$\overline{F_t}$	Mean fluorescence of *n* samples	Dye dilution	...	...
f	Pipe friction factor	Pressure–time	...	...
g	Local gravitational acceleration	Value of acceleration due to gravity at a given geographical location. (See Tables 2-3-2M and 2-3-2)	m/s^2	ft/sec^2
H	Total head	Sum of potential, pressure, and velocity heads at given point in the water passage. $H = Z + h + h_v$	m	ft
H_1	Total head of high-pressure section	Sum of potential, pressure, and velocity heads at machine high-pressure section. $H_1 = Z_1 + h_1 + h_{v1}$	m	ft
H_2	Total head of low-pressure section	Sum of potential, pressure, and velocity heads at machine low-pressure section. $H_2 = Z_2 + h_2 + h_{v2}$	m	ft
H_G	Gross head	Water elevation difference between upper pool and lower pool. $H_G = Z_{1p} - Z_{2p} = HWL - TWL$	m	ft
H_L	Head loss	Total head loss between any two sections of water passage.	m	ft
H_{L1}	Head loss on high-pressure side	Head loss between machine and upper pool, including entrance/exit, trashrack, conduit, and valve losses. $H_{L1} = Z_{1p} - H_1$	m	ft
H_{L2}	Head loss on low-pressure side	Head loss between machine and lower pool, including entrance/exit, trashrack, conduit, and valve loss. $H_{L2} = H_2 - Z_{2p}$	m	ft
H_N	Net head	Difference between total head of high-pressure section and total head of low-pressure section corrected for buoyancy of water in air. $H_N = (Z_1 + h_1 - Z_2 - h_2)\,[1 - (\rho_a/\rho)] + h_{v1} - h_{v2}$	m	ft
H_{spec}	Specified head	Allowable deviations	m	ft
H_T	Net head at test conditions	Allowable deviations	m	ft
HWL	Headwater level	Z_{1p} relative to the mean sea level NOTE: An engineering judgment is necessary to determine whether the effect of flow in the pool on its elevation is negligible or whether a correction is needed.	m	ft
h	Pressure head	Height of water column under prevailing conditions equivalent to static pressure at given point in the water passage. $h = p\,/[g\,(\rho - \rho_a)]$	m	ft
h_1	Pressure head at high-pressure section	Height of water column under prevailing conditions equivalent to gage pressure at horizontal centerline of machine high-pressure section, A_1. $h_1 = p_1\,/[g\,(\rho - \rho_a)]$	m	ft

Table 2-3-1 Letter Symbols and Definitions (Cont'd)

Symbol	Term	Definition/Formula/ Reference/Remark	Units SI	Units U.S. Customary
h_2	Pressure head at low-pressure section	Height of water column under prevailing conditions equivalent to gage pressure at horizontal centerline of machine low-pressure section, A_2. $h_2 = p_2 /[g (\rho - \rho_a)]$	m	ft
h_a	Barometric pressure head	Height of water column under prevailing conditions equivalent to atmospheric pressure (absolute) at given latitude and elevation. $h_a = p_a /[g (\rho - \rho_a)]$	m	ft
h_f	Average pressure differential in the static line portion of a pressure–time trace corrected for instrument offset	Pressure–time	m	ft
h_i	Average pressure differential in the running line portion of a pressure–time trace corrected for instrument offset	Pressure–time	m	ft
h_m	Measured pressure differential between pressure–time sections	Pressure–time	m	ft
h_{mf}	Measured average static line pressure differential between pressure–time sections	Pressure–time	m	ft
h_{mi}	Measured average running line pressure differential between pressure–time sections	Pressure–time	m	ft
h_o	Pressure differential between pressure–time sections corrected for instrument offset	Pressure–time	m	ft
h_v	Velocity head	Height of water column under prevailing conditions equivalent to kinetic pressure head in a given flow section. $h_v = v^2/2g$	m	ft
h_{vp}	Vapor pressure head	Height of water column equivalent to vapor pressure (absolute) of water at temperature of turbine discharge or pump inlet.	m	ft
K	Shape factor	Ultrasonic	...	...
	Differential (Winter–Kennedy) flowmeter coefficient	Index testing	...	...
k_f	Constant in windage and friction calculation for Francis turbine	Power measurement	...	...
k_i	Constant in windage and friction calculation for impulse turbine	Power measurement	...	...
k_p	Constant in windage and friction calculation for propeller turbine	Power measurement	...	...
L	Length	...	m	ft
	Average distance between the pressure–time tap planes	Pressure–time	m	ft
	Distance between two ultrasonic transducers	Ultrasonic	m	ft
L_i	Distance between transducer faces along the i^{th} chordal path	Ultrasonic	m	ft
L_{wi}	Distance across conduit along the i^{th} chordal path	Ultrasonic	m	ft
M	Mass	...	kg	slug
N_p	Number of blades for a propeller-type runner	Power measurement	...	...

Table 2-3-1 Letter Symbols and Definitions (Cont'd)

Symbol	Term	Definition/Formula/Reference/Remark	Units SI	Units U.S. Customary
$NPSH$	Net positive suction head (NPSH)	The absolute pressure head at the first-stage runner reference elevation (Z_c), minus the vapor pressure head of the liquid. $NPSH = (h_a + Z_2 + h_2 - Z_c - h_{vp}) \times [1 - (\rho_a/\rho)]$	m	ft
n	Speed	Rotational speed	rpm	rpm
	Number of current meters in an intake section	Current meters	...	...
	Number of samples of test water	Dye dilution	...	...
	Exponent in differential (Winter–Kennedy) flowmeter equation	Index testing	...	...
n_{spec}	Specified shaft rotational speed	Allowable deviations	rpm	rpm
n_T	Test shaft rotational speed	Allowable deviations	rpm	rpm
P	Turbine power output or pump power input	Power delivered by the turbine shaft or applied to the pump shaft.	kW	HP
	Generator loss due to windage and friction	Power measurement	kW	HP
P_e	Generator power output or motor power input	Net electrical power delivered by generator or supplied to motor.	kW	HP
PF	Power factor	Guiding principle	...	...
P_T	Turbine power output or pump power input at test conditions	Turbine computations	kW	HP
P_w	Water power	Power equivalent of flow rate at net head. $P_w = \rho\, g\, Q\, H_N$ / 1 000 (SI Units) $P_w = \rho\, g\, Q\, H_N$ / 550 (U.S. Customary Units)	kW	HP
P'	Power corrected to specified conditions in Zone 2	Allowable deviations	kW	HP
p	Pressure	Static pressure at any point in water passage relative to prevailing atmospheric pressure. NOTE: If the elevation of the gage is different from the elevation the static pressure is referred to, the following correction is required: $p = p_g + [(Z_g - Z)\, g\, (\rho - \rho_a)]/1\,000$	kPa	lbf/in.^{2}
p_1	Pressure at high-pressure section	Static pressure at horizontal centerline of machine high-pressure section A_1.	kPa	lbf/in.^{2}
p_2	Pressure at low-pressure section	Static pressure at horizontal centerline of machine low-pressure section A_2.	kPa	lbf/in.^{2}
p_a	Atmospheric pressure	Absolute atmospheric pressure at local conditions (see Tables 2-3-8M and 2-3-8).	kPa	lbf/in.^{2}
p_{abs}	Absolute pressure	$p_{abs} = p_g + p_a$ Static pressure at any point in water relative to perfect vacuum.	kPa	lbf/in.^{2}
p_g	Gage pressure	Static pressure measured by a gage or transducer at the gage elevation, relative to prevailing atmospheric pressure.	kPa	lbf/in.^{2}
p_{vp}	Vapor pressure	Absolute vapor pressure of water at a given temperature (see Tables 2-3-3M and 2-3-3).	kPa	lbf/in.^{2}

Table 2-3-1 Letter Symbols and Definitions (Cont'd)

Symbol	Term	Definition/Formula/ Reference/Remark	Units SI	Units U.S. Customary
Q	Flow rate	Volume of water passing through the machine per unit time, including water for seals and thrust relief but excluding water supplied for the operation of auxiliaries and the cooling of all bearings.	m³/s	ft³/sec
Q'	Flow corrected to specified conditions in Zone 2	Allowable deviations	m³/s	ft³/sec
Q_f	Leakage flow rate	Pressure–time	m³/s	ft³/sec
Q_i	Indicated flow rate from Winter–Kennedy flowmeter	Index testing	m³/s	ft³/sec
Q_m	Integrated current-meter flow rate before correction for blockage	Current meters	m³/s	ft³/sec
Q_{rel}	Relative flow rate	Index testing	m³/s	ft³/sec
Q_T	Flow rate at test conditions	Allowable deviations	m³/s	ft³/sec
q	Injection rate of dye	Dye dilution	m³/s	ft³/sec
S	Frontal area of current-meter support structure	Current meters	m²	ft²
	Standard deviation of fluorescence of *n* samples	Dye dilution	...	...
S_m	Frontal area of current-meter propellers	Current meters	m²	ft²
T	Temperature	...	°C	°F
T_r	Reference temperature	Dye dilution	°C	°F
T_s	Temperature of sample water	Dye dilution	°C	°F
TWL	Tailwater level	Z_{2p} relative to the mean sea level	m	ft
		NOTE: An engineering judgment is necessary to determine whether the effect of flow in the pool on its elevation is negligible or whether a correction is needed.		
t	Time	...	s	sec
t_d	Downstream transit time of an ultrasonic pulse	Ultrasonic	s	sec
t_f	Time at the end of the pressure–time integration interval	Pressure–time	s	sec
t_i	Time at the start of the pressure–time integration interval	Pressure–time	s	sec
t_{n-1}	Student's t-statistic for 95% confidence	Dye dilution	...	...
t_u	Upstream transit time of an ultrasonic pulse	Ultrasonic	s	sec
u	Velocity of the runner at diameter, *D*	$u = \omega \frac{D}{2} = \frac{\pi D n}{60}$	m/s	ft/sec

Table 2-3-1 Letter Symbols and Definitions (Cont'd)

Symbol	Term	Definition/Formula/Reference/Remark	Units SI	Units U.S. Customary
V	Mean axial component of water velocity over a chordal path	Ultrasonic	m/s	ft/sec
V_c	Mean transverse component of velocity over a chordal path	Ultrasonic	m/s	ft/sec
V_i	Average velocity along the i^{th} chordal path	Ultrasonic	m/s	ft/sec
v	Mean velocity	Flow rate divided by flow-section area.	m/s	ft/sec
v_1	Mean velocity at high-pressure section	Flow rate divided by high-pressure flow section area.	m/s	ft/sec
v_2	Mean velocity at low-pressure section	Flow rate divided by low-pressure flow section area.	m/s	ft/sec
W_i	Weighting factor for the i^{th} chordal path	Ultrasonic	...	...
W_i'	Modified weighting factor along the i^{th} chordal path	Ultrasonic	...	...
Y	Sign factor for transverse velocity component	Ultrasonic	...	...
Z	Potential head	Elevation of a measurement point relative to a common datum.	m	ft
Z_1	Potential head at high-pressure section	Elevation of horizontal centerline of machine high-pressure section relative to a common datum.	m	ft
Z_{1p}	Potential head of upper pool	Elevation of upper pool relative to a common datum. Also see "Headwater level."	m	ft
Z_2	Potential head at low-pressure section	Elevation of horizontal centerline of machine low-pressure section relative to a common datum.	m	ft
Z_{2p}	Potential head of lower pool	Elevation of lower pool relative to a common datum. Also see "Tailwater level."	m	ft
Z_c	Potential head at runner reference elevation	Elevation of cavitation reference location relative to a common datum. (Fig. 2-4-1)	m	ft
Z_g	Potential head at gage elevation	Elevation of a pressure gage typically used to measure p_g (Figs. 2-3-1 through 2-3-5).	m	ft
α	Angular location of Winter–Kennedy taps in spiral case	Index testing	deg	deg
ΔH	Pump head correction to specified conditions	Pump computations	m	ft
Δh	Flowmeter differential pressure	Index testing	kPa	lbf/in.^{2}
ΔP	Pump power correction to specified conditions	Pump computations	kW	HP
ΔQ	Pump flow correction to specified conditions	Pump computations	m^3/s	ft^3/sec
η	Efficiency	Turbine: P/P_W, Pump: P_W/P	...	...
ρ	Density of water	Mass per unit volume of water at measured temperature and pressure (see Table 2-3-5).	kg/m^3	slugs/ ft^3
ρ_a	Density of dry air	Mass per unit volume of ambient air at measured temperature and barometric pressure (see Tables 2-3-6M and 2-3-6).	kg/m^3	slugs/ ft^3

Table 2-3-1 Letter Symbols and Definitions (Cont'd)

Symbol	Term	Definition/Formula/ Reference/Remark	Units SI	Units U.S. Customary
ρ_{Hg}	Density of mercury	Mass per unit volume of mercury at measured temperature and barometric pressure (see Tables 2-3-7M and 2-3-7).	kg/m^3	slugs/ ft^3
σ	Cavitation factor	$\sigma = \frac{NPSH}{H}$	...	...
ϕ	Angle between acoustic path and direction of water flow	Ultrasonic	deg	deg
ω	Angular speed	Radians per second	rad/s	rad/sec

GENERAL NOTES:
(a) See Figs. 2-3-1 through 2-3-5.
(b) The following subscripts are used to give the symbols a specific meaning:
(1) “0” indicates static or zero flow conditions.
(2) “1” refers to the high pressure side of the machine, or as otherwise defined.
(3) “2” refers to the low pressure side of the machine, or as otherwise defined.
(4) “g” refers to a gage.
(5) “p” refers to a pump or to a pool.
(6) “spec” refers to specified conditions stated in purchase specification.
(7) “T” indicates measured value during test, or as otherwise defined.
(8) “t” refers to a turbine.
Density of a liquid used in a manometer for the pressure measurement is related to the mid-height of the liquid column.

Table 2-3-2M Acceleration of Gravity as a Function of Latitude and Elevation, SI Units (m/s^2)

Latitude, ϕ (deg)	Altitude Above Mean Sea Level, Z, m 0	500	1 000	1 500	2 000	2 500	3 000	3 500
0	9.78036	9.77881	9.77727	9.77573	9.77418	9.77264	9.77110	9.76956
10	9.78191	9.78037	9.77882	9.77728	9.77574	9.77419	9.77265	9.77111
20	9.78638	9.78484	9.78330	9.78175	9.78021	9.77867	9.77712	9.77558
30	9.79324	9.79170	9.79016	9.78861	9.78707	9.78553	9.78399	9.78244
40	9.80167	9.80013	9.79858	9.79704	9.79550	9.79396	9.79241	9.79087
50	9.81065	9.80911	9.80757	9.80602	9.80448	9.80294	9.80139	9.79985
60	9.81911	9.81756	9.81602	9.81448	9.81293	9.81139	9.80985	9.80830
70	9.82601	9.82446	9.82292	9.82138	9.81983	9.81829	9.81675	9.81520
80	9.83051	9.82897	9.82743	9.82588	9.82434	9.82280	9.82126	9.81971
90	9.83208	9.83054	9.82899	9.82745	9.82591	9.82436	9.82282	9.82128

Table 2-3-2 Acceleration of Gravity as a Function of Latitude and Elevation, U.S. Customary Units (ft/sec^2)

Latitude,	Altitude Above Mean Sea Level, Z, ft						
ϕ (deg)	0	2,000	4,000	6,000	8,000	10,000	12,000
0	32.0878	32.0816	32.0754	32.0693	32.0631	32.0569	32.0508
10	32.0929	32.0867	32.0805	32.0744	32.0682	32.0620	32.0558
20	32.1076	32.1014	32.0952	32.0890	32.0829	32.0767	32.0705
30	32.1301	32.1239	32.1177	32.1115	32.1054	32.0992	32.0930
40	32.1577	32.1515	32.1454	32.1392	32.1330	32.1269	32.1207
50	32.1872	32.1810	32.1748	32.1687	32.1625	32.1563	32.1501
60	32.2149	32.2087	32.2026	32.1964	32.1902	32.1841	32.1779
70	32.2375	32.2314	32.2252	32.2190	32.2129	32.2067	32.2005
80	32.2523	32.2462	32.2400	32.2338	32.2277	32.2215	32.2153
90	32.2575	32.2513	32.2451	32.2390	32.2328	32.2266	32.2204

GENERAL NOTES:

(a) Reference: Lide, D.R., Editor, *CRC Handbook of Chemistry and Physics*, 90th Edition, CRC Press, New York, 2009.

(b) Gravitational acceleration formula given in the reference noted in (a) above:

$$g = 9.780356(1 + 0.0052885 \sin^2 \phi - 2\ 0.0000059 \sin^2 2\phi) - 3.086 \times 10^{-6} Z$$

where acceleration g is in m/s^2, latitude ϕ is in degrees, and elevation Z is in meters.

(c) Conversion to U.S. Customary units: g (ft/sec^2) = g (m/s^2)/0.3048

(d) The standard value of gravitational acceleration adopted by the International Bureau of Weights and Measures is g = 9.80665 m/s^2 or 32.17405 ft/s^2.

Table 2-3-3M Vapor Pressure of Distilled Water as a Function of Temperature, SI Units (kPa)

Temperature T, °C	Vapor Pressure, p_{vp}, kPa	Temperature T, °C	Vapor Pressure, p_{vp}, kPa
0	0.6112	...	...
1	0.6571	21	2.488
2	0.7060	22	2.645
3	0.7581	23	2.811
4	0.8135	24	2.986
5	0.8726	25	3.170
6	0.9354	26	3.364
7	1.002	27	3.568
8	1.073	28	3.783
9	1.148	29	4.009
10	1.228	30	4.247
11	1.313	31	4.497
12	1.403	32	4.759
13	1.498	33	5.035
14	1.599	34	5.325
15	1.706	35	5.629
16	1.819	36	5.947
17	1.938	37	6.282

Table 2-3-3M Vapor Pressure of Distilled Water as a Function of Temperature, SI Units (kPa) (Cont'd)

Temperature T, °C	Vapor Pressure, p_{vp}, kPa	Temperature T, °C	Vapor Pressure, p_{vp}, kPa
18	2.065	38	6.632
19	2.198	39	7.000
20	2.339	40	7.384

GENERAL NOTES:
(a) Reference: Parry, W.T., et al, ASME International Steam Tables, 2nd Edition, American Society of Mechanical Engineers, New York, 2009.
(b) The vapor pressure of water can be calculated between the temperatures $0 < T < 40°C$ using the following empirical equation:

$$p_{vp} = 10^{2.7862 + 0.0312\,T - 0.000104\,T^2}$$

with an error smaller than ±0.009 kPa.
(c) Conversion factors to U.S. Customary Units
$T\,(°F) = T(°C) \times 1.8 + 32$
$p_{vp}\,(\text{lbf/in.}^2) = p_{vp}\,(\text{kPa}) \times 1000 \times (0.3048/12)^2/0.45359237/9.80665$

Table 2-3-3 Vapor Pressure of Distilled Water as a Function of Temperature, U.S. Customary Units (lbf/in.^{2})

Temperature, T, °F	Vapor Pressure, p_{vp}, lbf/in.^{2}	Temperature, T, °F	Vapor Pressure, p_{vp}, lbf/in.^{2}
32	0.08865	...	...
34	0.09607	74	0.41599
36	0.10403	76	0.44473
38	0.11258	78	0.47518
40	0.12173	80	0.50744
42	0.13155	82	0.54159
44	0.14205	84	0.57772
46	0.15328	86	0.61593
48	0.16530	88	0.65632
50	0.17813	90	0.69899
52	0.19184	92	0.74405
54	0.20646	94	0.79161
56	0.22206	96	0.84178
58	0.23868	98	0.89468
60	0.25639	100	0.95044
62	0.27524	102	1.0092
64	0.29529	104	1.0710
66	0.31662	106	1.1361
68	0.33927	108	1.2046
70	0.36334	110	1.2766
72	0.38889	112	1.3523

GENERAL NOTES:
(a) Reference: Parry, W.T., et al, ASME International Steam Tables, 2nd Edition, American Society of Mechanical Engineers, New York, 2009.
(b) The vapor pressure of water can be calculated between the temperatures $0 < T < 40°C$ using the following empirical equation:

$$p_{vp} = 10^{2.7862 + 0.0312\,T - 0.000104\,T^2}$$

with an error smaller than ±0.009 kPa.
(c) Conversion factors to U.S. Customary Units
$T\,(°F) = T(°C) \times 1.8 + 32$
$p_{vp}\,(\text{lbf/in.}^2) = p_{vp}\,(\text{kPa}) \times 1000 \times (0.3048/12)^2/0.45359237/9.80665$

Table 2-3-4M Density of Water as a Function of Temperature and Pressure, SI Units (kg/m^3)

Temperature, T, °C	Absolute Pressure, p_{abs}, kPa									
	100	101.325	500	1 000	2 000	3 000	4 000	5 000	10 000	15 000
0	999.85	999.85	1 000.05	1 000.30	1 000.81	1 001.32	1 001.82	1 002.32	1 004.82	1 007.30
1	999.90	999.90	1 000.11	1 000.36	1 000.86	1 001.36	1 001.86	1 002.36	1 004.85	1 007.30
2	999.94	999.95	1 000.15	1 000.40	1 000.90	1 001.39	1 001.89	1 002.39	1 004.85	1 007.29
3	999.97	999.97	1 000.17	1 000.42	1 000.91	1 001.41	1 001.90	1 002.40	1 004.85	1 007.27
4	999.98	999.98	1 000.17	1 000.42	1 000.91	1 001.41	1 001.90	1 002.39	1 004.82	1 007.23
5	999.97	999.97	1 000.16	1 000.41	1 000.90	1 001.39	1 001.88	1 002.36	1 004.78	1 007.17
6	999.94	999.94	1 000.14	1 000.38	1 000.87	1 001.36	1 001.84	1 002.33	1 004.73	1 007.11
7	999.90	999.91	1 000.10	1 000.34	1 000.83	1 001.31	1 001.79	1 002.27	1 004.66	1 007.03
8	999.85	999.85	1 000.04	1 000.29	1 000.77	1 001.25	1 001.73	1 002.21	1 004.58	1 006.93
9	999.78	999.78	999.98	1 000.22	1 000.69	1 001.17	1 001.65	1 002.13	1 004.49	1 006.83
10	999.70	999.70	999.89	1 000.13	1 000.61	1 001.08	1 001.56	1 002.03	1 004.38	1 006.71
12	999.50	999.50	999.69	999.93	1 000.40	1 000.87	1 001.34	1 001.81	1 004.13	1 006.44
14	999.25	999.25	999.43	999.67	1 000.14	1 000.60	1 001.07	1 001.53	1 003.84	1 006.12
16	998.95	998.95	999.13	999.36	999.83	1 000.29	1 000.75	1 001.21	1 003.50	1 005.76
18	998.60	998.60	998.78	999.01	999.47	999.93	1 000.39	1 000.85	1 003.11	1 005.36
20	998.21	998.21	998.39	998.62	999.07	999.53	999.98	1 000.44	1 002.69	1 004.92
22	997.77	997.77	997.96	998.18	998.64	999.09	999.54	999.99	1 002.23	1 004.44
24	997.30	997.30	997.48	997.71	998.16	998.61	999.05	999.50	1 001.73	1 003.93
26	996.79	996.79	996.97	997.19	997.64	998.09	998.53	998.98	1 001.19	1 003.38
28	996.24	996.24	996.42	996.64	997.09	997.53	997.97	998.42	1 000.62	1 002.80
30	995.65	995.65	995.83	996.05	996.50	996.94	997.38	997.82	1 000.01	1 002.18
32	995.03	995.03	995.21	995.43	995.87	996.31	996.75	997.19	999.37	1 001.54
34	994.38	994.38	994.56	994.78	995.22	995.66	996.09	996.53	998.71	1 000.86
36	993.69	993.69	993.87	994.09	994.53	994.96	995.40	995.84	998.00	1 000.15
38	992.98	992.98	993.15	993.37	993.81	994.24	994.68	995.11	997.27	999.41
40	992.23	992.23	992.40	992.62	993.06	993.49	993.93	994.36	996.52	998.65

GENERAL NOTES:

(a) The densities given above were computed from the following equation:

$$\rho = \frac{p^*}{R(T+273.15)}\left[\sum_{i=1}^{18} -n_i I_i \left(7.1-\frac{p}{p^*}\right)^{I_i-1}\left(\frac{T^*}{(T+273.15)}-1.222\right)^{J_i}\right]^{-1}$$

where

ρ = density of water (kg/m^3)

T = water temperature (°C)

p = absolute pressure (kPa)

constants:

p^* = 16,530 kPa

T^* = 1,386 K

R = 0.461526 kJ/kg · K

Refer to Table 2-3-5 for coefficients I_i, J_i, and n_i.

(b) Intermediate values may be interpolated or calculated from the equation given in in General Note (a).

(c) The values in this table were computed from the equation in General Note (a), using the following conversion factors:

T (°F) = T (°C) × 1.8 + 32

p_{abs} (lbf/in.^{2}) = p_{abs} (kPa) × 1,000 × (0.3048/12)^2/0.45359237/9.80665

ρ (slug/ft^3) = ρ (kg/m^3) × (0.3048)^4/0.45359237/9.80665

(d) Standard atmospheric pressure is 101.325 kPa (refer to Tables 2-3-8M and 2-3-8).

Table 2-3-4 Density of Water as a Function of Temperature and Pressure, U.S. Customary Units (slug/ft³)

Temperature, T, °F	Pressure, p_{abs}, lbf/in.²									
	14	14.696	15	25	50	100	200	500	1,000	2,000
32	1.94002	1.94002	1.94003	1.94009	1.94026	1.94060	1.94128	1.94331	1.94668	1.95333
34	1.94014	1.94015	1.94015	1.94022	1.94039	1.94072	1.94140	1.94341	1.94675	1.95334
36	1.94023	1.94023	1.94023	1.94030	1.94047	1.94080	1.94147	1.94347	1.94678	1.95333
38	1.94027	1.94027	1.94027	1.94034	1.94051	1.94084	1.94150	1.94349	1.94677	1.95327
40	1.94027	1.94028	1.94028	1.94034	1.94051	1.94084	1.94150	1.94347	1.94673	1.95318
42	1.94024	1.94024	1.94024	1.94031	1.94047	1.94080	1.94145	1.94341	1.94665	1.95306
44	1.94016	1.94017	1.94017	1.94024	1.94040	1.94072	1.94137	1.94332	1.94654	1.95291
46	1.94006	1.94006	1.94006	1.94013	1.94029	1.94061	1.94126	1.94319	1.94639	1.95272
48	1.93992	1.93992	1.93992	1.93999	1.94015	1.94047	1.94111	1.94303	1.94621	1.95250
50	1.93974	1.93975	1.93975	1.93981	1.93997	1.94029	1.94093	1.94284	1.94600	1.95225
55	1.93917	1.93918	1.93918	1.93924	1.93940	1.93971	1.94034	1.94222	1.94534	1.95151
60	1.93841	1.93842	1.93842	1.93848	1.93864	1.93895	1.93957	1.94143	1.94451	1.95061
65	1.93748	1.93748	1.93749	1.93755	1.93770	1.93801	1.93862	1.94046	1.94351	1.94954
70	1.93639	1.93639	1.93639	1.93645	1.93660	1.93691	1.93752	1.93934	1.94236	1.94833
75	1.93514	1.93514	1.93514	1.93520	1.93535	1.93566	1.93626	1.93806	1.94105	1.94697
80	1.93374	1.93375	1.93375	1.93381	1.93396	1.93426	1.93486	1.93665	1.93961	1.94549
85	1.93221	1.93221	1.93222	1.93228	1.93242	1.93272	1.93332	1.93509	1.93804	1.94388
90	1.93055	1.93055	1.93055	1.93061	1.93076	1.93106	1.93165	1.93341	1.93635	1.94215
95	1.92876	1.92876	1.92876	1.92882	1.92897	1.92926	1.92985	1.93161	1.93453	1.94030
100	1.92685	1.92685	1.92685	1.92691	1.92706	1.92735	1.92794	1.92969	1.93260	1.93835
105	1.92482	1.92483	1.92483	1.92489	1.92503	1.92533	1.92591	1.92766	1.93055	1.93628
110	1.92269	1.92269	1.92269	1.92275	1.92290	1.92319	1.92377	1.92551	1.92840	1.93412

GENERAL NOTES:

(a) The densities given above were computed from the following equation:

$$\rho = \frac{p^*}{R(T+273.15)}\left[\sum_{i=1}^{18} -n_i I_i \left(7.1 - \frac{p}{p^*}\right)^{I_i-1}\left(\frac{T^*}{(T+273.15)} - 1.222\right)^{J_i}\right]^{-1}$$

where

ρ = density of water (kg/m³)

T = water temperature (°C)

p = absolute pressure (kPa)

constants:

p^* = 16,530 kPa

T^* = 1,386 K

R = 0.461526 kJ/kg · K

Refer to Table 2-3-5 for coefficients I_i, J_i, and n_i.

(b) Intermediate values may be interpolated or calculated from the equation given in in General Note (a).

(c) The values in this table were computed from the equation in General Note (a), using the following conversion factors:

T (°F) = T (°C) × 1.8 + 32

p_{abs} (lbf/in.²) = p_{abs} (kPa) × 1,000 × (0.3048/12)²/0.45359237/9.80665

ρ (slug/ft³) = ρ (kg/m³) × (0.3048)⁴/0.45359237/9.80665

(d) Standard atmospheric pressure is 14.696 lbf/in.² (refer to Tables 2-3-8M and 2-3-8).

Table 2-3-5 Coefficients I_i, J_i, and n_i

i	I_i	J_i	n_i
1	1	−1	−1.89900E-02
2	1	0	−3.25297E-02
3	1	1	−2.18417E-02
4	1	3	−5.28383E-05
5	2	−3	−4.71843E-04
6	2	0	−3.00017E-04
7	2	1	4.76613E-05
8	2	3	−4.41418E-06
9	2	17	−7.26949E-16
10	3	−4	−3.16796E-05
11	3	0	−2.82707E-06
12	3	6	−8.52051E-10
13	4	−5	−2.24252E-06
14	4	−2	−6.51712E-07
15	4	10	−1.43417E-13
16	5	−8	−4.05169E-07
17	8	−11	−1.27343E-09
18	8	−6	−1.74248E-10

GENERAL NOTES:

(a) Reference: Parry, W.T., et al, ASME International Steam Tables, 2nd Edition, American Society of Mechanical Engineers, New York, 2009.

(b) The referenced ASME steam tables are based on the IAPSW Industrial Formulation 1997.

(c) The above coefficients are a subset of the full Region 1 formulation defined in the reference, and yield densities within 0.01 kg/m^3 (≈ 0.001%) of the full formulation in the range $0 < T < 70$ °C and $0.5 < p < 20{,}000$ kPa.

Table 2-3-6M Density of Dry Air, SI Units (kg/m^3)

Altitude, Z, m	Temperature, T, °C								
	−20	−10	0	10	15	20	30	40	50
0	1.3944	1.3414	1.2923	1.2466	1.2250	1.2041	1.1644	1.1272	1.0923
500	1.3137	1.2637	1.2175	1.1745	1.1541	1.1344	1.0970	1.0620	1.0291
1 000	1.2368	1.1898	1.1462	1.1058	1.0866	1.0680	1.0328	0.9998	0.9689
1 500	1.1636	1.1194	1.0784	1.0403	1.0223	1.0048	0.9717	0.9407	0.9115
2 000	1.0940	1.0524	1.0139	0.9780	0.9611	0.9447	0.9135	0.8844	0.8570
2 500	1.0277	0.9887	0.9525	0.9188	0.9029	0.8875	0.8582	0.8308	0.8051
3 000	0.9648	0.9281	0.8941	0.8626	0.8476	0.8331	0.8057	0.7799	0.7558
3 500	0.9050	0.8706	0.8387	0.8091	0.7951	0.7815	0.7557	0.7316	0.7090
4 000	0.8482	0.8160	0.7861	0.7584	0.7452	0.7325	0.7083	0.6857	0.6645

GENERAL NOTES:

(a) Reference: *U.S. Standard Atmosphere*, U.S. Government Printing Office, Washington, D.C., 1976.

(b) Air density ρ_a (kg/m^3) at temperature T (°C) and elevation Z (m) is computed from the U.S. Standard Atmosphere 1976 formulation for pressure, using the ideal gas law to account for the effect of temperature

$$\rho_a = \frac{352.9838}{273.15+T}\left(1-2.2558\times10^{-5}\cdot Z\right)^{5.2559}$$

The use of the geometric elevation Z instead of the geopotential elevation specified in the reference produces densities accurate to within ±0.033%.

(c) Conversion factor: ρ_a (slug/ft^3) = ρ_a (kg/m^3) × (0.3048)^4/0.45359237/9.80665

Table 2-3-6 Density of Dry Air, U.S. Customary Units (slug/ft^3)

Altitude, Z, ft	Temperature, T, °F						
	0	20	40	60	80	100	120
0	0.002682	0.002570	0.002467	0.002372	0.002284	0.002203	0.002127
1,000	0.002586	0.002479	0.002379	0.002288	0.002203	0.002124	0.002051
2,000	0.002494	0.002390	0.002294	0.002206	0.002124	0.002048	0.001977
3,000	0.002404	0.002303	0.002211	0.002126	0.002047	0.001974	0.001906
4,000	0.002316	0.002220	0.002131	0.002049	0.001973	0.001902	0.001837
5,000	0.002232	0.002138	0.002053	0.001974	0.001901	0.001833	0.001770
6,000	0.002149	0.002060	0.001977	0.001901	0.001831	0.001765	0.001704
7,000	0.002069	0.001983	0.001904	0.001831	0.001763	0.001700	0.001641
8,000	0.001992	0.001909	0.001833	0.001762	0.001697	0.001636	0.001580
9,000	0.001917	0.001837	0.001764	0.001696	0.001633	0.001575	0.001520
10,000	0.001844	0.001767	0.001697	0.001631	0.001571	0.001515	0.001463
11,000	0.001774	0.001700	0.001632	0.001569	0.001511	0.001457	0.001407
12,000	0.001706	0.001635	0.001569	0.001509	0.001453	0.001401	0.001353

GENERAL NOTES:

(a) Reference: *U.S. Standard Atmosphere*, U.S. Government Printing Office, Washington, D.C., 1976.

