ASME PTC 18-2020

(Revision of ASME PTC 18-2011)

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
Two Park Avenue • New York, NY • 10016 USA

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The American Society of Mechanical Engineers
Two Park Avenue, New York, NY 10016-5990

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NOTICE

All Performance Test Codes must adhere to the requirements of ASME 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 the Code. It is expected that the Code user is fully cognizant of Sections 1 and 3 of ASME PTC 1 and has read them prior to applying this Code.

ASME Performance Test Codes provide test procedures that 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 and 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 American Society of Mechanical Engineers (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 ASME Council 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 ASME and three each from the American Society of Civil Engineers, the American Institute of Electrical Engineers, and the 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 the 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 committee on Prime Movers of the International Electrotechnical Commission at the New York meeting held 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 the 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 Standards Committee and by the ASME Council 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; and 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 by the American National Standards Institute (ANSI) Board of Standards Review as an American National Standard 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 ASME PTC 18-1992, Hydraulic Turbines. Since two separate but similar Codes now existed, the ASME 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 preceding 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 ASME PTC 18 and ASME PTC 18.1.

Following the publication of the 2002 revision of ASME 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 was characterized by the following features: increased harmonization of text with other ASME Performance Test Codes according to ASME 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 — increased ultrasonic flow-measurement accuracy with additional paths. This edition deleted from the code the seldom-used Venturi, volumetric and pressure–time Gibson flow-measurement methods and the seldom practical direct method of power measurement. Also in this edition, the Relative Flow Measurement–Index Test was removed from the main text of the Code to a nonmandatory appendix.

Following the publication of the 2011 revision of ASME PTC 18, the PTC 18 Committee began work on the next revision to consider current trends in field performance testing of hydraulic units including flow measurement at intakes and environmental performance measures. The 2020 revision includes the following changes:

(a) Thermodynamic method for efficiency measurement has been added.

(b) Current meter flow measurement method has been expanded to include measurements taken at the intake.

(c) Additional integration methods for ultrasonic flow measurement have been added.

(d) Key concepts of uncertainty calculations with emphasis on applicability to hydroturbines and harmonization with international codes have been added.

(e) Guidance for measuring flow at intakes using the acoustic scintillation flow measurement method (nonmandatory appendix) has been added.

A discussion of field testing of turbines equipped with aerating systems installed for the purpose of improving dissolved oxygen is, at this time, included as a nonmandatory appendix and, depending on stakeholder interest, may be expanded in subsequent publications.

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.

ASME PTC 18-2020 was approved by the Board on Standardization and Testing on October 28, 2020, and approved as an American National Standard by the ANSI Board of Standards Review on October 30, 2020.

ASME PTC COMMITTEE
Performance Test Codes

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

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

Secretary, PTC Standards Committee
The American Society of Mechanical Engineers
Two Park Avenue
New York, NY 10016-5990
http://go.asme.org/Inquiry

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

The Committee welcomes proposals for revisions to this Standard. 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.

Proposing a Case. Cases may be issued to provide alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Standard and the paragraph, figure, or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Standard to which the proposed Case applies.

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

Requests for interpretation should preferably be submitted through the online Interpretation Submittal Form. The form is accessible at http://go.asme.org/InterpretationRequest. Upon submittal of the form, the Inquirer will receive an automatic e-mail confirming receipt.

If the Inquirer is unable to use the online form, he/she may mail the request to the Secretary of the PTC Standards Committee at the above address. The request for an interpretation should be clear and unambiguous. It is further recommended that the Inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry in one or two words.
Edition:	Cite the applicable edition of the Standard 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. Please provide a condensed and precise question, composed in such a way that a “yes” or “no” reply is acceptable.
Proposed Reply(ies):	Provide a proposed reply(ies) in the form of “Yes” or “No,” with explanation as needed. If entering replies to more than one question, please number the questions and replies.
Background Information:	Provide the Committee with any background information that will assist the Committee in understanding the inquiry. The Inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

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

Moreover, ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Standard requirements. If, based on the inquiry information submitted, it is the opinion of the Committee that the Inquirer should seek assistance, the inquiry will be returned with the recommendation that such assistance be obtained.

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 or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

Attending Committee Meetings. The PTC Standards Committee regularly holds meetings and/or telephone conferences that are open to the public. Persons wishing to attend any meeting and/or telephone conference should contact the Secretary of the PTC Standards Committee. Future Committee meeting dates and locations can be found on the Committee Page at http://go.asme.org/PTCcommittee.

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, power, and thermodynamic losses 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 appendices providing recommended procedures for additional test methods and guidance for unique test conditions.

1-3 UNCERTAINTIES

The test procedures specified herein and the limitations placed on measurement methods and instrumentation are capable of providing total uncertainties, calculated in accordance with the procedures of PTC 19.1 and of 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

ASME PTC 2 and referenced portions of ASME PTC 19 Series 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.

multiplexing: the technology that is able to combine multiple communication signals together in order for them to traverse an otherwise single signal communication medium simultaneously.

NIST: National Institute of Standards and Technology.

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 (or guide vane), blade, or needle openings.

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

pump: a machine operating in the pumping mode.

pump-turbine: a 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.

supplier (or manufacturer): those directly concerned with the production of the equipment that is subject to testing.

systematic errors: are 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

(a) systematic error
(b) 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 general symbols, terms, definitions, equations, references, and units of variables used in this Code are listed in Table 2-3-1. See Figures 2-3-1 through 2-3-5 for a graphical definition of certain terms. Method-specific symbols, equations, and definitions are provided in the respective sections.

2-4 PHYSICAL PROPERTIES

See Mandatory Appendix I, Tables I-1-1 through I-1-9 (Tables I-1-1C through I-1-8C) for physical properties of fluids and constants.

2-5 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 Figure 2-5-1.

2-6 CENTRIFUGAL PUMPS

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

2-7 SUBSCRIPTS USED THROUGHOUT THE CODE

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

Subscript	Description
0	Static or zero flow conditions, a pool (HWL, TWL, etc.)
1	High pressure side of the machine
2	Low pressure side of the machine
a	Air, ambient
abs	Absolute
atm	Atmospheric, barometric
C	Runner cavitation reference elevation
G	Gross
g	Gage
L	Loss
N	Net
p	A pump
spec	Conditions as stated in purchase specification
T	Measured value during test, or as otherwise defined
t	A turbine
v	Velocity
vp	Vapor pressure
w	Water

Table 2-2-1 Conversion Factors Between SI 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 1 slug = 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 = 1.8T°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/s = 28.3168 m^3/s
Density	1,000 kg/m^3 = 1.94032 slugs/ft^3 1,000 kg/m^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_0 = 9.80665 m/s^2	g_0 = 32.1740 ft/sec^2

GENERAL NOTES:

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

π = 3.14159265359

g_0 = 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.

Table 2-3-1 Letter Symbols and Definitions

Symbol	Term	Definition/Equation/Reference/Remark	Units: SI	Units: U.S. Customary
A	Flow section area	Area of agreed water passage cross section normal to general direction of flow	m^2	ft^2
A_1	Area of high pressure section	Area of agreed flow section in machine high pressure passage	m^2	ft^2
A_2	Area of low pressure section	Area of agreed flow section in machine low pressure passage	m^2	ft^2
D	Machine reference diameter	Pelton: pitch diameter Kaplan and propeller: discharge ring diameter at runner blade center line elevation Francis: runner throat or discharge diameter	m	ft
g	Local gravitational acceleration	Value of acceleration due to gravity at an agreed upon geographical location and elevation. [See Table I-1-1 (Table I-1-1C).] Unless otherwise agreed to by the parties to the test, the local gravitational acceleration, g, shall be determined per Table I-1-1 (Table I-1-1C) for the elevation of horizontal centerline of high pressure section, Z_1, and latitude at the midpoint between the vertical centerlines of the first and last machine and shall then be used at all other locations and elevations within the test site.	m/s^2	ft/sec^2
HWL	Headwater level	Z_{1o} relative to the mean sea level	m	ft
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	Pressure head	Height of water column under prevailing conditions equivalent to pressure, p, at the corresponding flow section area $h = p/[g\ (\rho - \rho_a)]$	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_1	Pressure head at high pressure section	Height of water column under prevailing conditions equivalent to pressure at high pressure section, p_1 $h_1 = p_1/[g(\rho - \rho_a)]$	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

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

Symbol	Term	Definition/Equation/Reference/Remark	Units	
			SI	U.S. Customary
h_2	Pressure head at low pressure section	Height of water column under prevailing conditions equivalent to pressure at low pressure section, p_2 $h_2 = p_2/[g(\rho - \rho_a)]$	m	ft
h_{atm}	Barometric pressure head	Height of water column under prevailing conditions equivalent to atmospheric pressure, p_{atm} (absolute) $h_{atm} = p_{atm}/(g\rho)$	m	ft
H_G	Gross head	Water elevation difference between upper pool and lower pool corrected for buoyancy of water in air $H_G = (Z_{1o} - Z_{2o})\ [1 - (\rho_a/\rho)] = (\text{HWL} - \text{TWL})\ [1 - (\rho_a/\rho)]$	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 the upper pool and machine high pressure section, including entrance/exit, trashrack, conduit, and valve loss as may be applicable $H_{L1} = (Z_{1o} - Z_1 - h_1)\ [1 - (\rho_a/\rho)] - h_{v1}$	m	ft
H_{L2}	Head loss on low pressure side	Head loss between the machine low pressure section and lower pool, including entrance/exit, trashrack, conduit, and valve loss as may be applicable $H_{L2} = (Z_2 + h_2 - Z_{2o})\ [1 - (\rho_a/\rho)] + h_{v2}$	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 $H_N = (Z_1 + h_1 - Z_2 - h_2)\ [1 - (\rho_a/\rho)] + h_{v1} - h_{v2}$ [Note (1)]	m	ft
h_v	Velocity head	Height of water column under prevailing conditions equivalent to kinetic pressure head calculated in a given flow section $h_v = v^2/2g$	m	ft
h_{v1}	Velocity head at high pressure section	Height of water column under prevailing conditions equivalent to kinetic pressure head calculated in the machine high pressure section $h_{v1} = {v_1}^2/2g$	m	ft
h_{v2}	Velocity head at low pressure section	Height of water column under prevailing conditions equivalent to kinetic pressure head calculated in the machine low pressure section $h_{v2} = {v_2}^2/2g$	m	ft

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

Symbol	Term	Definition/Equation/Reference/Remark	Units SI	Units U.S. Customary
NPSH	Net positive suction head	The difference between absolute total head of low pressure section and potential head at the first stage runner reference elevation, Z_c, minus the vapor pressure head, h_{vp}. $NPSH = h_{atm2} + Z_2 + h_2 + h_{v2} - Z_c - h_{vp}$ The parties to the test may decide to modify the above formula for NPSH by eliminating the velocity head at low pressure section, h_{v2}, specifically in case that the same was done for the respective model test results.	m	ft
n	Speed	Rotational speed of the machine main shaft	rpm	rpm
P	Turbine power output or pump power input	Power delivered by the turbine shaft or applied to the pump shaft	kW	hp
P_W	Water power	Power equivalent to flow rate at net head $P_w = \rho g Q H_N/1000$ (SI units) $P_w = \rho g Q H_N/550$ (U.S. Customary units) [Note (2)]	kW	hp
p	Pressure	Static pressure at any point in water passage relative to prevailing atmospheric pressure [Note (3)]	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_{abs}	Absolute pressure	Static pressure at any point in water passage relative to perfect vacuum $p_{abs} = p_g + p_{atm}$	kPa	lbf/in.^{2}
p_{atm}	Atmospheric pressure	Absolute atmospheric pressure at a given altitude, Z. If suitable barometer is not available at the test site, the atmospheric pressure shall be determined per Table I-1-5 (Table I-1-5C) [Note (4)].	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 the average temperature of water, T_W [see Table I-1-2 (Table I-1-2C)].	kPa	lbf/in.^{2}
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	m^3/s	ft^3/sec

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

Symbol	Term	Definition/Equation/Reference/ Remark	Units SI	Units U.S. Customary
TWL	Tailwater level	Z_{2o} relative to the mean sea level	m	ft
T_a	Average temperature of air	Average temperature of ambient air at the test site	°C	°F
T_W	Average temperature of water	Average temperature of water in the water passages	°C	°F
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 section area, A_1	m/s	ft/sec
v_2	Mean velocity at low pressure section	Flow rate divided by low pressure section area, A_2	m/s	ft/sec
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_{1o}	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 common datum	m	ft
Z_{2o}	Potential head of lower Pool	Elevation of lower pool relative to a common datum. Also see "tailwater level."	m	ft
Z_c	Runner Reference Elevation	Elevation of cavitation reference location relative to common datum (see Figure 2-5-1)	m	ft
Z_g	Potential head at gage elevation	Elevation of a pressure gage typically used to measure p_g (see Figures 2-3-1 through 2-3-5)	m	ft
η	Efficiency	Turbine: P/P_W Pump: P_W/P	...	...