(b) Air density ρ_a (kg/m^3) at temperature T (°C) and elevation Z (m) is computed from the U.S. Standard Atmosphere 1976 formulation for pressure, using the ideal gas law to account for the effect of temperature

$$\rho_a = \frac{352.9838}{273.15+T}\left(1-2.2558\times10^{-5}\cdot Z\right)^{5.2559}$$

The use of the geometric elevation Z instead of the geopotential elevation specified in the reference produces densities accurate to within ±0.033%.

(c) Conversion factor: ρ_a (slug/ft^3) = ρ_a (kg/m^3) × (0.3048)^4/0.45359237/9.80665

Table 2-3-7M Density of Mercury, SI Units (kg/m³)

Temperature, °C	Density, kg/m³	Temperature, °C	Density, kg/m³
−10	13,619.8	16	13,555.7
−9	13,617.3	17	13,553.3
−8	13,614.8	18	13,550.8
−7	13,612.4	19	13,548.3
−6	13,609.9	20	13,545.9
−5	13,607.4	21	13,543.4
−4	13,605.0	22	13,541.0
−3	13,602.5	23	13,538.5
−2	13,600.0	24	13,536.1
−1	13,597.6	25	13,533.6
0	13,595.1	26	13,531.2
1	13,592.6	27	13,528.7
2	13,590.2	28	13,526.3
3	13,587.7	29	13,523.8
4	13,585.2	30	13,521.4
5	13,582.8	31	13,518.9
6	13,580.3	32	13,516.5
7	13,577.8	33	13,514.1
8	13,575.4	34	13,511.6
9	13,572.9	35	13,509.2
10	13,570.5	36	13,506.7
11	13,568.0	37	13,504.3
12	13,565.5	38	13,501.8
13	13,563.1	39	13,499.4
14	13,560.6	40	13,497.0
15	13,558.2	...	...

GENERAL NOTES:
(a) Reference: ASME Fluid Meters, 6th Edition, 1971, Table II-1-2
(b) The above table is computed from the equation

$$\rho = (851.457 - 0.0859301T + 6.20046 \times 10^{-6}T^2) \times 0.3048 / 9.80665$$

where density ρ is in slugs/ft³ and temperature T is in degrees Fahrenheit. Computed values agree with the referenced table to within ±0.0001%
(c) The above table is computed for atmospheric pressure. At 100 atm, the density of mercury changes by only 0.018%. Therefore, the compressibility of mercury at pressures normally seen in hydraulic machine operations may be neglected.
(d) Conversion factors to U.S. Customary Units:

$$T\ (^\circ F) = T\ (^\circ C) \times 1.8 + 32$$

$$\rho\ (\text{slugs/ft}^3) = \rho\ (\text{kg/m}^3) \times (0.3048)^4/0.45359237/9.80665$$

Table 2-3-7 Density of Mercury, U.S. Customary Units (slugs/ft^3)

Temperature, °F	Density, slugs/ft^3	Temperature, °F	Density, slugs/ft^3
20	26.4108	72	26.2728
22	26.4054	74	26.2675
24	26.4001	76	26.2622
26	26.3948	78	26.2569
28	26.3895	80	26.2517
30	26.3841	82	26.2464
32	26.3788	84	26.2411
34	26.3735	86	26.2358
36	26.3682	88	26.2306
38	26.3629	90	26.2253
40	26.3576	92	26.2200
42	26.3523	94	26.2147
44	26.3470	96	26.2095
46	26.3416	98	26.2042
48	26.3363	100	26.1989
50	26.3310	102	26.1937
52	26.3257	104	26.1884
54	26.3204	106	26.1832
56	26.3151	108	26.1779
58	26.3098	110	26.1726
60	26.3045	...	...
62	26.2992	...	...
64	26.2940	...	...
66	26.2887	...	...
68	26.2834	...	...
70	26.2781	...	...

GENERAL NOTES:

(a) Reference: ASME Fluid Meters, 6th Edition, 1971, Table II-1-2

(b) The above table is computed from the equation

$$\rho = (851.457 - 0.08593017T + 6.20046 \times 10^{-6}T^2) \times 0.3048 / 9.80665$$

where density ρ is in slugs/ft^3 and temperature T is in degrees Fahrenheit. Computed values agree with the referenced table to within $\pm$0.0001%

(c) The above table is computed for atmospheric pressure. At 100 atm, the density of mercury changes by only 0.018%. Therefore, the compressibility of mercury at pressures normally seen in hydraulic machine operations may be neglected.

(d) Conversion factors to U.S. Customary Units:

$$T\ (°F) = T\ (°C) \times 1.8 + 32$$

$$\rho\ (\text{slugs/ft}^3) = \rho\ (\text{kg/m}^3) \times (0.3048)^4/0.45359237/9.80665$$

Table 2-3-8M Atmospheric Pressure, SI Units (kPa)

Altitude, Z, m	Atmospheric Pressure, p_a, kPa
0	101.325
500	95.461
1 000	89.875
1 500	84.556
2 000	79.495
2 500	74.682
3 000	70.108
3 500	65.764
4 000	61.640

GENERAL NOTES:
(a) Reference: U.S. Standard Atmosphere, U.S. Government Printing Office, Washington, D.C., 1976.
(b) Air pressure p_a (kPa) at elevation Z (m) is computed from the U.S. Standard Atmosphere 1976 formulation

$$p_a = 101.325(1 - 2.2558 \times 10^{-5}Z)^{5.2559}$$

(c) The use of the geometric elevation Z instead of the geopotential elevation specified in the reference produces pressures accurate to within ±0.033%.
(d) Conversion factor:

$$p_a\ (\text{lbf/in.}^2) = p_a\ (\text{kPa}) \times 1\,000 \times (0.3048/12)^2/0.45359237/9.80665$$

Table 2-3-8 Atmospheric Pressure, U.S. Customary Units (lbf/in.^{2})

Altitude, Z, ft	Atmospheric Pressure, p_a, lbf/in.^{2}
1,000	14.1726
2,000	13.6644
3,000	13.1711
4,000	12.6923
5,000	12.2277
6,000	11.7770
7,000	11.3398
8,000	10.9159
9,000	10.5048
10,000	10.1064
11,000	9.7204
12,000	9.3463

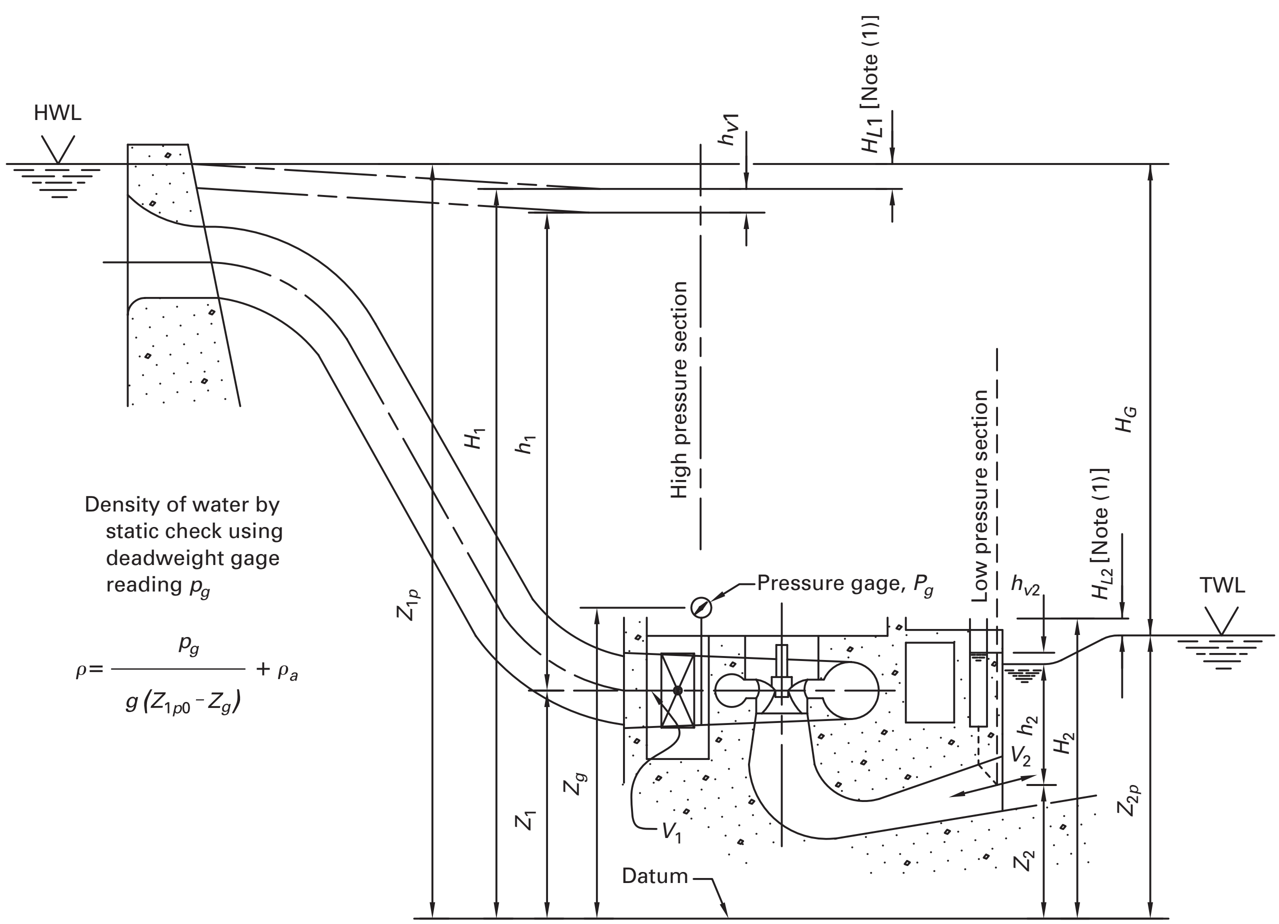
GENERAL NOTES:
(a) Reference: U.S. Standard Atmosphere, U.S. Government Printing Office, Washington, D.C., 1976.
(b) Air pressure p_a (kPa) at elevation Z (m) is computed from the U.S. Standard Atmosphere 1976 formulation

$$p_a = 101.325(1 - 2.2558 \times 10^{-5}z)^{5.2559}$$

(c) The use of the geometric elevation Z instead of the geopotential elevation specified in the reference produces pressures accurate to within ±0.033%.
(d) Conversion factor:

$$p_a\ (\text{lbf/in.}^2) = p_a\ (\text{kPa}) \times 1\,000 \times (0.3048/12)^2/0.45359237/9.80665$$

Fig. 2-3-1 Head Definition, Measurement and Calibration, Vertical Shaft Machine With Spiral Case and Pressure Conduit



GENERAL NOTES:

(a) Z_{1p0} (not shown) will be level Z_{1p} at zero flow rate.

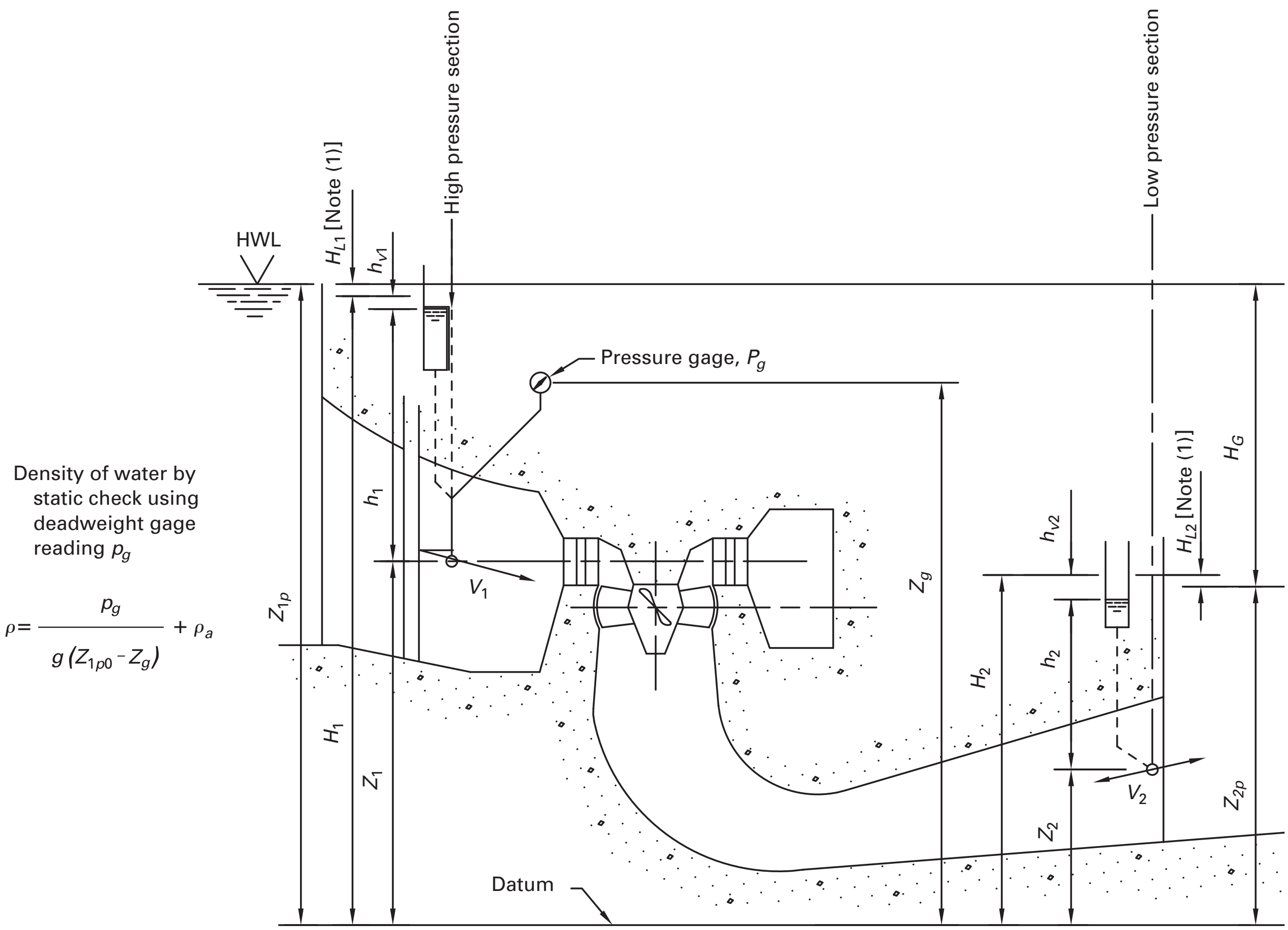
(b) Z_{2p0} (not shown) will be level Z_{2p} at zero flow rate.

(c) Net head is defined as $H_H = (Z_1 + h_1 - Z_2 - h_2)(1 - [\rho_a/\rho]) + h_{v1} - h_{v2}$

NOTE:

(1) Head losses, H_{L1} and H_{L2} are shown for the turbine mode. For the pump mode, the head losses will be of the opposite sign.

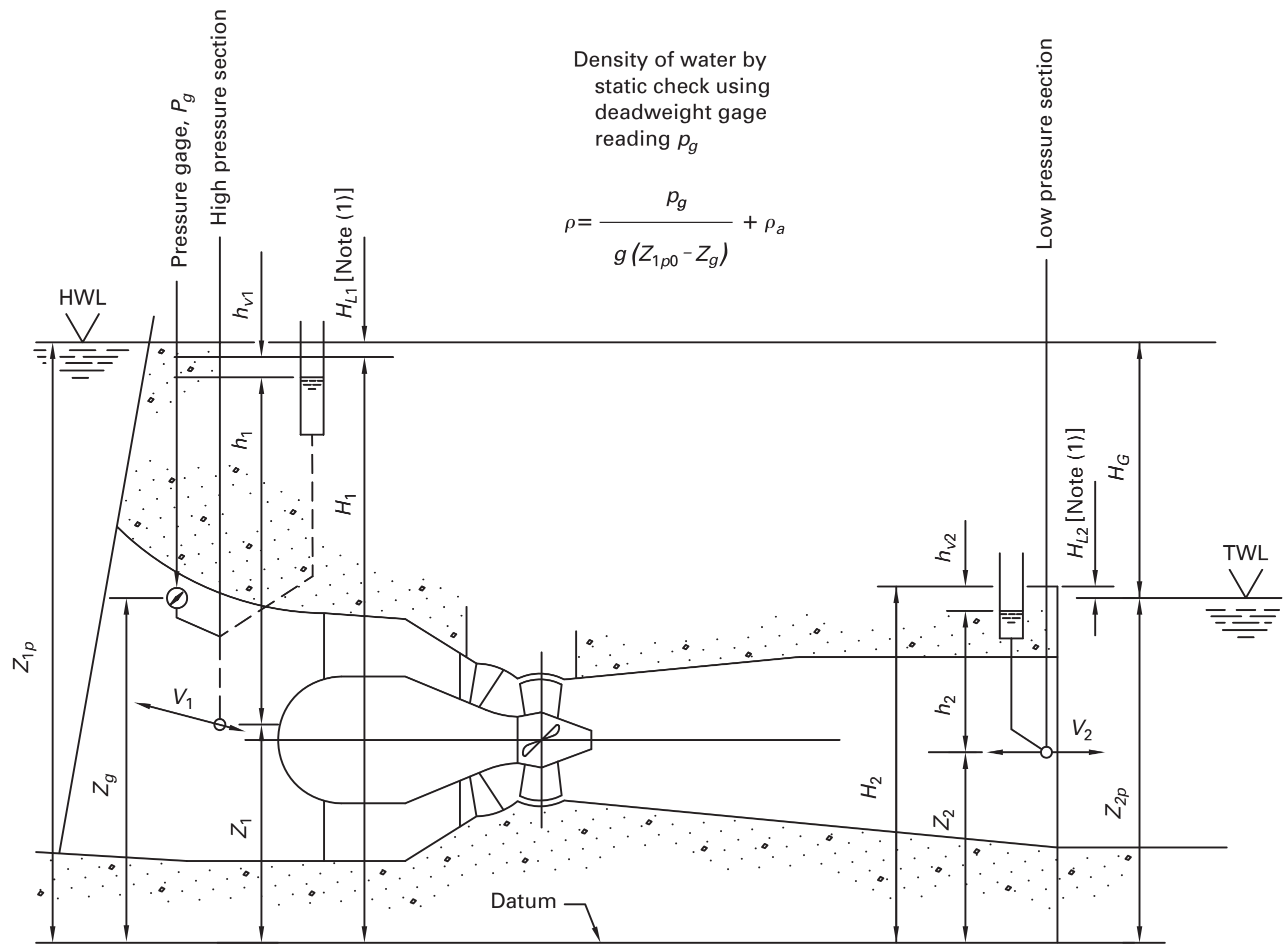
Fig. 2-3-2 Head Definition, Measurement and Calibration, Vertical Shaft Machine With Semi-Spiral Case



GENERAL NOTES:
(a) Z_{1p0} (not shown) will be level Z_{1p} at zero flow rate.
(b) Z_{2p0} (not shown) will be level Z_{2p} at zero flow rate.
(c) Net head is defined as $H_H = (Z_1 + h_1 - Z_2 - h_2)(1 - [\rho_a/\rho]) + h_{v1} - h_{v2}$

NOTE:
(1) Head losses, H_{L1} and H_{L2} are shown for the turbine mode. For the pump mode, the head losses will be of the opposite sign.

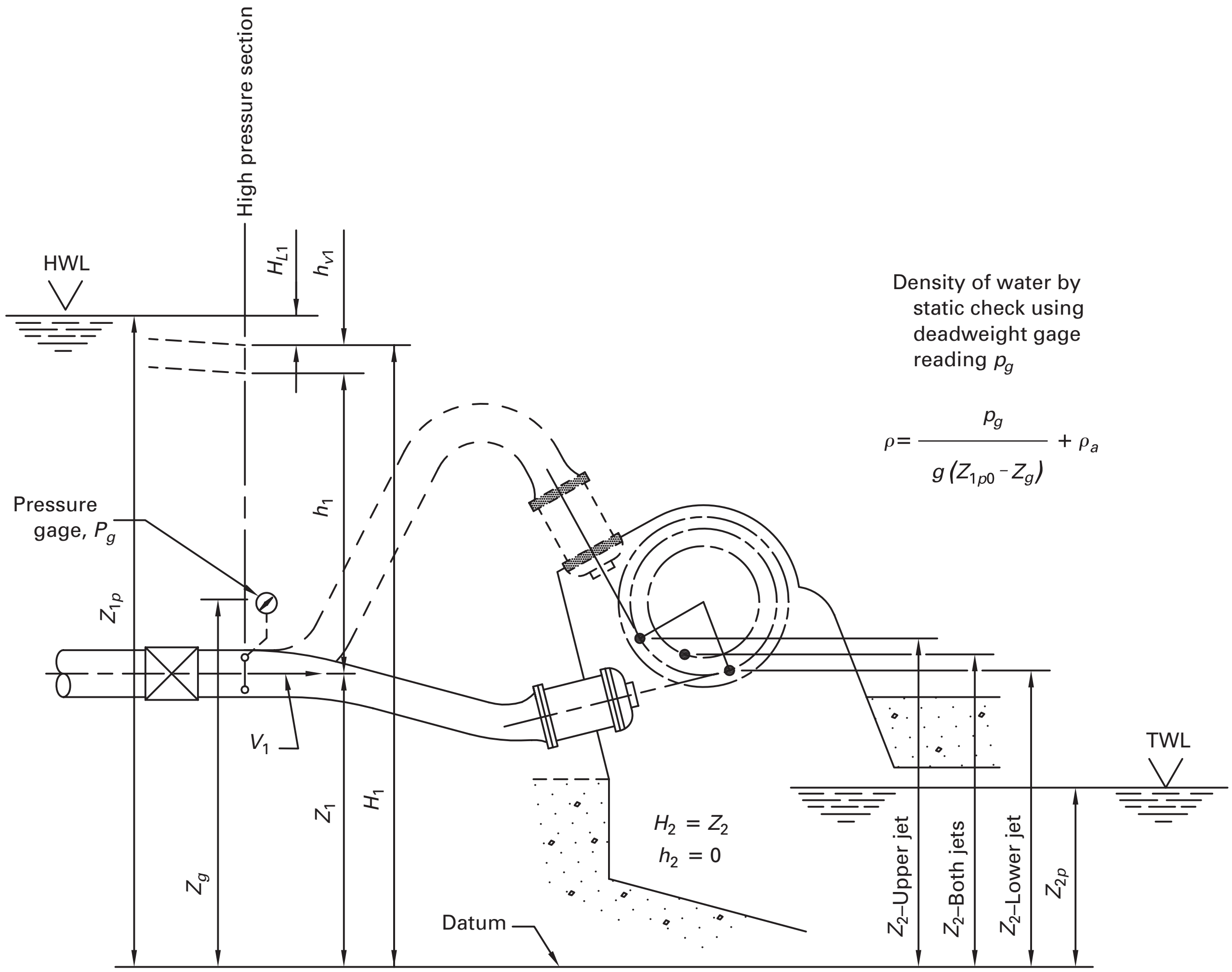
Fig. 2-3-3 Head Definition, Measurement and Calibration, Bulb Machine



GENERAL NOTES:
(a) Z_{1p0} (not shown) will be level Z_{1p} at zero flow rate.
(b) Z_{2p0} (not shown) will be level Z_{2p} at zero flow rate.
(c) Net head is defined as $H_H = (Z_1 + h_1 - Z_2 - h_2)(1 - [\rho_a/\rho]) + h_{v1} - h_{v2}$

NOTE:
(1) Head losses, H_{L1} and H_{L2}, are shown for the turbine mode. For the pump mode, the head losses will be of the opposite sign.

Fig. 2-3-4 Head Definition, Measurement and Calibration, Horizontal Shaft Impulse Turbine (One or Two Jets)



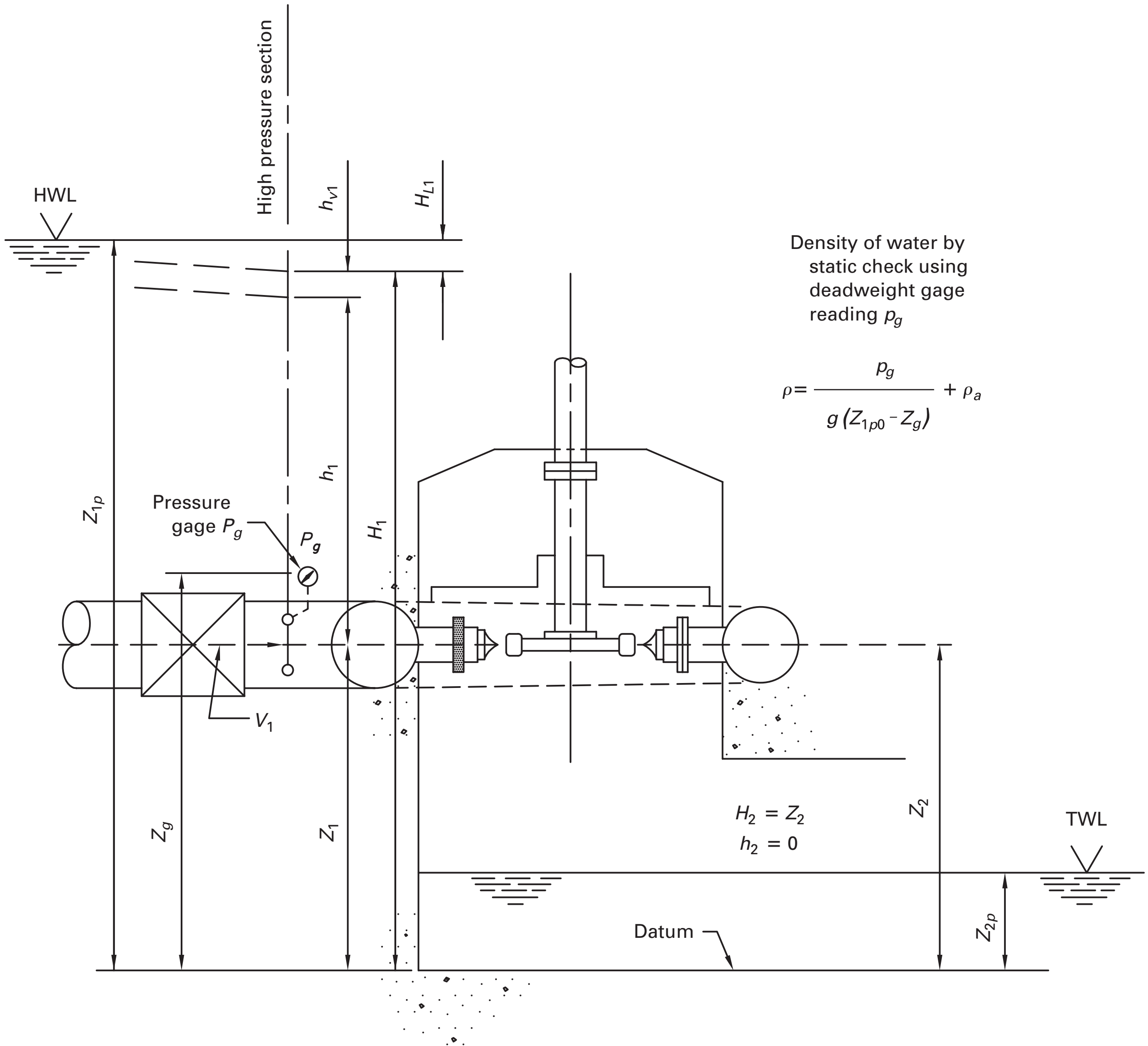
GENERAL NOTES:

(a) Z_{1p0} (not shown) will be level Z_{1p} at zero flow rate.

(b) Z_{2p0} (not shown) will be level Z_{2p} at zero flow rate.

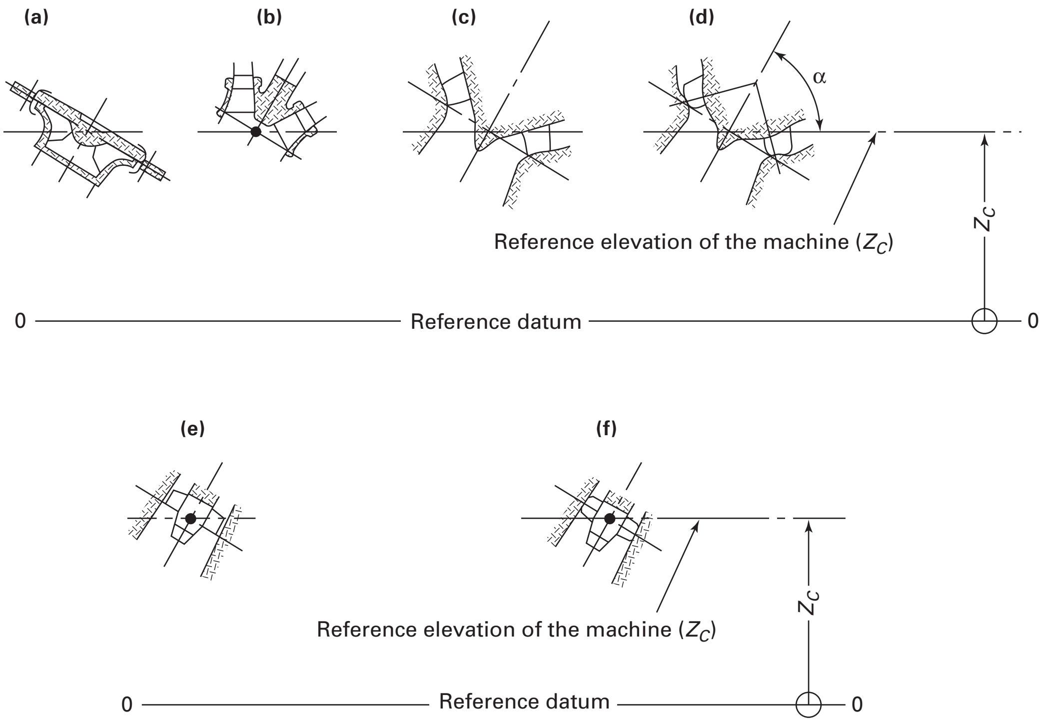
(c) Net head is defined as $H_H = (Z_1 + h_1 - Z_2 - h_2)(1 - [\rho_a/\rho]) + h_{v1} - h_{v2}$

Fig. 2-3-5 Head Definition, Measurement and Calibration, Vertical Shaft Impulse Turbine



GENERAL NOTES:
(a) Z_{1p0} (not shown) will be level Z_{1p} at zero flow rate.
(b) Z_{2p0} (not shown) will be level Z_{2p} at zero flow rate.
(c) Net head is defined as $H_H = (Z_1 + h_1 - Z_2 - h_2)(1 - [\rho_a/\rho]) + h_{v1} - h_{v2}$

Fig. 2-4-1 Reference Elevation, Z_c, of Turbines and Pump-Turbines



0 deg ≤ α ≤ 90 deg

(a) Radial machines, such as Francis turbines and pump–turbines; for multistage machines; low-pressure stage.
(b) Diagonal (mixed–flow, semi–axial) machines with fixed runner/impeller blades and with runner/impeller band.
(c) Diagonal (mixed–flow, semi–axial) machines with fixed runner/impeller blades without runner/impeller band.
(d) Diagonal (mixed–flow, semi–axial) machines with adjustable runner/impeller blades.
(e) Axial machines, such as propeller turbines and pump–turbines with fixed runner/impeller blades.
(f) Axial machines, such as Kaplan turbines and pump–turbines with adjustable runner/impeller blades.

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Section 3
Guiding Principles

3-1 GENERAL

The object of the test shall be agreed by the parties to the test and shall be defined in writing before the test(s) commence.

In tests conducted in accordance with this Code, the parties to the test shall be represented and shall have equal rights in determining the test methods and procedures unless agreed to otherwise. Any agreement reached among the parties to the test shall be in writing.

Acceptance testing shall be performed only after dependable operation and after the machine has been found by inspection to be in a condition satisfactory, to the parties to the test, to undergo the test. The parties to the test should agree, after consideration of plant operation, head, and flow-rate conditions when the test is to be performed. This shall be as soon as possible after the machine is handed over to the owner and within the specified warranty period, unless otherwise agreed in writing by the parties to the test.

The parties to the test shall be entitled to have such members of their staff present during the test as required to assure them that the test is conducted in accordance with this Code and in accordance with any written agreements made prior to the test.

Unless otherwise provided, head losses between the high-pressure and low-pressure sections are charged to the machine. Other head losses including those due to conduits upstream and/or downstream of the machine intakes, trashracks, gates, valves, and the discharge-velocity head loss at the conduit exits shall not be charged to the turbine or credited to the pump.

At installations where an absolute flow-rate measurement is not practical or desirable, the index method (Nonmandatory Appendix D) may be used. Index testing makes use of the relative flow rate in order to determine relative machine efficiency.

In the case of a machine with both adjustable wicket gates and adjustable runner blades, index testing should be carried out before the performance test to determine the best gate and blade combination. The positions of the wicket gates and runner blades for various positions of the operating mechanisms shall be accurately measured, and suitable reference scales shall be provided. These scales shall be accessible during operation and their indications shall be recorded during the test.

For pumped storage installations, with small reservoirs, tests can be conducted conveniently over the entire operating head range. One or more runs at the various gate openings shall be conducted at each of several heads, using machined metal spacers, if necessary, for accurately and positively blocking the gate servomotors at each position.

For pumped storage installations with large reservoirs it may be convenient to conduct tests at only one point in the head range. At each constant head, sufficient test runs shall be conducted at the same gate opening using metal spacers, if necessary, to reduce the positioning error.