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

Symbol	Term	Definition/Equation/Reference/Remark	Units	
			SI	U.S. Customary
ρ	Density of water	Mass per unit volume of water at measured temperature and measured or calculated pressure. [See Table I-1-6 (Table I-1-6C).] Unless otherwise agreed to by the parties to the test, density of water, ρ, used for calculations throughout this Code shall be determined per Table I-1-6 (Table I-1-6C) for the average temperature of water, T_W, and pressure at high pressure section, p_1.	kg/m^3	slugs/ft^3
ρ_a	Density of dry air	Mass per unit volume of ambient air at measured temperature and given altitude. [See Table I-1-3 (Table I-1-3C).] Unless otherwise agreed to by the parties to the test, density of air, ρ_a, used for calculations throughout this Code shall be determined per Table I-1-3 (Table I-1-3C) for the average temperature of air, T_a, and the elevation of horizontal centerline of the high pressure section, Z_1	kg/m^3	slugs/ft^3
σ	Cavitation factor	σ = NPSH/H_N	…	…

GENERAL NOTES
(a) See Figures 2-3-1 through 2-3-5 for head definitions.
(b) See Mandatory Appendix I, Tables I-1-1 through I-1-9 (Tables I-1-1C through I-1-8C) for physical properties of fluids and constants.
(c) Wherever applicable for the potential and pressure differential heads, factor "1 − (ρ_a/ρ)" corrects the height of the respective differential water column for buoyancy of water in air.

EXAMPLE: With 50°F water temperature and 60°F ambient temperature at sea level, the value of the factor would be: 1 − (ρ_a/ρ) = 1 − (0.002372/1.93975) = 0.99878. It means that for this numerical example, the apparent height of the water column is reduced by 0.122%.

(d) Density of water used in a manometer for the pressure measurement is referenced to the mid height of the water column.

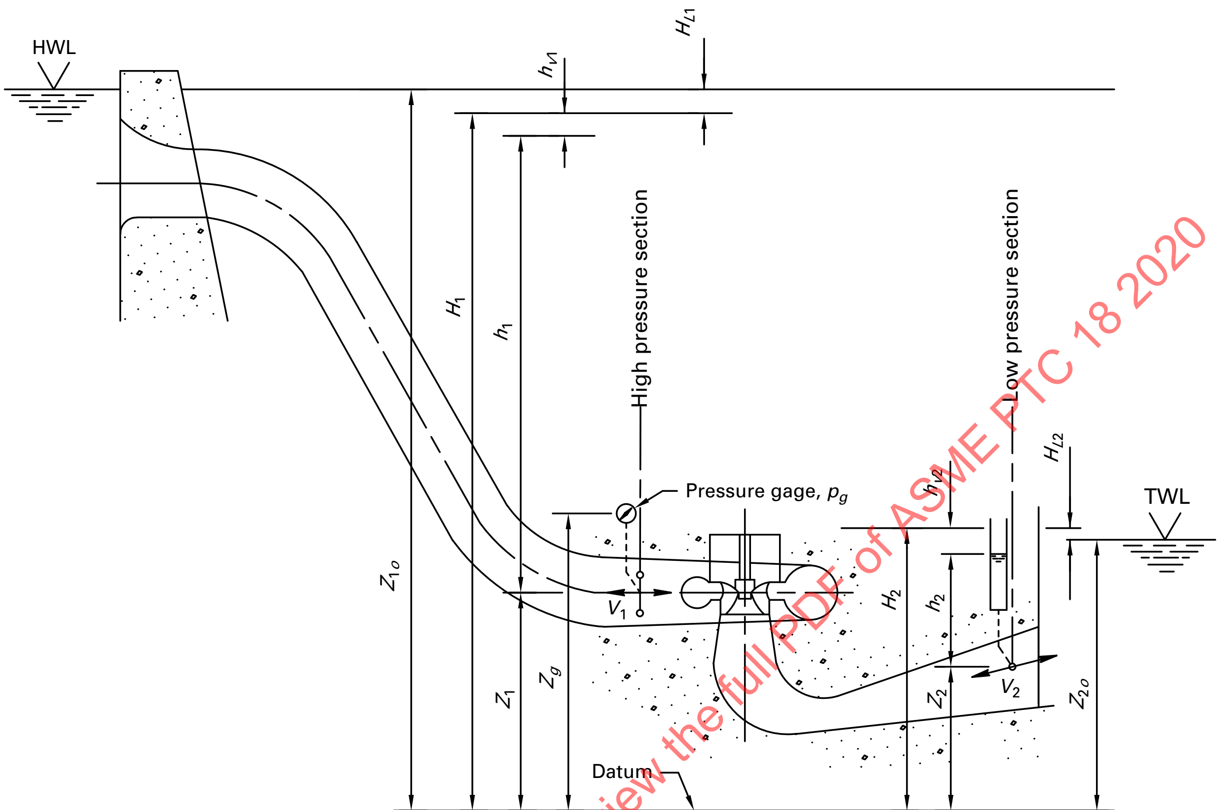
NOTES:
(1) Net head could also be defined as gross head minus head loss on high pressure side minus head loss on low pressure side: $H_N = H_G - H_{L1} - H_{L2}$
(2) Term "hydraulic capacity" is also commonly used.
(3) If the elevation of the gage is different from the elevation the static pressure is referred to, the following correction is required:

$$p = p_g + [(Z_g - Z)g(\rho - \rho_a)]$$

(4) If the elevation of the barometer is different from the elevation to which the atmospheric pressure is to be referred to (for example Z_2), the following correction is required:

$$p_{atm2} = p_{atm} + (Z_2 - Z)g\rho_a$$

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



GENERAL NOTES:

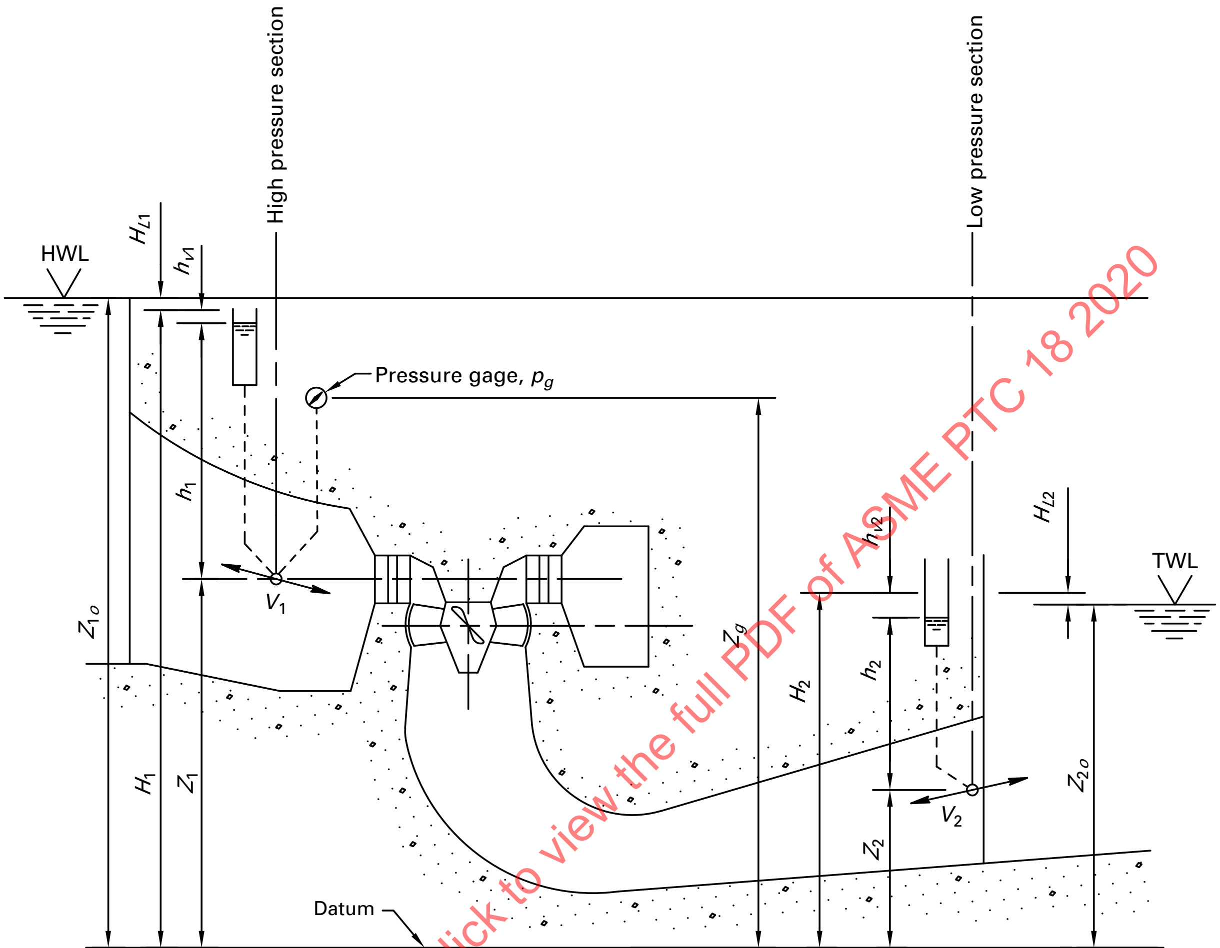
(a) Net head is defined as $H_N = (Z_1 + h_1 - Z_2 - h_2)[1 - (\rho_a/\rho)] + h_{v1} - h_{v2}$.

(b) The buoyancy of water in air factor, $[1 - (\rho_a/\rho)]$, is neglected in the graphic representation of head losses, H_{L1} and H_{L2}. In this figure, head losses are shown for the turbine mode. For the pump mode, the head losses will be of the opposite sign.

(c) Density of water by static check reading is as follows:

$$\rho = \frac{p_g}{g(Z_{1o} - Z_g)} + \rho_a$$

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



GENERAL NOTES:

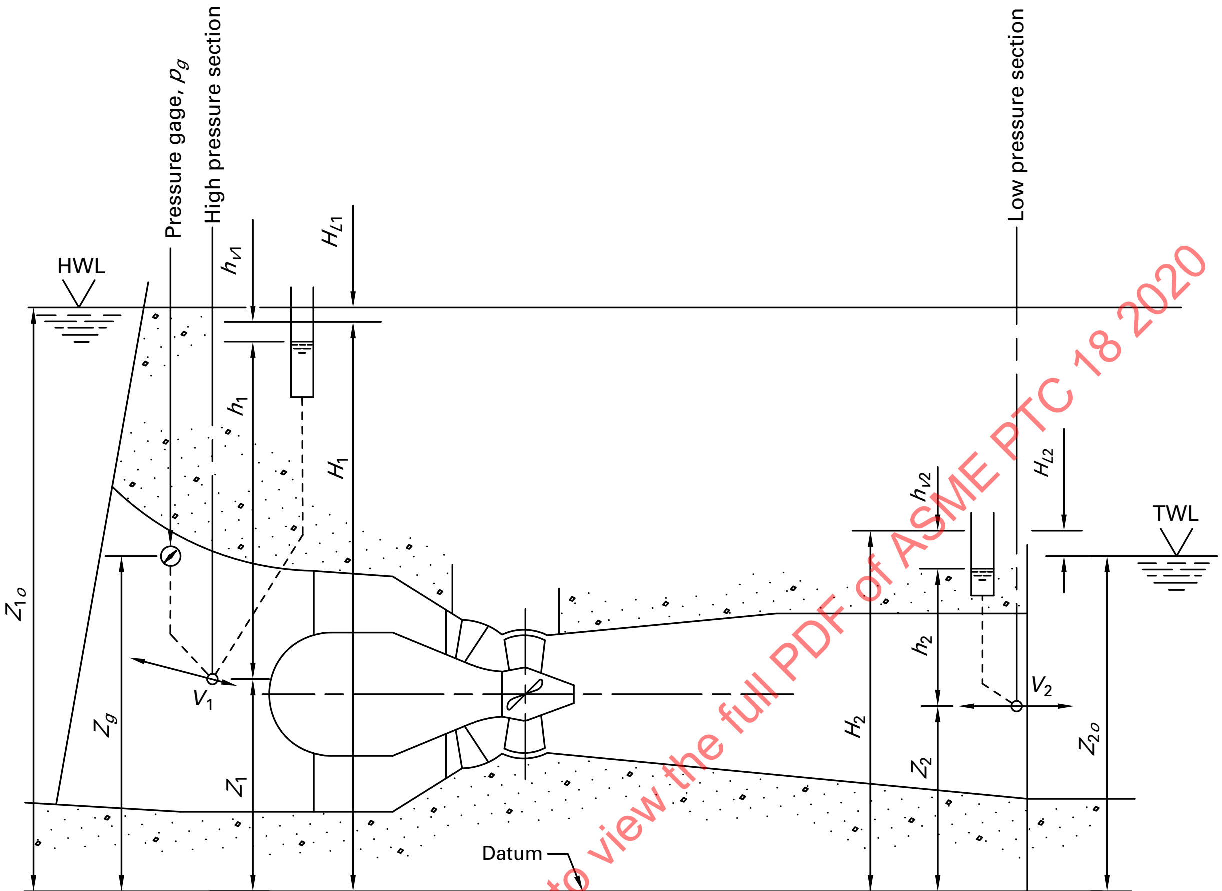
(a) Net head is defined as $H_N = (Z_1 + h_1 - Z_2 - h_2)[1 - (\rho_a/\rho)] + h_{v1} - h_{v2}$.

(b) The buoyancy of water in air factor, $[1 - (\rho_a/\rho)]$, is neglected in the graphic representation of head losses, H_{L1} and H_{L2}. In this figure, head losses are shown for the turbine mode. For the pump mode, the head losses will be of the opposite sign.