3-2 PREPARATIONS FOR TESTING

3-2.1 General Precaution

Reasonable precautions should be taken when preparing to conduct a test within the uncertainty of this Code. Indisputable records shall be made to identify and distinguish the machine to be tested and the exact method of testing selected. Descriptions, drawings, or photographs may all be used to give a permanent, explicit record. Instrument location shall be predetermined, agreed by the parties to the test, and described in detail in test records. Redundant, calibrated instruments should be provided for those instruments susceptible to in-service failure or breakage.

3-2.2 Inspection Before Test

Prior to the start of the test, an inspection of the machine and its water passages shall be made to verify that

(a) trash racks, water passages, and all machine components, which affect performance, are in satisfactory condition

(b) the water does not carry undue quantities of air, bark, leaves, weeds, or other foreign elements, which may unfavorably affect the flow rate or operation of the instrumentation

(c) pressure taps, piezometer tubes, and connecting pipes are clear of obstructions and are properly formed and located

3-2.3 Provisions for Testing

To ensure fulfillment of the conditions of this Code, attention should be given to provisions for testing when the plant is being designed and preferably before the machine is purchased. This applies particularly to the arrangements for measurement of flow rate, head, power, and speed. The method for measuring flow rate should be selected during the design stage and stated in the procurement document. Typical items that should be decided during the design stage and prior to construction are

(a) flow-rate measurement method and devices
(b) location of high-pressure and low-pressure sections
(c) number and location of pressure taps and instrument connections
(d) location of flow-rate measurement section
(e) location and type of piping for pressure and flow rate measuring devices to be used during the test
(f) provisions for power measurement

3-2.4 Planning a Performance Test

In addition to the discussion in subsection 3-1, the following information is useful in planning a performance test:

(a) Determine the availability of test equipment and trained personnel for the measurement of large flow rates with the accuracy required. Obtaining this equipment and the personnel experienced in its installation, adjustment, operation, and the analysis of the results is a major consideration.

(b) Consider the time for testing and plant outage required for each method. Some methods require unwatering to install and remove test equipment. Others require only limited interruption for inspection and testing. These factors are significant to the overall cost of the test. Some methods require a long series of readings for each run. Other methods require only a few seconds to make a single reading for each run. The pressure–time method requires that the interconnected electrical system absorb sudden shedding of load; water passages and other structures may be subject to increased stresses.

3-2.5 Agreements

Prior to conducting any tests there shall be agreement by the parties to the test on the exact method of testing and the methods of measurement. The agreement shall also reflect the requirements of any applicable specification. Any discernible omissions or ambiguities as to any of the conditions shall be resolved before the test is started. Typical items on which written agreement shall be reached are

(a) object of test.
(b) type of test.
(c) location and timing of test.
(d) test boundaries.
(e) need for and application of results of any index tests.
(f) method of determining acceptable condition of the machine prior to testing.
(g) selection of instruments (number, location, type), data-acquisition, and processing equipment.
(h) method of calibration of instruments before and after the test.
(i) confidentiality of test results.
(j) number of copies of original data required.
(k) data to be recorded, method of recording, and archiving data.
(l) operating conditions: head, speed, tailwater level, and power factor (PF). It is recommended that the cavitation factor σ during the test be equal to or greater than the cavitation factor corresponding to the normal operating conditions to avoid effects resulting from the onset of cavitation. It is recommended that PF be at unity, wherever possible.
(m) flow rate measurement device(s) and method to be used.
(n) methods for determining the bearing and generator losses.
(o) methods to be used for measurement of speed, head, and power.
(p) values of measurement uncertainty and method of determining overall test uncertainty; methods for estimating systematic uncertainties, calculating random uncertainties (see Nonmandatory Appendices), and performing a pre-test uncertainty analysis.
(q) method of operating the machine under test, including that of any auxiliary equipment, the performance of which may influence the test result, such as air admission valve(s) to be in the specified (open or closed) position, or be operated in the normal automatic mode (by the unit controls).
(r) methods of maintaining constant operating conditions as near as possible to those specified, including permissible fluctuation of measured variables.
(s) method of determining duration of operation under test conditions before test readings are started.
(t) system alignment or isolation.
(u) organization of personnel, including designation of chief of test.
(v) duration and number of test runs, including start and stop procedures.
(w) test schedule and scope (which machines are to be tested and when).
(x) extent and estimated duration of the test. This shall include a statement of the minimum number of runs and the operating conditions, loads and gate settings at which runs are to be made.
(y) method of ensuring synchronization of readings.
(z) frequency of observations.
(aa) base reference conditions.
(bb) methods of correction and values used for corrections for deviations of test conditions from those specified.
(cc) methods of computing results.
(dd) method of comparing test results with specified performance.

(ee) conditions for rejection of outlier data or runs.

(ff) intent of contract or specification if ambiguities or omissions appear evident.

(gg) pre-test inspections.

(hh) arbitration procedure.

(ii) any objections, noted deficiencies, need for additional devices, changes, and calibrations.

3-2.6 Chief of Test

The parties to the test shall designate an experienced chief of test who shall

(a) ensure preparation of a written test plan

(b) possess appropriate qualifications to supervise all on-site calibrations, measurements, and calculations necessary to determine the performance of the machine under test, and possess sufficient experience to recognize potentially unsafe test conditions

(c) exercise authority over all test personnel, and ensure their safety related to the conduct of the test

(d) supervise the conduct of the test in accordance with this Code and any written agreements made prior to the test

(e) report test conditions and ensure computation of results and the preparation of the final report (see Section 6)

(f) ensure that test instruments have been properly calibrated or have valid calibration documents

(g) assume responsibility for all test measurements

(h) make every reasonable effort to ensure that any controversial matters pertaining to the test are resolved

3-3 TESTS

Dimensions and information regarding the machine, associated equipment, and water conduits shall be obtained prior to the test. All drawings of importance for the test and all relevant data, documents, specifications, calibration certificates, and reports on operating conditions shall be examined by the chief of test and made available to the parties to the test.

Preliminary test runs, with records, serve to determine if the machine is in suitable condition to test, to check instruments and methods of measurement, to check adequacy of organization and procedures, and to train personnel. All parties to the test may request the execution of reasonable preliminary test runs. Observations during preliminary test runs should be carried through to the calculation of results as an overall check of procedure, layout, and organization. If such preliminary test run complies with all the necessary requirements of the appropriate test code, it may be used as an official test run within the meaning of the applicable code.

For acceptance and other official tests, the manufacturer or supplier shall have reasonable opportunity to examine the machine, correct defects, and render the machine suitable to test. The manufacturer, however, is not thereby empowered to alter or adjust the machine or conditions in such a way that regulations, contract, safety, or other stipulations are altered or voided. The manufacturer may not make adjustments to the machine for test purposes that may prevent immediate, continuous, and reliable operation at all capacities or outputs under all specified operating conditions. Any actions taken must be documented and immediately reported to all parties to the test.

Acceptance and other official tests shall be conducted as promptly as possible following initial machine operation.

The machine should be operated for sufficient time to demonstrate that intended test conditions have been established, e.g., steady state. Agreement on procedures and time should be reached before commencing the test.

Once testing has started, readjustments to the machine that can influence the results of the test should require repetition of any test runs conducted prior to the readjustments. No adjustments should be permissible for the purpose of a test that are inappropriate for reliable and continuous operation following a test under any and all of the specified outputs and operating conditions.

Data shall be taken by automatic data-collecting equipment or by a sufficient number of competent observers. Automatic data-logging and advanced instrument systems shall be calibrated to the required accuracy. No observer shall be required to take so many readings that lack of time may result in insufficient care and precision. Consideration shall be given to specifying duplicate instrumentation and taking simultaneous readings for certain test points to attain the specified accuracy of the test.

Agreement shall be reached in advance as to the personnel required to conduct the test. Personnel shall have the experience and/or training necessary to enable them to take accurate and reliable readings from the instruments assigned to them. Intercommunication arrangements between all test personnel and all test parties and the chief of test should be established. Complete written records of the test, even including details that at the time may seem irrelevant, should be reported. Controls by ordinary operating (indicating, reporting, or integrating) instruments, preparation of graphical logs, and close supervision should be established to give assurance that the machine under test is operating in substantial accord with the intended conditions. For an acceptance test, accredited representatives of the purchaser and the machine supplier should be present at all times to assure themselves that the tests are being conducted with the test code and prior agreement.

Preliminary results shall be computed during the course of the test and these results, together with selected important measurements, shall be plotted on graphs. Any run, which appears to be inconsistent with the other runs or appears to exceed limits of deviation or fluctuation, shall be repeated. However, test records of all runs shall be retained.

3-4 INSTRUMENTS

Electronic data acquisition is recommended where the data system has the required accuracy and resolution, the readout is clear, and periodic verification readings are made by independent means.

Careful inspections and checks of all instrumentation shall be carried out before, during, and after the test.

Transducers shall be located to minimize the effect of ambient conditions on uncertainty, e.g., temperature or temperature variations. Care shall be used in routing lead wires to the data-collection equipment to prevent electrical noise in the signal. Manual instruments shall be located so that they can be read with precision and convenience by the observer. All instruments shall be marked uniquely and unmistakably for identification. Calibration tables, charts, or mathematical relationships shall be readily available to all parties of the test. Observers recording data shall be instructed on the desired degree of precision of readings.

The timing of instrument observations shall be determined by an analysis of the time lag of both the instrument and the process so that a correct and meaningful mean value and departure from allowable operating conditions may be determined. Sufficient observations shall be recorded to prove that steady-state conditions existed during the test where this is a requirement. A sufficient number of observations shall be taken to reduce the random component of uncertainty to an acceptable level.

3-5 OPERATING CONDITIONS

3-5.1 Operating Philosophy

The tests should be conducted as closely as possible to specified operating conditions and thus reduce and minimize the magnitude and number of corrections for deviations from specified conditions. Each run shall be conducted under the best steady-state conditions obtainable at the operating point. Once a test has started, adjustments to the machine under test or the test equipment, which may affect test results, shall not be permitted. Should adjustments be deemed necessary by the parties to the test, prior runs shall be evaluated and voided if necessary and the test restarted.

3-5.2 Test Run Conditions

Test runs should be made under conditions of constant speed, constant head, and constant power within the following limits of variation during an individual run:

(a) Variations in measured speed should not exceed ±0.5% of the average speed measured.

(b) Variations in measured head should not exceed ±1.0% of the average head measured.

(c) Variations in measured power output or input should not exceed ±1.5% of the average measured power.

3-5.3 Permissible Deviations

The machine under test should be operated to ensure its performance is bounded by the permissible fluctuations and permissible deviations specified. Should the actual average conditions of any test deviate from the corresponding specified conditions, they shall be treated individually as follows:

(a) The actual average speed, n_T, and net head, H_T, for each individual test run may deviate from n_{spec} and H_{spec} by as much as ±5% and ±10%, respectively, provided the value of the ratio $n_T/(H_T)^{0.5}$ does not differ from that of $n_{spec}/(H_{spec})^{0.5}$ by more than ±1%. The measured flow rate, head, net positive suction head, and power shall be converted to values that correspond to $n_{spec}/(H_{spec})^{0.5}$ by using the applicable equations of Section 5 of this Code. No efficiency correction is required (see Figs. 3-5.3-1 and 3-5.3-2, Zone 1).

(b) If the conditions of (a) above are not met but n_T is within ±5% of n_{spec}, H_T is within ±10% of H_{spec}, and $n_T/(H_T)^{0.5}$ is within ±5% of $n_{spec}/(H_{spec})^{0.5}$ then the measured values of flow rate, head, net positive suction head, and power may be converted to specified values using characteristic test curves of an identical or homologous machine tested over the operating range in question and the applicable equations of Section 5 of this Code (see Figs. 3-5.3-1 and 3-5.3-2, Zone 2).

(c) The method of making the conversion for operation at other selected speeds, the permissible deviation from specified conditions, and the basis for making correction for electrical and mechanical characteristics shall be determined by prior agreement.

(d) If, in the pumping mode, it is not possible to test within the specified head range, discharge throttling may be used to perform the test, by agreement, within the specified head range.

3-6 DATA RECORDS

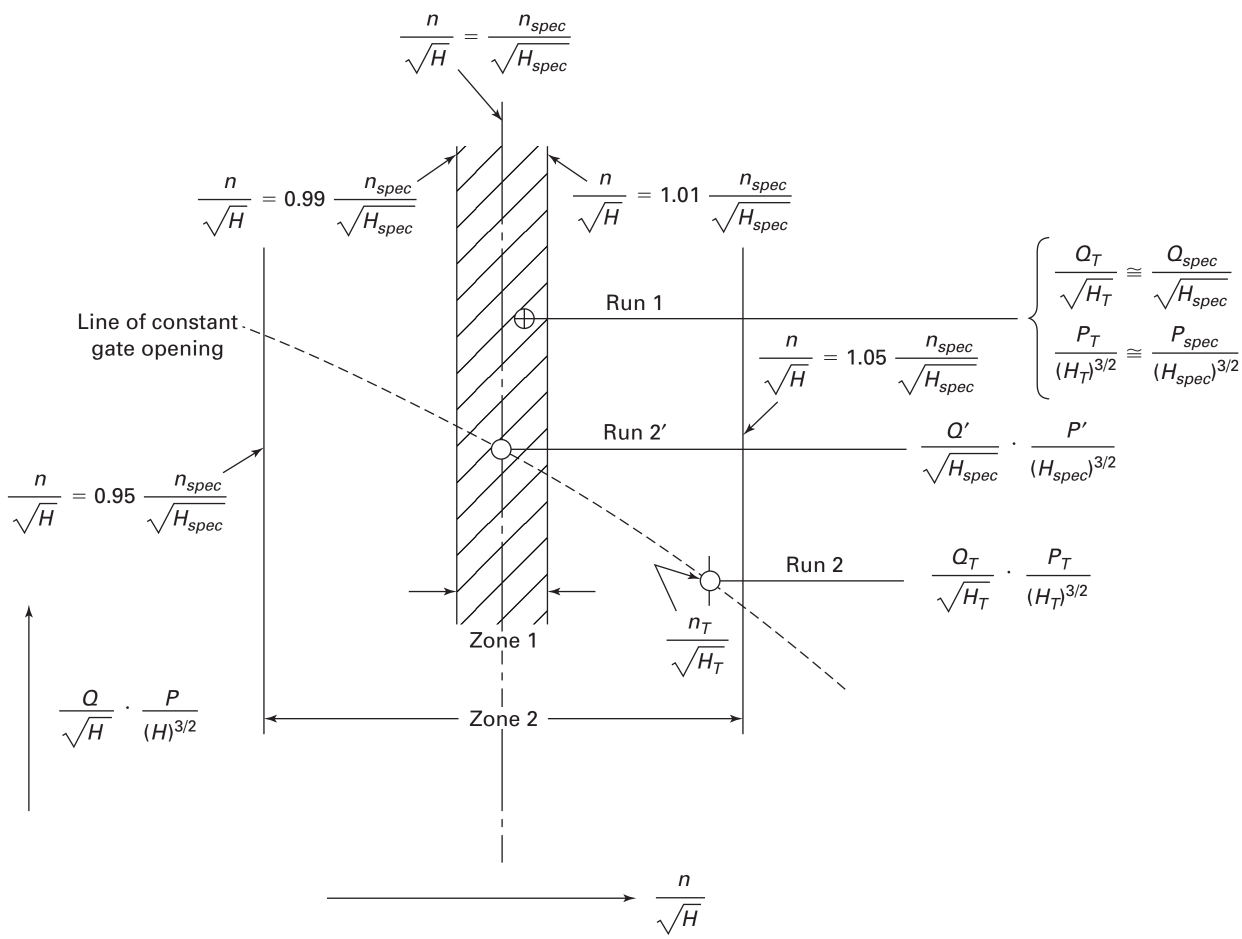
3-6.1 True Copies

True copies of all official test data taken manually or electronically, test logs, notes, sample calculations, results, and plots along with pre-test instrument calibrations shall be provided to the parties to the test prior to the dismantling of the test instrumentation or departure of the test group from the site. Programs that are used to calculate results may be considered as proprietary. However, sufficient information needs to be provided for the true copies, which permits the duplicated data to be used to calculate the test results. These copies will provide the parties to the test with all information plus ensure the safekeeping and integrity of the test data.

3-6.2 Original Data

The original log; data sheets, files, and disks; recorder charts; tapes; etc., being the only evidence of actual test conditions, must permit clear and legible reproduction.

Fig. 3-5.3-1 Limits of Permissible Deviations From Specified Operating Conditions in Turbine Mode

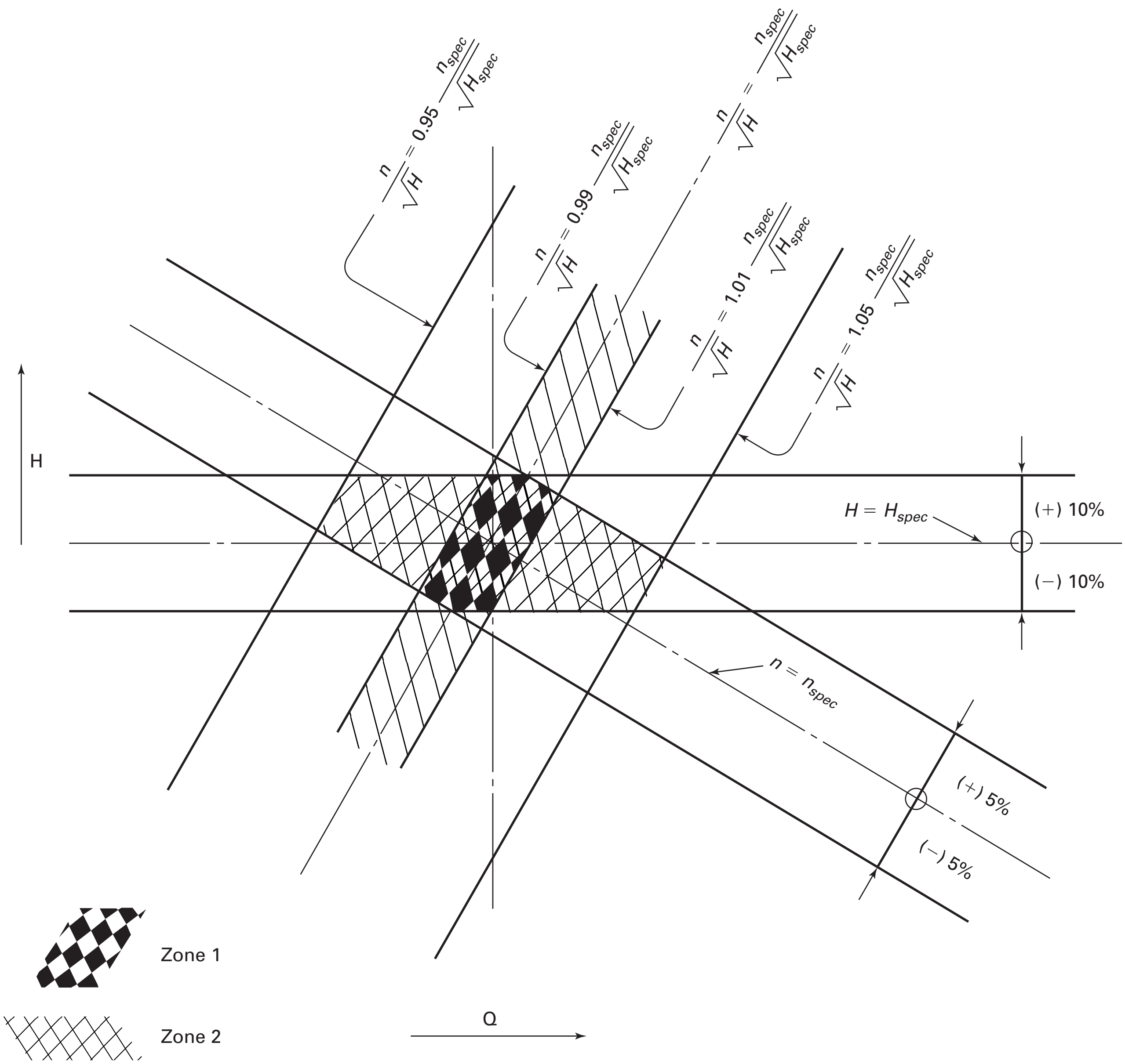


Copying by hand is not permitted. The completed data records shall include the date and time of day the observation was recorded. The observations shall be the actual readings without application of any instrument corrections. The test log should constitute a complete record of events including details that at the time may seem trivial or irrelevant. Erasures, destruction, or deletion of any data record, page of the test log, or of any recorded observation is not permitted. If corrected, the alteration shall be entered so that the original entry remains legible and an explanation is included. For manual data collection, the test observations shall be entered on carefully prepared forms that constitute original data sheets authenticated by the observer's signatures. For automatic data collection, printed output or electronic files shall be authenticated by the chief of test and other representatives of the parties to the test. When no paper copy is generated, the parties to the test must agree in advance to the method used for authenticating, reproducing, and distributing the data. Copies of the electronic data files must be copied onto tape or disks and distributed to each of the parties to the test. The data files shall be in a format that is easily accessible to all. Data residing on a machine should not remain there unless a backup, permanent copy on a separate medium is made.

3-6.3 Analysis and Interpretation

During the conduct of a test, or during the subsequent analysis or interpretation of the observed data, an obvious inconsistency may be found. If so, reasonable effort should be made to adjust or eliminate the inconsistency. The method used should be explained clearly in the report of results. If this is not possible, questionable test runs should be repeated.

Fig. 3-5.3-2 Limits of Permissible Deviations From Specified Operating Conditions in Pump Mode



Section 4
Instruments and Methods of Measurement

4-1 GENERAL

This Section describes the instruments and methods to be used for measuring head, flow rate, power, speed, and time.

Instruments shall be located so they can be read with precision and convenience by the observers. All instruments shall be clearly and properly identified, and their calibration tables or charts shall be readily available. Observers shall be instructed in the proper reading of the instruments and the desired precision of the readings.

The precision of all measuring instruments shall be compatible with the degree of accuracy agreed to by the parties to the test. The instrument manufacturers, identifying numbers, owner of instruments, and length and type of electrical leads, where applicable, shall be stated in the final report. Refer to IEEE Standard 120.

Additional instrumentation may be necessary to maintain the uncertainties required by subsection 1-3 when testing at machine operating conditions substantially different than the best operating range of the instrumentation.

All instruments/instrument transformers shall be calibrated before and after the test. Those instruments that cannot be calibrated on site shall bear a valid calibration certificate from an accredited laboratory. Before carrying out the test, the necessary correction and calibration curves of all instruments employed shall be available, so that within a short time following a test run, preliminary calculations can be made. After completion of the test, a repeat calibration may be omitted by agreement by the parties to the test. Instrument calibrations shall be included in the final report.

4-2 ELECTRONIC DATA ACQUISITION

The use of electronic data acquisition systems (EDAS) has considerably decreased the amount of labor required to accomplish performance testing and has greatly lowered the uncertainty of the results. However, the use of an EDAS is not without pitfalls. An EDAS must be used with knowledge of the signals being processed and the rate of change of quantities being measured.

This subsection is not a complete EDAS design guide but will mention topics specific to using an EDAS during machine testing.

Planning and designing an EDAS to be used for performance testing requires consideration of the following:

(a) sensors or transducers
(b) cabling
(c) calibration
(d) uncertainty
(e) data sufficiency
(f) data management
(g) operational considerations
(h) acquisition speeds
(i) resolution
(j) noise rejection
(k) data verification

Transducer selection must be made with full knowledge of the characteristics of the parameter being measured and of the EDAS that will record the output from the transducer. Cabling must be designed so as not to pick up unwanted noise or attenuate the measured signal. Cables may pick up noise spikes when using high-frequency radios in the vicinity of the cables or the EDAS. Transducer calibration should be performed with the system cabling and excitation active in the system.

Uncertainty should be a primary consideration when designing an EDAS for machine performance testing. The EDAS must have sufficient resolution so that uncertainty levels can meet Code requirements. Sufficient data should be recorded to allow low random uncertainty.

Raw-data signals should be recorded with the EDAS along with data converted to engineering units so that discrepancies may be readily evaluated, and to aid in system troubleshooting. The EDAS must be designed so that verification of engineering parameters can be performed on site.

The machine under test should be operated such that the system stability is attained prior to data collection. Scan rates of time-varying signals must be sufficient to ensure that the complete characteristic of the signal is obtained, yet should be slow enough so that the amount of data saved is not excessive to the extent that it does nothing to improve the test measurements or lower the random uncertainty. As an example, scanning-transducer outputs connected to a machine operating under steady-state conditions at 1 000 cycles per second for 1 min, would generate an extremely large amount of data yet may still not adequately describe operation at that gate setting.

Calibration procedures should be carefully developed well in advance of the test using benchmarks established prior to the test.

4-3 HEAD AND PRESSURE MEASUREMENT

4-3.1 Bench Marks

A fixed elevation reference point called a main bench mark shall be provided at each machine installation. The elevation of this main bench mark shall be accurately determined, preferably in relation to some established datum such as a geodetic bench mark. The main bench mark shall be clearly labeled to avoid any possibility of error. The elevations of auxiliary bench marks for free water surface levels and pressure gages shall be accurately determined in relation to the main bench mark prior to starting the test. All bench marks and elevation reference points in the head-measuring system shall be retained undisturbed until the final test report is accepted.

4-3.2 Static-Head Conditions

The pressure measuring system should be used to measure the static-head conditions. This will aid in verifying the value of the density of water, the functioning of the pressure-measurement system, and the accuracy of the water-level elevations.

4-3.3 Free-Water Elevation

The measurement section for the determination of a free-water elevation shall be chosen to satisfy the following requirements:

(a) the flow shall be steady and free from disturbances

(b) the cross-sectional area used to determine the mean water velocity shall be accurately defined and readily measurable

The inlet-water elevation in machine installations with open canals or intakes shall be measured at the agreed inlet section downstream from the trashracks.

The outlet-water elevation shall be determined at the agreed section at the end of the outlet conduit. If this is not practical, a different measurement section may be used in each case at the shortest possible distance from the agreed flow section. The total head determined at the measurement sections shall be corrected by the head loss in the intervening passages between the agreed flow section and the actual measurement section computed by the Darcy–Weisbach or similar formula.

4-3.4 Measuring Wells and Stilling Boxes

If the free water surface is not accessible or sufficiently calm at either the machine inlet or outlet, measuring wells may be used. These wells may also be used to confine and protect submersible pressure cells when they are used for water-surface elevation measurement.

4-3.4.1 Pipe-Type Stilling Wells. The following guidelines apply when submersible pressure cells suspended in pipe-type stilling wells are used:

(a) The diameter of the pipe should provide a clearance of at least 12 mm (1/2 in.) around the pressure cell, to allow the water surface in the pipe to follow the water surface at the measurement location.

(b) If there is no mean flow past the measurement location, then a simple open-ended pipe may be inserted into the water. This is often the case in gate slots at elevations above the conduit ceiling, or against a wall that is above the machine discharge conduit (e.g., downstream face above a draft tube in turbine mode).

(c) When used in inlet-gate slots with multiple inlet conduits, at least one measurement location should be provided in each slot.

(d) When used at draft-tube exit, at least one measurement location should be provided for each exit bay with a minimum of two per draft tube.

(e) If the stilling well is installed in the flow, it should be as small in diameter as practical, and should be attached to a wall or other location where the flow velocity is low. The end of the well should be capped, and at least six square-edged holes with a diameter of at least 6 mm (1/4 in.) and a combined area of no more than one-quarter of the cross-sectional area of the pipe should be evenly spaced around the pipe on a plane at least two pipe diameters below the pressure cell. When installed in the flow in this manner, the uncertainty in the head measurement can be estimated as one-half of the velocity head at the stilling well location.

(f) The output of the pressure cell should be sampled at a sufficient frequency that water-surface fluctuations occurring in the pipe can be accurately averaged over the test run.

4-3.4.2 Float-Gage Type Stilling Well. The following guidelines apply if a float-gage type stilling well is used:

(a) The area of the measuring well should be such that the float gage may respond freely and without interference from the sides of the stilling well.

(b) All connections should be normal to the passage wall at the measurement section and should be covered with a noncorrosive smooth plate having perforations of 6 mm to 10 mm (1/4 in. to 3/8 in.) diameter, with the area of the perforations equal to or greater than 25% of the connection. Such cover plates should be flush with the wall of the measurement section to eliminate any disturbance.

(c) The connection between the measurement section and the well should have an area of at least 0.01 m^2 (0.1 ft^2).

(d) A flushing valve should be provided at the bottom of the well. It is recommended that at least two measuring wells be provided at each measurement section, one on each side of the passage at the measurement section.

4-3.5 Plate Gage

A plate gage consisting of a metal disk suspended from a calibrated flexible steel tape may be used to determine the water elevation in relation to an auxiliary bench mark at the measurement section.

4-3.6 Point or Hook Gage

A point gage or hook gage may be used to determine the level of calm water (e.g., inside stoplog slots, measuring wells, stilling boxes, or upstream of weirs).

4-3.7 Float Gage

A float gage may be used and is recommended where the water level is variable. The float diameter should be at least 200 mm (8 in.). When the float is manually displaced, it shall return to within 5 mm (0.2 in.) of its original position. A float diameter of 200 mm (8 in.) is considered adequate for use with a stilling box 250 mm^2 (10 in.^{2}), which often is the largest size suitable for installation in stoplog slots.

4-3.8 Staff Gage

A fixed staff gage, installed flush with the wall of the measurement section, may be used where the head is greater than 10 m (33 ft).

4-3.9 Electronic Water Level Indicator

A water level indicator with an integral scale and audible and visual indicator may be used when the probe reaches water level and the circuit is completed.

4-3.10 Time-of-Flight Techniques

Water surface level may be measured by time-of-flight remote-sensing devices, such as radar and ultrasonic rangers, provided the devices provide accuracy sufficient to meet the overall uncertainty requirements of the test. When these devices are used, care must be taken to ensure that the cone-shaped beam of the transmitted signal is unaffected by obstructions such as adjacent walls. In the case of an ultrasonic device, the measurement must be temperature-compensated to account for the variation in the speed of sound in air as a function of temperature. Care must be taken to ensure that movement of the transducer does not affect the distance measurement. A procedure for installation and calibration of the transducer must be developed in advance to allow for the fabrication of special support fixtures required.

4-3.11 Liquid Manometers

If the free water surface in the measurement section is inaccessible, its elevation may be determined by means of two or more liquid-column manometers. The recommended liquid manometer is a differential type with inverted U-tube. One leg of the U-tube is connected to a reference vessel in which water is maintained at a fixed level. The other leg is connected to the free water level. If the free water level to be measured is above the manometer, the water in the upper portion of the U-tube must be depressed by means of compressed air or nitrogen. If, however, the free water level to be measured is below the manometer, the levels in the two U-tube legs must be raised by suction. The connecting tubes to the manometer must allow for ready purging to remove any gas pockets and to maintain the same water temperature throughout the system. Dissolved gases in the water may continue to be released over time during the course of the measurements, so periodic inspection is required. A procedure for installation and calibration of the transducer must be developed in advance to allow for the fabrication of special support fixtures required. They must be sufficiently airtight to avoid leakage of air into sections below atmospheric pressure. The weight of the unbalanced gas column in a differential manometer shall be taken into account. Further details on manometers can be found in PTC 19.2, *Pressure Measurement*.

4-3.12 Measurements by Means of Compressed Gas

The free water elevation may be determined by means of compressed gas, air or nitrogen, inside a tube (bubbler system). One end of the tube is connected through a regulating valve to a small compressor(s) or gas bottle(s). The other end is open and located at a known elevation below the water surface to be measured. Pressure loss in the tube is small because the flow rate is 3 to 8 bubbles per minute. Gas consumption is small because it is necessary only for small bubbles to escape continuously from the open end of the tube. The bubbler works best in still water, because dynamic effects may cause errors.

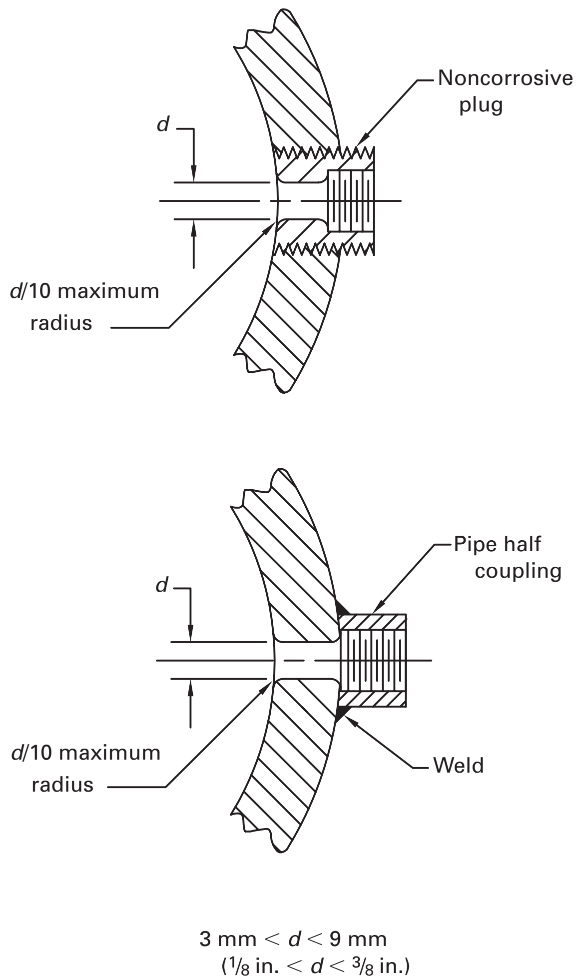
4-3.13 Number of Devices

The number of devices used should be determined by the condition of the water surface at the measurement location. If the water surface is relatively level and undisturbed, as is often the case at an intake, then one measurement at the centerline may be sufficient. Otherwise, it may be necessary to have one elevation measurement device at the centerline of each intake or discharge bay.