(c) Density of water by static check reading is as follows:

$$\rho = \frac{p_g}{g(Z_{1o} - Z_g)} + \rho_a$$

Figure 2-3-3 Head Definition, Measurement and Calibration, Bulb Machine



GENERAL NOTES:

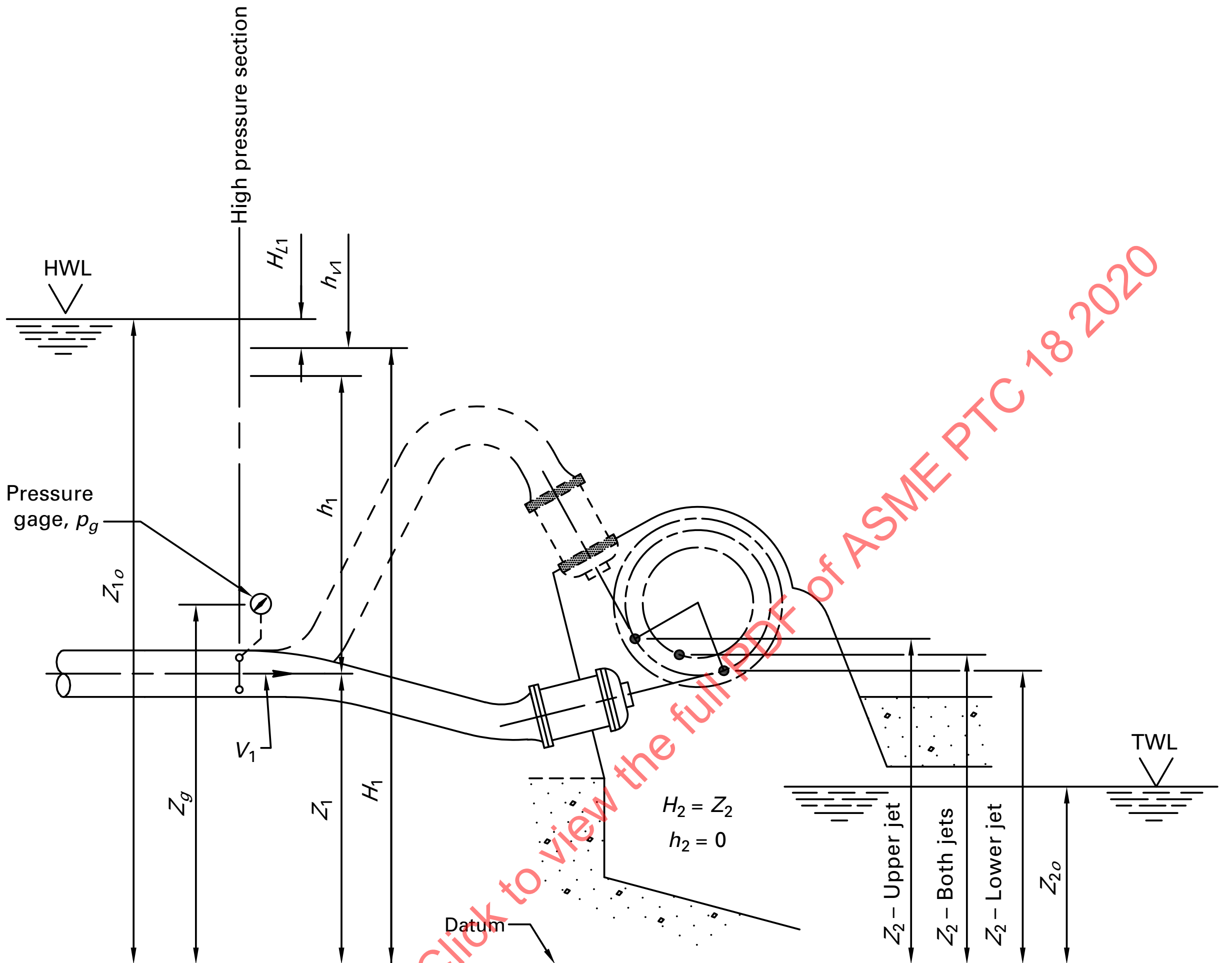
(a) Net head is defined as $H_N = (Z_1 + h_1 - Z_2 - h_2)[1 - (\rho_a/\rho)] + h_{v1} - h_{v2}$.

(b) The buoyancy of water in air factor, $[1 - (\rho_a/\rho)]$, is neglected in the graphic representation of head losses, H_{L1} and H_{L2}. In this figure, head losses are shown for the turbine mode. For the pump mode, the head losses will be of the opposite sign.

(c) Density of water by static check reading is as follows:

$$\rho = \frac{p_g}{g(Z_{1o} - Z_g)} + \rho_a$$

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



GENERAL NOTES:

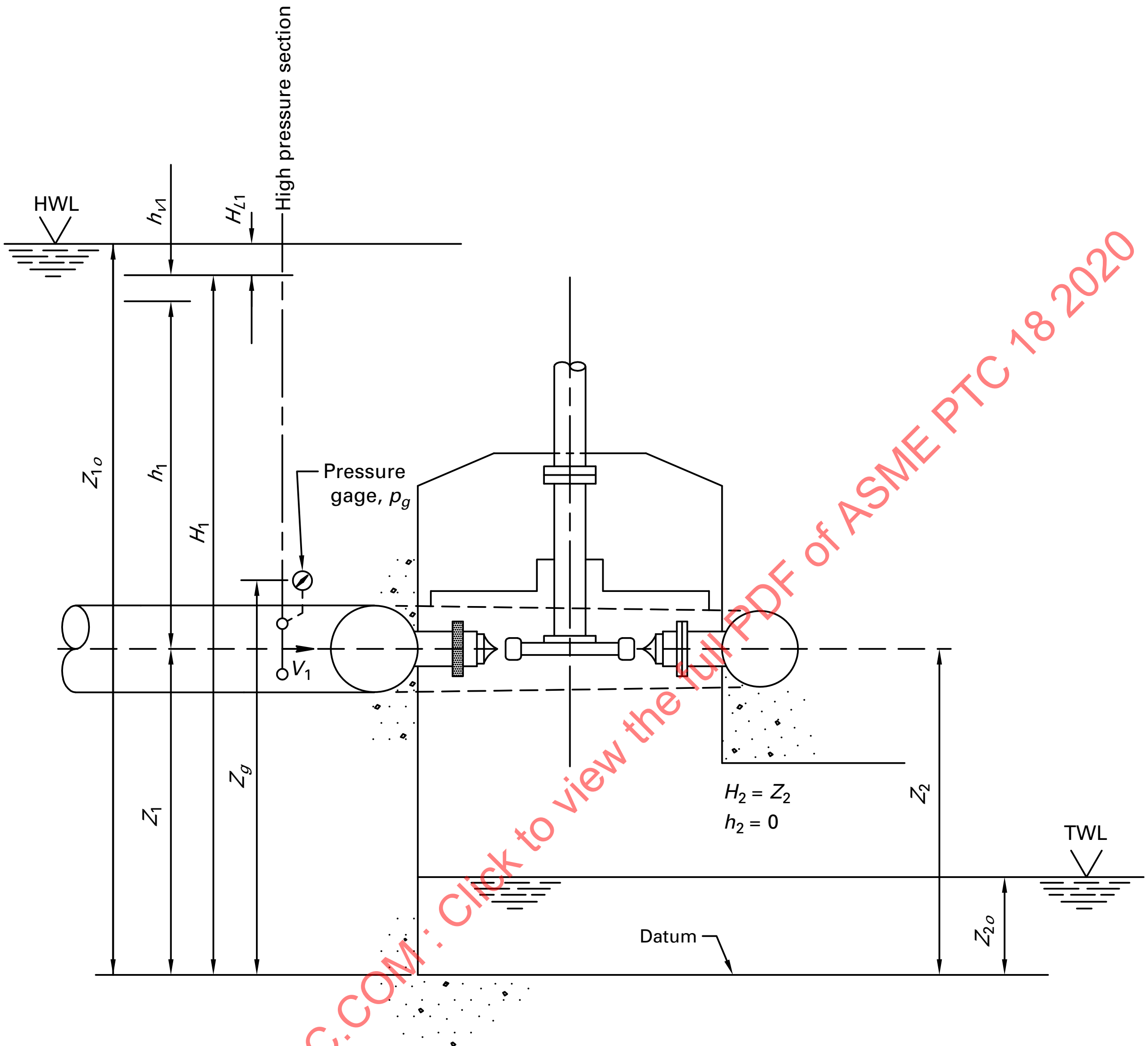
(a) Net head is defined as $H_N = (Z_1 + h_1 - Z_2 - h_2)[1 - (\rho_a/\rho)] + h_{v1} - h_{v2}$.

(b) The buoyancy of water in air factor, $[1 - (\rho_a/\rho)]$, is neglected in the graphic representation of head losses, H_{L1} and H_{L2}.

(c) Density of water by static check reading is as follows:

$$\rho = \frac{p_g}{g(Z_{1o} - Z_g)} + \rho_a$$

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



GENERAL NOTES:

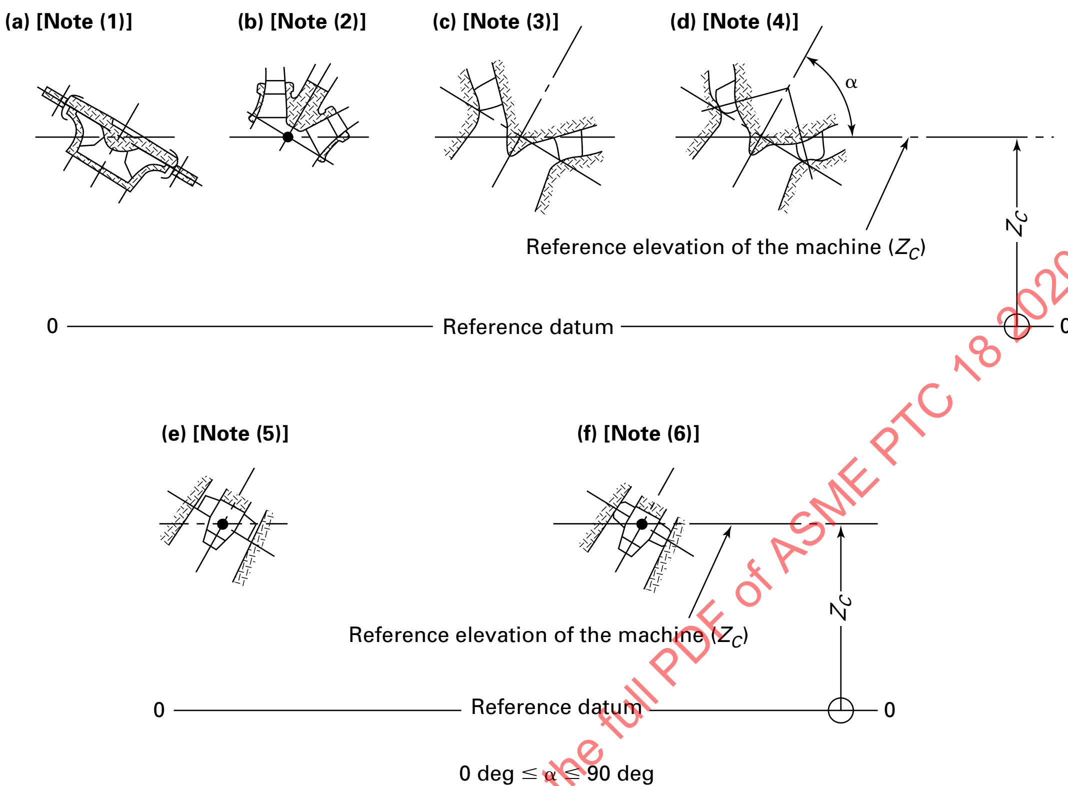
(a) Net head is defined as $H_N = (Z_1 + h_1 - Z_2 - h_2)[1 - (\rho_a/\rho)] + h_{v1} - h_{v2}$.

(b) The buoyancy of water in air factor, $[1 - (\rho_a/\rho)]$, is neglected in the graphic representation of head losses, H_{L1} and H_{L2}.

(c) Density of water by static check reading is as follows:

$$\rho = \frac{p_g}{g(Z_{1o} - Z_g)} + \rho_a$$

Figure 2-5-1 Reference Elevation, Z_c, of Turbines and Pump-Turbines



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NOTES:
(1) Radial machines, such as Francis turbines and pump-turbines; for multistage machines; low-pressure stage.
(2) Diagonal (mixed-flow, semi-axial) machines with fixed runner/impeller blades and with runner/impeller band.
(3) Diagonal (mixed-flow, semi-axial) machines with fixed runner/impeller blades without runner/impeller band.
(4) Diagonal (mixed-flow, semi-axial) machines with adjustable runner/impeller blades.
(5) Axial machines, such as propeller turbines and pump-turbines with fixed runner/impeller blades.
(6) Axial machines, such as Kaplan turbines and pump-turbines with adjustable runner/impeller blades.

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 commences.

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 safe operation of the machine has been demonstrated and after the machine has been found by inspection to be in a condition satisfactory to the parties to 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. Testing shall be done as soon as possible within the specified warranty period, unless otherwise agreed to 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, trash racks, 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 (see Nonmandatory Appendix A) 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 be used to give a permanent, explicit record. Instrument location shall be predetermined, agreed to 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 that 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.

(c) Schedule the test to occur when seasonal reservoir level and tailwater level provide test conditions that closely approximate the specified net head operating conditions and satisfy the requirements of para. 3-5.3.

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 (see Nonmandatory Appendix A).

(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 and method of recording, and archiving data.

(l) operating conditions: head, speed, tailwater level, power factor (PF), and cavitation factor.

(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) methods for estimating head losses between the instrument locations and the high-pressure or low-pressure sections, if required (see Nonmandatory Appendix B).

(q) methods for concurrent measurement of any other performance indicators, if applicable, e.g., cavitation or dissolved oxygen (see Nonmandatory Appendix E).

(r) values of measurement uncertainty and method of determining overall test uncertainty.

(s) methods for estimating systematic uncertainties, calculating random uncertainties (see Section 7), and performing a pretest uncertainty analysis.

(t) method of operating the machine under test, including that of any auxiliary equipment, the performance of which may influence the test result, e.g., air admission valve(s) in the specified (open or closed) position, or operated in the normal automatic mode (by the unit controls).

(u) methods of maintaining constant operating conditions as near as possible to those specified, including permissible fluctuation of measured variables.

(v) method of determining duration of operation under test conditions before test readings are started.

(w) system alignment or isolation.

(x) organization of personnel, including designation of chief of test.

(y) duration and number of test runs, including start and stop procedures.

(z) test schedule and scope (which machines are to be tested and when).

(aa) 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.

(bb) method of ensuring synchronization of readings.

(cc) frequency of observations.

(dd) base reference conditions.

(ee) methods of correction and values used for corrections for deviations of test conditions from those specified.

(ff) methods of computing results, including integration methods where more than one method may be applicable.

(gg) method of comparing test results with specified performance.

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

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

(jj) pretest inspections.

(kk) arbitration procedure.

(ll) 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) 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 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. Available relevant data, drawings, 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, check instruments and methods of measurement, check adequacy of organization and procedures, and 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 supplier shall have reasonable opportunity to examine the machine, correct defects, and render the machine suitable to test. The supplier, 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, i.e., 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 that 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 the magnitude and minimize the 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.

It is recommended that the cavitation factor σ during the test should be equal to the cavitation factor σ_0 corresponding to the nominal (or specified) operating conditions. If a deviation is unavoidable then such deviation should be kept to a minimum and σ should always be greater than σ_0 to avoid effects resulting from the onset of cavitation. It is recommended that the power factor should be at unity wherever possible.

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 Figures 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 model tested over the operating range in question and the applicable equations of Section 5 (see Figures 3-5.3-1 and 3-5.3-2, Zone 2). Either a model test or CFD model, as agreed upon by the parties, may be used for this correction.

(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.

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 all observer 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 storage devices and distributed to each of the parties to the test. The data files shall be in a format that is easily accessible to all.

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.

Figure 3-5.3-1 Limits of Permissible Deviations From Specified Operation Conditions in Turbine Mode

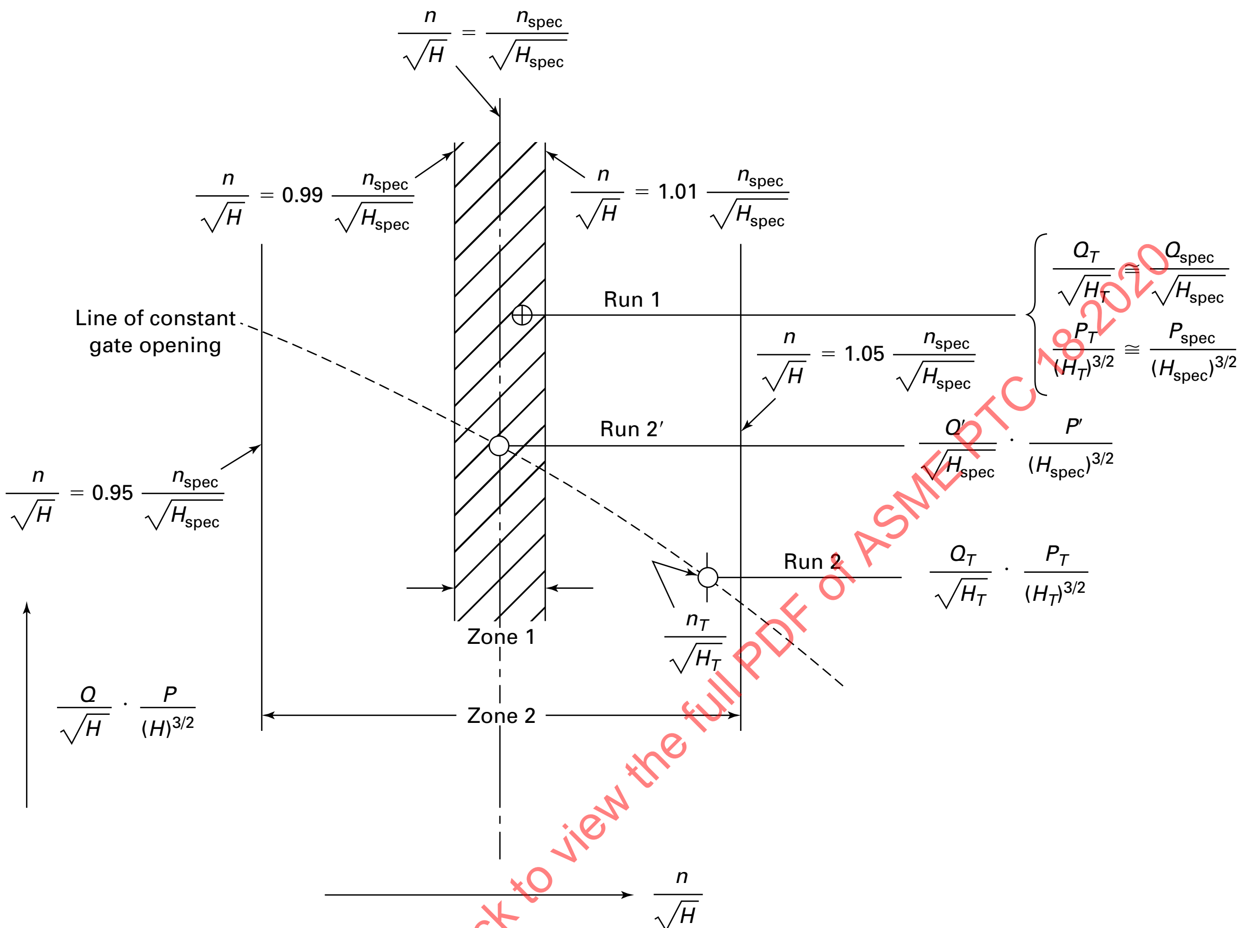
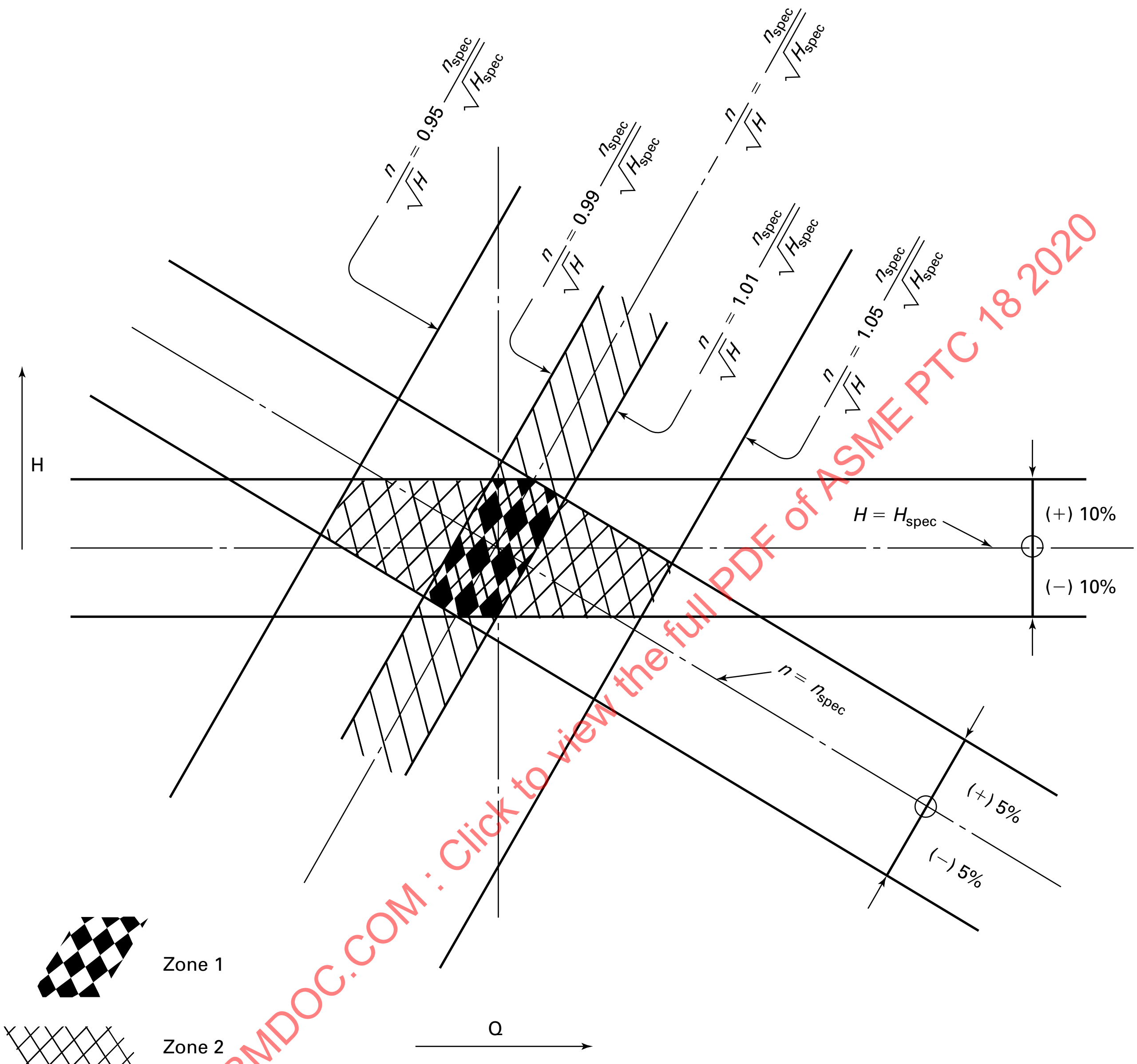


Figure 3-5.3-2 Limits of Permissible Deviations From Specified Operating Conditions in Pump Mode



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 120-1989.

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 of the parties to the test. Instrument calibrations shall be included in the final report.

4-2 DATA ACQUISITION AND DATA PROCESSING

The use of data acquisition systems (DAS) 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 a DAS is not without pitfalls. A DAS shall be used with knowledge of the signals being processed and the rate of change of quantities being measured.

Planning and designing a DAS 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

Uncertainty should be a primary consideration when designing a DAS for machine performance testing. The DAS shall 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 DAS along with data converted to engineering units to readily evaluate discrepancies and aid in system troubleshooting. The DAS shall 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 shall be sufficient to ensure that the complete characteristic of the signal is obtained, yet should be slow enough that the amount of data saved is not so excessive it does nothing to improve the test measurements or lower the random uncertainty.

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

4-2.1 Introduction and Definitions

Data acquisition and processing is the conversion of measured signals into appropriate engineering units using several components e.g., transducers, multiplexers, signal converters, conditioners, and computers. The final output is a presentation of measured quantities in engineering units as meaningful performance data.

The measured signals are either fluctuating or time varying. In most cases, the average value of the signals can be used to determine the hydraulic performance of a turbine. Care should be taken to ensure a sufficient number of samples are taken for each test point. Sampling shall be made at a sufficient frequency and duration to properly represent and capture the signal.

Some important definitions are as follows:

aliasing: a phenomenon that occurs when an analog signal is sampled at a rate less than twice that of the frequency of the highest-frequency signal or noise component (Nyquist rate); such under-sampling will produce spurious low-frequency signals (aliases) that cannot be distinguished from the original signal.

frequency of interest: the frequency of interest is the range over which the transducer shall accurately represent the signal dynamically and the range that the data acquisition system samples the transducer.

resolution: the smallest change in the signal that a measurement process can represent.

sample rate: the rate the transducer is sampled in order to properly represent the signal or reconstruct the signal.

signal: a continuous fluctuating or time varying quantity to be measured.

transducer: a measuring device, that converts the signal from one form to another (mechanical to electrical or vice versa) and provides an output quantity with a known relationship to the input quantity.

For further information and other definitions of terms listed in subsection 4-2, see ASME PTC 19.22.

4-2.2 General requirements

The output from the data acquisition and data processing system shall properly represent the dynamic and/or static characteristics of the signal. Proper representation shall mean the ability to reconstruct the raw signal from the acquired data.

Documented calibration procedures shall exist for all instruments in use. Records of all measurement standards and measuring equipment used to establish compliance to specified requirements shall be maintained.

During a performance test, the averages of each of the measured quantities shall be obtained by measurements performed during the same time interval.

4-2.3 Data acquisition

The DAS may be arranged in different ways (including manual methods) depending on the hardware available and the requirements of the data acquisition.