4-3.14 Pressure Measurement by Pressure Taps

When pressure taps are used to measure the static head at the inlet and/or discharge sections, there shall be at least four pressure taps equally spaced around a circular conduit. There shall be two pressure taps located on each vertical side (at the one-quarter and three-quarter heights) of a rectangular conduit or at least one at mid-height of both vertical sides of each part of a multiple conduit section. To avoid air and dirt, no pressure taps shall be located at the top or bottom.

Fig. 4-3.14-1 Pressure Tap

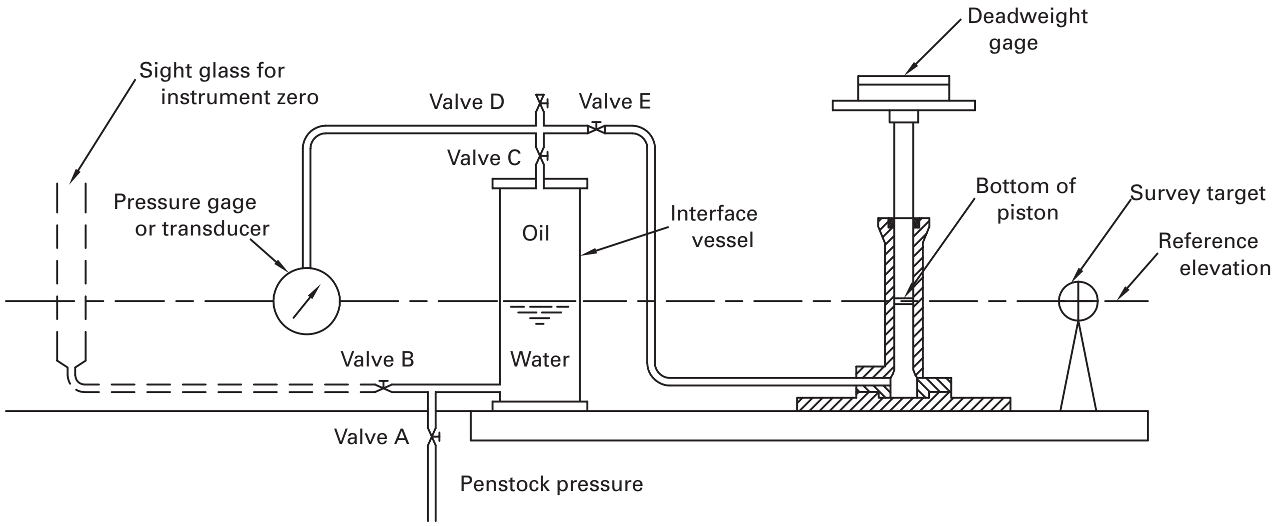


Each pressure tap should be flush with the wall, with the tap axis normal to the wall, and without local flow disturbances (see Fig. 4-3.14-1). If modifications to these requirements are necessary (for example, by using a surface-mounted piezometer plate), the impacts of the modifications on measurement uncertainty shall be addressed in the uncertainty analysis.

Care shall be exercised in locating the inlet pressure taps to avoid flow vortices. Location of pressure taps shall be at least three conduit diameters downstream from an elbow, butterfly valve, or other flow-disturbing configuration, and one conduit diameter upstream from the machine inlet section or the manifold inlet section of an impulse turbine. If the distance between the machine and the flow-disturbing configuration is too short to allow the recommended location, the pressure taps shall be located at least one conduit diameter upstream from the flow-disturbing configuration, and the computed head loss in the intervening segment of conduit shall be deducted from the measured head. If the conduit is rectangular, one equivalent conduit diameter shall be the average of height and width.

The wall of the conduit shall be smooth and parallel to the flow for a distance of at least 450 mm (18 in.) upstream and 150 mm (6 in.) downstream from the pressure tap. The surface shall not deviate by more than 0.75 mm (0.03 in.) from a 450 mm (18 in.) straight edge applied parallel to flow for 150 mm (6 in.) on either side of the pressure tap. Each pressure tap orifice shall be of uniform diameter, d, 3 mm to 9 mm (1/8 in. to 3/8 in.), for a depth of at least $2d$ from the wall where d is the diameter of the orifice. The orifice edge shall be free from burrs or irregularities and shall be rounded to a radius not greater than $d/10$. In concrete conduits, each pressure tap shall be located at the center of a corrosion-resistant plate at least 300 mm (12 in.) diameter, embedded flush with the surrounding concrete. Pressure taps shall be individually valved so they can be read separately. Pressure taps may be manifolded after the valve provided the manifold piping is not less

Fig. 4-3.15-1 Calibration Connections for Pressure Gages or Pressure Transducers



than 12 mm (1/2 in.) inside diameter when measuring devices other than pressure cells are used, and 6 mm (1/4 in.) inside diameter when pressure cells are used. All connections shall be leak-free. Care must be taken to ensure that all pressure-sensing lines are regularly bled and that no air has entered the system.

The condition of measurement, including velocity distribution, and condition of pressure taps shall be such that no pressure tap in the section of measurement shall vary in its reading from the reading of any other by more than 1% of the net head or 20% of velocity head at full gate and specified head, whichever is larger. If any pressure-tap reading appears to be in error, the source of the discrepancy shall be determined and removed, or the reading of the tap shall not be used in computing the head. At least two taps shall be used at each measurement section. If this is not possible, a new measurement section shall be selected, and an appropriate correction shall be made for the intermediate head loss. Pressure taps and connecting piping to the devices should be regularly flushed between runs.

4-3.15 Pressure Measurement

For the measurement of pressure, liquid manometers or deadweight gage testers shall be considered to be primary devices. Precision Bourdon gages or precision pressure transducers are secondary devices, and may be used for pressure measurements provided they are calibrated before and after the test against a primary device or an NIST-traceable transfer standard. It is recommended that the calibrations of all secondary devices be checked on-site before and after testing, and during testing if specified by the test plan or if requested by the chief of test. These on-site pre- and post-calibration checks are sufficient to meet the requirements of this paragraph so long as the calibration checks are made using primary devices or NIST-traceable transfer standards. It is advantageous to have a primary device or transfer standard connected in parallel with the secondary device so that at any time during the test, all parties may be satisfied that the gage readings or the recorded measurements are in agreement with the primary device (see Fig. 4-3.15-1 and para. 4-3.16). This is especially important if the test instruments must be shipped or exposed to potentially harsh environments between the test site and an off-site calibration facility.

4-3.16 Pressure Measurement With Running Calibration

Figure 4-3.15-1 shows a precision spring pressure gage or a precision pressure transducer connected in parallel with a deadweight gage (primary device) to the penstock through an interface vessel, so that at any time before, during, or after the test, all parties may be satisfied that the gage readings or recorded measurements are in agreement with the primary device. The interface vessel permits operation of the deadweight gage with the required oil and provides for operation of the gage or the transducer with oil at same temperature.

The two modes of operation, pressure measurement with the gage or the transducer, and calibration of the instruments with the deadweight gage, are obtained by switching valves. For pressure measurement, valves A and C are open and valves B, D, and E are closed. For instrument calibration, valves A, C, and D are closed; E is open; and valve B and sight glass are only used for checking the point of zero gage pressure. Valve D can be used either to release trapped air from the interface vessel or to fill the vessel and pressure line with oil. Valve B is used to relieve pressure in the vessel or adjust the interface level to the reference elevation.

An in-line calibration check does not need to include the point of zero gage pressure, nor does it need to cover the full instrument range. It must however, include a pressure, p_L, just below the expected test pressure(s) and a pressure, p_H, just above the expected test pressure(s). When used for pretest or post-test calibration, at least five calibration points shall be included. The applied weights and respective gage readings or transducer outputs are recorded, but the gage/transducer is not adjusted.

The instrument calibration is determined by a best-fit straight line fit to the calibration data. All calibrations and calibration checks should be evaluated and plotted as they are acquired. Should the difference between calibrations or calibration checks performed during the test program exceed acceptable limits, the causes of such difference shall be determined and eliminated, and the calibration procedure repeated.

4-3.17 Determination of Gravity

When using a deadweight tester or a pressure transducer, the determination of gravity should be made at the elevation of the tester's piston. If a mercury column is used, the mid-height of the column should be the elevation used to determine gravity.

4-3.18 Determination of Density of Water

In freshwater situations, the density of water may be determined by static water-level measurement or by use of standard tables of pure water density, such as those given in Table 2-3-4M, taking into account the following:

(a) average temperature of the water column

(b) compressibility at the mid-height of the water column

(c) dissolved and suspended solids

Water temperature must be periodically recorded to determine variations during the test.

When the test water is heavily silt-laden or brackish, the density of the water shall be determined by measurement. Pressure-measurement devices shall be used at the test site under static conditions to determine the conversion factor from units of measurement indicated by the device, to the value of the density of water. In determining the water density, the buoyancy effect of air must be considered. Since instrument problems and survey errors can influence this measurement, it is advisable to confirm this value by computation.

4-4 FLOW MEASUREMENT

4-4.1 Introduction

This Code describes the current meter, pressure–time, ultrasonic, and dye dilution methods of flow measurement, and the thermodynamic method of measuring efficiency. These methods meet the criteria of the Test Code Committee for soundness of principle, limits of accuracy available, and demonstrated application under laboratory and field conditions. It is expected that these methods permit the selection of at least one method of flow measurement suited to field conditions encountered in testing.

Flow-measurement methods of single current meters, acoustic time-of-flight, Doppler profiling, and acoustic scintillation in unit intakes are being evaluated for future versions of the Code but are not considered sufficiently developed or proven for inclusion at this time.

The current meter method (para. 4-4.2) measures velocities at several specified locations in a test section of closed conduits.

The pressure–time method (para. 4-4.3) measures the impulse resulting from the deceleration of flow in a closed conduit. The method is not suitable for pumping-mode tests.

The ultrasonic method (para. 4-4.4) is based on the principle that transit times of ultrasonic pulses propagated downstream are reduced by fluid velocity, while transit times of pulses propagated upstream are increased.

The dye dilution method (para. 4-4.5) involves the constant rate injection of a dye tracer into the flow stream, and drawing off samples downstream at a distance where mixing is complete. The dilution of the dye is proportional to the flow.

The thermodynamic method for efficiency determination is based on the water temperature difference measured across the machine. The temperature difference is proportional to efficiency losses. The flow rate is then computed from the efficiency and other measured variables. The thermodynamic method is specifically suitable for machines with heads in excess of 100 m (U.S. Customary equivalent). Due to the limited use and experience with this method in North America, details of this method are not included in this Code. If the thermodynamic method is desired to be performed either as the primary or secondary method, it is the recommendation of this Code to refer to the current version of IEC Standard 60041, *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps, and pump-turbines*, Chapter 14. "Thermodynamic method for measuring efficiency."

Any of the preceding methods of measuring flow rate may be used by mutual consent of the parties to the test, provided the guiding principles stated in Section 3 of this Code are observed. The method of measurement should be determined at the design stage of the power station so that the appropriate test appurtenances can be installed during construction.

4-4.2 Current Meter Method

The current meter method establishes the flow rate in a conduit by measuring velocities at discrete points (point velocities) in the flow section area. The measured point velocities are integrated over the measurement cross section to obtain the mean velocity, which when multiplied by the measurement section area determines the flow rate. Only flow measurement sections in closed conduits are considered. Measurement procedures in accordance with ISO 3354, *Measurement of clear water in closed conduits–velocity area method using current meters,* are recommended.

With respect to measurements in closed conduits, both circular and rectangular, the following points shall be observed for the measurement section:

(a) The velocity distribution shall, as nearly as possible, be that of fully developed turbulent flow in a straight conduit of uniform cross section.

(b) The mean velocity for any run shall not be less than 75% of the maximum velocity measured by any of the individual current meters.

(c) If the conduit is of lapped construction, the measurement plane should be in the smaller section.

(d) If the measurement section does not meet the requirements of (a) or (b), it is necessary to investigate for oblique or reverse flows using a flow directional sensing device such as a directional vane with an angular transducer. All velocity points must be included in the overall velocity calculation with the appropriate contribution. Points exceeding the current meter's maximum oblique angular capability will increase the estimate of the overall velocity uncertainty.

(e) Trashracks, support structures, and accumulated trash will also affect the velocity distribution and turbulence levels, and the effect must be evaluated. It is recommended the trash racks be cleaned prior to testing.

Ideally, all velocity measurements are made simultaneously. However, in large measurement sections, this is not practical due to the large number of meters required. Measurements with several current meters mounted on movable frames that can be repositioned at fixed locations between readings can be used.

However, when all velocity measurements are not made simultaneously, it is necessary to check for steadiness of flow during the sampling period using the Winter–Kennedy taps or another suitable method. For small variations in flow rate, the flow reference can be used to adjust all velocity measurements to the same reference flow rate.

The duration of measurement for each run shall be at least 2 min. Should the water velocity be subject to periodic pulsations, the duration of measurement shall include an even number (at least four) of complete periods of the pulsation.

The time measurement shall be accurate to at least 0.05%.

The current meters and their supports disturb the velocity distribution in the conduit. This leads to a positive error in the flow-rate measurement. The magnitude of this error depends on the number and type of current meters being used and the projected frontal area of the supports.

The flow rate, Q, corrected for blockage, is given by

$$Q = [1 - 0.125\,(S/A) - 0.03\,(S_m/A)]Q_{measured}$$

where

A = area of the measurement section
d_i = tip diameter of the propeller
n = number of current meters
S = frontal area of the support structure
S_m = propeller area $\left(\sum_{i=1}^{n} \pi d_i^2/4\right)$

The summation of area is for all current meters whether of the same or different tip diameters. An uncertainty of $\pm(1/12)(S/A)$ is introduced into the flow measurement by the supports. This may limit the amount of blockage that can be tolerated.

Only axial-flow electric-signaling current meters shall be used. The bearing arrangement and lubrication are of special importance, and care should be taken that waterborne solids should not enter the bearing, and corrosion or water hardness should not cause deterioration of the calibration. The effect of changes in water temperature shall be determined by calibration. It is recommended that meters be capable of detecting reverse flow.

All current meters shall be mounted with their axes parallel to the conduit axis. The mounting rods and meter attachments shall be stiff enough so that deflection and vibration caused by the flow are negligible. The minimum distance between the axis of any current meter and the conduit wall or the blade tip of any adjacent current meter shall be 0.75 times the blade tip diameter of the current meter.

The current meters shall be calibrated in a towing tank with the same type of mounting as used during the test. Where meters are closely spaced, the calibration shall include the effects of adjacent meters. The calibration shall include oblique flow up to 10 deg. In no case may the calibrated rating curve be extrapolated.

The current meters shall be inspected before and after the test. Any blade deformation or other defect subsequent to calibration shall require a recalibration of the meter at the request of any party to the test.

4-4.2.1 Uncertainty. The uncertainty in flow measurement using the Current Meter Method within the specifications of this Code is estimated to be within ±1.2% for conduits ranging in diameter from 1.2 m to 1.5 m (4 ft to 5 ft), and within ±1% for conduits larger than 1.5 m (5 ft) in diameter.

4-4.3 Pressure–Time Method

This method for measuring the flow rate is applicable where the water flows through a closed conduit of either uniform or converging cross section. It is based upon the relation between change of pressure in a section of the penstock and change of velocity of the volume of water contained in that section. The differential diagram application of the pressure–time method shall be used. Differential diagrams record the pressure variations between two measurement sections with no intermediate free surface points of relief and are affected only by the friction loss and change in momentum between the two sections. The effect of conduit friction loss outside of the differential test section, changes in intake or conduit friction, and changes in intake or surge tank-water levels are identical at both pressure measurement sections, and thus are eliminated from the differential-pressure readings.

This subsection describes the use of the digital form of the pressure–time method, which is the preferred method. The traditional method using the Gibson apparatus may still be used. Refer to PTC 18-2002 for details on the implementation of the traditional method.

The minimal condition for the use of this method is that the product of L and v shall not be less than 46.5, where L is the length between the two pressure-measurement sections in meters, and v is the mean velocity in the test section in meters per second when the machine is carrying full load. (The corresponding value in U.S. Customary Units is 500, where L is in feet and v is in feet per second.) Values of L shall exceed the larger of 10 m (33 ft) or twice the internal diameter of the conduit. Intakes with multiple passageways require that simultaneous independent pressure–time diagrams be taken in each passageway of the intake.

The leakage past the wicket gates or other closing device used in producing the pressure rise should be measured separately when the wicket gates or the closing device are in the closed position under the actual test head. If this is not possible, the leakage measured when the unit is at standstill shall be adjusted to the pressure drop across the wicket gates or closing device measured at the end of each pressure–time run. Such leakage, when adjusted to test conditions, shall not be greater than 2% of full-load flow rate, and the leakage measurement error shall not exceed 0.1% of full-load flow rate.

The areas of each of the two pressure-measurement sections and the distance between them shall be measured with sufficient precision to keep the total uncertainty of the flow measurement within test requirements. Construction-drawing dimensions shall be used only as a check on these measurements, not for calculations.

Four pressure taps, 3 mm to 9 mm (1/8 in. to 3/8 in.) in diameter, shall be installed at each measurement section in positions diametrically opposed and in a plane normal to the axis of the section. The four taps of each measurement section shall be valved individually. This may be accomplished at the pressure tap or at the manifold/pressure transducer. The pressure taps should be connected to the pressure transducer or manifolds using tubing that is as short as practical, and be at least 6 mm (1/4 in.) inside diameter. Connecting piping may be rigid or flexible, so long as the material and construction is nonelastic and nonexpanding, and it can be shown that the piping will convey the pressure signal without introducing damping in excess of that specified in para. 4-4.3.1(a). For this purpose, the connecting piping shall be considered to be a part of the transducer. If necessary, piping should be supported to prevent resonant mechanical vibration.

In circular conduits, the pressure taps at each measurement section shall be located at 45 deg to the centerline of the section. In rectangular conduits, the pressure taps shall be located at one-quarter and three-quarter heights on the vertical walls.

Two methods are acceptable for connecting the pressure taps to the pressure transducer: the manifold method and the separate-transducers method.

(a) In the manifold method, the pressure taps at a section are brought to a manifold for that section. To ensure that there is no pressure bias due to flow in the pressure-sense lines between pressure taps, either a triple-tee piping arrangement or a chamber-type manifold may be used to combine the pressure-sense lines. If a chamber-type manifold is used, the cross-sectional area of the manifold should be at least 10 times the combined area of the sense lines from the piezometer taps. This will ensure no significant pressure bias due to flow within the manifold will exist. The pressure transducer is connected to the manifolds using tubing that meets the requirements given above. To the extent practical, all pressure tap sense lines should be of equal length.

(b) In the separate-transducers method, each pair of taps (corresponding taps from the upstream and downstream sections) is connected to a separate transducer. The tubing used must meet the requirements given above, and, to the extent practical, all pressure-tap sense lines should be of equal length.

Flow conditions in the conduit shall be such that, at each measurement section, the difference between the pressure measured at any one tap and the pressure measured at all taps in the same measurement section shall not exceed $0.2v^2/2g$. The average of the readings from any pair of opposite taps shall not differ from the average of the other pair of taps in the same measurement section by more than $0.1v^2/2g$. This will require consideration of such items as velocity distribution, length of straight run of conduit, and wall conditions at the individual taps. Compliance with the velocity head criteria shall be required at three representative gate settings within the specified range and should also be checked at flow extremes to estimate flow-measurement accuracy outside this range.

Pressure readings shall be checked prior to beginning the test. If any pressure tap appears to be in error, the source of the error shall be determined and removed. If this is not possible, the nonconforming tap and its opposite shall be eliminated from the flow measurement. Not less than one pair of opposite taps shall be used at each measurement section. Spot checks of the velocity-head criteria shall be made immediately following the test to confirm compliance with the required criteria.

The flow rate that is to be measured in the conduit shall be set by limiting the movement of the wicket gates or other closing device in the opening direction at the desired position, preferably by means of mechanical blocks, without restricting the closing function for emergencies.

While the generator remains connected to the system, a pressure–time diagram shall be obtained by closing the wicket gates or other closing device in one continuous movement, recording the resultant change in pressure on the data-acquisition system. Other measurements necessary for each test run include fluid temperatures and the simultaneous recording of wicket-gate position.

The digital pressure–time method will normally record the pressure signal with a sufficiently high-frequency response such that excessive pressure noise in the penstock may make it impossible to accurately integrate the pressure–time diagram. Because of this possibility, it is advantageous to perform a preliminary pressure–time measurement well in advance of the formal testing for verifying that a suitable pressure signal can be obtained.

4-4.3.1 Differential Pressure Transducer. The following requirements shall govern the selection and use of the differential pressure transducer or transducers used for pressure–time testing:

(a) The response time of the transducer shall be less than 0.2 s.

(b) The full-scale volumetric displacement of the transducer shall be no more than 0.082 cm^3 (0.005 $in.^3$).

(c) The transducer shall have an uncertainty of no more than 0.25% of the expected peak signal, including the effects of hysteresis and linearity.

(d) The transducer shall be calibrated prior to and after testing using a manometer, dead weight tester, or transfer standard. It is recommended that this calibration be performed on-site, using the same wiring and data acquisition system as will be used during testing. Upon agreement of the parties to the test, a lab-certified transfer standard with an uncertainty of no more than 0.1% of the maximum expected signal may be used.

(e) Most differential pressure transducers will exhibit some change in calibration if the static or line pressure of the measurement is raised, even if the pressure differential across the transducer stays the same. If this static pressure effect on the transducer will lead to more than 0.2% uncertainty between calibration and test conditions, the transducer shall be calibrated at the average static pressure expected during the tests.

(f) If the effect of a change in ambient temperature between calibration and test conditions will lead to more than 0.2% uncertainty in the transducer calibration, the transducer shall be maintained at a temperature close enough to the calibration temperature to achieve an ambient temperature effect of less than 0.2% uncertainty.

(g) Calibration and span adjustment of the differential pressure transducer shall include allowance for negative pressure differentials that will be experienced during a pressure–time test.

(h) Any signal conditioning or pressure damping device used in the hydraulic circuit with the differential pressure detector must be applied with caution to ensure that the characteristics of the device do not alter the method. All signal conditioning, including hardware or software filtering or smoothing, shall be approved by all parties to the test.

(i) In the case of an undamped sensing element, the natural frequency of the transducer shall be at least 10 times greater than the maximum frequency expected in the pressure signal.

(j) No over-range or under-range of the transducer shall be present in the integrated portion of the pressure–time signal.

4-4.3.2 Data-Acquisition System. The following requirements shall govern the selection and use of the data-acquisition system used for pressure–time testing:

(a) The differential pressure signal shall be sampled at a rate of at least 100 samples per second.

(b) The data-acquisition system shall have an uncertainty of no more than 0.1% of the maximum value of the acquired signal.

(c) The timing uncertainty of the samples shall be such that the sample intervals vary by no more than 0.1%.

4-4.3.3 Acquisition of the Pressure–Time Signal

(a) Data acquisition must commence sufficiently in advance of the start of gate closure and continue sufficiently long after completion of gate closure to allow accurate delineation of the running and static lines. As a general rule, acquisition of the pressure–time signal should start at least 10 s before the start of gate closure and should continue for at least 20 s after gate closure. Preliminary tests should be performed to ensure that these intervals are adequate. These intervals should be re-evaluated as the testing progresses.

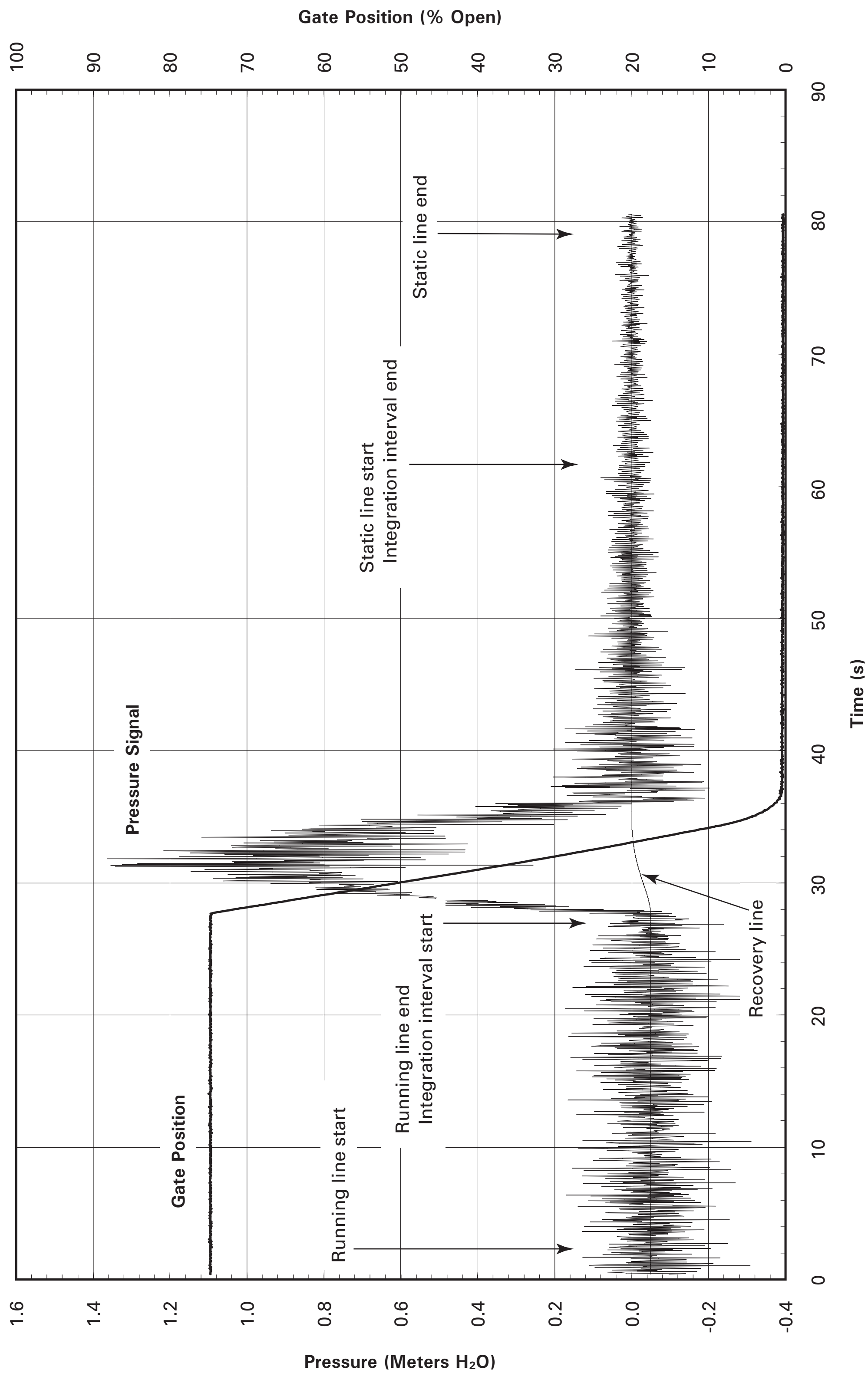
(b) Every differential pressure signal sample value shall be stored permanently in its raw form and made available to all parties to the test.

(c) The criteria to be used for discarding spurious test data shall be agreed to by the parties to the test. The digital system shall keep a record of all data rejected and the reason why they were rejected.

(d) It is recommended that the wicket-gate position be recorded and displayed with the pressure–time signal. This will facilitate delineation of the pressure–time diagram.

4-4.3.4 Delineation of the Pressure–Time Diagram. An example of a typical digital pressure–time signal is shown in Fig. 4-4.3.4-1.

Fig. 4-4.3.4-1 Example of Digital Pressure–Time Signal



4-4.3.4.1 Running Line Delineation. The starting point on the running line is chosen 10 s to 30 s before gate closure. The point chosen should have a pressure value close to the midpoint of the peaks in the running line interval (i.e., near the average).

The ending point on the running line should have a pressure value close to the midpoint of the peaks (i.e., near the average), and be close (within a pressure wave cycle or two) to the point at which the wicket gate position signal shows the start of wicket gate closure.

4-4.3.4.2 Static Line Delineation. The starting and ending points on the static line should be chosen at a point in the trace after complete wicket gate closure in which no mean pressure oscillations are apparent. These points should have a pressure value close to the midpoint of the peaks in the static line interval (i.e., near the average). A static line length of 10 s to 20 s will generally be sufficient.

4-4.3.4.3 Integration Interval Delineation. The starting point of the integration interval should be the same as the ending point of the running line interval. The ending point of the integration interval should be the same as the starting point of the static line interval.

4-4.3.5 Integration of Digital Pressure–Time Signal. Paragraphs 4-4.3.5.1 and 4-4.3.5.2 describe the analytical background and implementation for determination of discharge by integration of a pressure–time signal obtained using digital data-acquisition methods.

The discharge-computation computer program shall be based on the principles of numerical integration described in the paragraphs below.

The computer program with all relevant information shall be made available for review by the parties to the test.

The test report shall include a copy of the graphical presentation of the pressure–time signals showing the running, recovery, and static lines, and the start and end points for the integration.

4-4.3.5.1 Analytical Description of Numerical Integration. The fundamental pressure–time integral is given by

$$Q_i - Q_l = \frac{gA}{L}\int_{t_i}^{t_f}(h+l)dt$$

where

A = average penstock area
g = local acceleration of gravity
h = pressure-head difference between piezometer tap planes at local conditions
L = distance between piezometer tap planes
l = pressure loss due to friction between piezometer tap planes
Q_l = flow rate after completion of wicket gate closure (leakage flow)
Q_i = flow rate prior to wicket gate closure (i.e., flow to be measured)
t = time
t_f = end of integration interval
t_i = beginning of integration interval

Also, the following variables for this analysis are defined:

h_f = static (final) line average head at local conditions
h_i = running (initial) line average head at local conditions
ρ = density of water

The relationship between pressure and head (water column at local conditions) is given by

$$\Delta p = \rho g h$$

In the above equation, h is measured in terms of local water column (i.e., in meters or feet of water at local temperature, pressure, and gravitational acceleration). An appropriate conversion of the pressure difference, Δp, to the desired pressure units may be required. If a water manometer is used for calibration, a correction for the difference in density due to temperature between the calibration water and the test water may be necessary.

The pressure recovery term, l, is assumed to follow a fully turbulent velocity-squared pressure law as follows:

$$l = f\frac{L}{D}\frac{Q(t)^2}{2gA^2} = -\frac{h_i}{Q_i^2}Q(t)^2$$

where

$$-\frac{h_i}{Q_i^2} = f\frac{L}{D2gA^2} = k = \text{Constant}$$

By agreement of the parties to the test, a power of less than two on the flow term may be used in the pressure-recovery law, so long as appropriate adjustments are made to all subsequent equations in the following paragraphs.

4-4.3.5.2 Numerical Integration of Pressure–Time Integral. The pressure–time integral based on the above pressure recovery relationship is given by

$$Q_i = \frac{gA}{L}\int_{t_i}^{t_f}\left[\left(h-h_o\right)-\frac{h_i-h_f}{Q_i^2-Q_l^2}Q(t)^2\right]dt + Q_l$$

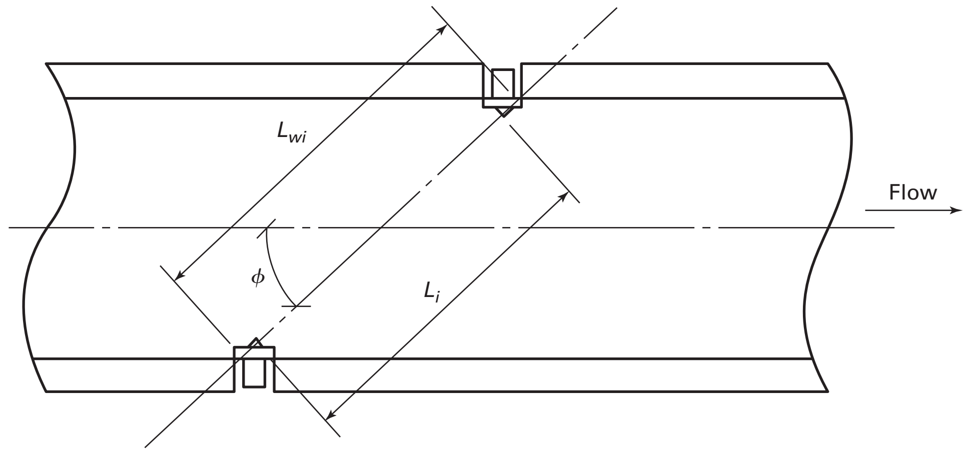
where

$$h_o = \frac{Q_i^2 h_{mf} - Q_l^2 h_{mi}}{Q_i^2 - Q_l^2}$$

Q_i = initial flow rate (measured flow)

A derivation of this integral is given in Nonmandatory Appendix E. This integral may be integrated numeri-

Fig. 4-4.4.1-1 Ultrasonic Method: Diagram to Illustrate Principle



L_{wi} = distance across the conduit from wall to wall across chordal paths
L_i = distance in the fluid along chordal path between transducers
ϕ = angle between acoustic path and the direction of water flow

cally using a trapezoidal or higher-order integration scheme. Because the initial flow rate appears on both sides of the equation, an iterative solution procedure must be employed.

Numerical evaluation of this integral proceeds as follows:

Step 1: An estimate for the value of the flow before gate closure Q_i is made.

Step 2: Using the assumed value for Q_i, the integral of the above equation is evaluated for each point in the pressure–time data series, until $Q(t_f)$, the final flow value at $t = t_f$, is obtained.

Step 3: If $|Q(t_f) - Q_1| \leq 0.001Q_i$, then convergence has been achieved, and the value of Q_i used in the integration is the flow rate obtained by the pressure–time integration. If convergence is not achieved, these steps are repeated.

Because the integral involves the flow, $Q(t)$, quadratically and on both sides of the equation, a quadratic solution for $Q(t)$, at each time step is preferable. If a converging solution cannot be achieved using a quadratic solution, then the value of $Q(t)$ from the previous time step may be used in the pressure-recovery term in the pressure–time integral.

4-4.3.6 Uncertainty. The uncertainty in flow measurement using the Pressure–Time Method within the specifications of this Code is estimated to be within ±1.0%.