Possible arrangements and examples of different data acquisition systems include time multiplexing systems and parallel measuring systems. The design and configuration of both systems shall be sufficient to sample data with adequate resolution and rate so aliasing on time varying signals does not occur. The system shall have sufficient throughput to sample at the prescribed rate over a sufficient duration to capture the event. Additionally, the system shall be capable of storing these values for later review.

4-2.4 Component requirements

The components in the measurement process shall be able to operate over the frequency range of interest.

Components transferring the quantity to the transducer, for example pressure piping, can cause spurious effects and cause errors in the measurements. Care should be taken to avoid these phenomena.

The temperature dependence of all components of the measurement system must be known to establish the limits within which their performance is stable. Temperatures outside of the limits of the components should be avoided or alternate components should be used.

Properties such as linearity and hysteresis shall be documented during calibration.

4-2.4.1 Transducer. Transducers used for the measurement of performance parameters that have temperature influences should operate in a stable temperature environment. They should be located where they are not influenced by external factors (e.g., from direct sunlight, heating panels, ventilation channels). Transducers shall be used within the manufacturer's specifications.

The dynamic behaviour of the transducers shall be known, particularly in the frequency of interest.

Care should be taken when using transducers and signal conditioners that may have special inherent damping, filtering, or adjustable response times. Additionally, transducers with extremely high deflection of the sensing element should be avoided. Such transducers with high deflection can cause erroneous measurements in both fluctuating and time varying measurements.

4-2.4.2 Cables and termination. The signal path between transducers and amplifier shall be designed in such a way that external influences (noise) on the signals (e.g., from power lines or temperature variations) are minimized. Proper shielding and grounding shall be observed. Connectors and terminations shall have stable, reliable mechanical and electrical properties.

Even if all the above precautions have been taken, influences from radio devices, control signals, or power lines on the measurement can result in spurious or erroneous data. The design of the data acquisition system should facilitate diagnosing these influences.

4-2.4.3 Signal conditioning. The output from transducers with analogue output are often amplified and filtered in a signal conditioning unit. Care should be taken to ensure the signal conditioning unit does not adversely filter or alter the signal over the frequency of interest range.

4-2.4.3.1 Filter. When choosing filters, an evaluation of the following properties shall be made:

(a) AC signals: cut-off frequency, attenuation roll off, passband ripple, and time delay

(b) DC signals: offset, temperature drift and linearity

In analyses where simultaneous measurement of two or more signals is important, be aware of delays in the conditioning and data acquisition systems. Filters cause delays (phase shift) that are a function of the filter type and the cut-off frequency (Figure 4-2.4.3.1-1).

The cut-off frequency of a low-pass filter shall be a maximum of half the sampling frequency in order to avoid aliasing effects. This is illustrated in Figure 4-2.4.3.1-2. In practice, a cut-off frequency of one-third or less of the sampling rate is used to ensure that aliased components of the signal are not captured in the roll off frequency range (f_c to f_s). Typical low order filters have roll off frequencies of 10 dB per decade and may pass unwanted frequencies. Care should be taken to ensure that the sampling rate is much higher than the roll off characteristic of the filter or the filter roll off characteristics are sufficiently steep to prevent higher frequencies from aliasing effects.

4-2.4.4 Multiplexer. The effective multiplexing rate of the analog to digital converter (ADC) shall be compared to the requirements for each signal since the ADC is sampling several channels sequentially. Typically, maximum sampling rate for each channel is reduced in proportion to the number of channels in use.

The switching system is either a relay or a solid state switching type. Relay switching is usually more accurate than solid state switching, but has a lower switching rate. When switching between different voltage levels, be aware of interference effects between neighboring channels. Generally, these errors increase with the switching rate.

4-2.4.5 Analog-to-Digital Converter (ADC). Before the continuous analog signal can be read by the computer, the signals must be converted into digital numbers.

Important parameters for ADC's are the conversion time, resolution, accuracy, input range, temperature drift and linearity.

The resolution of an ADC is defined as the number of bits the converter uses to quantize the analog signal. A 3-bit converter divides the range into $2^3 = 8$ quantities or a resolution of one part in eight which is in turn encoded into a binary number.

For performance tests, a minimum requirement shall be 12-bit resolution ($2^{12} = 4\,096$) or 1 part in 4 096. This resolution is based on the complete span of the transducer being measured to minimize quantizing errors. For dynamic measurements, care shall be taken to ensure that the A/D sample rate is sufficient. Typically sample rates should be at least twice the highest frequency component of the signal. In some cases, the sample rate can be as high as 10 times the highest frequency component if data analysis such as fast Fourier transforms is anticipated.

Conversion time should be sufficient to allow each channel in multiplexed systems to properly sample the signals at the Nyquist rate over the frequency of interest.

Input range of the analog signal should maximize the quantization of the signal.

4-2.4.6 Computer. The controller in the data acquisition system is the computer. It shall have the following functions: configure and synchronize the data acquisition, manipulate the data to convert into engineering units, and communicate with peripheral equipment. The same software should have the ability to perform calibrations and present results.

The computer interface should have a sufficient data transfer rate to prevent data loss between the analog converter devices and computer storage.

4-2.4.7 Data processing. Typical software tasks are

(a) control of the data acquisition
(b) calculation of calibration coefficients
(c) conversion of electrical values into engineering units
(d) calculation of average values and other statistics
(e) calculation of performance data
(f) data logging for sufficient statistical analysis
(g) presentation of results
(h) data storage

The raw data for each parameter in an acceptance performance test shall be available after the evaluation of a test point in order to perform a manual calculation and verify the computer code.

If possible, essential performance data should be continuously displayed during the test to give an overview of the turbine performance. The number of samples and the sampling rate should be sufficient to show accurate mean signal values and a satisfactory representation of the dynamic characteristics of any time varying signals.

4-2.5 Check of the DAS

Each measurement process shall have a complete schematic diagram showing its main components. This will help the parties to decide where checks should be made if particular problems occur, or when oscillating signals require closer investigation.

4-2.5.1 Check for Bias Effects. Means shall be provided in order to verify that the data acquisition system does not have any bias effect.

4-2.5.2 Software. The software code can be verified by an alternative computation using the raw data read at input to the data acquisition system and comparing it with the result from the computer.

Figure 4-2.4.3.1-1 Time Delay

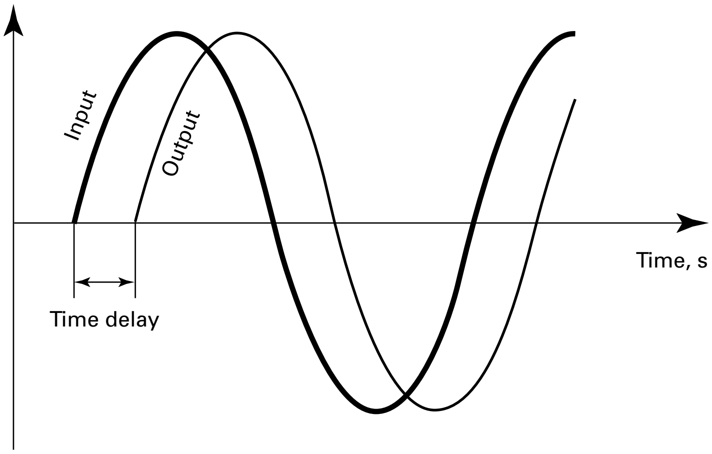
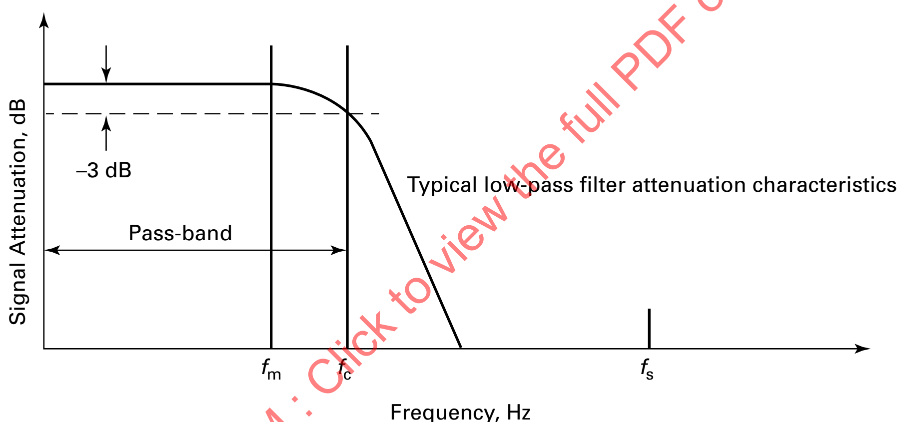


Figure 4-2.4.3.1-2 Filtering and Sampling Frequencies



Legend:
f_c = the cut-off frequency of low-pass filter
f_m = the maximum frequency component of interest
f_s = the sampling rate

GENERAL NOTE: To obtain desired frequency content, $f_c > f_m$. To avoid aliasing in the pass-band, $f_s \geq 2f_c$.

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 e.g., 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 trash racks.

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 and velocity head difference in the intervening passages between the agreed flow section and the actual measurement section computed by the Darcy–Weisbach or similar formula. Nonmandatory Appendix B provides guidance for determination of head loss in some special cases.

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 ($\frac{1}{2}$ 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 it 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 ($\frac{1}{4}$ 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 2 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 ($\frac{1}{4}$ in. to $\frac{3}{8}$ 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 yield accuracy sufficient to meet the overall uncertainty requirements of the test. When these devices are used, care shall be taken to ensure that the cone-shaped beam of the transmitted signal is unaffected by obstructions, e.g., adjacent walls. In the case of an ultrasonic device, the measurement shall be temperature compensated to account for the variation in the speed of sound in air as a function of temperature. Care shall be taken to ensure that movement of the transducer does not affect the distance measurement.

A procedure for installation and calibration of the transducer shall 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 shall 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 shall be raised by suction. The connecting tubes to the manometer shall 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 shall be developed in advance to allow for the fabrication of special support fixtures required. They shall 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 ASME PTC 19.2.

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 may be sufficient. Otherwise, it may be necessary to have multiple elevation measurement devices at intake or discharge bays.

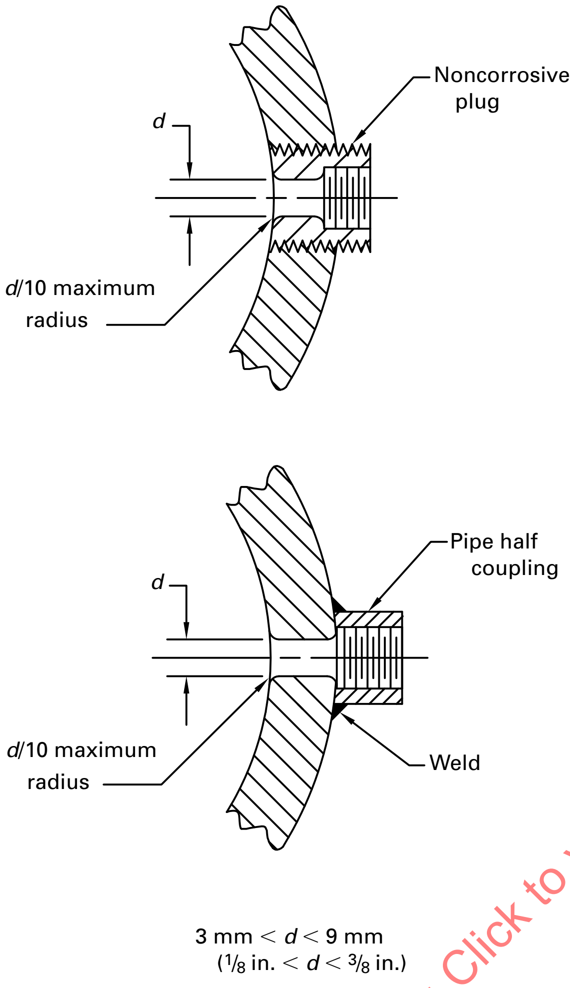
4-3.14 Pressure Measurement by Pressure Taps

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.

Each pressure tap should be flush with the wall, with the tap axis normal to the wall, and without local flow disturbances (see Figure 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 3 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.

Figure 4-3.14-1 Pressure Tap



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 ($\frac{1}{8}$ in. to $\frac{3}{8}$ 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.) in diameter, embedded flush with the surrounding concrete.

Where pressure taps were never installed or have become unusable and external access to the conduit is not available, pressure plates may be installed inside the conduit to measure local static pressure (Figure 4-3.14-2). Pressure plates shall be a minimum of 350 mm (14 in.) long, and a maximum of 25 mm (1 in.) thick with 15 deg or 3:1 semi-elliptical leading and trailing edges (or more gradual taper). The pressure tap shall be in the center of the plate and meet the requirements of Figure 4-3.14-1. Installed tubing shall conveniently exit the conduit without disrupting flow streamlines for static pressure measurement. Experimentation has shown that 5 mm ($\frac{3}{16}$ in.) weld beads do not have a measurable effect on piezometer plate measurements. Installation welds should be ground so as not to influence measurements. Where practical, the internally mounted tubing should be run downstream to a point at least 1 diameter from the centre of the meter section before any circumferential tubing is installed.