4-4.4 Ultrasonic Method

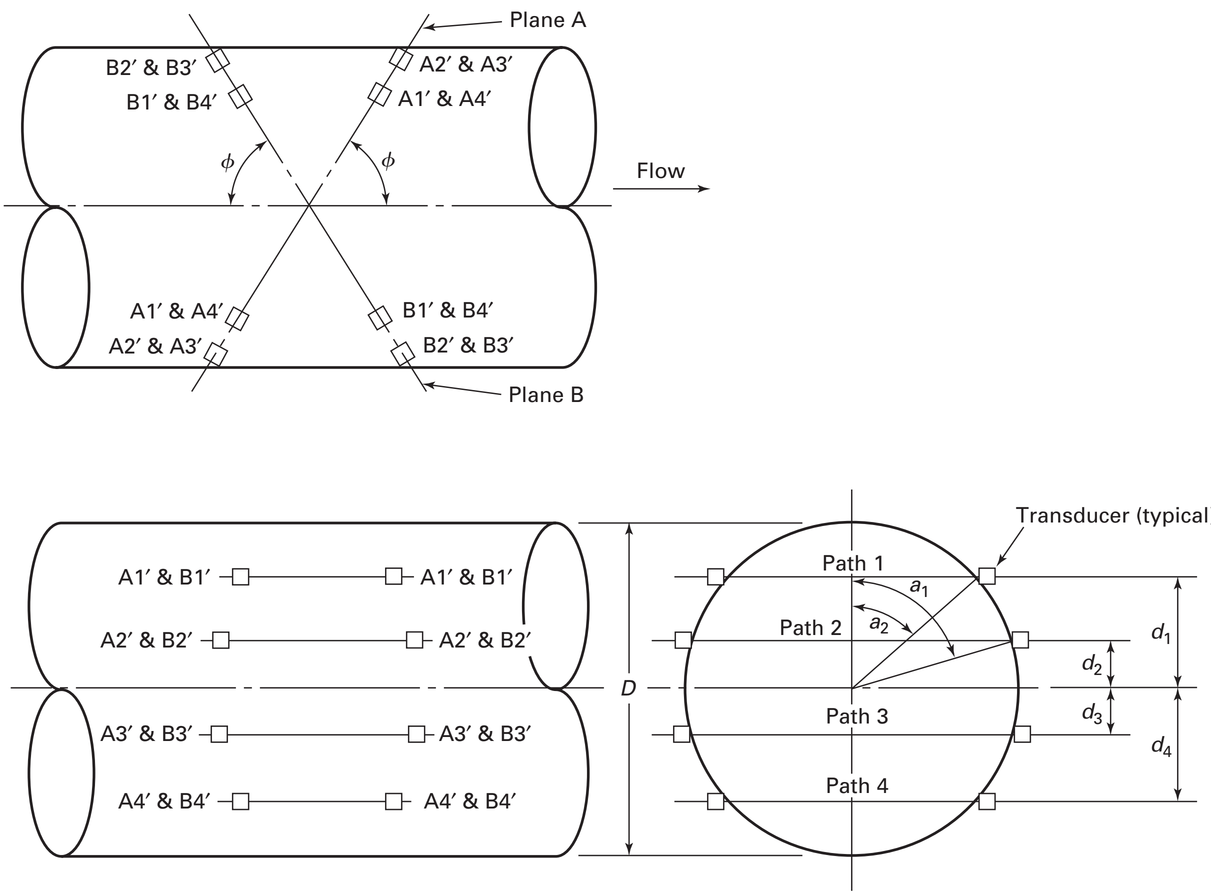
4-4.4.1 General. This method of flow rate measurement is based on the principle that the ultrasonic pulse transit times along chordal paths are altered by the fluid velocity. An ultrasonic pulse sent upstream travels at a slower speed than an ultrasonic pulse sent downstream (see Fig. 4-4.4.1-1). By measuring separately the transit times of pulses sent in the two directions, the average velocity of the fluid crossing the path of the pulse is determined vectorially.

Many transit-time measurements are required to establish an average and to minimize the random error for each run. The fluid velocity is determined by suitable integration of the individual velocity measurements.

The ultrasonic flow rate measurement equipment includes transducers (used alternately as transmitter or receiver) installed in the measurement section and electronic equipment to operate the transducers, make the measurements, process the data, and display or record the results. It should also include a verification program to ensure that the equipment, including software, is functioning properly.

Several methods of ultrasonic flow measurement exist, but not all have demonstrated that they are capable of achieving the accuracy required for field performance tests. Methods acceptable to this Code are based on the measurement of the transit time of ultrasonic pulses in each of two crossed measurement planes, although in some cases one plane may be used (see Fig. 4-4.4.1-2).

Fig. 4-4.4.1-2 Ultrasonic Method: Typical Arrangement of Transducers for an 8-Path Flowmeter in a Circular Conduit



Excluded from this Code are devices based on the measurement of the refraction of an ultrasonic beam by fluid velocity, and devices that measure the Doppler frequency shift of an ultrasonic wave reflected by the flowing water or by moving particles. In this Code, the application of the ultrasonic method is limited to closed conduits of uniform cross section, either circular or rectangular.

4-4.4.2 Circular Conduits. In circular conduits, the application of ultrasonic methods using two planes with four chordal paths each has been demonstrated to measure the flow rate with an accuracy acceptable under this Code (see Fig. 4-4.4.1-2).Two planes are used to reduce the systematic uncertainty due to transverse flow components. The arrangement and location of these chords shall permit the use of recognized numerical integration methods as shown in Table 4-4.4.2-1.

4-4.4.3 Rectangular Conduits. Similarly, the use of the above-described methods in conduits of rectangular cross sections are expected to provide flow rate measurements of acceptable accuracy provided the paths are located so that recognized numerical integration methods may be applied (see Fig. 4-4.4.3-1). In Table 4-4.4.2-1, values for the location of the paths for two recognized numerical integration methods are shown.

4-4.4.4 Distortions of Velocity Profile. A systematic error due to transducer protrusion into the flow is introduced and shall be considered in an uncertainty analysis. The uncertainty depends on the Reynolds number and the shape of the transducer mount (projecting or recessed):

(a) the local distortion of the velocity profile, along the chordal path, as it is disturbed by flow over the protruding transducer assembly

(b) incomplete sampling of the velocity along the chord that arises from the transducer not being flush mounted in the conduit (see Fig. 4-4.4.4-1)

These effects tend to be in opposite directions (undersampling of the velocity profile overestimates flow and velocity-path disturbance, creating a low bias) but do not typically cancel completely. Combined bias errors have been estimated to undervalue the flow rate by 0.35% for 1-m path lengths to 0.05% for 5-m path lengths. The systematic error for any installation is highly dependent on

Table 4-4.4.2-1 Integration Parameters for Ultrasonic Method: Four Paths in One Plane or Eight Paths in Two Planes

Legendre Method			Jacobi–Gauss Method		
Method	4(8) path			4(8) path	
Chordal Path, l	Weight, w_i	Position, d	Chordal Path, l	Weight, w_i	Position, d
1	0.34786	0.86114	1	0.3693	0.8090
2	0.65215	0.33998	2	0.5976	0.3090
3	0.65215	−0.33998	3	0.5976	−0.3090
4	0.34786	−0.86114	4	0.3693	−0.8090
Shape factor k	Circular section 0.994 Rectangular section 1.0000			Circular section 1.00 Rectangular Section 1.03425	

GENERAL NOTE: Where the weight (w_i) is applied to the ith path at the position d that corresponds to the ratio of the chord elevation to the radii or height of the water passage channel ($D/2$).

the transducer design and may vary from the above values. When the ratio of the protrusion of the transducer to the path length exceeds 0.25%, then validated CFD analysis or hydraulic laboratory testing of the transducer must be performed. Correction factors and the associated uncertainty, including the shape and design of the transducer, shall be documented.

Other factors, including mounting apparatus, may alter the flow streamlines in the vicinity of the meter section. Experience has shown that piping for signal cables attached to the conduit along the circumference of the conduit alters the flow streamlines when placed either upstream or downstream of the internally mounted transducers. Circumferential runs of such piping shall be placed a minimum of one conduit diameter downstream of the meter section when the ratio of the diameter of the conduit to the piping is 50 to 1. When smaller ratios exist (i.e., smaller conduit diameters), the piping should be placed further downstream. In the case of a pump-turbine, the circumferential conduit run shall be placed a minimum of two conduit diameters from the center of the meter transducer section.

4-4.4.5 Theory and Operating Principles. Since flowmeters used in the Ultrasonic Method measure only transit times of pulses between transducers, it is necessary that the flowmeter system utilize appropriate methods and techniques to minimize errors due to

(a) timing delays in cables
(b) timing errors due to cables of unequal length
(c) internal timing delays
(d) timing errors due to signal processing
(e) delays in the nonwater portion of the acoustic path (transducer material and face or window)

The above delays in the electronic circuitry and cables and the times for the ultrasonic pulse to traverse any nonwater parts of the ultrasonic path, shall be determined and taken into account.

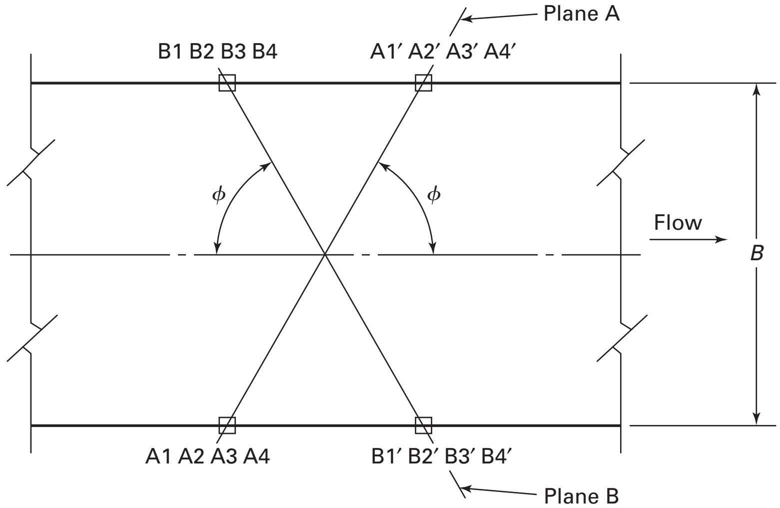
If the requirements for ultrasonic flow rate measurement equipment in para. 4-4.4.1 are fulfilled, then by measuring the transit time of an ultrasonic pulse along a given path in both the upstream and downstream directions, the flow measurement will be independent of the water's composition, pressure, and temperature.

To measure transit time along a given path, the transducers are arranged so that pulses are transmitted upstream and downstream at an angle relative to the axis of the pipe (see Fig. 4-4.4.1-2). Angles from 45 deg to 65 deg have been shown to be satisfactory for ultrasonic flow rate measurement methods.

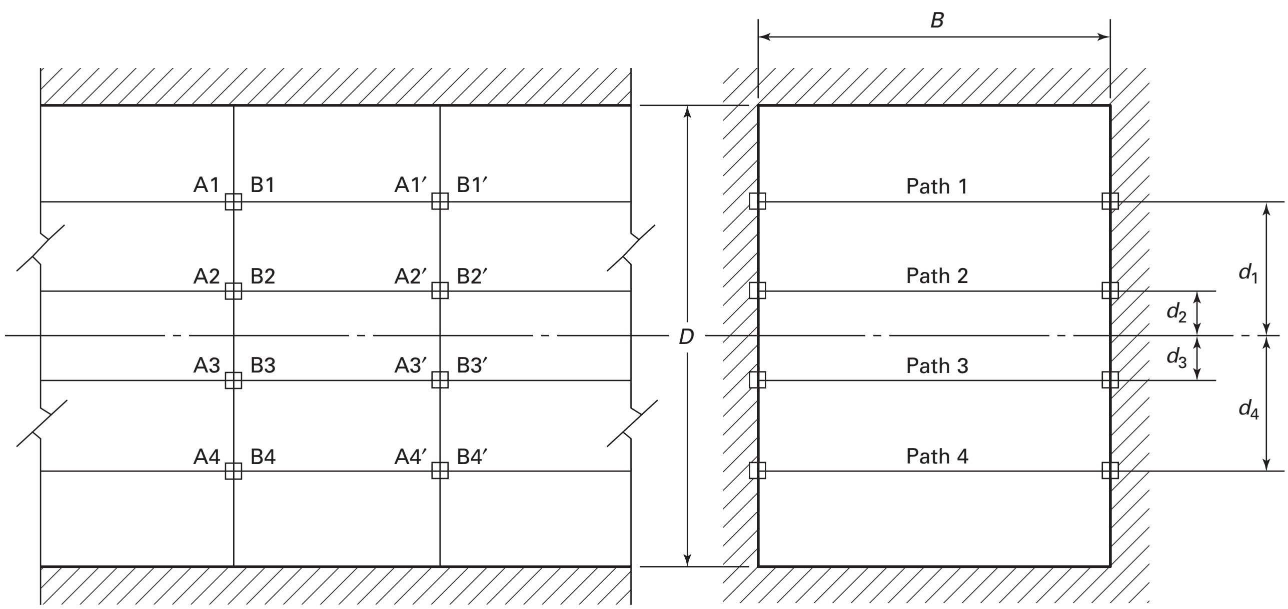
If there are no transverse flow components in the conduit, and if the time delays referred to in (a) through (e) above are taken into account, the transit time of an ultrasonic pulse is given by

$$t = \frac{L}{c + EV\ \cos\Phi}$$

Fig. 4-4.4.3-1 Ultrasonic Method: Typical Arrangement of Transducers

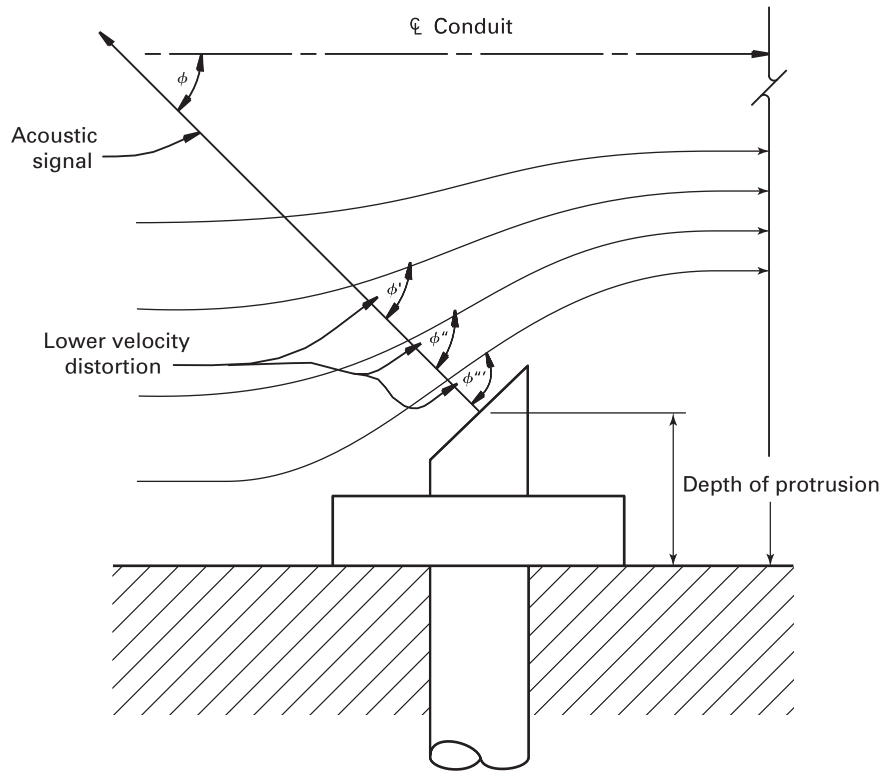


Plan



Elevation **Section**

Fig. 4-4.4.4-1 Distortion of the Velocity Profile Caused by Protruding Transducers



where

c = speed of sound in the water at the operating condition, m/s (ft/sec)

E = +1 for signals traveling downstream
= −1 for signals traveling upstream

L = distance in the water along chordal path between the transducer faces, m (ft)

V = mean axial component of the flow velocity over distance L, m/s (ft/sec)

Φ = angle between the longitudinal axis of the conduit and the measurement planes, deg

Since the transducers are generally used both as transmitters and receivers, the difference in transit time may be determined with the same pair of transducers. Thus, the mean axial velocity crossing the path is given by

$$V = \frac{L}{2\cos\Phi}\left(\frac{1}{t_d} - \frac{1}{t_u}\right)$$

where t_d and t_u are the transit times of an ultrasonic pulse downstream and upstream, respectively.

If there are transverse flow components, then

$$t = \frac{L}{c + E(V\cos\Phi + YV_c\sin\Phi)}$$

where

V_c = transverse component of the flow velocity having a component parallel to the acoustic path and averaged over the distance, L

Y = factor equal to +1 or −1 depending upon the direction of the transverse component of the flow parallel to the chordal path, and depending upon the orientation of the chordal path (i.e., path in Plane A or B in Fig. 4-4.4.1-2). For a given transverse flow component, $Y = \pm 1$ for a chordal path in Plane A, and ± 1 for a chordal path in plane B.

The average axial velocity crossing a path is given by

$$V = -YV_c(\tan\Phi) + \frac{L}{2\cos\Phi}\left(\frac{1}{t_d} - \frac{1}{t_u}\right)$$

With two measurement planes as in para. 4-4.4.2, the velocities are averaged, and the errors due to transverse flow are eliminated because the term $(-YV_c \tan \Phi)$ cancels.

The flow rate, Q, can be obtained from the general equation

$$Q = \frac{kD}{2}\sum_{i=1}^{n} W_i V_i L_{wi} \sin \Phi$$

where

- D = dimension of the conduit parallel to the intersection of the two measurement planes, as shown in Figs. 4-4.4.1-2 and 4-4.4.3-1
- k = numerical integration correction coefficient (shape factor) that accounts for the error introduced by the integration technique chosen for the shape of the conduit
- L_{wi} = distance across the conduit (wall to wall) along the chordal path, i, m (ft)
- n = number of chordal paths
- V_i = average velocity along path, i, as calculated from measured transit times, m/s (ft/sec)
- W_i = weighting coefficients depending on the number of paths and the integration technique used

In a rectangular conduit of uniform cross-section, ($L_{wi} \sin \Phi$) is equal to the width, B, of the measurement section (see Fig. 4-4.4.3-1).

The inherent difficulty of some integration techniques to integrate over sections of different configuration requires a shape factor, k, to be used. See Table 4-4.4.2-1. (Table 4-4.4.2-1 provides weighting coefficients, w_i, chordal path positions, d_i; and k factors for four acoustic paths in one plane.)

The velocity profile may be distorted by a bend. When two planes are used, the intersection of the two measurement planes shall be in the plane of the bend to minimize the effects of the transverse flow components on the accuracy of the measurement. Individual measurements of velocity shall be made for each path in order to obtain an indication of any distortion in the velocity profile and the magnitude of any transverse flow components. When one plane is used, it shall be oriented in the same manner as described above for two planes.

4-4.4.6 Turbine-Mode Tests. For turbine-mode tests using four paths in each of two planes, there shall be a straight length of at least 10 conduit diameters between the measurement section and any major upstream irregularity. However, experience has shown that the accuracy stated in the last paragraph of 4-4.4 can be obtained with four paths in each of two planes as close as five diameters downstream of smooth elbows not exceeding 55 deg turning angle, and with a ratio of elbow radius to conduit diameter of at least three.

There shall be a straight length of at least three conduit diameters between the measurement section and any important downstream irregularity.

When the above conditions cannot be met, more acoustic paths are required to achieve the accuracy required in this Code. Figures 4-4.4.6-1 and 4-4.4.6-2 and Table 4-4.4.6-1 can be used when piping configurations do not permit sufficient upstream and downstream conditions. The degree of perturbation on velocity distribution is highly dependent on the severity and proximity of upstream piping changes. It is very difficult to predict the influence of valves, bifurcations, elbows of differing angle, and/or manifolds upstream of the acoustic meter and the velocity distribution. If significant swirl or nonaxial flow components arising from the upstream conditions exist, then 18 acoustic paths in two planes should be used.

4-4.4.7 Pump-Mode Tests. In the pump mode, the discharge velocity profile is not axisymmetric when the measurement section is close to the pump discharge. The velocity profile becomes more symmetric as the measurement section is located away from the runner. There can also be rotational-flow components in the pump discharge. These effects are canceled by measurement using a flow meter with two crossing planes.

Generally, when a distance of 10 or more conduit diameters between the pump discharge and measurement section is not practical, then nine acoustic paths in each of two planes should be used for flow rate measurement.

4-4.4.8 Factors That May Cause Asymmetry of the Velocity Profile. Although the use of two planes compensates for most transverse velocity components, the measurement section shall be chosen as far as possible from any disturbances that could cause asymmetry of the velocity profile, or swirl. Upstream factors that may produce transverse velocity components or distortion of the velocity profile include

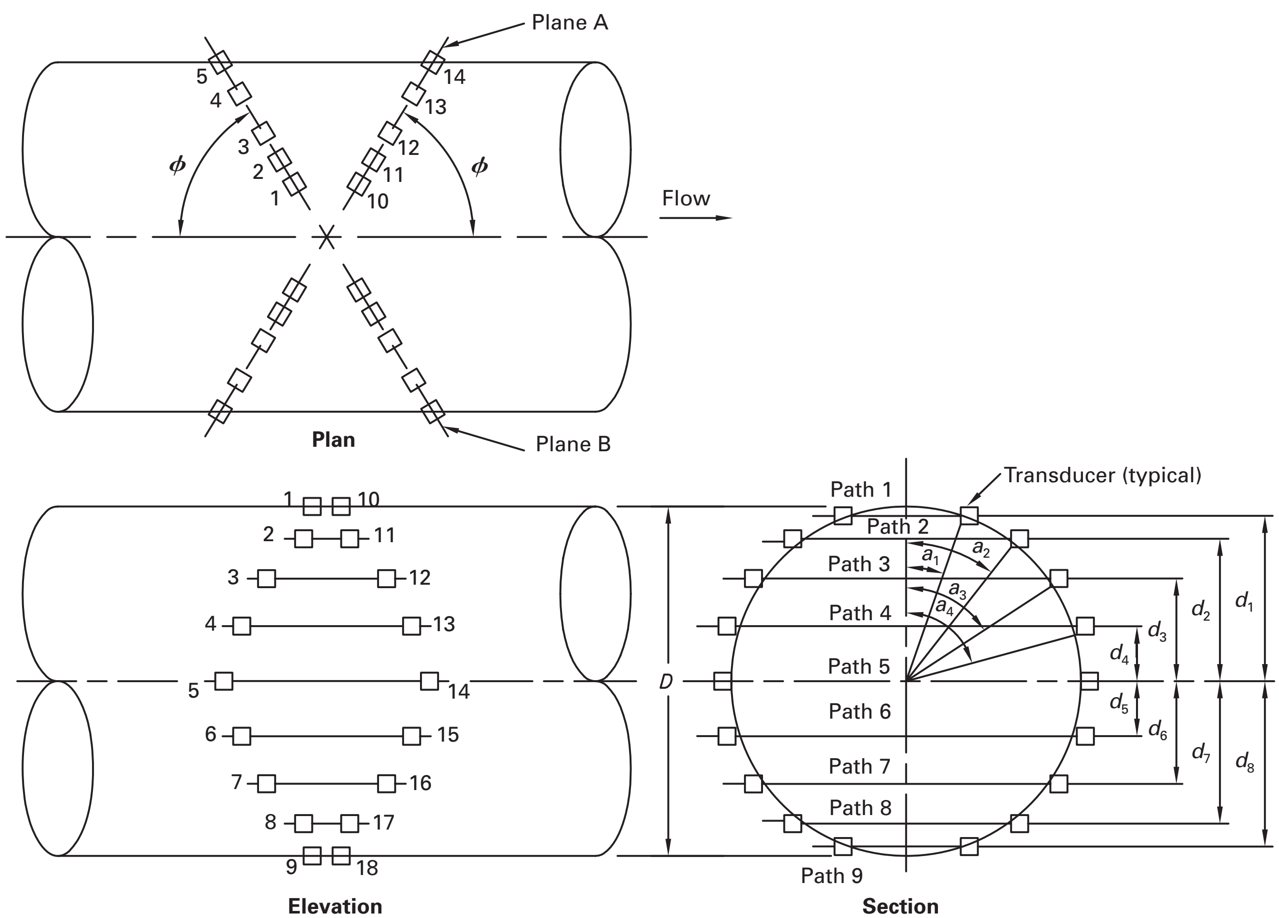
(a) intake shape
(b) type and number of bends
(c) changes in conduit diameter
(d) placement of valves, taps, and bifurcations
(e) pump-generators operating in pumping mode

When the above conditions cannot be met, more acoustic paths or other techniques, such as modeling, may be required to achieve the uncertainty limits of this Code. When such conditions exist, the flowmeter manufacturer shall propose, and all parties shall agree on, an appropriate configuration or correction.

4-4.4.9 Using 18 Acoustic Paths. Figures 4-4.4.6-1 and 4-4.4.6-2 and Table 4-4.4.6-1 illustrate application of the Ultrasonic Method using two crossed planes of nine paths each.

4-4.4.10 Integration Methods. The Gauss–Legendre and the Jacobi–Gauss quadrature integration methods meet the requirements of this Code. At least four chordal paths in each plane shall be used for a proper determination of the flow rate. For a four-path arrangement, the location of the paths and the weighting coefficients for

Fig. 4-4.4.6-1 Ultrasonic Method: Typical Arrangement of Transducers for an 18-Path Flowmeter in a Circular Conduit



the Gauss–Legendre and Jacobi–Gauss quadrature integration methods are as shown in Table 4-4.4.2-1. When conditions do not permit sufficient straight length of penstock, up to 18 acoustic paths in a crossed plane arrangement can be used.

When the Jacobi–Gauss method is applied to a circular section with the paths located at the specified distance from the center, the general formula is often used in the simpler form

$$Q = \frac{D^2}{2} \sum_{1}^{n} W'_i V_i$$

where

$$W'_i = W_i \frac{L_{wi} \sin \Phi}{D}$$

For four paths

$W'_1 = W'_4 = 0.217079$
$W'_2 = W'_3 = 0.568320$

and for nine paths

$W'_1 = W'_9 = 0.00300$
$W'_2 = W'_8 = 0.10854$
$W'_3 = W'_7 = 0.20562$
$W'_4 = W'_6 = 0.28416$
$W'_5 = 0.31416$

$L_{wi} \sin \Phi = D \sin \alpha_i$ where α_i defines the angular location of path ends relative to the direction along which D is measured (see Fig. 4-4.4.1-2).

4-4.4.11 Transducer Installation. Transducer positions and conduit dimensions shall be accurately measured in the field. The uncertainties in the measurements shall be accounted for in the analysis in para. 4-4.4.15. Installation of transducers and measurement of as-built pipe dimensions and transducer locations shall be done according to manufacturer-approved methods. Installation personnel shall be experienced with, or under the direct supervision of personnel experienced with, the installation of multiple parallel-path ultrasonic flow measurement systems in hydroelectric applications.

Special care shall be taken when measuring large conduits that may not have perfectly symmetrical shapes. A representative average diameter shall be determined in

Fig. 4-4.4.6-2 Ultrasonic Method: Typical Arrangement of Transducers for an 18-Path Flowmeter in a Rectangular Conduit

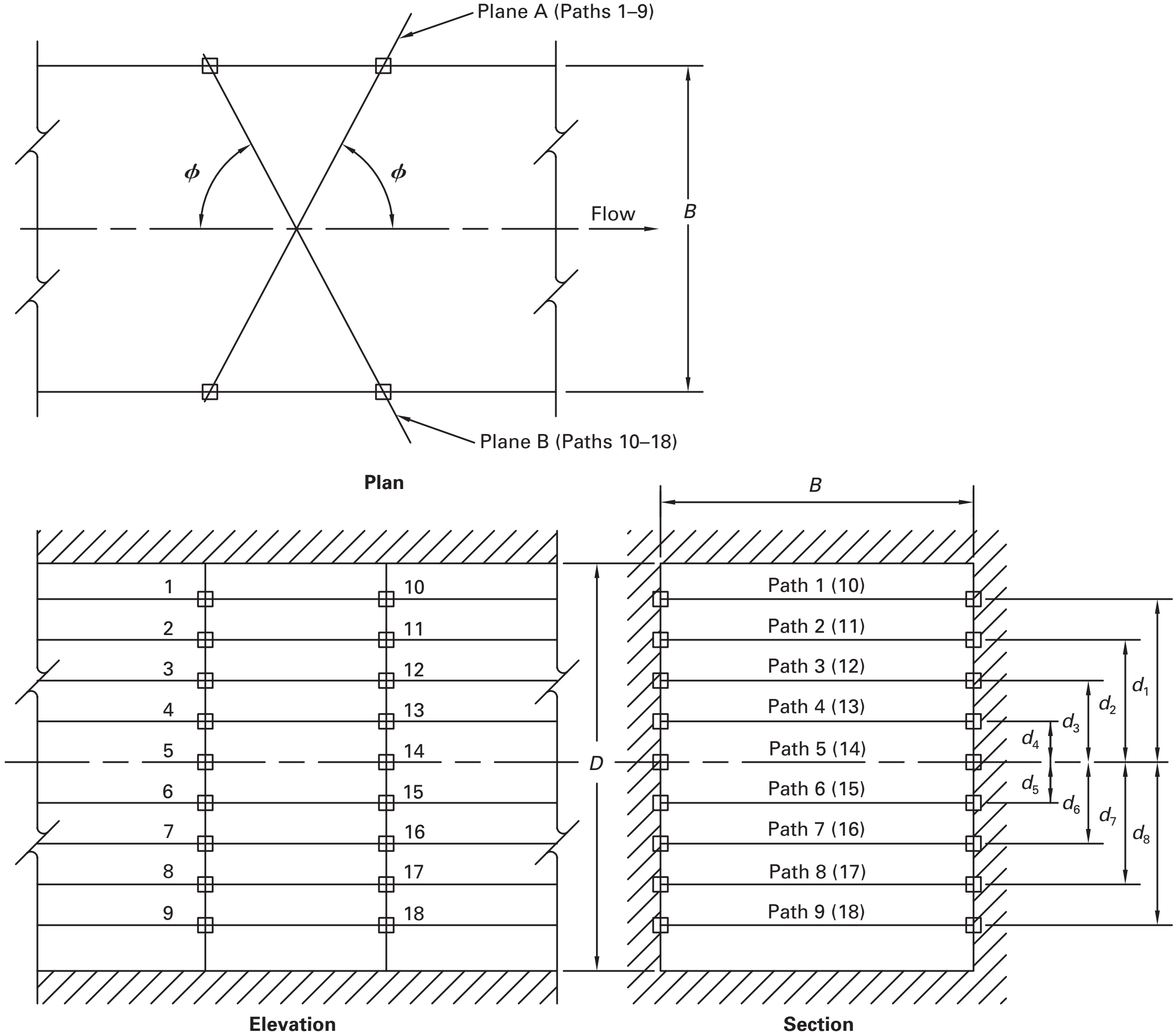


Table 4-4.4.6-1 Integration Parameters for Ultrasonic Method: 18 Paths in Two Planes

Legendre Method			Jacobi–Gauss Method		
9(18) path			9(18) path		
Chordal Path, I	Weight, w_i	Position, d	Chordal Path, I	Weight, w_i	Position, d
1	0.08127	0.96816	1	0.09708	0.9511
2	0.18064	0.83603	2	0.18466	0.8090
3	0.26061	0.61337	3	0.25416	0.5878
4	0.31234	0.32425	4	0.29878	0.3090
5	0.33023	0	5	0.31416	0.0000
6	0.31234	−0.32425	6	0.29878	−0.3090
7	0.26061	−0.61337	7	0.25416	−0.5878
8	0.18064	−0.83603	8	0.18466	−0.8090
9	0.08127	−0.96816	9	0.09708	−0.9511
	Circular section 0.9994 Rectangular section 1.0000			Circular section 1.00 Rectangular section 1.0083	

GENERAL NOTE: Where the weight(w_i) Is applied to the i^{th} path at the position d that corresponds to the ratio of the chord elevation to the radii or height of the water passage channel ($D/2$).

the measurement section, perpendicular to the direction of the measurement paths as shown in Fig. 4-4.4.11-1. At least five equally spaced diameter measurements shall be taken including one at the center of the measurement section and one at each end (see Fig. 4-4.4.11-1). These measurements shall be averaged to be representative of the dimension, D. A sufficient number of other measurements shall be taken to determine the shape of the conduit for the purpose of determining the effect of the conduit shape on the numerical integration correction coefficient, k.

Accurate measurements of the dimension, D; the chordal path lengths, L, between transducer faces; path lengths, L_w, between the wall of the conduit along the chordal paths; the location of the acoustic paths; and their angles relative to the center of the conduit are to be used in the calculation of the flow rate.

Errors in transducer locations shall be incorporated in the uncertainty analysis.

4-4.4.12 Differential Travel Times. The product of v and D shall be large enough to permit an accurate determination of the difference in pulse transit times, taking into account the accuracy of the timer. Measurements with flow velocities that produce low differential travel times shall be measured with electronics that have timing resolution better than 1 in 10 000.