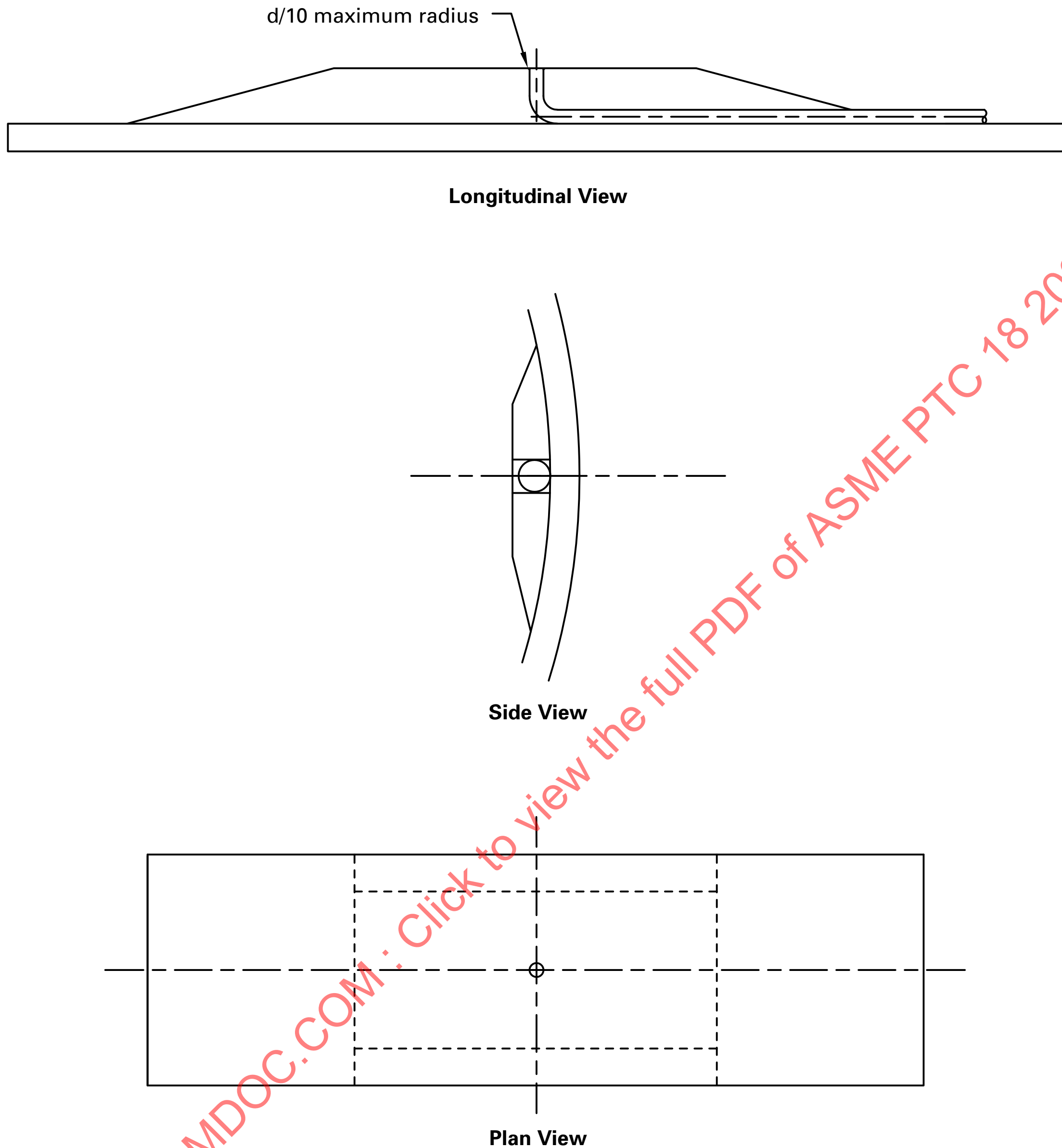
Pressure taps shall be individually valved so they can be read separately. Pressure taps may be manifolded after the valve, provided the manifold piping is not less than 12 mm ($\frac{1}{2}$ in.) inside diameter when measuring devices other than pressure cells are used, and 6 mm ($\frac{1}{4}$ in.) inside diameter when pressure cells are used. All connections shall be leak free. Care shall 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.

4-3.15 Pressure Measurement

For the measurement of pressure, liquid manometers or deadweight gage testers shall be considered 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 a 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

Figure 4-3.14-2 Pressure Plate Tap

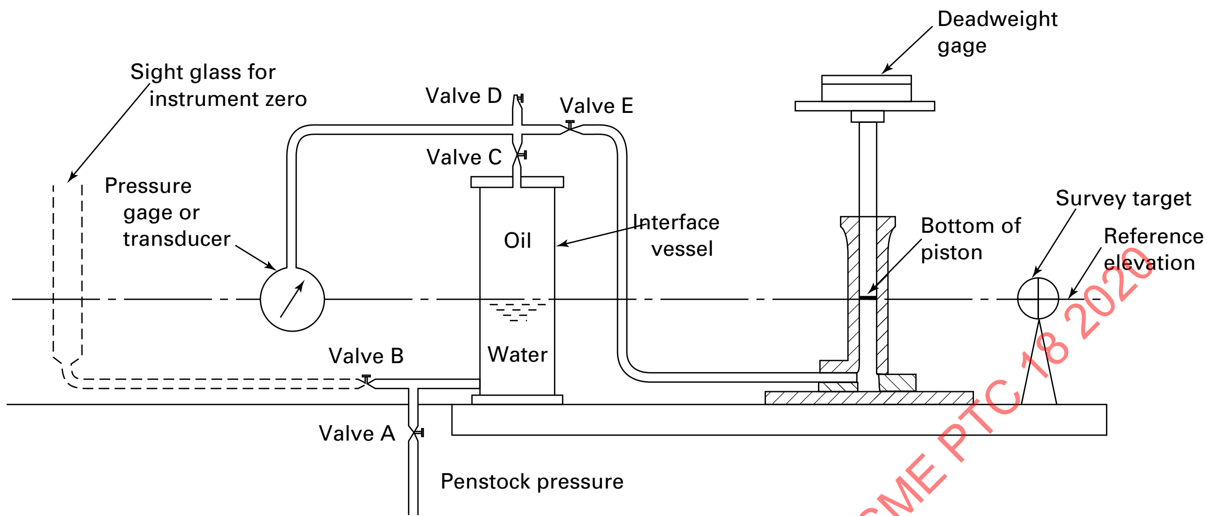


standard connected in parallel with the secondary devices so that at any time during the test, all parties may be satisfied that the gage readings or the recorded measurements are in agreement with the primary device (see Figure 4-3.15-1 and para. 4-3.16). This is especially important if the test instruments 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.

Figure 4-3.15-1 Calibration Connections for Pressure Gages or Pressure Transducers



The two modes of operation, pressure measurement with the gage or the transducer, and instrument calibration 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 shall however, include a pressure, p_L, just below the expected test pressure(s) and a pressure, *pH*, just above the expected test pressure(s). When used for pretest or posttest 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 I-1-6 (Table I-1-6C), 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 shall 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 shall 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. 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.

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

The pressure–time method (para. 4-4.3) measures the impulse resulting from the deceleration of flow in a closed conduit.

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 sampling downstream at a distance where mixing is complete. The dilution of the dye is proportional to the flow.

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 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.

Flow-measurement using acoustic scintillation in unit intakes is being evaluated for future versions of the Code but is not considered sufficiently proven for inclusion at this time. Nonmandatory Appendix C provides guidance on the use of acoustic scintillation for flow measurement.

4-4.2 Current Meter Method

The current meter method establishes the flow rate in a conduit by measuring velocities at discrete points in the flow section area. The measured point velocities are integrated over the measurement cross section to obtain the flow rate. Measurement procedures in accordance with ISO 3354 are recommended. Current meters and methods of measurement should fulfill the requirements of ISO 2537, and 3455 respectively.

The following general requirements shall be followed for any current meter testing. Specific requirements for current meters in closed conduits (penstocks) and current meters in intakes are provided in paras. 4-4.2.1 and 4-4.2.2, respectively.

Current meters require a mounting structure/frame that can either be in a fixed position or movable. Moveable frames can be either repositioned to fixed locations to measure point velocities, or traverse the water passage while continuously recording velocity data. Regardless, the current meters shall be installed with their axis set perpendicular to the measurement plane and only self-compensating (axial-flow) current meters shall be used. Mounting rods and frame elements shall be stiff enough that deflection and vibration caused by the flow are negligible. The minimum distance between the axis of any current meter and the water passage wall or the blade tip of any adjacent current meter shall be 0.75 times the blade tip diameter of the current meter. The maximum spacing between meters is based on achieving adequate resolution required for integration [see para. 4-4.2.2(g)].

Only electric-signaling current meters shall be used. The bearing arrangement and lubrication are of special importance. Care should be taken to prevent waterborne solids from entering the bearing and causing corrosion or water hardness to deteriorate the calibration. If, based on the intake geometry, there is potential for reverse flow at the metering plane, then meters should be capable of detecting reverse flow.

Current meters shall be calibrated in a towing tank with the same type of mounting and frame position as used during the test. Calibration should initially be completed every 300 h of use. This frequency can be reduced if successive calibrations exhibit repeatable equations. Calibration equations should be considered valid for clean current meters in good working order; dirty bearings or meter damage will change the relationship between revolutions per second and velocity. The calibration shall include the effect of oblique flow and, where practical, changes in water temperature. If temperature dependent calibration is not feasible for all current meters used in a test, the effect of temperature should be assessed through manufacturer information or through calibration of a smaller number of meters. Calibration shall be performed over the range of velocities expected for the test; in no case should the calibrated rating curve be extrapolated to higher or lower velocities.

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.

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 can be made with several current meters mounted on movable frames that can traverse the water passage(s) to collect the required point velocities for integration. 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 measurements to the same reference flow rate or head.

The duration of measurement for each fixed-position shall be at least 2 min. For continuous measurement methods, the traverse time should be a minimum of 5 min and the traveling velocity of the carriage should not exceed 5% of the average flow velocity. For measurements showing that the water velocity is subject to periodic pulsations, the duration of measurement shall include an even number (at least four) of complete periods of the pulsation.

The current meters and their supports disturb the velocity distribution in the conduit. It is assumed that smaller scale velocity effects (wake region vs. compressed streamlines) are accounted for by including the mounting system in the calibration setup. On a larger scale, however, the blockage effect of the frame can lead to a positive error in the flowrate measurement. The magnitude of this error depends on the number and type of current meters used and the projected frontal area of the supports. The flow rate, Q, reduced to correct for blockage, is given by

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

where

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

The summation of area is for all current meters, whether of the same or different tip diameters. It is recommended that the blockage effect can be ignored if the blockage is less than 2% of the intake area (ISO 3354). An uncertainty is introduced into the flow measurement by the supports. This should be taken as the greater of ±(1/12)(S/A) or (2/3)[1 − 0.125(S/A) − 0.03(S_m/A)]. This may limit the amount of blockage that can be tolerated when combined with other uncertainties and compared to the overall allowable test uncertainties (see para. 4-4.2.3) for a test that meets the conditions of this Code.

4-4.2.1 Current Meters in Closed Conduits. With respect to measurements in closed conduits, both circular and rectangular, the following additional criteria 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) All point velocity measurements from individual current meters shall be within 25% of the mean velocity for any run. ISO 3354 provides additional guidance through the use of an asymmetry index.

(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 (see also ISO 3354, asymmetry index). All velocity points shall 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 flow measurement uncertainty and calibration should include angles up to 10 deg.

4-4.2.2 Current Meters in Intakes. Although flow conditions are not as ideal as those for a straight conduit as described in para. 4-4.2.1(a), current meters can also be used for velocity measurement in intakes, largely because the principle of integration of a detailed velocity profile over the intake area is sound and because it typically requires low facility outage time for implementation. A typical low head unit with a converging intake is illustrated in Figure 2-3-2.

Due to the large number of points measured, the process usually involves traversing a rack of current meters vertically through a number of successive elevations. This process can take 1 to 2 hr for each test run. The resulting grid of point velocity measurements is numerically integrated over the flow area to yield the flow rate [see (c) and (d) below]. Normally the current meter frames are positioned at fixed elevations in the flow field, but an alternate approach is to continuously record data as the frame traverses the intake vertically, so that a continuous movement profile can be obtained and integrated.

The use of current meters for measuring velocities for integration in intakes requires careful consideration of the following potential difficulties:

(a) Velocity Profile. Because the flow in an intake is not fully developed, the velocity profile should be reviewed for the presence of reverse flows or other unusual and unexplainable velocity profile characteristics. Trash racks, support structures, and accumulated trash may affect the velocity distribution and turbulence levels, and this effect must be evaluated. It is recommended the trash racks be inspected for debris and, if necessary, cleaned prior to testing. Velocity measurements that significantly deviate from expected values shall be scrutinized; characteristics of the profile should be explainable (e.g., pier separation) and repeatable among successive tests.

(b) Blockage Effect. Blockage effects for a moving frame may depend on the position of the frame in the intake. For example, a significant portion of the frame may be positioned out of the effective flow area when the top boundary is being measured. Similarly, the blockage effect may also be affected when measuring near the bottom of the intake where flow could be prevented from passing below the frame. As per para. 4-4.2, it is recommended that the projected frontal area of the frame be less than 2% of the intake area so that the effect can be considered negligible.

(c) Metering Plane Dimensions. In many cases, the metering section in an intake will be at a location that is not possible to dewater, such as upstream of the intake stoplog slots. In such cases, the dimensions of the intake should be taken as the best available data, e.g., as-constructed or as-built drawings and the uncertainty should be evaluated appropriately. An approach

to quantifying this uncertainty may be to use appropriate concrete formwork tolerances from the construction industry that should be representative of the tolerances typical at the time of construction.