4-4.4.13 Checks of Equipment. Provision in the design and construction of the flow meter shall be made for checking that the equipment is operating correctly. This shall permit such checks as

(a) showing pulses and their detection on an oscilloscope

(b) internal electronic tests of the program, variables, and constants necessary to evaluate the proper calculation of velocities and flow from measured travel times

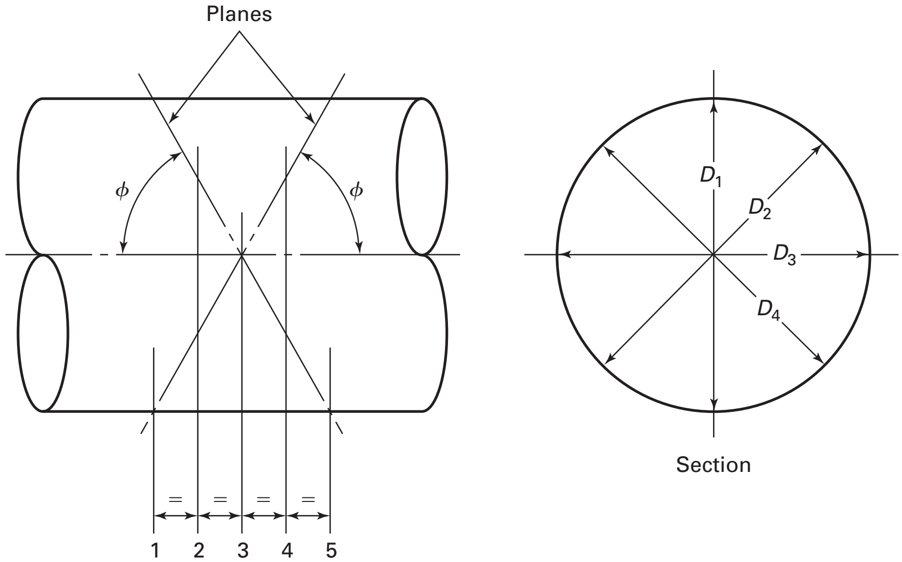
(c) comparison of calculated values of the speed of sound using the measured chordal path transit times and path lengths with published values as a function of water temperature and pressure

(d) measurement of the average velocity along each path

It is desirable to measure the ultrasonic pulse transit times independently and compare them with the results given by the measurement system.

4-4.4.14 Disruption of the Ultrasonic Flow Measurement. Bubbles, sediment, and acoustic noise may disrupt the operation of the ultrasonic flow measurement system and should be avoided. If the disruption results in missed samples, enough valid samples shall be obtained to be compatible with the assumptions used in the error analysis. The design of the data acquisition and data processing system shall provide for the

Fig. 4-4.4.11-1 Locations for Measurements of *D*



checking of the proportion of lost pulses. The design and construction of the flow meter shall include

(a) signal recognition and amplification capability

(b) signal quality analysis and reporting or display capability

(c) signal timing and rejection capability

(d) appropriate signal and mathematical filtering

(e) timing circuitry self-test routines

(f) internal electronic tests of the program and constants

(g) comparison of calculated values of the speed of sound using the measured chordal path transit times and path lengths with published values corrected for water temperature

(h) measurement of the average velocity along each path

4-4.4.15 Uncertainty. Both random uncertainties and systematic uncertainties shall be taken into account. For a detailed analysis, see PTC 19.1. The following sources of uncertainty have been identified:

(a) measurement of path lengths, L_i and L_{wi}

(b) measurement of chordal path angles

(c) measurement of path spacing and conformity with the positions prescribed

(d) measurement of D

(e) time measurement and time resolution

(f) nonwater path time estimation

(g) internal computational precision

(h) error due to flow distortion around the transducers

(i) error due to change in dimensions when the conduit is pressurized or undergoes a thermal expansion or contraction

(j) existence of transverse flow components

(k) flow profile distortions

(l) spatial variations of speed of sound

(m) spatial variation of flow velocity along the conduit

(n) fluctuations of flow velocity and speed of sound

Paragraphs (a) through (i) are usually calculated and combined into an instrument systematic error. This systematic error for paras. (j) through (m) shall be estimated and combined with the instrument systematic error in a root-sum-square relationship to produce an overall systematic error. Paragraph (n) is associated with fluctuations and random uncertainty.

The uncertainty in flow measurement using the Ultrasonic Method within the specifications of this Code is estimated to be within ±1%.

4-4.5 Dye Dilution Method

4-4.5.1 Principles of the Method. The dye dilution method involves injecting a dye at a known constant rate into the flow to be measured. The concentration of the dye in the flow is measured at a point sufficiently downstream of the injection point for complete mixing to have occurred. The flow rate is proportional to the dilution undergone by the dye. The recommended dye for this method is the fluorescent dye Rhodamine WT. This dye is detectable and stable in very low concentrations, nontoxic, resistant to adsorption, readily soluble, not usually present in natural water systems, and its fluorescence is proportional to its concentration in water, which can be accurately measured with a fluorometer.

The mass balance equation for the dye injected into the flow is

$$qC_1 + QC_0 = (q + Q)C_2$$

where
C_1 = concentration of injected dye
C_2 = concentration of diluted dye in flow
C_o = background concentration of dye in flow
Q = flow rate to be determined
q = dye injection rate

Noting that C_1 is much greater than C_2 (usually by a factor of 10^7), this equation can be rearranged to yield

$$Q = q\frac{C_1}{(C_2 - C_0)}$$

It is not practical to measure the concentration of the injected dye C_1 directly due to its extremely high concentration. A measure of this concentration can be determined by precisely diluting a sample of the injected dye until it is in the range of the test sample to produce a standard to which test samples will be compared. The injected dye concentration is then given by

$$C_1 = D_s \cdot C_s$$

where
C_s = concentration of the standard (i.e., the precisely diluted injection dye)
D_s = dilution factor of the standard

The flow equation can now be written

$$Q = qD_s\frac{C_s}{C_2 - C_0}$$

Because the fluorescence of a sample is directly proportional to the dye concentration, the flow to be determined is given by

$$Q = qD_s\frac{F_s}{F_t}$$

where
F_s = fluorescence readings of the standard
F_t = fluorescence readings of the test sample

It is not necessary to determine the actual concentrations. Only the ratio of the fluorescence of the standard to the fluorescence of the test sample is required.

Figure 4-4.5.1-1 shows a schematic representation of the dye dilution technique.

4-4.5.2 Five Steps. There are five steps in executing the dye dilution method, presented as follows:

(a) selecting the injection and sampling points
(b) preparing the dye injection solution and standards
(c) injecting and measuring the injection rate of the dye
(d) collecting samples of diluted dye
(e) analyzing the concentration of the diluted dye samples and calculating the flow

4-4.5.2.1 Selecting the Injection and Sampling Points. The injection system must be designed to ensure that the dye is completely mixed with the flow at the sampling section. Paragraph 4-4.5.2.5 gives a procedure to determine whether adequate mixing is occurring.

The selection of the injection system depends on accessibility to the conduit and on the inherent mixing occurring in the conduit between the injection and sampling points. Mixing is aided by bends and obstructions in the flow stream. For a single-point wall tap injection, up to 200 diameters of straight conduit may be required. See Fig. 4-4.5.2.1-1 for additional guidance.

Where the conduit is not long enough to provide thorough mixing for a single injection point, mixing can be improved by using a multi-orifice injection manifold; high-velocity injection normal or backwards into the flow stream; or turbulence generators located downstream of the injection point.

In the case of the pumping mode of pump-turbines, a convenient injection point is into the draft tube, either through the draft-tube access door or a manifold within the tailrace water passage. The flow into the pump casing also provides additional mixing.

Injecting outside of the water passages or water conduits directly connected to the machine, e.g. upstream from a machine intake or downstream from a machine discharge, is not permitted due to possible recirculation and consequential loss of dye.

It is important to ensure that there is no flow path where concentrated dye can leave the main flow prior to the dye being fully mixed. The entire injection system should be protected from sunlight as much as possible.

4-4.5.2.2 Preparing the Injection Solution and Standards. Rhodamine WT is usually supplied in concentrated form, requiring some pre-dilution before injection. Although any concentration of injection dye may be used, in practice the strength of the injection mixture and the rate of injection are selected to achieve between 5 ppb and 10 ppb in the test sample, providing the optimum concentration for Rhodamine WT for detection by the fluorometer, while at the same time staying below the limit typically permitted in the environment (check with regulating authority). The injection solution should be prepared using water from the system under test. It is critical that this water be collected in a manner that avoids any possible contamination (collect prior to start of test). This ensures that any background fluorescence or other influence affects the standard and the test sample equally. Tap water containing chlorine should not be used because chlorine reduces the fluorescence of the dye. If the system water is turbid, the suspended sediment should be allowed to settle, and the clear water

Fig. 4-4.5.1-1 Schematic Representation of Dye Dilution Technique

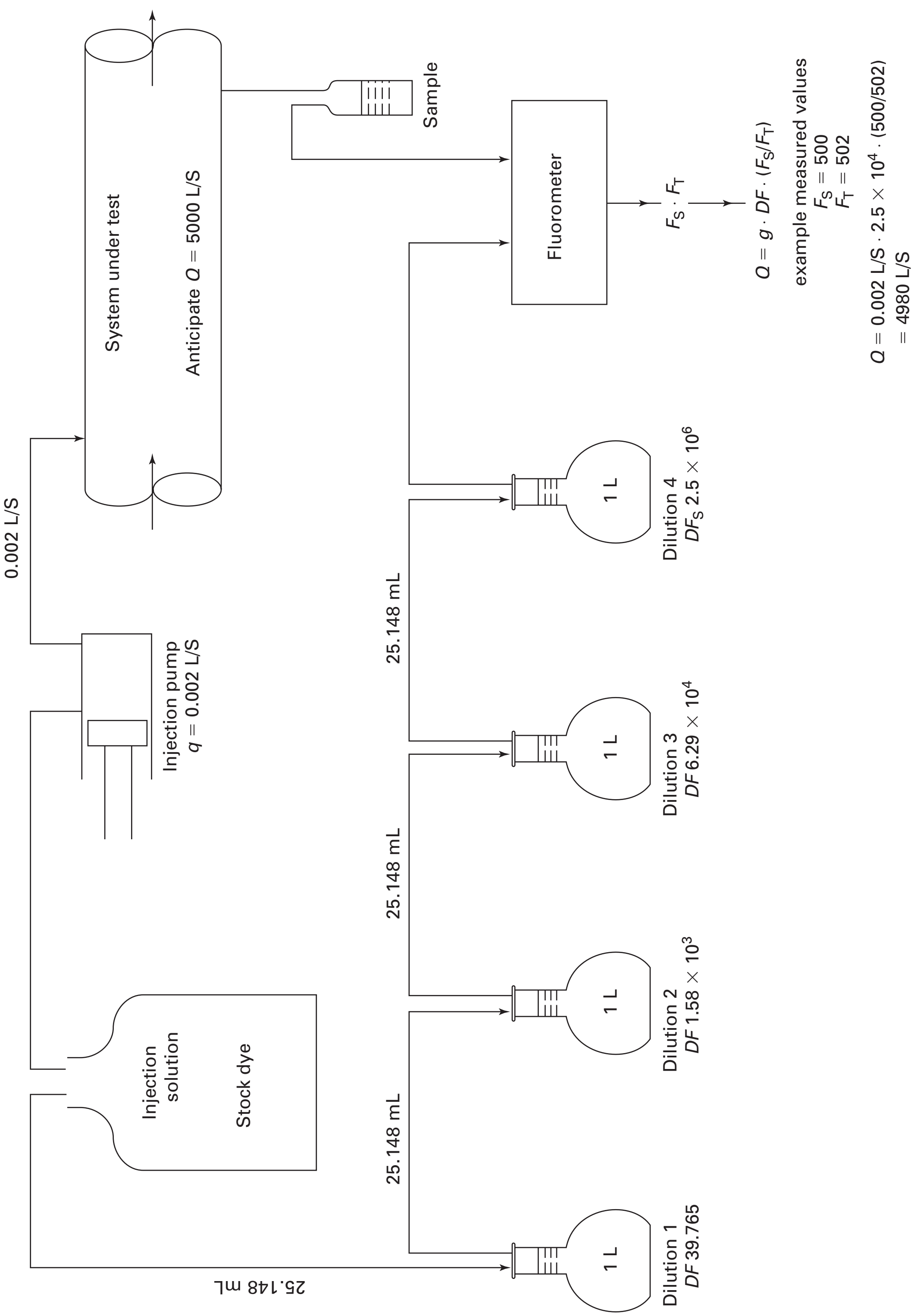
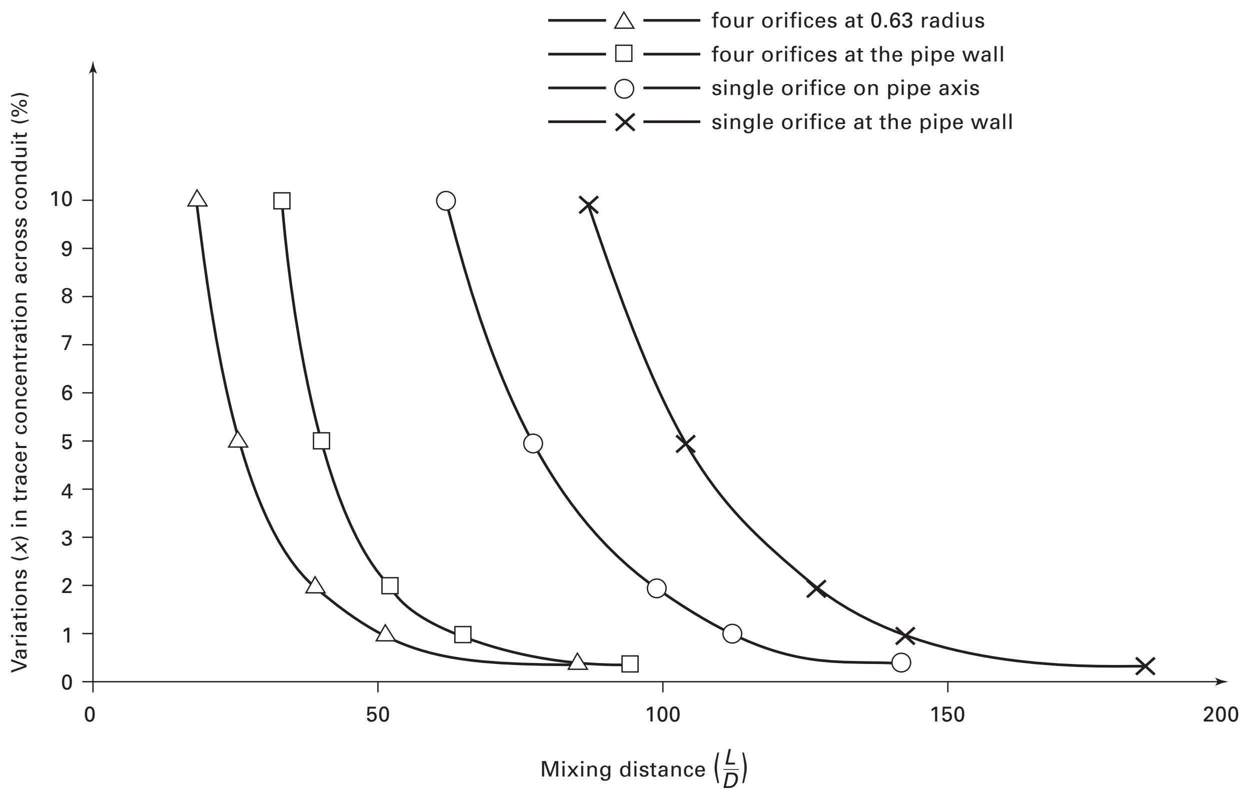


Fig. 4-4.5.2.1-1 Experimental Results: Allowable Variation in Tracer Concentration



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should be decanted and used for the injection solution. Sufficient solution should be prepared to supply a full series of tests, and the solution should be stored in a clean, inert, nonadsorptive, light-proof, sealable container. It is advisable to prepare the injection solution in a separate container from the supply container.

Care must be taken to ensure that the injection mixture is fully homogeneous. This can be obtained by vigorous mixing with a mechanical stirrer or a closed circuit pump. The mixture must be stirred frequently and thoroughly prior to each injection.

Figure 4-4.5.1-1 shows a typical arrangement of standard preparation. The standards are prepared to be near the expected final mixed dilution of 5 ppb to 10 ppb. At least two separate sets of standard solutions should be prepared and compared to the test sample for analysis.

The diluted dye concentration and dilution factor have a linear relationship. However, when a large range of flow rates is to be measured, the use of a constant injection mixture and the use of sets of standards prepared to match the expected test sample concentration are recommended.

The standards should be prepared in an environment conducive to precise measurement of dye and water quantities and the avoidance of contamination. The standards must be prepared with the same injection solution used in the test runs.

The target dilution factor is

$$D_S = \frac{Q}{q}$$

Because this value is typically on the order of 10^7, standards are prepared by serial dilution, in which successive solutions are diluted in turn until the required overall dilution factor is obtained.

A four-serial dilution is usually performed, in which the target D for each step is

$$D = (Q/q)^{0.25}$$

The dilutions can be performed gravimetrically or volumetrically. It is essential that no contamination from a higher concentration solution enters a lower concentration solution, and accurate measurement in each step must be made. Rigid adherence to sound laboratory practice must be followed.

4-4.5.2.3 Injecting and Measuring the Injection Rate of the Dye. The dye must be injected at a constant rate with minimum pulsations. This may be accomplished by using a precision positive displacement pump, such as a gear, peristaltic, or piston pump, driven by a synchronous motor to ensure constant speed. A variable rate pump is useful to allow proportioning of the injection rate with the flow rate to be measured.

Injection rates of dye are typically on the order of 1 mL/s to 10 mL/s to minimize the volume of dye required when many injections are made during a test series. If the distance between the pump and the injection point is large, resulting in a long transit time, the dye may be injected into a secondary flow that transports the dye to the injection point in the main flow. The transport water flow rate must be relatively constant. It is not necessary to know the flow rate of the transport water because that water is added to the system and makes up part of the total volume being measured.

The duration of injection must be long enough so that a steady concentration of at least several minutes duration is established at the sampling cross-section. A suitable injection duration is determined by trial injections.

The injection rate must be measured by a primary method, either volumetric or gravimetric. The volumetric method would be by timing the filling or emptying of a volumetric flask. The gravimetric method would be by timing the weight change due to filling or emptying of a container. Because the dye dilution method is volumetric, the gravimetric method must also take into account the specific weight of the dye during the calibration. The calibration must be conducted using a dye mixture at the same concentration used during the test injections. When a precision pump is used, calibration before and after the test is acceptable. Otherwise, the injection rate must be calibrated for each test run. The calibration must provide an uncertainty in injection rate no greater than 0.25%, including the uncertainty of the volumetric flask or weigh scales and the timing device.

The injected dye delivery system should shield the dye from exposure to direct sunlight.

4-4.5.2.4 Collecting Samples of the Diluted Dye. The sampling point must be located far enough downstream from the injection location to ensure that both spatial and temporal variations in dye concentration are less than 0.5%. This must be confirmed by analysis of preliminary trial runs at least at maximum and minimum test flow rates before the official tests proceed.

The sampling system should shield the collected samples from exposure to direct sunlight.

The spatial variation of dye concentration across the conduit at the sampling cross-section is determined by taking samples from at least four points, using either a probe sampling across the conduit diameter or radial taps on the conduit wall. The variation among the samples must meet the following criterion:

$$\left(\frac{1}{\overline{X}}\right)\frac{t_{n-1}\,(S)}{\sqrt{n}} \leq 0.5\%$$

where

n = number of samples
S = standard deviation of fluorescence of n samples
t_{n-1} = Student's t coefficient for 95% confidence
$\overline{X}$ = mean fluorescence of n samples

If this criterion is not met, improvements must be made to increase the mixing process, by means such as increasing the mixing length, increasing the number of injection points, adding turbulence generators, or using high velocity injection.

When it is confirmed that the spatial variation is satisfactory, the individual sampling points may be joined together in a manifold. Equal flow from each point must be ensured.

The temporal variation of dye concentration at the sampling location is measured by analysis of repeated sample fluorescence data taken while monitoring during the sampling period. The variation of the fluorescence must meet the following criterion:

$$\left(\frac{1}{\overline{X}}\right)\frac{t_{n-1}\,(S)}{\sqrt{n}} \leq 0.5\%$$

where

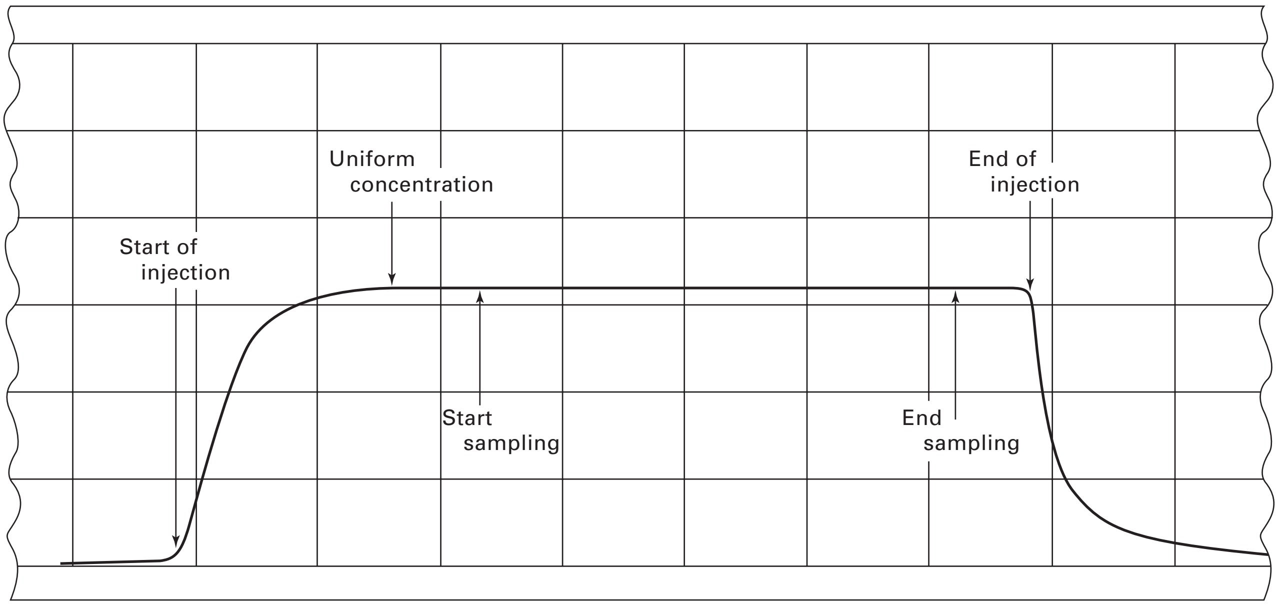
n = number of recorded fluorescent values
S = standard deviation of recorded fluorescence values
t_{n-1} = Student's t coefficient for 95% confidence
$\overline{X}$ = mean of recorded fluorescent values

If this criterion is not met, the duration of the sampling period or the mixing in the conduit must be increased.

During the sampling process it is necessary to monitor the increase in concentration as the dye passes the sampling point. This gives direct confirmation that the dye concentration has fully developed and is stable prior to and during sample collection. Figure 4-4.5.5-1 shows a typical chart trace.

A continuous sample of water from the sample point (at least 4 L/min) is bled from the system and passed through a monitoring fluorometer and then to a drain downstream from the sample point. As the injected dye passes the sampling point, the fluorescence is monitored by chart recorder or data acquisition system. When the dye concentration is steady, a sample is directed to a collecting bottle for later analysis. Sample

Fig. 4-4.5.5-1 Typical Chart Recording During Sampling



bottles should be laboratory quality, clean, and opaque to light. For analysis by Method A described in para. 4-4.5.3, at least 1 L of sample should be collected. The bottles should be stored away from light until the analysis is conducted.

The sample should be collected throughout the steady period of the dye concentration. Sufficient sample volume should be collected to allow for spare samples, if repeat analysis is necessary. Where the sampling site is not suitable for analysis procedures, the samples can be transported to another location.

A procedure for a flow-through analysis by Method B is presented in para. 4-4.5.2.5.2.

4-4.5.2.5 Analyzing the Concentration of the Diluted Dye Samples and Calculating the Flow. The flow is calculated using the equation given in para. 4-4.5.1 as follows:

$$Q = q \cdot D_s \cdot \left(\frac{F_s}{F_t} \right)$$

The fluorescence intensity of Rhodamine WT is dependent on temperature according to the following equation:

$$F_c = F_m \cdot e^{0.026(T_s - T_r)}$$

where

F_c = corrected fluorescence at reference temperature T_r (°C)

F_m = measured fluorescence at sample temperature T_s (°C)

NOTE: An exponent value of 0.026 may be used as an initial trial value. However, it is recommended that the value for each fluorometer be experimentally determined.

The temperature of the test sample and the standard solution must be within 0.2°C of the same temperature when each is analyzed. If it is not possible to achieve a temperature difference within 0.2°C, the fluorescence of the samples must be corrected to the same temperature before comparison.

Analysis of the sample may be performed in either of two ways as noted in paras. 4-4.5.2.5.1 and 4-4.5.2.5.2.

4-4.5.2.5.1 Analysis Method A. The fluorometer is equipped with a special glass cuvette into which the sample is placed for analysis. Sufficient sample should be collected to allow at least six fillings of the cuvette plus a backup set. The test sample bottles and standards bottles should be placed in a circulating water bath to equalize temperature to within 0.2°C, and the bottles should remain there throughout the analysis procedure. The temperature monitoring should be conducted in bottles containing dummy samples collected from the flow stream at the same time as the samples.

The fluorescence of the test sample and the standard solution is measured by inserting a cuvette of each, in turn, into the fluorometer and recording the value. The period of time the samples and standards remain in the cuvette of the fluorometer for analysis must be consistent since the bright light of the fluorometer heats up the sample. This should be repeated at least six times and an average value should be obtained. Increased repetition of analysis reduces the uncertainty in the estimate of the true dye concentration. Six repetitions usually provide sufficient accuracy without unduly lengthening the analysis process.

4-4.5.2.5.2 Analysis Method B. The fluorometer is equipped with a flow-through measuring cell, and the sample is circulated through the cell from either the sample bottle or directly from the system under test. As the sample passes through the measuring cell, its fluorescence and temperature are automatically measured, and the fluorescence level is adjusted to a predetermined reference temperature. This data is then transmitted to a data logger. The circulation loop must be flushed thoroughly with the sample before beginning the data collection. Approximately one-third of the sample should be used for flushing. The sample should be measured at least every 5 s for a duration of at least 1 min. The temperature should be measured within ±0.1°C.

The standard solutions are analyzed using the same procedure, adjusting their measured fluorescence to the same reference temperature as the test sample. The standard solutions must be analyzed immediately before or after the test sample.

The advantage of this method is that analysis is rapid, and the sample and standards are less susceptible to contamination due to repeated handling. However, larger samples are required than with Method A, and the larger samples may be more difficult to transport to another location for analysis if conditions at the sampling site are not suitable.

4-4.5.3 Accuracy. The accuracy of the dye dilution method is dependent on several factors, including

(a) accuracy of the dye injection rate
(b) homogeneity of the injection mixture
(c) completeness of mixing at the sampling location
(d) accuracy of measurement of sample and standard fluorescence
(e) fluorescence temperature correction of sample and standard
(f) accuracy of the weight and volume measurements in the preparation of the standards

4-4.5.4 Uncertainty. The uncertainty in each of the above parameters should be evaluated for contributions from systematic and random sources. The recommended maximum combined uncertainty in each parameter is listed below.

(a) injection rate: 0.25%
(1) systematic: accuracy of instruments used to calibrate injection pump
(2) random: statistical variation in pumping rate measured by repeated calibrations of injection pump
(b) homogeneity of injection mixture: 0.25%
(c) completeness of mixing: 0.5%, spatial and temporal variation as defined in para. 4-4.5.2.5.
(d) measurement of sample and standard fluorescence: 1.25%
(1) systematic: accuracy of fluorometer, readout should not be less than 50% full scale
(2) random: variation in repeated measurement of each sample and standard can be reduced by performing additional measurements
(e) fluorescence temperature correction of sample and standard: 0.5%, maximum 0.2°C temperature difference between sample and standard
(f) measurements in calculation of dilution factor of standard: 0.25%, accuracy of weigh scales, volumetric flasks, specific weight of solutions

The overall uncertainty in flow measurement is reduced by increasing the number of standards used in the comparison to sample.

The uncertainty in flow measurement using the Dye Dilution Method within the specifications of this Code is estimated to be within ±1.5%.

4-5 POWER MEASUREMENT

4-5.1 Indirect Method

Power output from the turbine or power input to the pump shall be determined by the indirect method.

The indirect method utilizes electrical measurements of power output from the generator or input to the motor, the previously determined generator or motor losses, and appropriate corrections for the operating conditions during the test.

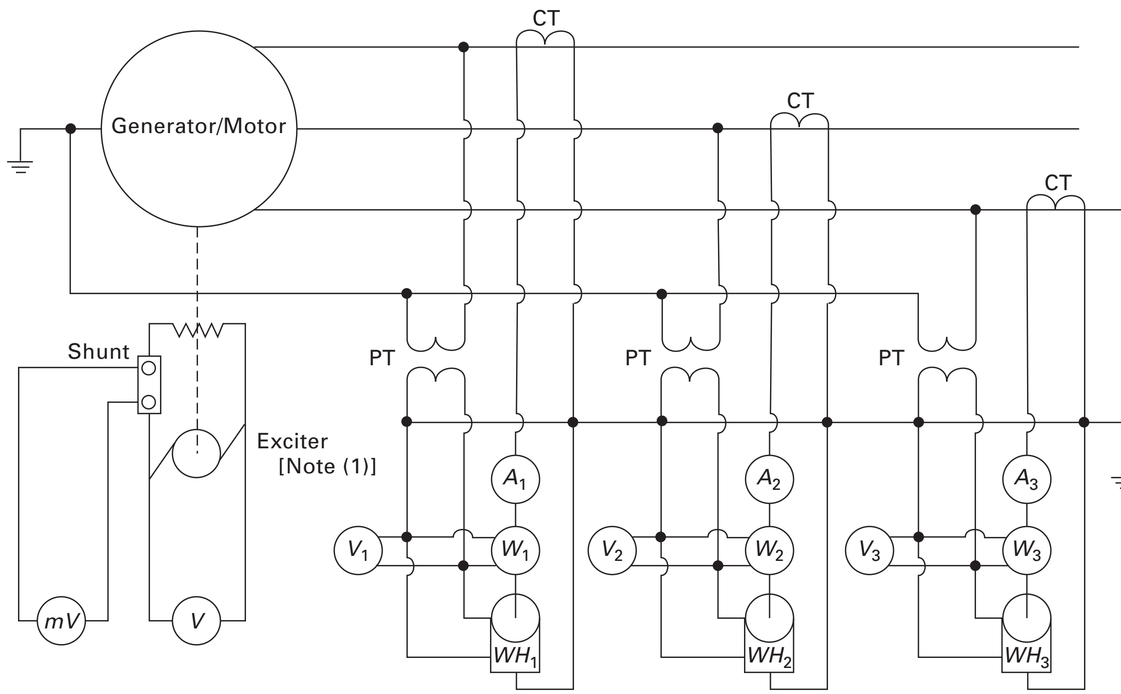
In the indirect method, the generator or motor is utilized as a dynamometer for measuring the power output from the turbine or the power input to the pump. Turbine power output is then determined by adding the generator losses to the measured generator power output, and pump power input is determined by subtracting the motor losses from the measured motor power input. The generator or motor losses shall have been previously determined, for the conditions such as output, voltage, power factor, speed, direction of rotation, and temperature expected during the test of the turbine or pump.

All losses specified in Institute of Electrical and Electronics Engineers (IEEE) Standard 115, Test Procedures for Synchronous Machines, shall be determined. The I^2R losses so determined shall be corrected for the temperature, armature current, and field current measured during the performance test.

The power supplied to separately driven generator auxiliary equipment, such as excitation equipment, motor driven cooling fans, and motor driven or circulating pumps is frequently supplied from other power sources rather than directly from the turbine. If these losses are included in the total losses for the generator, they shall be determined separately and excluded.

Measurement of effective power output at the generator terminals or effective power input at the motor

Fig. 4-5.1-1 Three-Wattmeter Connection Diagram



NOTE:
(1) If mechanically connected exciter is used.

terminals shall be made in accordance with IEEE Standard 120, Electrical Measurements in Power Circuits.

During the turbine or pump test, the generator or motor shall be operated as near to specified voltage and unity power factor as existing conditions permit. Should the voltage be other than specified and/or the power factor be other than unity, suitable corrections in the computation of the power output or input and losses shall be made.

The power shall be measured by means of wattmeters or watt-hour meters. Subsequent reference in this Code to wattmeters shall include watt-hour meters as an equivalent substitute.

The connections, which are used for reading power, depend on the connections of the generator or motor. If the neutral of the generator or motor is brought out and is connected to the network or to ground during the test, the three-wattmeter connection as in Fig. 4-5.1-1 shall be used. If the neutral is brought out, but not connected to the network or to ground during the test, a three-wattmeter connection, similar to Fig. 4-5.1-1 with the neutral connected to the potential transformer primary neutral, or the two-wattmeter connection for measuring three phase power (Fig. 4-5.1-2), shall be used. The three-wattmeter method affords simpler and more nearly correct calculation of corrections of ratio and phase angle errors of the instrument transformers and for scale corrections of the wattmeters or registration errors for the watt-hour meters if such corrections are required.

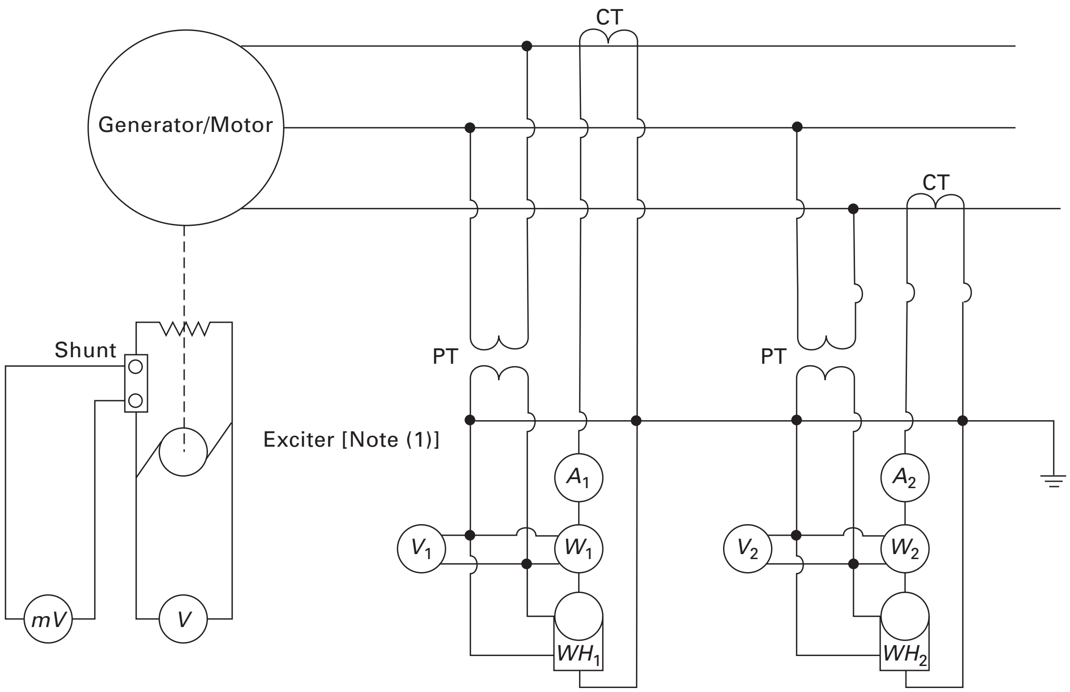
If the neutral is not available, the two-wattmeter method shall be used for measuring three-phase power. One point of each secondary circuit shall always be connected to a common ground as shown in the figures.

Proper corrections shall be made for temperature effects in the instruments. In cases of excessive temperature variation, an enclosure shall be used to ensure suitable temperatures for the instruments.

The indicating instruments shown in Figs. 4-5.1-1 and 4-5.1-2 give a check on power factor, load balance, and voltage balance, and show the proper connections to be applied so that power output and losses may be accurately determined.

If the power output or input is measured by indicating instruments, the number of readings shall depend upon the duration of the run and the load variations. Sufficient readings shall be taken to give a true average of the output or input during the run, and, in case of the pressure–time method of flow-rate measurement, prior to when the wicket gates or other closing devices begin to close. Simultaneous readings of the wattmeters are recommended. If the power output or input is measured by rotating standard type integrating watt-hour meters, they shall operate simultaneously throughout the period of the run. The duration of operation of the integrating meters shall be measured by timing devices sufficiently accurate to permit the determination of time to an accuracy of at least ±0.2%. The power output or input shall be measured over a period of time that includes the period during which the flow rate is being measured, except in the case of the pressure–time

Fig. 4-5.1-2 Two-Wattmeter Connection Diagram



NOTE:
(1) If mechanically connected exciter is used.

method of flow rate measurement where the power output or input shall be measured immediately prior to when the wicket gates or other closing devices begin to close.

Instrument transformers used for the test shall be calibrated prior to installation or immediately prior to the test by comparison with standards acceptable to the parties to the test. When existing station (meter class) transformers are used, the burden of the transformer secondary circuits shall be measured with the test instrumentation connected. If the burden of the transformers is exceeded, then station metering circuits may be temporarily disconnected for the duration of the test. The instrument transformers shall be tested to determine the ratio of transformation and the phase angle deviations for secondary burdens, which are equivalent to actual instrument burdens of the instruments to be used during the performance test. The correction data shall be available before the start of testing.

The burden of the current transformers and potential transformers shall be checked after all power test equipment is connected. The voltage and current of the secondary loops of the transducers shall be measured as close to the secondary transformer terminals as possible to ensure that all station and test equipment is on the load side of the measurements. Care should be taken to ensure that the burden measurement apparatus shall be placed on the source side of station instrumentation as shown on Fig. 4-5.1-3. As a word of caution, the secondary loops of the potential transformers should never be shorted. Also, the secondary current transformers should never be opened while the generator is running. The voltage and current transformers volt-amp measurements shall be checked to ensure that the volt-amp rating is not exceeded. If measurements show that the secondary ratings are within 5% of their rated VA burden, then station equipment should be removed from the secondary loops before testing and the volt-amp burden of each secondary transformer loop shall be re-measured.

4-5.2 Windage and Friction

All generator or motor windage and friction losses shall be charged to the generator or motor and all turbine or pump friction losses shall be charged to the turbine or pump. During the generator or motor test, the turbine or pump should be uncoupled from the generator or motor to permit determination of the generator or motor windage and friction.

If it is impractical to uncouple the turbine or pump during the generator or motor efficiency test, the approximate value of windage and friction of the machine may be calculated by the following formulas:

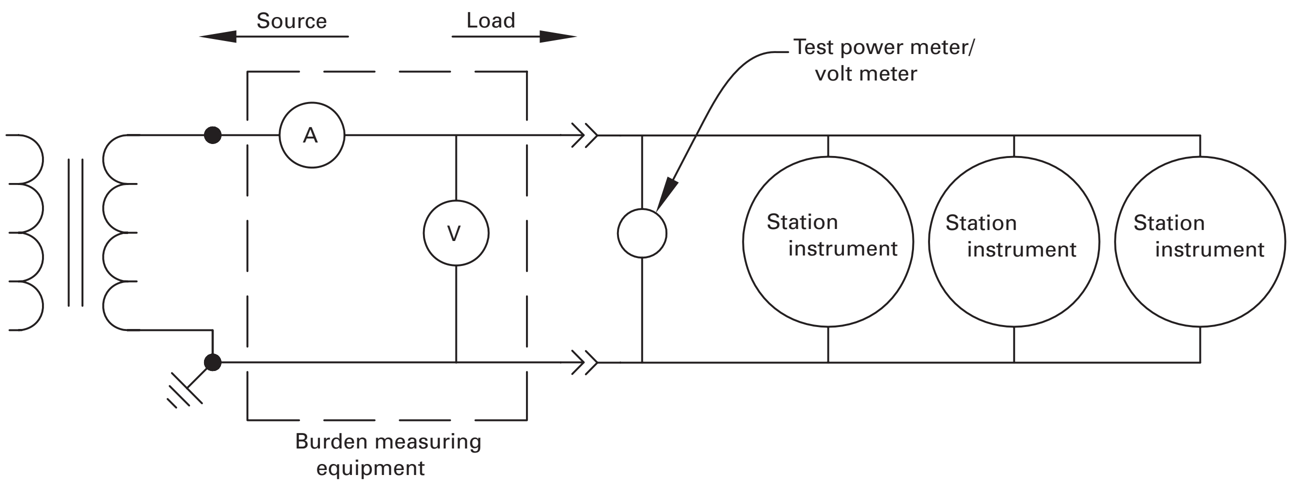
(a) Francis Turbine or Centrifugal Pump

$$P = K_f B D^4 n^3$$

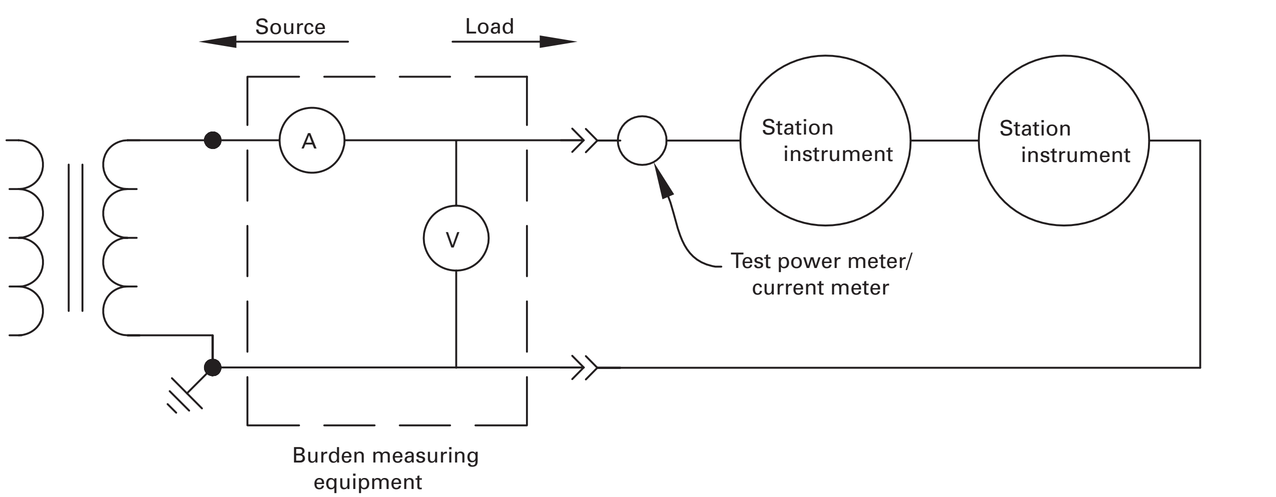
where

B = height of distributor, m (ft)
D = outside diameter of runner, m (ft)
K_f = empirical constant, the average value of which is 3.8×10^{-2} (1×10^{-4})

Fig. 4-5.1-3 Measuring Instrument Burden



(a) Typical Each Voltage Phase



(b) Typical Each Current Phase

n = speed of rotation, revolutions per second
P = turbine or pump windage and friction turning in air, kW

The above formula was determined from tests on Francis turbine runners and may be used for centrifugal pump-turbine runners rotating in the turbine direction.

(b) Propeller Type Turbine or Pump (Including Kaplan)

$$P = K_p(B_t + 0.25\, B_h)^{0.5}\, D^4\, n^3(5 + N_p)$$

where

B_h = distance parallel to the axis of the runner, measured from the inlet edge to the outlet edge of the runner blade adjacent to the runner hub (hub height), m (ft)
B_t = distance parallel to the axis of the runner, measured from the inlet edge to the outlet edge of the runner at its outer periphery (tip height), m (ft)
D = outside diameter of the runner, m (ft)
K_p = empirical constant as determined from a series of tests conducted in the field on both fixed and movable blade propeller turbines. The value found is 1.05×10^{-3} (5×10^{-6}) with fixed and movable blade propeller runners
N_p = number of runner blades
n = speed of rotation, revolutions per second
P = turbine or pump windage and friction turning in air, kW

The windage and friction test should preferably be made with the Kaplan runner blades in the closed or flat position. In both cases (a) and (b), the test to determine the combined windage and friction shall be made under the following conditions:

(1) cooling water supplied to seal rings
(2) wicket gates open
(3) spiral case drained and access door open
(4) draft tube access door open

(c) Impulse Turbine

$$P = K_i\, B\, D^4\, n^3$$

where

B = width of bucket, m (ft)
D = outside diameter of runner, m (ft)
K_i = empirical constant, as determined from a series of tests, the average value of which is 8.74×10^{-3} (2.3×10^{-5})
n = speed or rotation, revolutions per second
P = turbine windage and friction turning in air, kW

The values of generator or motor windage and friction shall be measured in the shop, or after installation, with special attention to the turbine or pump conditions outlined herein for windage and friction tests (para. 4-5.2). In units containing direct connected exciters of sufficient capacity, the windage and friction may be measured by driving the generator with the exciter. Windage and friction, when not directly measurable, shall be taken either from shop tests of generators of similar size and design or, preferably, from a deceleration test made after installation.

Other methods of determining windage and friction may be used by prior agreement by the parties to the test.

Turbine output shall be generator output plus those generator losses supplied directly by the turbine. Pump input shall be motor input less all motor losses. Any power input provided to shaft-driven auxiliaries not necessary for normal turbine or pump operation shall be added to the turbine power output and deducted from the motor output. Electrical power input to generator and turbine auxiliaries necessary for normal turbine operation shall be deducted from the measured generator power output plus applicable generator losses to determine net turbine power output. Pump power input shall be measured motor power minus applicable motor losses, plus electrical power input to auxiliaries necessary for normal continuous pump operation. Generator or motor losses obtained by shop tests may be used in this determination if corrected to turbine or pump test conditions and agreed upon by the parties to the test.

If possible, all auxiliaries driven from the machine being tested shall be disconnected during the test. If the generator or motor is excited from a mechanically connected exciter, the calculated input to the exciter shall be added to the appropriate generator or motor losses in determining the turbine output or pump input. Correction shall be made in the same manner for any other auxiliaries connected either mechanically or electrically.

Correction shall also be made for any other auxiliaries necessary for proper operation and related to the performance of the turbine, but not directly connected to it. If compressed air is required for turbine operation at certain wicket gate openings, the compressor motor input or equivalent energy usage shall be deducted from measured generator output.

4-6 SPEED MEASUREMENT

4-6.1 General

Accurate measurement of the rotational speed of the turbine is essential when the power output is measured by a direct method such as a transmission dynamometer. However, when the turbine power output is determined by an indirect method such as the measurement of the output of the synchronous generator, the rotational speed can be computed from the system frequency.

4-6.2 A-C Interconnected Power Grid

The power systems in nearly all the 48 contiguous states and many of the provinces of Canada are interconnected for power exchange and frequency control. System frequency is compared to a very high-grade crystal-controlled clock. Short-term deviations are recorded and long-term deviations are integrated to zero. The crystal-controlled clock is checked by standard time signals transmitted by the United States National Institute of Standards and Technology radio station WWV located at Fort Collins, CO.

For a turbine or pump test with a synchronous generator or motor connected to an alternating current interconnected grid, the speed is not expected to vary from true interval by more than ±0.02% under normal operating conditions. For a Code test, the actual system frequency must be measured somewhere in the power system and its value recorded.

4-6.3 Isolated Alternating Current Systems or Short-Term Measurements

Electronic timers and counters that are available can be used in two ways. A crystal-controlled time base accurately measures pulses for a period of 1 s to 10 s. During a preset period, the counter integrates the number of cycles or pulses. Alternatively, using the same equipment, time for one cycle is measured. A 1-MHz timing crystal will read 16.667 ms for one cycle. The "hold" time can be set for one second to allow a reading, and then another cycle is sampled automatically.

4-6.4 Induction Generators of Motors or Direct Current System

The first choice in this case is a mechanically driven revolution counter using the same electronic equipment as above. A projection on the shaft provides an electrical pulse either by contactor or electromagnetic pickup.

The electronic devices mentioned above are provided with an independent crystal oscillator as a time base. The frequency of this crystal shall be checked in the laboratory before the test.

Pulse generating wheels must be solidly connected to the unit shaft. Tachometer generators shall be driven by a mechanical connection such as a flexible shaft. Friction or belt drives shall not be used.

4-7 TIME MEASUREMENT

The most accurate measurement and portable time base available at present is a crystal-controlled oscillator. All manufacturers of crystal oscillators offer crystal oscillators that are temperature-compensated. Typically, temperature-compensation ranges [0°C to 50°C] encompass what is normally found in ambient temperatures. Uncertainties vary from 1 ppm for a crystal that is temperature-compensated, to 300 ppm when not temperature compensated. Crystal-controlled oscillators shall be checked for stability and drift. Oscillators used in field-testing applications should be temperature-compensated. They shall be operated according to the manufacturer's instructions.

Section 5
Computation of Results

5-1 MEASURED VALUES: DATA REDUCTION

Following each test, when all test logs and records have been completed and assembled, they should be examined critically to determine whether or not the limits of permissible deviations from specified operating conditions have exceeded those prescribed by the individual test code. Adjustments of any kind should be agreed upon and explained in the test report. If adjustments cannot be agreed upon, the test run(s) may have to be repeated. Inconsistencies in the test record or test result may require tests to be repeated in whole or in part in order to attain test objectives. Corrections resulting from deviations of any of the test operating conditions from those specified are applied when computing test results.

The averages of the readings or recordings with appropriate calibrations and/or corrections for each run shall be used for the computation of results. Any reading suspected of being in error shall be tested by the criteria for outliers in Nonmandatory Appendix C. Preliminary computations (subsection 3-3) made during the course of the test, together with plots of important measured quantities versus wicket-gate servomotor stroke, are useful for indicating errors, omissions, and irregularities, and shall appear in the final report as a reference.

Before disconnecting any instruments, all test logs and records shall be completed and assembled, and then critically examined to detect and correct or eliminate irregularities. It should be determined also at that time whether or not the limits of permissible deviations (para. 3-5.2) from specified operating conditions, and/or the limits of permissible fluctuations (para. 3-5.3), have been exceeded.

Prompt examination of readings may indicate the need for inspection and adjustment of the machine or of test instrumentation, thereby minimizing the number of runs that may have to be voided and repeated.

The averages of all readings shall be corrected using the average of the pretest and post-test calibration curves for each instrument.

5-2 CONVERSION OF TEST RESULTS TO SPECIFIED CONDITIONS

5-2.1 Turbine Mode

When the readings indicate that test conditions have complied with the requirements of paras. 3-5.2 and 3-5.3(a), the measured flow rate (Q_T) and turbine power output (P_T) at head (H_T) shall be converted to the values for specified head (H_{spec}) by

$$Q \text{ at } H_{spec} = Q_T \left(\frac{H_{spec}}{H_T}\right)^{0.5}$$

$$P \text{ at } H_{spec} = P_T \left(\frac{H_{spec}}{H_T}\right)^{1.5}$$

When the test conditions have complied with the above provisions, the turbine efficiency, which requires no correction, is

(SI Units)

$$\eta = \frac{\text{turbine power output } (P)}{\text{water power } (P_W)} = \frac{1\,000P}{\rho g Q H_{spec}} = \frac{1\,000P_T}{\rho g Q_T H_T}$$

(U.S. Customary Units)

$$\eta = \frac{550P}{\rho g Q H_{spec}}$$

Values of ρ and g are given in Tables 2-3-4 and 2-3-2, respectively.

When the test conditions have complied with the provisions of paras. 3-5.2 and 3-5.3(b), but not with para. 3-5.3(a), the values of Q for H_{spec} and P for H_{spec} as calculated above shall be corrected to Q' and P', respectively, by multiplicative factors derived from known characteristic curves of a previously tested homologous turbine, by the following steps:

Step 1: For each run, the following is calculated:

$$k_{uT} = \frac{\pi n_T D}{60(2gH_T)^{0.5}} = \text{speed coefficient}$$

$$q_T = Q_T \frac{1}{D^2 {H_T}^{0.5}} = \text{unit flow rate}$$

$$p_T = P_T \frac{1}{D^2 {H_T}^{1.5}} = \text{unit power output}$$

where D equals runner diameter, and "unit" means rationalized to 1 m diameter, 1 m head (1 ft diameter, 1 ft head).

Step 2: Using the above referenced test curves determine

p' = unit power at specified head and speed coefficient ($k_{u\text{-}spec}$) for the gate opening that produces q_T at k_{uT}

q' = unit flow rate at specified head and speed coefficient ($k_{u\text{-}spec}$) for the gate opening that produces q_T at k_{uT}

where

$$k_{u\text{-}spec} = \frac{\pi\, n_{spec} D}{60\,(2gH_{spec})^{0.5}}$$

Step 3: Calculate flow rate and power at specified head by

$$Q' = Q_T \left(\frac{q'}{q_T}\right)\left(\frac{H_{spec}}{H_T}\right)^{0.5}$$

$$P' = P_T \left(\frac{p'}{p_T}\right)\left(\frac{H_{spec}}{H_T}\right)^{1.5}$$

5-2.1.1 Efficiency. The corrected values, Q' and P', at H_{spec} shall be used to calculate the efficiency at each test run.

(SI Units)

$$\eta' = \frac{1\,000P'}{\rho g Q' H_{spec}}$$

(U.S. Customary Units)

$$\eta' = \frac{550P'}{\rho g Q' H_{spec}}$$

A curve of efficiency as a function of power shall be plotted.

5-2.2 Pump Mode

Assuming that the measured values indicate that test conditions have complied with the requirements of paras. 3-5.2 and 3-5.3(a), the calculated test results shall be converted to the specified speed (n_{spec}) by using the following equations:

$$Q \text{ at } n_{spec} = Q_T \frac{n_{spec}}{n_T}$$

$$H \text{ at } n_{spec} = H_T \left(\frac{n_{spec}}{n_T}\right)^2$$

$$NPSH \text{ at } n_{spec} = NPSH_T \left(\frac{n_{spec}}{n_T}\right)^2$$

$$P \text{ at } n_{spec} = P_T \left(\frac{n_{spec}}{n_T}\right)^3$$

Where the test conditions have complied with the provisions of para. 3-5.3(a),the machine efficiency (η), which requires no correction for these conversions, is given by

(SI Units)

$$\eta = \frac{\rho g Q H}{1\,000P}$$

(U.S. Customary Units)

$$\eta = \frac{\rho g Q H}{550P}$$

Where the test conditions have complied with the provisions of para. 3-5.3(b) but not with those of para. 3-5.3(a), the values of Q at n_{spec}; H at n_{spec}; and P at n_{spec} shall be adjusted by the addition (or subtraction) of incremental values ΔQ, ΔH, and ΔP, respectively, derived by reference to characteristic curve of previously tested homologous machine.

5-2.2.1 Efficiency. The machine efficiency, η', using the corrected values of

$Q' = Q + \Delta Q$ at n_{spec}
$H' = H + \Delta H$ at n_{spec}
$P' = P + \Delta P$ at n_{spec}
is given by

(SI Units)

$$\eta' = \frac{\rho g Q' H'}{1\,000P'}$$

(U.S. Customary Units)

$$\eta' = \frac{\rho g Q' H'}{550P'}$$

Values of ρ and g are given in Tables 2-3-4 and 2-3-2, respectively.

A curve of efficiency as a function of flow rate shall be plotted.

5-3 EVALUATION OF UNCERTAINTY

Regardless of the excellence of the test, there will always be an uncertainty in the result. The uncertainty of the final results and all intermediate results shall be estimated using the general procedures described in Nonmandatory Appendix B, which is a summary of the more complete treatment in the current version of PTC 19.1.

5-4 COMPARISON WITH GUARANTEES

Turbines are usually guaranteed for power output and efficiency at one or more specified net heads. Efficiency may be guaranteed at one or more specified power outputs or wicket gate or needle openings. All guarantees are at the specified synchronous speed unless otherwise stated.

Pumps are usually guaranteed for flow rate and efficiency at one or more specified heads.

Efficiency may be guaranteed at one or more flow rates. All guarantees are at specified speed unless stated otherwise.

When the head varies during the test, the values of efficiency and power output or flow for several heads may be determined. In such instances, a mean curve of guaranteed efficiency for comparison with the test curve of efficiencies at mean head can be determined by interpolation.

Test results shall be reported as actual computed values, corrected for instrument calibrations and converted to specified conditions. A statement shall be included in the test report that results are estimated to have a plus or minus percentage uncertainty, as determined by evaluation of uncertainties described in Nonmandatory Appendix B.

Section 6
Final Report

6-1 RESPONSIBILITY OF CHIEF OF TEST

The chief of test shall be responsible for preparation of the final report and shall sign the report.

6-2 PARTIES TO THE TEST

The parties to the test shall receive copies of the draft and final report.

6-3 ACCEPTANCE TESTS

For acceptance tests, the report shall include

(a) a brief summary of the purpose of the tests, the principal results, and conclusions.

(b) description of special conditions or pretest agreements.

(c) identification of the parties to the test and a list of the key personnel taking part in the test, including their organizational affiliations.

(d) a summary of the specified operating conditions and guarantees.

(e) descriptions, drawings, and/or photographs of the machine under test, the plant layout, inlet conditions, and outlet conditions, including any unusual features that may influence test results.

(f) the names of manufacturers and nameplate data listing power, flow rate, speed, and head.

(g) description of the inspected water passages, pressure taps, and underwater components.

(h) description of the test equipment and test procedures, including the arrangement of the equipment and list of instruments. Instrumentation descriptions should include manufacturer, key specifications, manufacturer's stated accuracy, identifying number or tag, owner, length and type of electrical leads (where relevant), calibration curves, and certificates of calibration.

(i) test date.

(j) log of test events.

(k) tabulations or summaries of all measurements and uncorrected readings.

(l) methods of calculation for all quantities computed from the raw data.

(m) reference information such as generator efficiency curve.

(n) copies of instrumentation calibration documentation.

(o) corrections for deviations from specified conditions.

(p) statement regarding cavitation factor observed during the tests.

(q) analysis of the uncertainty of the test results.

(r) summary of results.

(s) tabular and graphical presentation of the final test results.

(1) For turbines, the graphical presentation should include

(a) efficiency versus power output

(b) flow rate versus power output

(c) power output versus wicket gate opening or needle position and blade angle, where applicable

(d) flow rate versus wicket gate opening or needle position and blade angle, where applicable

(2) For pumps, the graphical presentation should include

(a) head versus flow rate

(b) flow rate versus power input

(c) efficiency versus flow rate

(d) efficiency versus wicket gate opening

(t) appendices as required to describe details of dimensions of water passages, additional drawings and illustrations as needed for clarification, and any other supporting documentation that may be required to make the report a complete, self-contained document of the entire test.

(u) documentation of any unresolved disagreements between the parties to the test.

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NONMANDATORY APPENDIX A
TYPICAL VALUES OF UNCERTAINTY

A-1 GENERAL

Uncertainties in this Code are specified at the 95% confidence interval as described in Nonmandatory Appendix B. The following paragraphs present typical uncertainties (including both systematic and random errors) that may be attainable with calibrated instrumentation and normal test conditions.

The values listed below for specific measurements are for general guidance only and should not be used without supporting calculations and verifications. Systematic and random uncertainties should be calculated in accordance with Nonmandatory Appendix B and the current version of PTC 19.1. This general list is not comprehensive, and all uncertainties associated with each test measurement should be identified and separately addressed.

A-2 FLOW RATE UNCERTAINTY, U_Q

(a) Current meter method

(1) conduits from 1.2 m to 1.5 m (4 ft to 5 ft) diameter, ±1.2%

(2) conduits of more than 1.5 m (5 ft) diameter, ±1.0%

(b) Pressure–time method, ±1.0%

(c) Ultrasonic method (two crossing planes, four paths each), ±1.0%

(d) Dye dilution method, ±1.5%

A-3 HEAD UNCERTAINTY, U_H

(a) Measurement of free water level difference, h

(1) point gage, hook gage, or float gate

(a) $\pm(1/h)$% (SI Units)

(b) $\pm(3.2/h)$% (U.S. Customary Units)

(2) plate gage, fixed

(a) $\pm(5/h)$% (SI Units)

(b) $\pm(16.4/h)$ % (U.S. Customary Units)

(b) Pressure uncertainty

(1) deadweight gage, ±0.1%

(2) height of mercury, h'

(a) $\pm(0.1/h)$% (SI Units)

(b) $\pm(0.32/h)$% (U.S. Customary Units)

(c) Spring pressure gage, ±0.5%

(d) Transducers, ±(0.1 to 0.5)%

A-4 POWER UNCERTAINTY, U_P

(a) By measurement at the terminals of

(1) DC generators, ±1.0%

(2) AC generators, ±0.5%

(b) Depending upon the method employed for the determination of generator losses, and in cases where shunts are used for large direct currents, U_p may be greater than the above values. For example, the uncertainty in power at a test point can be calculated as follows:

(1) watt/watthour meter uncertainty: ±0.25%

(2) potential transformer uncertainty: ±0.5%

(3) current transformer uncertainty: ±0.5%

(4) timer uncertainty: ±0.0001%

(5) uncertainty in generator efficiency: ±0.1%

(c) The calculated uncertainties are then computed as described in Nonmandatory Appendix B from the root-sum-square of the above uncertainties as follows:

$$U_P = \pm\,(0.25^2 + 0.5^2 + 0.5^2 + 0.0001^2 + 0.1^2)^{0.5}$$

$$U_P = \pm\,0.76\%$$

At other measuring points, the overall uncertainty would be different. With the use of accurate modern electronic instrumentation, it may be significantly smaller.

A-5 SPEED UNCERTAINTY

Electric counter and other precision speed measuring devices = ±0.1%.

NONMANDATORY APPENDIX B
UNCERTAINTY ANALYSIS

B-1 BASIS FOR UNCERTAINTY CALCULATION

Regardless of the care taken in their design and implementation, all tests will yield measurements and results that are different from the true values that would have been determined with perfect measurements. Thus, the true or exact result is uncertain. The objective of the uncertainty analysis is to rationally quantify the uncertainty in the test results (e.g., machine efficiency).

This Nonmandatory Appendix presents an approach to uncertainty analysis that is commonly used in the hydroelectric industry. It differs from the more rigorous approach presented in PTC 19.1, *Test Uncertainty,* in the handling of Student's t statistic and the associated determination of the number of degrees of freedom.

Because hydroturbine efficiency measurements often have sample sizes on the order of 5 measurements (e.g., determination of peak efficiency as a contractual guarantee), the assumption that $t = 2$ (large degrees of freedom) is not always justified. In these cases, the approach presented here differs from that of PTC 19.1 in that the t statistic is applied to each elemental uncertainty with degrees of freedom determined from the individual sample sizes, instead of applying a single value of t with degrees of freedom determined by the Welch–Satterthwaite formula to the combined elemental uncertainties.

In the case of large sample sizes, the two approaches yield identical results. In the case of small sample sizes, the approach presented here will generally yield slightly larger uncertainties.

Uncertainties for this Code are computed at the 95% confidence level. This means that for any measurement or computed result, the true result is expected to be within the uncertainty value of the measured result 95% of the time. Conversely, the true result will not be within the uncertainty value of the measured result 5% of the time.

The summary presented here applies only to the case in which the various uncertainties can be considered independent of one another. The latest version of PTC 19.1 should be consulted if there is any question as to the applicability of this assumption.

B-2 SUMMARY OF METHODOLOGY

The methodology presented here uses turbine mode efficiency as an example. This basic methodology applies to any part of the uncertainty analysis, e.g., the detailed determination of the uncertainty in the head measurement.

The basic steps in determining the uncertainty of any parameter are as follows:

(a) Develop the equation or equations that define the desired result in terms of the measurements (or parameters) upon which the results depend.

(b) Determine how sensitive the desired result is to changes in the parameters from which it is computed.

(c) Determine the uncertainty in these parameters.

(d) Use the sensitivity determined above to quantify the effect on the result of uncertainty in each parameter upon which it depends.

(e) Combine these individual uncertainty effects to determine the overall uncertainty of the final result.

B-3 GENERAL APPROACH AND TURBINE EFFICIENCY EXAMPLE

The general approach for uncertainty analysis is presented here, using turbine efficiency as an example. The equation that defines turbine efficiency is

$$\eta_T = \frac{P_T}{\rho g Q H}$$

The uncertainty in the measured efficiency will therefore be a function of the uncertainty in the measurements of turbine power, P_T; flow, Q; net head, H; water density, ρ; and gravity, g. Each of these measurements will depend, in general, upon the results of measurements of several other parameters. For instance, net head will depend on both the static and velocity heads at the inlet and the discharge. Consequently, it will depend on the measurements of flow rate, conduit area, inlet pressure, discharge pressure, etc.

For any individual parameter, P, the uncertainty in the measurement is determined by a combination of systematic uncertainties that are generally due to uncertainty in instrumentation calibrations, geometric measurements, etc., and random uncertainties that generally arise from variations in the quantity being measured or noise in the measurement system.

The systematic uncertainty, B, is determined from analysis of calibration equipment, calibration history, measuring equipment, manufacturer's specifications, published guidelines, etc. The random uncertainty, S, is generally determined from the statistics of the

Table B-3-1 Two-Tailed Student's *t* Table for the 95% Confidence Level

Degrees of Freedom $\nu = n - 1$	t	Degrees of Freedom $\nu = n - 1$	t
1	12.706	16	2.120
2	4.303	17	2.110
3	3.182	18	2.101
4	2.776	19	2.093
5	2.571	20	2.086
6	2.447	21	2.080
7	2.365	22	2.074
8	2.306	23	2.069
9	2.262	24	2.064
10	2.228	25	2.060
11	2.201	26	2.056
12	2.179	27	2.052
13	2.160	28	2.048
14	2.145	29	2.045
15	2.131	30	2.042

GENERAL NOTE: Student's t may be computed from the following empirical equation for other values of ν:

$$t = 1.96 + \frac{2.36}{\nu} + \frac{3.2}{\nu^2} + \frac{5.2}{\nu^{3.84}}$$

measurement record. Under the assumptions stated earlier in this Appendix, a measure of the random uncertainty is the standard deviation, S_P, about the mean of N measurements of an individual parameter, P, at a particular test condition. The standard deviation is defined as

$$S_P = \left(\frac{1}{N-1} \sum_{i=1}^{N} (P_i - \overline{P})^2 \right)^{\frac{1}{2}}$$

where

P_i = individual measured value of parameter P

$\overline{P}$ = the average of the measured values of parameter P

The random uncertainty in actual value of the mean S_P is given by

$$S_{\overline{P}} = t \cdot S_P \big/ \sqrt{N}$$

where

t = Student's t-statistic for adjusting to the 95% confidence interval (see Table B-3-1)

This equation for $S_{\overline{P}}$ shows that the random uncertainty can be reduced by taking more measurements, N, with the caveat that the measurements be spaced far enough apart that there is no correlation of the random component between the individual measurements.

The overall uncertainty, U_P, in the measured value of a parameter, P, is then given by the root-sum-square (RSS) equation

$$U_P = \sqrt{B_P^2 + (tS_{\overline{P}})^2}$$

When a result is determined from several individual parameters, the individual (elemental) systematic and random uncertainties are combined by the RSS method.

$$B_P = \sqrt{B_{P1}^2 + B_{P2}^2 + \ldots + B_{PK}^2}$$

and

$$S_{\overline{P}} = \sqrt{(tS_{\overline{P}1})^2 + (tS_{\overline{P}2})^2 + \ldots + (tS_{\overline{P}K})^2}$$

where B_{PI} and tS_{PI} are the elemental systematic and random uncertainties, respectively.

The final result of an uncertainty calculation does not depend on the order in which the combining of the elemental uncertainties is performed. Under the RSS method, the same result is obtained if all systematic and random uncertainties are computed separately, then combined; if the systematic and random uncertainties for an individual measurement are computed and combined, and the measurement uncertainties are combined over all measurements; or if all elemental systematic and random uncertainties are combined in one step. However, it is often useful to determine the overall systematic and random uncertainties separately, as this may give insight as to the most likely areas for improvement in test uncertainty.