When the metering plane is located below an opening, such as a stoplog slots with a relatively large dimension parallel to the flow, it can be difficult to accurately define the ceiling flow boundary. In such cases the uncertainty in the vertical dimension can be reduced by positioning the current meters as close as reasonably possible to the upstream limit of the opening and then monitoring the velocity signal as the meters are lowered into the intake. It is recommended that the velocity profile in the vicinity of this theoretical boundary be explored in detail. Care should be taken to ensure negative velocities are not introducing error. For witnessed contractual tests, it is recommended that the selected upper boundary be agreed upon by relevant parties to the test.

(d) Statistical Stationarity of Test Conditions. Because intake tests may be of longer duration, particular attention should be given to ensuring the variation of test conditions (head and power) remain within allowable tolerances (para. 3-5.2). Furthermore, it is recommended that the test duration be minimized as much as is practicable, while respecting the importance of sufficient detail in the measurement grid. The use of a single current meter with both horizontal and vertical traversing is discouraged because of the excessive time involved. If test conditions meet the requirements under para. 3-5.2, homology can be used to adjust velocities and power for each row of data, with the adjustment being from the head (gross or net) for the particular row to that of the full test run.

(e) Calibration of Current Meters. In addition to the requirements in para. 4-4.2, uncertainty of current meter response to oblique flows should be evaluated, and this should cover the expected range of off-angles.

(f) Measuring Grid (see also ISO 3354). Because the velocity distribution in intakes is not likely to be uniform as it would be for fully developed flow, consideration shall be given to provide a sufficient number of point velocities with grid spacing appropriate for the shape of the velocity distribution. For velocity profiles that are expected to be non-uniform, the minimum number of velocity measurements should be more than 24 times the cube-root of the intake area. For example, testing an intake that is 64 m^2 in area would require a minimum of 96 measurement points.

For measurement grids in close proximity to upstream trash racks, it is recommended that the grid have at least 2, preferably 3, times as many rows as there are main horizontal structural cross members of the rack. To confirm the suitability of the test grid (for fixed elevation measurement methods), it is advisable to perform a more detailed profile exploration prior to the actual test, ideally near a key guarantee point such as peak efficiency or full gate. It may not be practical to increase the number of horizontal positions, but the resolution of the vertical profiles can be easily increased, provided test conditions remain stationary during this increased test run duration. This denser grid can be used to inform selection of the actual test grid, and can later be used for comparison with tested profiles to evaluate uncertainty associated with the number of test points. An alternative to this approach is to uniformly remove points from the measured profile to evaluate the effect on the flow measurement. The measuring grid used for testing shall be mutually agreed upon by the parties to a commercial test.

For moveable frames, there will be potential for a certain amount of side-to-side movement within the intake as well as uncertainty with respect to the vertical position of the points. The expected amount of horizontal and vertical play of the frame can be determined and used to assess uncertainty. This can be estimated by way of a sensitivity analysis whereby the flow rate is recalculated assuming the grid was shifted to each side as well as vertically.

(g) Velocity Profile Integration. It is recommended that a numerical method be used for velocity integration, with provisions related to problems related to intakes. These provisions include an accounting for open ceiling and/or situations where the intake at the measuring section is not hydraulically isolated from any other flow path. Additional guidance on this follows:

(1) Integration Methods

(-a) For velocity profile integration, it is recommended that calculations use a numerical method involving interpolation of smooth splines fit to the test data.

(-b) Alternatively, an averaging of interior elements (as a simplified option) can be used along with assumed boundary layer profiles. This boundary layer can be approximated using Karman's law and involves a selection of boundary layer coefficient, m. This coefficient is typically within the range 4 to 14, but can be greater than 14 for undeveloped convergent flow. The sensitivity of the overall flow estimate to this boundary layer coefficient can be assessed by recalculating flow using a range of assumed coefficient values.

(-c) For intakes with flow profiles that are not fully developed, graphical and arithmetic methods (such as in ISO 3354) are not recommended.

(2) Upper Boundary of Metering Section

(-a) Intake methods typically involve lowering instrumentation into bulkhead stoplog slots, where there is an opening in the water passage ceiling. Consideration should be given to the potential for streamline expansion relative to a predefined measurement grid. The effect of this expansion will depend on the width of the opening in the upstream-downstream direction. Narrow openings will have less effect than wide openings, in which case the flow profile may not be significantly affected. For wider openings, the effect of the open ceiling can be

minimized or avoided by maintaining a minimal distance between the measuring plane and the upstream edge of the opening.

(-b) If the gate slot with the metering section is not hydraulically isolated from any other flow path, potentially allowing for inflow downstream of the measurement section, a means of sealing the gate slot must be provided.

4-4.2.3 Uncertainty. The uncertainty in flow measurement using the current meter method within the specifications of this Code is estimated to be within

(a) ±1.20% for conduits ranging in diameter from 1.2 m to 1.5 m (4 ft to 5 ft)

(b) ±1.00% for conduits larger than 1.5 m (5 ft) in diameter

(c) ±1.75% for intake methods

4-4.3 Pressure-Time Method

The pressure-time method for measuring 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 test segment of the penstock and change of momentum of the volume of water contained in that segment. 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 test segment, 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.

4-4.3.1 Minimum Requirements. The minimal condition for the use of this method is that the product of L and v shall not be less than 46.5 (SI system) or 500 (U.S. Customary system), where L is the length between the two pressure measurement sections and v is the mean velocity in the test segment when the machine is carrying full load. 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.

4-4.3.2 Leakage Flow. 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.

4-4.3.3 Pressure Measurement Sections. The areas of the two pressure measurement sections and at three equally spaced sections between them shall be measured with sufficient precision to keep the total uncertainty of the flow measurement within test requirements. Additionally, the distance between measurement sections shall be measured at each tap location (e.g., upper-left tap to upper-left tap). In the case of a converging test segment, or where construction methods may lead to variation in the penstock area, more sections may be required to ensure that the flow measurement uncertainty is 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.) 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 excessive damping. 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. If measurement conditions are likely to be difficult, additional pressure tap pairs may be added.

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.

In the manifold method, the pressure taps at a section are connected 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 should 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 which meets the requirements given above. To the extent practical, all pressure tap sense lines should be of equal length.

In the separate transducers method, each pair of taps (corresponding taps from the upstream and downstream sections) are 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.

For either method, the high side of the differential pressure transducer should be connected to the downstream taps.

4-4.3.4 Pressure Tap Consistency. 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 conducted at the maximum expected flow rate.

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.

4-4.3.5 Operating Conditions. The flow rate that is to be measured in the conduit shall be set by limiting the movement of 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 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 the purpose of verifying that a suitable pressure signal can be obtained.

4-4.3.6 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 0.2 s or faster.

(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 an electronic calibrator. 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 electronic calibrator 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. It is recommended that a temperature-compensated differential pressure transducer be used.

(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.

4-4.3.7 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%.

4-4.3.8 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.

4-4.3.9 Delineation of the Pressure–Time Diagram. Two examples of typical digital pressure–time signals are shown. The first (Figure 4-4.3.9-1) is for the case in which water hammer or surge tank oscillations are not present. The second (Figure 4-4.3.9-2) is for the case when such oscillations are present.

(a) 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.

(b) Static Line Delineation. In the case of a short conduit for which water hammer or surge tank oscillations are not present as shown in Figure 4-4.3.9-1, 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.

In the case of a long conduit, water hammer or surge tank oscillations (after-waves) may be present as shown in Figure 4-4.3.9-2. In this case, the start of the static line interval should be chosen at the peak of the first after-wave following full gate closure. The end of the static line interval should be chosen at the peak of an after-wave for which the amplitude is significantly smaller than initial amplitude at the start of the static line interval.

(c) 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.

The end of the static line interval should be chosen at the peak of an after-wave for which the amplitude is significantly smaller than initial amplitude at the start of the static line interval, typically 1/10 or less.

4-4.3.10 Integration of Digital Pressure–Time Signal. Paragraphs 4-4.3.11 and 4-4.3.12 describe the analytical background and implementation for determination of discharge by numerical integration of a pressure–time signal obtained using digital data acquisition methods. A more complete derivation of the pressure–time integral is given in Nonmandatory Appendix D.

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.

4-4.3.11 Analytical Description of Numerical Integration. The fundamental pressure–time integral is given by

$$Q_i - Q_f = \frac{g}{F}\int_{t_i}^{t_f} (h + h_c + h_l)dt$$

where

$$F = \int_0^L \frac{dx}{A(x)} \cong \sum_j \frac{\Delta L_j}{A_j}$$

and

$$L = \sum_j \Delta L_j$$

and, in any set of dimensionally homogenous units:

A_j = average internal area between two adjacent conduit area measurement sections

$A(x)$ = conduit area as a function of distance along the conduit

Figure 4-4.3.9-1 Example of Digital Pressure–Time Signal in a Short Conduit

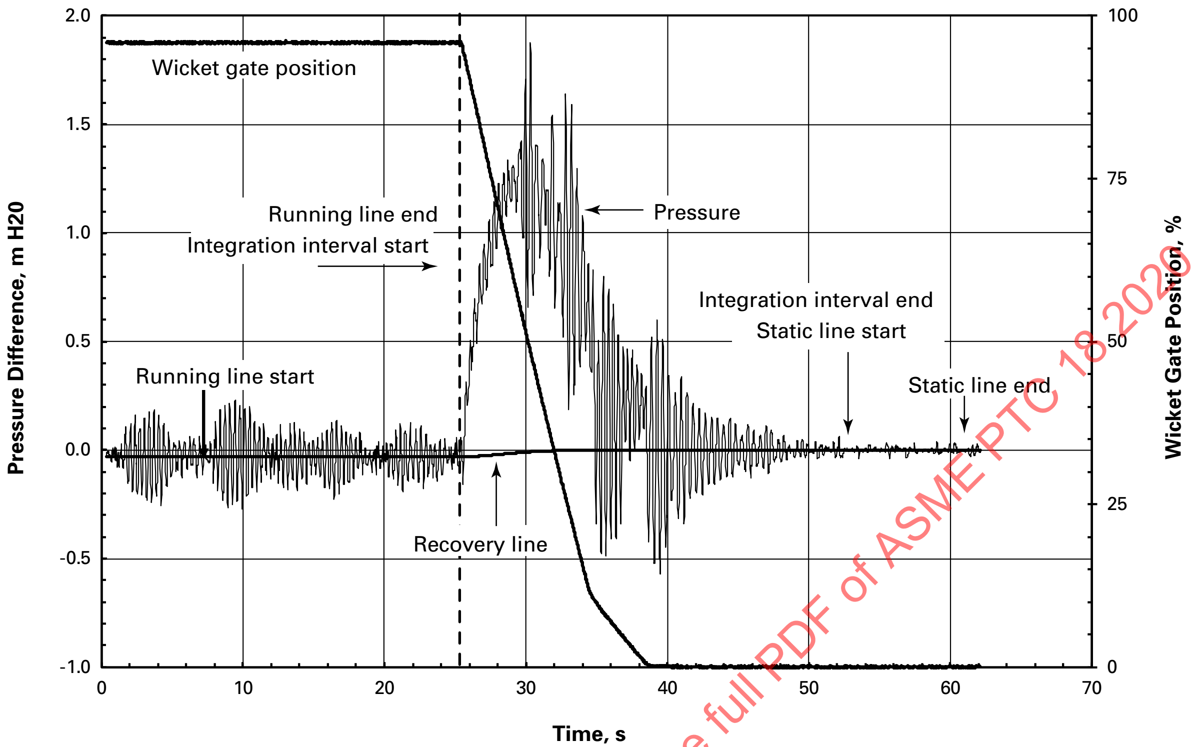
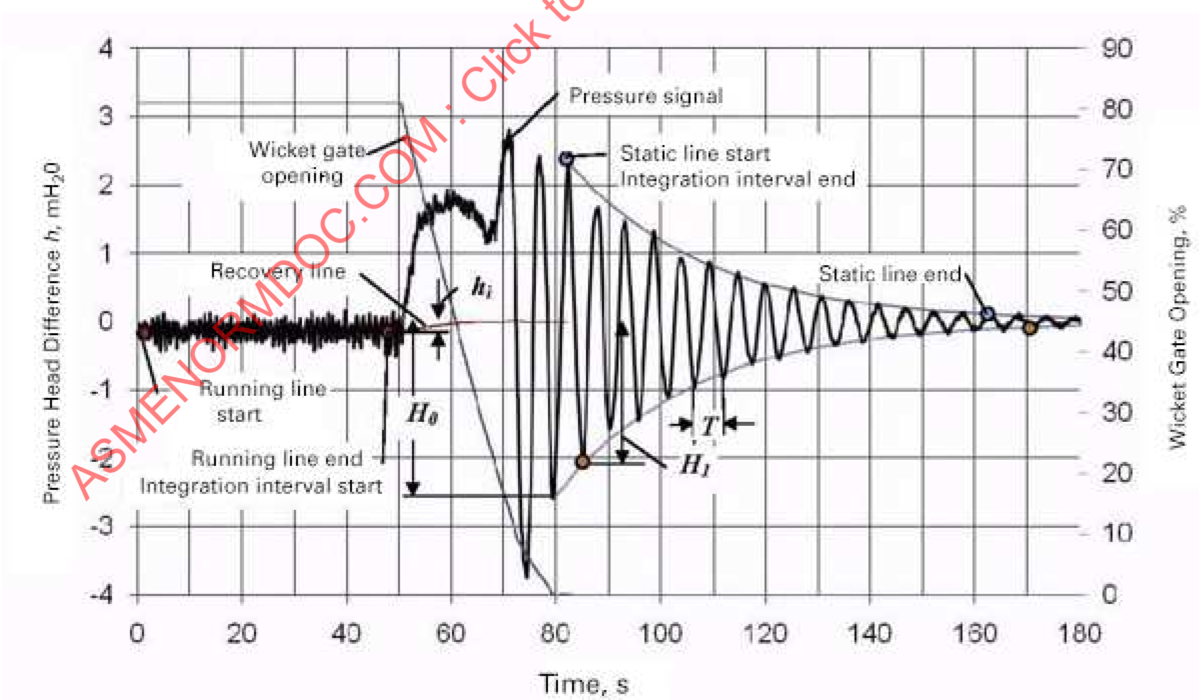