The relative sensitivity of a result, R, due to changes in a particular parameter, P, is given by using a Taylor series approximation to define a sensitivity coefficient for the parameter, T_P

$$T_P = \frac{\partial R}{\partial P}$$

The uncertainty in the result, δR, due to the uncertainty in the parameter, δP, is then given by

$$\delta R = T_P \cdot \delta P$$

Returning to turbine efficiency as an example, the sensitivity coefficients for efficiency, η, can be computed from the efficiency equation

$$T_P = \frac{\partial \eta}{\partial P_T} = \frac{1}{\rho g H Q}$$

$$T_H = \frac{\partial \eta}{\partial H} = -\frac{P_T}{\rho g H^2 Q}$$

$$T_g = \frac{\partial \eta}{\partial g} = -\frac{P_T}{\rho g^2 H Q}$$

$$T_Q = \frac{\partial \eta}{\partial Q} = -\frac{P_T}{\rho g H Q^2}$$

$$T_\rho = \frac{\partial \eta}{\partial \rho} = -\frac{P_T}{\rho^2 g H Q}$$

The overall uncertainty in the efficiency, E_η, is then given by

$$E_\eta = \left[\left(T_p \cdot \delta P_T\right)^2 + \left(T_Q \cdot \delta Q\right)^2 + \left(T_H \cdot \delta H\right)^2 + \left(T_\rho \cdot \delta \rho\right)^2 + \left(T_g \cdot \delta g\right)^2 \right]^{1/2}$$

The relative uncertainty in efficiency, U_η, can be determined from the preceding equations to be

$$U_\eta = \frac{E_\eta}{\eta} = \left[\left(\frac{\delta P_T}{P_T}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2 + \left(\frac{\delta H}{H}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta g}{g}\right)^2 \right]^{1/2}$$

The determination of the density of water is usually based on temperature measurement of the water. With an ordinary thermometer, this parameter is easily measured within 2°C uncertainty. At 20°C, this uncertainty leads to a relative uncertainty in the density of only about 0.04%. Thus, the uncertainty in density may be neglected. A similar line of reasoning applies to the determination of g.

B-4 COMBINING UNCERTAINTIES

Several other useful specific forms derived from the Taylor series method for propagation of uncertainties are given below.

B-4.1 Average of Two or More Parameters

If a result is computed as an average of two parameters

$$R = \tfrac{1}{2}(x + y)$$

then the uncertainty in the result is given by

$$U_R = \tfrac{1}{2}\left(U_x^2 + U_y^2\right)^{1/2}$$

Averages for more than two parameters can be computed in similar fashion. For instance, if three parameters are averaged to determine a result, then the uncertainty in the result is given by

$$U_R = \tfrac{1}{3}\left(U_1^2 + U_2^2 + U_3^2\right)^{1/2}$$

This combining of uncertainties for a result computed from an average is referred to as RSS averaging of the uncertainties.

NOTE: If the elemental uncertainties, U_i, are equal (for instance, in the measurement of flow rate in three intake bays of a Kaplan unit), the RSS average of three uncertainties is given by

$$U_R = \frac{U}{\sqrt{3}}$$

where $U_1 = U_2 = U_3 = U$. A similar result is obtained for any number of averaged parameters.

B-4.2 Sum or Difference of Two or More Parameters

If a result is computed as the sum or difference of two parameters

$$R = x \pm y$$

then the uncertainty in the result is given by

$$U_R = \left(U_x^2 + U_y^2\right)^{1/2}$$

Sum or differences of more than two parameters can be computed in similar fashion. For instance, if three parameters are summed to determine a result, then the uncertainty in the result is given by

$$U_R = \left(U_1^2 + U_2^2 + U_3^2\right)^{1/2}$$

NOTE: If the elemental uncertainties, U_i, are equal, the RSS sum of three uncertainties is given by

$$U_R = \sqrt{3}U$$

where $U_1 = U_2 = U_3 = U$. A similar result is obtained for any number of summed parameters.

B-5 APPLICATION OVER A RANGE OF OPERATING CONDITIONS

Measurements (e.g., power output) or determinations of results (e.g., turbine efficiency) of parameters over a range of operating conditions may be expected to follow a smooth curve. For instance, turbine efficiency (the dependent parameter) may be expected to be a smooth function of the power output (the independent parameter) for a given head. However, test measurements or results will deviate from a smooth curve plotted over a range of operating conditions, reflecting random (repeatability) errors in the underlying measurements. The deviation of these computed results from the smooth curve can be used to determine the uncertainty of a result over a range of operating conditions. In practice, the smooth curve fits are often made using polynomials of up to the fifth order, although other functions may be employed. The use of a least-squares curve fit to relate the two parameters is the most common method of fitting the smooth curve.

The standard deviation of the sample mean in this case is the standard deviation of the difference of the independent measured parameter (e.g., turbine efficiency) from the curve fit to that parameter as a function of the independent parameter. For instance, suppose turbine efficiency, η, is plotted as a function a power output, P, and a fifth-order polynomial relating these two parameters is determined by a least-squares technique, resulting in the following relationship:

$$\hat{\eta} = c_o + c_1 P + c_2 P^2 + c_3 P^3 + c_4 P^4 + c_5 P^5$$

where the c_0 through c_5 are the polynomial coefficients. The standard deviation of the difference between the test efficiencies and the curve fit is then given by

$$S_\eta = \left(\frac{1}{N - M - 1} \sum_{i=1}^{N} (\eta_i - \hat{\eta})^2 \right)^{1/2}$$

where

η_i = individual efficiencies

$\hat{\eta}$ = curve fit of the efficiency as a function of power

N = number of measurements

M = number of coefficients to be determined (for the polynomial coefficients in the example above, $M = 6$).

The standard deviation of the sample mean for the turbine efficiency over the range of power outputs is then given by

$$S_{\bar{\eta}} = S_\eta / \sqrt{N}$$

It should be noted that the random error determined from a curve fit will depend not only upon the scatter in the measurements, but also upon the appropriateness of the curve used for the curve fit. For instance, if turbine efficiency is considered as a function of power output, a second-order polynomial generally will not follow the true curve very well. This will lead to a relatively high estimate of uncertainty. The use of a higher-order curve may reduce this uncertainty while retaining the smoothness and reasonableness of the curve. However, care must be used, and the fit curve should be plotted and investigated for reasonableness. For polynomial curve fits, for instance, the number of data points should be at least 1.5 to 2 times the order of the curve fit. Fitting a fifth-order curve to six data points may result in a wildly oscillating curve. Experience has also shown that polynomial curve fits greater than fifth order often yield unsuitable curves. Such unreasonableness can be detected by simply plotting and inspecting the derived curve fit.

NONMANDATORY APPENDIX C
OUTLIERS

All measurement systems may produce spurious data points, also known as outliers, strays, mavericks, rogues, or wild points. These points may be caused by temporary or intermittent malfunctions of the measurement system. Data points of this type shall not be included as part of the uncertainty of the measurement. Such points are considered to be meaningless as steady-state test data, and shall be discarded.

The modified Thompson τ technique is recommended for testing possible outliers. The following is a summary of the technique. A more complete discussion with example is given in PTC 19.1-2005.

Let y_i be the value of the observation, y, that is most remote from $\hat{Y}$, the arithmetic mean value of all observations in the set, and S be the estimated standard deviation of all observations in the set. Then if the value, without regard to sign, of

$$d = \left| y_i - \hat{Y} \right|$$

is greater than the product τS, the value y_i is rejected as an outlier. The value of τ is obtained from Table C-1.

After rejecting an outlier, $\hat{Y}$ and S are recalculated for the remaining observations. Successive applications of this procedure may be made to test other possible outliers, but the usefulness of the testing procedure diminishes after each rejection.

All sets of readings should be examined for outliers before computations are made. All significant quantities, such as Q, H, P, and n, should be tested for outliers. The test should also be applied to curves fit to test data over a range of operating conditions.

Table C-1 Modified Thomspon τ Values (at the 5% Significance Level)

Sample Size, N	τ	Sample Size, N	τ
3	1.150	22	1.893
4	1.393	23	1.896
5	1.572	24	1.899
6	1.656	25	1.902
7	1.711	26	1.904
8	1.749	27	1.906
9	1.777	28	1.908
10	1.798	29	1.910
11	1.815	30	1.911
12	1.829	31	1.913
13	1.840	32	1.914
14	1.849	33	1.916
15	1.858	34	1.917
16	1.865	35	1.919
17	1.871	36	1.920
18	1.876	37	1.921
19	1.881	38	1.922
20	1.885	39	1.923
21	1.889	40	1.924

NONMANDATORY APPENDIX D
RELATIVE FLOW MEASUREMENT–INDEX TEST

D-1 DEFINITIONS

An index test is a method for determining the relative efficiency of a machine based on relative flow measurement. An index value is an arbitrarily scaled measure. Relative values are derived from the index values by expressing them as a proportion of the index value at a stipulated condition. Power and head are measured by any of the methods in this Code. Flow rate is measured as an index value by measuring a parameter that is a function of flow, such as differential pressure across a tapered section of penstock or Winter–Kennedy taps. Relative efficiency is expressed as a proportion of peak index efficiency.

D-2 APPLICATION

An index test may be used alone or as part of a performance test for any of the following purposes:

(a) to determine relative flow and efficiency in conjunction with turbine power output or pump power input. Such performance characteristics may be compared with the performance predicted from tests on a homologous model.

(b) to determine the overall operating point or points that define the most efficient operation or to extend information on performance over a wider range of net head, flow rate, or power than covered by performance tests.

(c) to determine the relationship between runner blade angle and wicket-gate opening for most efficient operation of adjustable blade turbines, and for the purpose of calibrating the blade control cam.

(d) to determine the optimum relative efficiency wicket-gate opening at various heads for pump operation.

(e) to assess the change in efficiency due to cavitation resulting from a change in lower pool level and/or net head.

(f) to monitor flow-rate data during the performance test.

(g) to obtain calibration data for permanent powerhouse flow-measuring instruments by assuming an absolute value of machine efficiency at some operating point.

(h) to assess the change in performance of the machine resulting from wear, repair, or modification.

When an index test is used to supplement results of a performance test, measurements of flow rate made for the performance test are used to calibrate the index of flow. The index test results may then be expressed in terms of efficiency rather than relative efficiency. In this case, the results should include a statement concerning the accuracy and confidence limits that apply to the calibration of flow-rate measurement.

For some applications, the index test may be used to obtain the combined relative efficiency of the turbine-generator unit or pump-motor unit.

D-3 RELATIVE FLOW RATE

D-3.1 General

An index test does not require any absolute measurement of flow rate. Examples of relative flow-rate measurement methods include the following:

(a) measurement of the pressure differences existing between suitably located taps on the turbine spiral or semi-spiral case (see para. D-3.2). This is the Winter–Kennedy method, described in ASCE paper, "Improved Type of Flow Meter for Hydraulic Turbines," by I. A. Winter (April 1933). This method is not suitable for relative flow measurement for pump operation.

(b) measurement of the pressure difference across a converging taper section of the penstock using the principle of a Venturi (see para. D-3.3).

(c) measurement of the difference between the elevation of water in the inlet pool and the inlet section of the machine (see para. D-3.4).

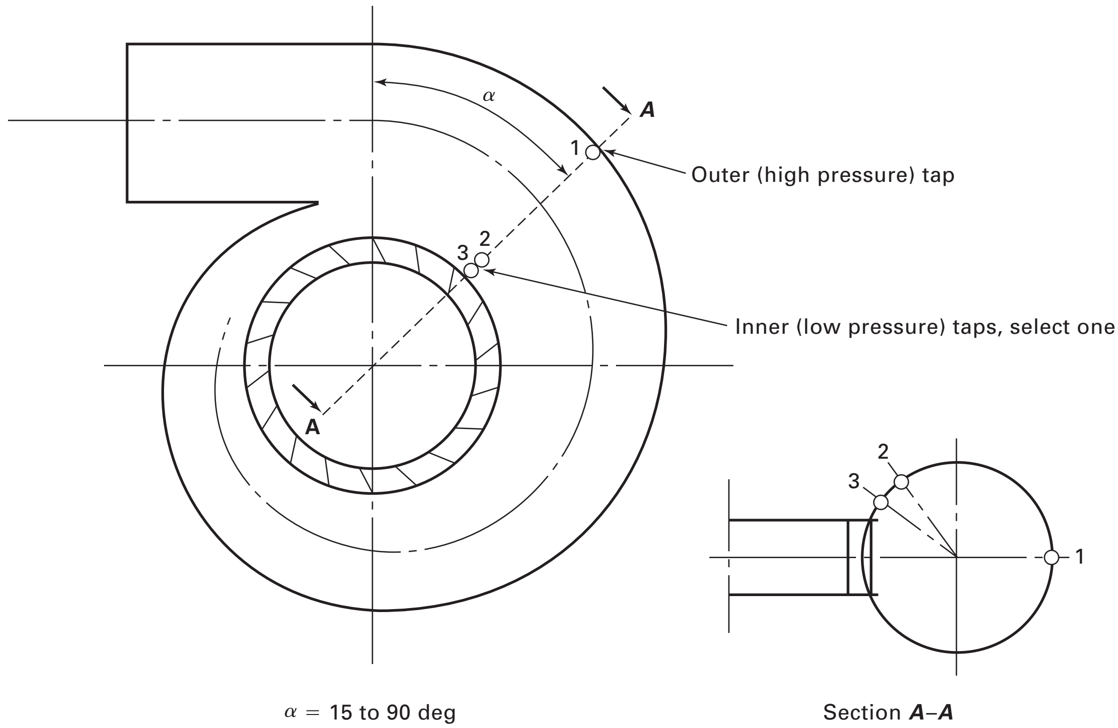
(d) measurement of differential pressure between two piezometers located on a conduit elbow (see para. D-3.5).

(e) measurement of differential pressure between suitably located taps on a bulb or tubular turbine (see para. D-3.6).

Differential pressure measurements should not be made at turbine discharge sections, low-pressure pump intake sections, or other sections where pressure variations are high in comparison with the total differential pressure, since the accuracy of the relative flow rate measurement will be significantly diminished.

Flow rate is taken as proportional to the nth exponent of the differential-pressure head [i.e., $Q_{rel} = k(\Delta h)^n$]. An approximate value of exponent n is 0.5. However, the value of the exponent may vary with the type of inlet case or conduit where relative flow is being measured, the location of the taps, and the flow rate. When an index test is part of the performance test, the value of n can be

Fig. D-3.2-1 Location of Winter–Kennedy Pressure Taps in Spiral Case



determined from measurements of flow rate made for the performance test.

Measurement of the needle stroke may be used on impulse turbines to determine an index of flow rate provided the needle stroke-versus-discharge characteristic shape has been checked by tests on a homologous model of the turbine needle valve. Care shall be taken to ensure that the needle, nozzle, and support vanes are clean and in good order during the test.

D-3.2 Relative Flow Rate Measurement by the Winter–Kennedy Method

The Winter–Kennedy method requires two pressure taps usually located in the same radial section of the spiral or semispiral case. See Figs. D-3.2-1 and D-3.2-2. One tap is located at the outer radius of the spiral or semispiral case, often on the horizontal (turbine distributor) centerline. The other tap is located at an inner radius outside the stay ring. Sometimes more than one tap is provided at the inner radius. The taps shall not be near rough-weld joints or abrupt changes in spiral or semispiral case section. The inner taps shall lie on a flow line between stay vanes.

D-3.3 Relative Flow Measurement by the Converging Taper Method

Two pressure taps shall be located at different size cross-sections of the conduit. The most stable pressure difference will be obtained if both taps are in the converging section of the conduit. The differential pressure thus obtained is not the maximum possible; therefore, it may be preferable to locate one tap a short distance upstream of the convergence and the second not less than half a diameter downstream of the convergence.

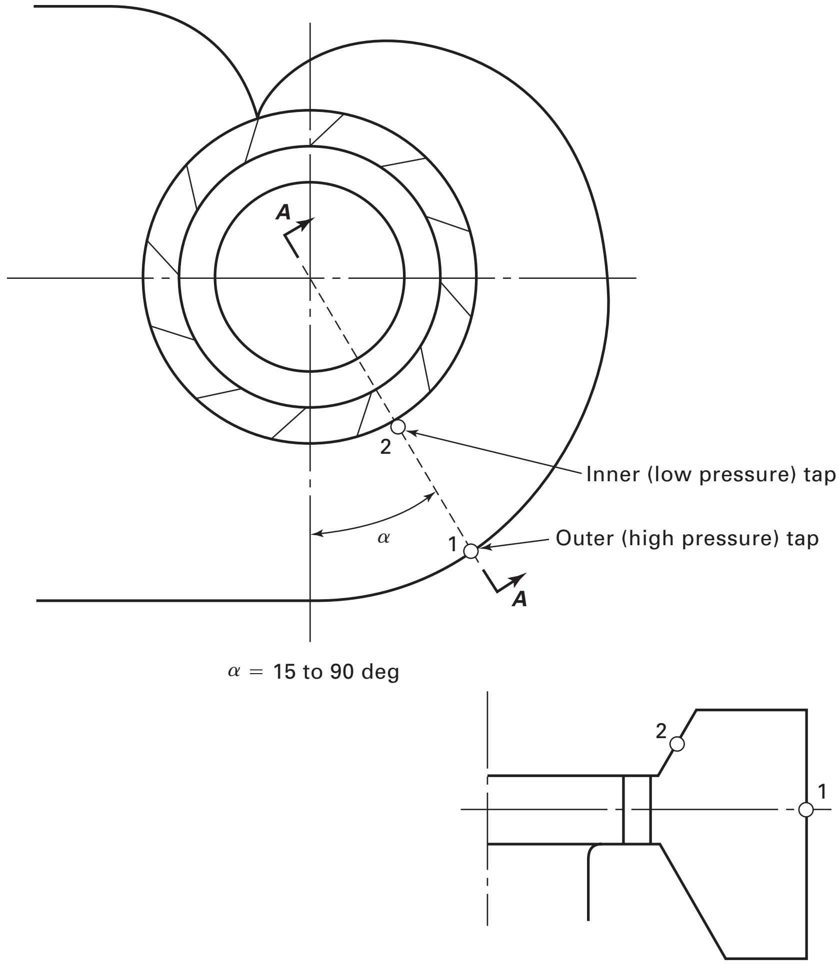
D-3.4 Relative Flow Rate by the Friction Head Loss and Velocity Head Method

The difference between the elevation of the water in the inlet pool (upper pool for turbine and lower pool for pump) and the pressure head near the entrance to the machine may be used to measure the relative flow rate. The differential reading consists of the friction head and other head losses between the inlet pool and the section at the point of measurement near the entrance to the machine, plus the velocity head at this section.

Attention should be given to the trash rack to ensure that the head loss through the trash rack is not affected by an accumulation of trash during the test.

For pumps, the section near the entrance to the machine shall be selected so that the proximity to the runner is not causing rotational flow, which can influence the pressure head reading. At installations with long high-pressure conduit, relative flow for pumps can be measured on the discharge conduit, provided that the measuring section on the high-pressure side of the pump is selected so that rotational flow from the pump discharge is not

Fig. D-3.2-2 Location of Winter–Kennedy Pressure Taps in Semi-Spiral Case



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influencing the pressure head reading. Often the net head taps on the pump inlet conduit (draft tube on a pump-turbine) versus tap(s) near the runner can be used.

If more than one machine is connected to the same conduit, the machine(s) other than the one under test shall be shut down, and the leakage through the wicket gates or shutoff valves of the other turbine(s) shall be measured, calculated, or estimated.

D-3.5 Relative Flow Measurement as a Differential Across an Elbow

The differential-pressure readings between two pressure taps located on a penstock elbow may be used to determine relative flow rate.

D-3.6 Relative Flow Measurement Using Suitably Located Taps on a Bulb or Tubular Turbine

Relative flow rate may be determined by measuring the differential pressure between a single high-pressure tap located at the stagnation point at the front of the bulb or the front of the access shaft to the bulb, and two low-pressure taps mounted on the converging section of turbine casing upstream of the wicket gates. The pressure taps must be located a sufficient distance upstream of the wicket gates so that the flow patterns at the pressure taps are not influenced by the wicket gate position.

D-3.7 Pressure Taps and Piping

The pressure taps shall comply with the dimensional requirements of para. 4-3.14. Since the differential heads to be measured may be small, special attention shall be given to removing surface irregularities.

When relative flow measurement is made over a long period of time, or if separate index tests are made at different times to assess the change in efficiency of a machine from wear, repair, or modification, it is necessary for the condition of the pressure taps and surrounding area to remain unchanged for the relative flow rate and/or relative efficiency to be comparable.

When the pressure taps are calibrated using a Code-approved method of measuring flow rate (subsection D-4), it is essential that the taps remain in their as-calibrated condition to give accurate results over time. This includes keeping the trash racks clean, as the pressure profile at the pressure-tap plane may be affected by wakes or turbulence resulting from different levels of trash.

D-3.8 Head and Differential Pressure Measurement

The head on the machine shall be measured using the methods given in paras. 4-3.1 through 4-3.16. To determine the net head on the machine, it is necessary to calculate velocity heads. Since only relative flow is determined, velocity heads can only be estimated. This may be done by assuming a value of turbine efficiency, usually the peak value, and thus estimate flow rate. The possible error introduced if the assumed efficiency is incorrect is negligible in the final determination of relative efficiency.

Differential pressure shall be measured using a gage selected to give accurate measurements over the expected range. The differentials may be measured using the methods given in subsection 4-3.

D-3.9 Effect of Variation in Exponent

Relative flow rate measurement using Winter–Kennedy taps, or converging taper sections, do not always give results in which flow rate is exactly proportional to the 0.5 exponent of the differential pressure. The values of the exponents that may be expected are 0.48 to 0.52.

The effects of variation in exponent n, in the relationship $Q_{rel} = k\,(\Delta h)^n$, on relative flow rate are shown on Fig. D-3.9-1. A change in exponent n rotates the relative efficiency curve, whereas a change of the coefficient k changes the shape of the curve. The two effects can often be separated.

The use of two independent pairs of Winter–Kennedy taps may provide a greater level of confidence in using the assumed exponent of 0.5. It is unlikely that two independent pairs of taps would each show the same departure from the exponent 0.5. Agreement in indicated flow rate Q_i, within ±0.5% over the range of $Q_{rel} = 0.5$ to $Q_{rel} = 1$, can be taken as confirmation of the correctness of the 0.5 exponent.

D-3.10 Power

Power output from the turbine or power input to the pump shall be determined using the methods described in subsection 4-5. It is also possible to use the control board instruments, but with less accuracy, provided that relatively small changes in power can still be measured.

D-3.11 Wicket Gate and Needle Opening and Blade Angle

The wicket-gate or needle opening and the blade angle, if not fixed, shall be recorded for each run. Attention shall be given to the accurate calibration of wicket-gate opening against an external scale. The calibration shall include a check that differences between individual wicket-gate openings are not significant. The wicket gates could be fully closed before the operating servomotors are fully closed; therefore servomotor stroke cannot be used as a measure of wicket-gate opening without proper calibration. It is preferable to calibrate wicket gate opening against a measurement of the wicket-gate lever angle or servomotor stroke, with the machine unwatered.

D-4 COMPUTATION OF INDEX TEST RESULTS

The test data shall provide for each test run values for relative-flow differential pressure, Δh; pressure heads, h_1, h_2, and potential heads, Z_1, Z_2; power, P; wicket-gate opening (needle stroke for impulse turbines); and blade position in the case of adjustable blade turbines. Plots of power, gross head, and differential pressure versus wicket-gate opening or needle stroke are useful for indicating errors, omissions, and irregularities. For adjustable blade turbines, a plot of $P_e/[(\Delta h^{0.5})(H)]$ versus P_e is helpful for determining the maximum efficiency point for each combination of blade angle and wicket-gate opening tested.

Relative flow rates are given by

$$Q_{rel} = k(\Delta h)^n$$

where

k = coefficient
n = exponent
Q_{rel} = relative flow rate
Δh = differential pressure head

When differential-pressure heads are taken during tests, and flow rate is also measured by a Code-approved method, these flow rates should be used to evaluate k and n. The recommended procedure is to fit a power curve equation to the test points by the least squares method. The form of the equation is

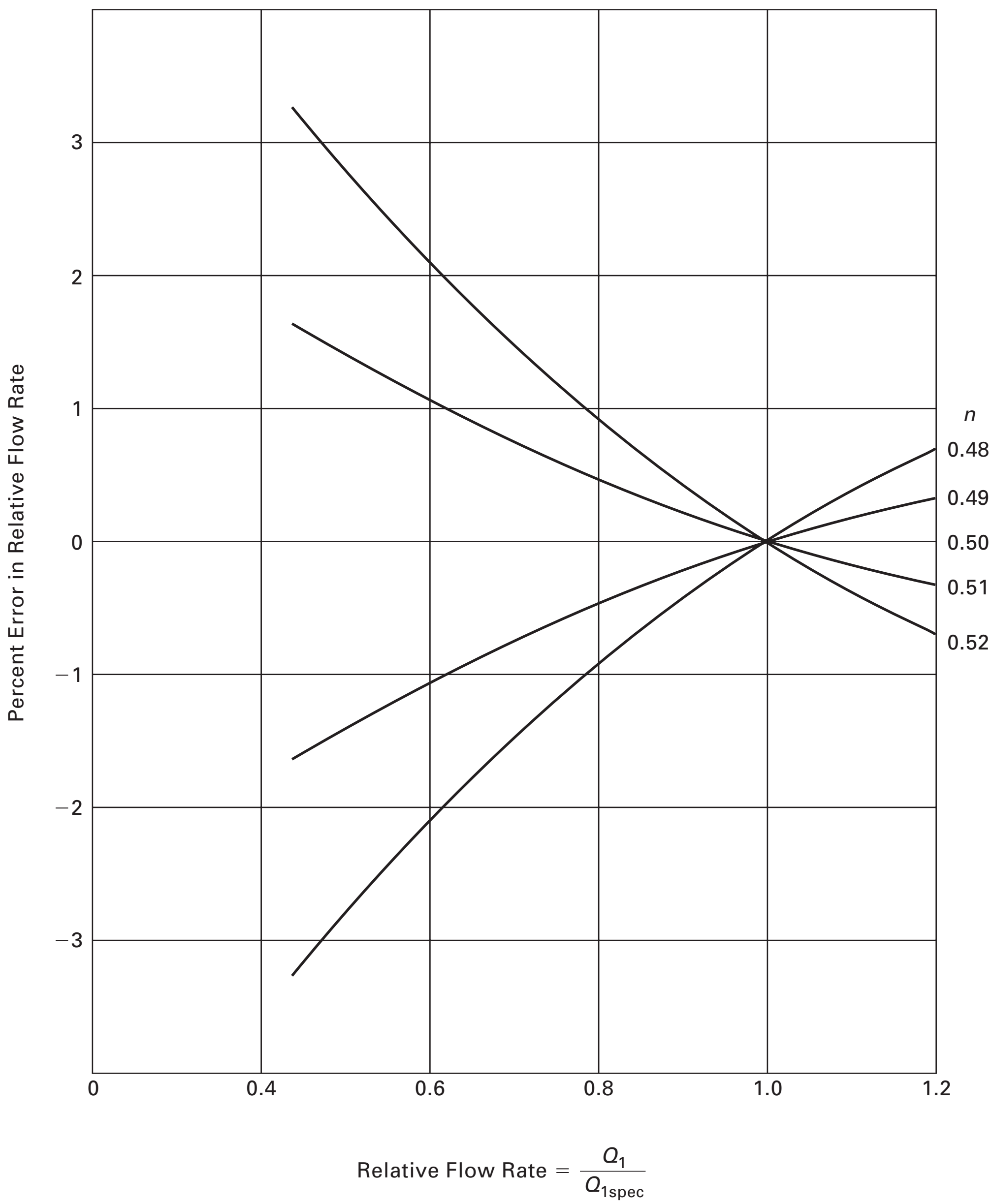
$$Q = k(\Delta h)^n$$

where

Q = flow rate from Code-approved measurement method

If measurements of flow rate by a Code-approved method are unavailable, then the value of the exponent n is assumed to be 0.5, and k is determined from

Fig. D-3.9-1 Effect of Variations in Exponent on Relative Flow Rate



GENERAL NOTE:
$Q_1 = k\Delta h^n$
Where h is the differential pressure across the taps. The error is that arising from assuming $n = 0.50$ when the true value can be, for instance, 0.48 or 0.52.

an estimate of maximum turbine or pump efficiency at the test head. The corresponding flow rate, Q, is then as follows:

(SI Units)

Turbine

$$Q = \frac{1\,000P}{\eta\rho g H}\ (\mathrm{m^3/s})$$

Pump

$$Q = \frac{1\,000\eta P}{\rho g H}\ (\mathrm{m^3/s})$$

(U.S. Customary Units)

Turbine

$$Q = \frac{550P}{\eta\rho g H}\ (\mathrm{ft^3/sec})$$

Pump

$$Q = \frac{550\eta P}{\rho g H}\ (\mathrm{ft^3/sec})$$

and

$$k = \frac{Q_{rel}}{(\Delta h)^{0.5}}$$

where η is the estimated maximum efficiency. The estimated maximum efficiency shall be obtained from tests of a homologous model operating at the same speed coefficient, k_u as the prototype, and with model test data corrected by a suitable scaling factor and efficiency step-up.

Determination of net head, H, in the above equation for flow rate requires that a trial value of Q_{rel} or k be used initially. If trial values of Q_{rel} or k differ from final values by more than ±0.1%, new trial values shall be selected and the calculation repeated.

After k and n have been satisfactorily determined, further computation of results shall be carried out as described in subsection 5-2.

For turbines, the curves of relative flow rate and relative efficiency versus turbine power output should be compared with the expected curves based on model test data to indicate the nature of any discrepancy between expected and prototype relative efficiency obtained from the test. Similarly, for pumps, curves of relative flow rate versus relative efficiency and head should be compared with expected curves based on model test data.

D-5 ASSESSMENT OF INDEX TEST ERRORS

Systematic errors in head or power measurement that are constant percentage errors, although unknown in magnitude, do not affect the results of an index test unless comparative results are required. The largest systematic error that can affect index test results arises from possible variation of the exponent n in the equation relating relative flow to differential pressure, Δh. The effect of such variation is given in Fig. D-3.9-1.

Random errors affect the results of an index test. A sufficient number of test runs should be made so that the uncertainty for the smoothed results due to random errors, when analyzed in accordance with the procedures set out in Nonmandatory Appendix B, does not exceed ±0.5% at 95% confidence limits. If the test conditions are such that this uncertainty cannot be obtained, the uncertainty that has been achieved shall be given in the index test report. A comparison of the results of index tests with performance predicted from model tests should consider test uncertainty.

NONMANDATORY APPENDIX E
DERIVATION OF THE PRESSURE–TIME FLOW INTEGRAL

The fundamental pressure–time integral is given by

$$Q_i - Q_f = \frac{gA}{L}\int_{t_i}^{t_f}(h+l)\,dt$$

where

A = average penstock area, m^2 (ft^2)
g = local acceleration of gravity, m/s^2 (ft/sec^2)
h = pressure head difference between piezometer tap planes, m (ft) water at local conditions
L = distance between piezometer tap planes, m (ft)
l = pressure head loss between piezometer tap planes, m (ft)
Q_f = flow rate after completion of wicket gate flow, m^3/s (cfs)
Q_i = flow rate prior to wicket gate closure, m^3/s (cfs)
t = time, s (sec)
t_f = end of integration interval, s (sec)
t_i = beginning of integration interval, s (sec)

Also, the following variables for this analysis are defined:

h_f = static (final) line average head, m (ft) water at local conditions
h_i = running (initial) line average head, m (ft) water at local conditions
ρ = density of water kg/m^3 (slugs/ft^3)

The relationship between pressure and head (water column at local conditions) is given by

$$\Delta p = \rho g h$$

In the above equation, h is measured in terms of local water column, i.e., in meters or feet of water at local temperature, pressure, and gravitational acceleration. An appropriate conversion to convert the pressure difference, Δp, to the desired pressure units may be required.

The pressure recovery term, l, is assumed to follow a fully turbulent velocity-squared pressure law as follows:

$$l = f\,\frac{L}{D}\,\frac{Q^2}{2gA^2} = -\frac{h_i}{Q_i^2}Q^2 \tag{E-1}$$

where

$$-\frac{h_i}{Q_i^2} = f\,\frac{L}{D2gA^2} = k = \text{constant}$$

By agreement of parties to the test, a power of less than 2 on the flow rate term may be used in the pressure-recovery law, provided that appropriate adjustments are made to all subsequent equations in this section.

If the pressure cell has an initial offset, it will not affect the integration of the pressure–time integral, as long as the offset does not change during the course of the run. The value of the offset can be determined directly from the pressure–time record as described in the following.

Assume a constant instrument offset, h_o, exists, so that the relationship between the true pressure, h, and the measured pressure, h_m, is given by

$$h_m = h + h_o$$

Then the true pressure is given by

$$h = h_m - h_o$$

By the head loss equation [eq. (E-1)], the initial flow can be given by

$$Q_i^{\,2} = -\frac{1}{k}h_i \tag{E-2}$$

Since k is taken to be constant, the following relationship also holds:

$$Q_f^{\,2} = -\frac{1}{k}h_f \tag{E-3}$$

Substituting eq. (E-1) in eqs. (E-2) and (E-3), and solving for k and h_o yields

$$\frac{1}{k} = -\frac{Q_i^{\,2} - Q_f^{\,2}}{h_{mi} - h_{mf}}$$

and

$$h_o = \frac{Q_i^{\,2}h_{mf} - Q_f^{\,2}h_{mi}}{Q_i^{\,2} - Q_f^{\,2}}$$

The factor h_o is termed the offset compensation. It can be thought of as compensating for instrument offset, and ensures that the computed running and static lines are consistent with the assumed recovery loss law.

The final form of the pressure–time integral used in the analysis is given by

$$Q_i - Q_f = \frac{gA}{L}\int_{t_i}^{t_f}\left[(h_m - h_o) - \frac{h_{mi} - h_{mf}}{Q_i^{\,2} - Q_f^{\,2}}Q^2\right]dt$$

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