Figure 4-4.3.9-2 Example of Digital Pressure–Time Signal in a Long Conduit



F = "pipe factor" as defined above
g = local acceleration of gravity
h = pressure head difference between piezometer tap planes at local conditions
h_c = velocity head difference between piezometer tap plans
h_l = friction loss between piezometer tap planes
L = distance between piezometer tap planes
ΔLj = distance between two adjacent conduit area measurement sections
Q_f = low 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
x = distance along the conduit axis

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

When the test segment has a converging cross-section, the dynamic head difference between two sections (1 and 2) is given by

$$h_c = \frac{Q^2}{2gA_2^2} - \frac{Q^2}{2gA_1^2} = -k_cQ^2$$

The friction head loss between the two piezometer tap planes is given by $h_l = -k_lQ|Q|$, where

$$k_l = -\frac{(h_i - h_f) + k_c(Q_i^2 - Q_f^2)}{Q_i\left|Q_i\right| - Q_f\left|Q_f\right|}$$

By agreement of the Parties to the Test, a power of less than 2 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.

If the pressure transducer has an offset defined by $h_m = h + h_0$, where

h = true pressure difference
h_0 = instrument offset
h_m = measured pressure difference

In the pressure–time integral, the true pressure difference is replaced by the measured pressure difference corrected for offset $h = h_m - h_0$.

The instrument offset is computed from

$$h_0 = h_{mi} + k_cQ_i^2 - \frac{(h_{mi} - h_{mf}) + k_c(Q_i^2 - Q_f^2)}{Q_i\left|Q_i\right| - Q_f\left|Q_f\right|}Q_i|Q_i|$$

and

$$k_l = -\frac{(h_{mi} - h_{mf}) + k_c(Q_i^2 - Q_f^2)}{Q_i\left|Q_i\right| - Q_f\left|Q_f\right|}$$

4-4.3.12 Numerical Integration of Pressure–Time Integral. The pressure–time integral based on the above pressure recovery relationships is given by:

$$Q_i = \frac{g}{F}\int_{t_i}^{t_f} [(h_m(t) - h_0) - k_dQ(t)^2 - k_l(Q(t)|Q(t)|)]dt$$
$$+Q_f$$

This integral may be evaluated numerically using a trapezoidal or higher-order integration scheme. Because the initial flow rate Q_i appears on both sides of the equation (explicitly on the left, implicitly in the definition of k_l on the right), an iterative solution procedure must be employed. Numerical evaluation of this integral proceeds as follows:

(a) An estimate for the value of the flow before gate closure Q_i is made.

(b) 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.

(c) If $|Q(t_f) - Q_f| \leq 0.0001Q_i$, 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 the flow $Q(t)$ 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.

4-4.3.13 Determination of Leakage Flow. Because the pressure–time method only measures that portion of the flow that is brought to a halt, any leakage flow past the wicket gates (or other shutoff device) must be determined separately. The choice of method for determination of leakage flow is typically highly site specific, thus no single method can be applied to all situations. Several techniques that have been used in the past are summarized in paras. 4-3.13.3.1 through 4-3.13.3.4.

Note that the accuracy of the leakage flow measurement does not need to match that of the pressure–time method. For example, if leakage flow is estimated to be 1% of the normal flow, an error of 10% in the leakage flow measurement leads only to a 0.1% error in the overall flow measurement.

4-3.13.3.1 Volumetric Measurement. A typical implementation of the volumetric method is to close the head gate and the wicket gates and measure the rate of drop in water surface level in an intake air shaft or the penstock. The rate of drop is usually determined using a pressure transducer connect to a pressure tap upstream of the wicket gates, such as a net head pressure tap. This method requires that the head gate be tightly sealed, which can be difficult to achieve or determine. Geometry of the air shaft or penstock is required.

4-3.13.3.2 Bypass Flow Measurement. This technique is applicable when there is a valve with a bypass line upstream of the wicket gates. The situation is sometimes encountered in high-head installations or pump-storage plants. With the wicket gates closed and the valve bypass line open, the leakage flow passes through the bypass line. The flow in the bypass line is measured, typically with a strap-on time-of-flight acoustic flowmeter.

4-3.13.3.3 Weir at Draft Tube Drain. If the draft tube has been unwatered and there is a drain, a low weir can be constructed around the drain, and the rate of leakage flow measured from the depth of water over the weir using standard weir equations.

4-3.13.3.4 Calculation From Wicket Gate Clearance Measurements. When direct measurement of the leakage flow is not feasible, leakage flow can be estimated from wicket gate top, bottom, and vertical clearance measurements. The discharge through the gaps is estimated from the clearances and the expected head across the wicket gates, with discharge coefficients being chosen to match the gate clearance geometry.

Other methods may be used upon agreement of the parties to the test.

4-4.3.14 Estimation of Uncertainty. The uncertainty in flow measurement using the Pressure–Time Method within the specifications of this Code is estimated to be within ± 1%.

4-4.4 Ultrasonic Transit Time Method

4-4.4.1 General. Ultrasonic transit time (UTT) is a 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 Figure 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, perform the measurements, process the data, and display and/or record the results. The equipment should also include a verification program to ensure that it 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 Figure 4-4.4.1-2). 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.

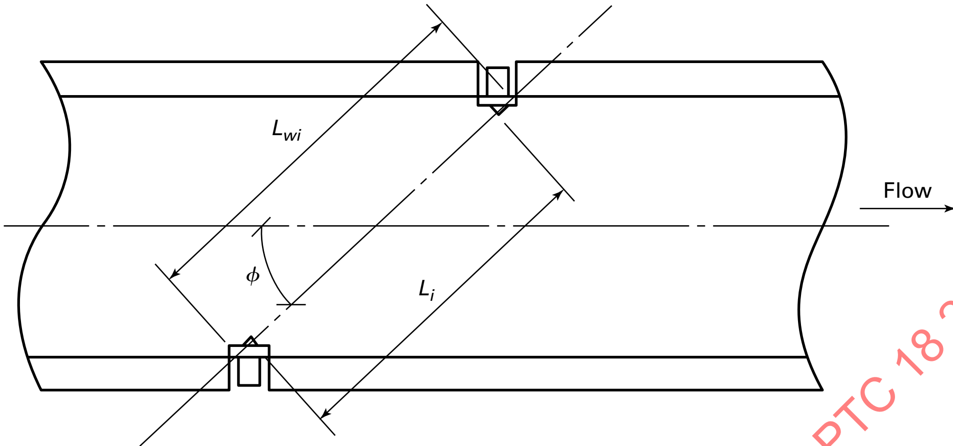
4-4.4.2 Circular Conduits. In circular conduits, the application of ultrasonic methods using two planes with four chordal paths each has been demonstrated to measure the flow rate with an accuracy acceptable under this Code (see Figure 4-4.4.1-2). Two planes are used to reduce the systematic uncertainty 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 Figure 4-4.4.3-1). In , 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) and two other notable effects as follows:

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

Figure 4-4.4.1-1 Ultrasonic Method: Diagram to Illustrate Principle



Legend:
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

Figure 4-4.4.1-2 Ultrasonic Method: Typical Arrangement of Transducers for an Eight-Path Flowmeter in a Circular Conduit

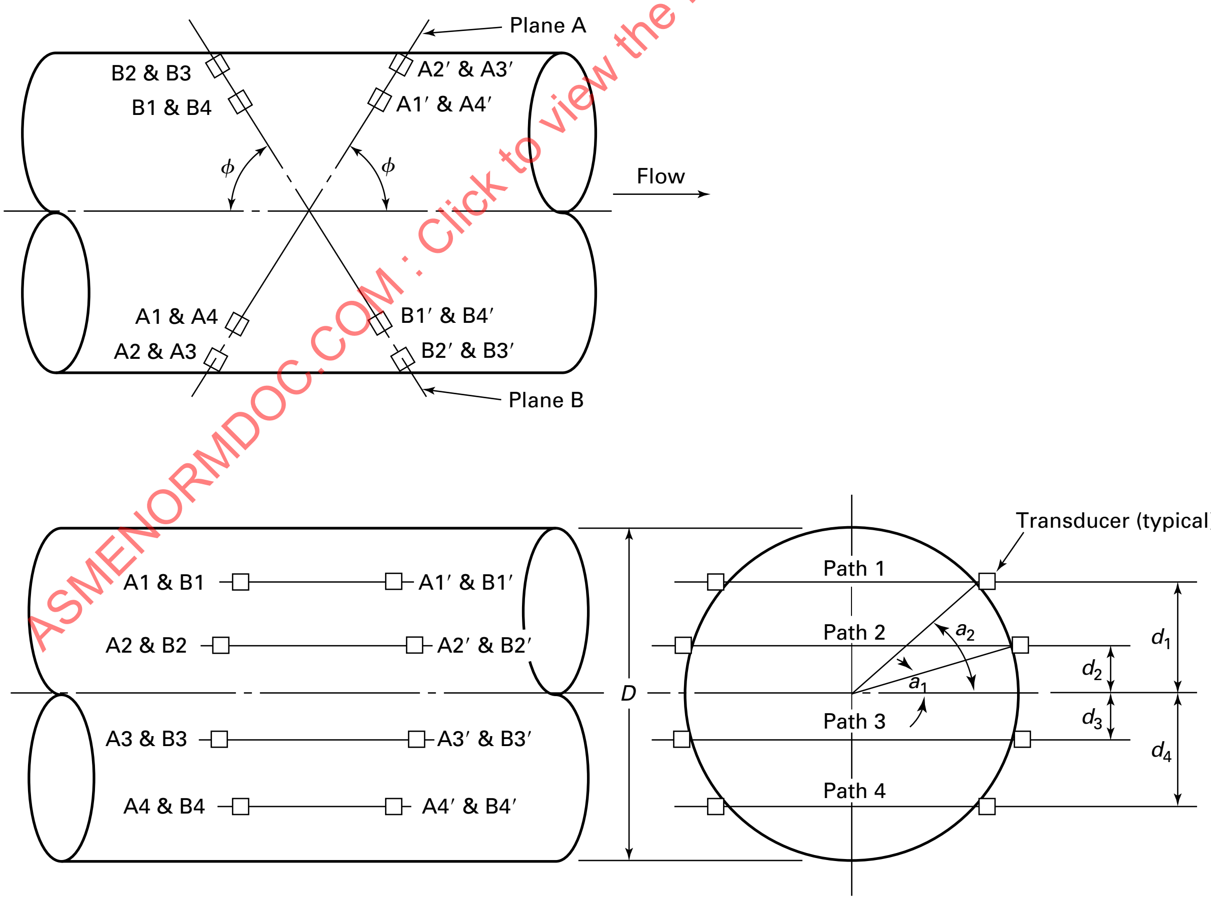


Table 4-4.4.2-1 Integration Parameters for Ultrasonic Method: Four Paths in One Plane or Eight Paths in Two Planes

Gauss–Legendre Method			Gauss–Jacobi Method		
Chordal Path, *i*	**Weight, w_i**	**Position, d_i**	**Chordal Path, *i***	**Weight, w_i**	**Position, d_i**
1	0.347855	0.86114	1	0.369316	0.809017
2	0.652145	0.33998	2	0.597566	0.309017
3	0.652145	−0.33998	3	0.597566	−0.309017
4	0.347855	−0.86114	4	0.369316	−0.809017
Section Shape	**Shape Factor k**		**Section Shape**	**Shape Factor k**	
Circular	0.994		Circular	1.000	
Rectangular	1.000		Rectangular	1.034	
Gauss–Legendre Positions With OWIRS Weights			**Gauss–Jacobi Positions With OWICS Weights**		
Chordal Path, *i*	**Weight, w_i**	**Position, d_i**	**Chordal Path, *i***	**Weight, w_i**	**Position, d_i**
1	0.336984	0.86114	1	0.365222	0.809017
2	0.655527	0.33998	2	0.598640	0.309017
3	0.655527	−0.33998	3	0.598640	−0.309017
4	0.336984	−0.86114	4	0.365222	−0.809017
Section Shape	**Shape Factor k**		**Section Shape**	**Shape Factor k**	
Rectangular	1.000		Circular	1.000	

GENERAL NOTE: For the parameters in this table, 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 of height of the water passage channel ($D/2$).

Figure 4-4.4.3-1 Ultrasonic Method: Typical Arrangement of Transducers

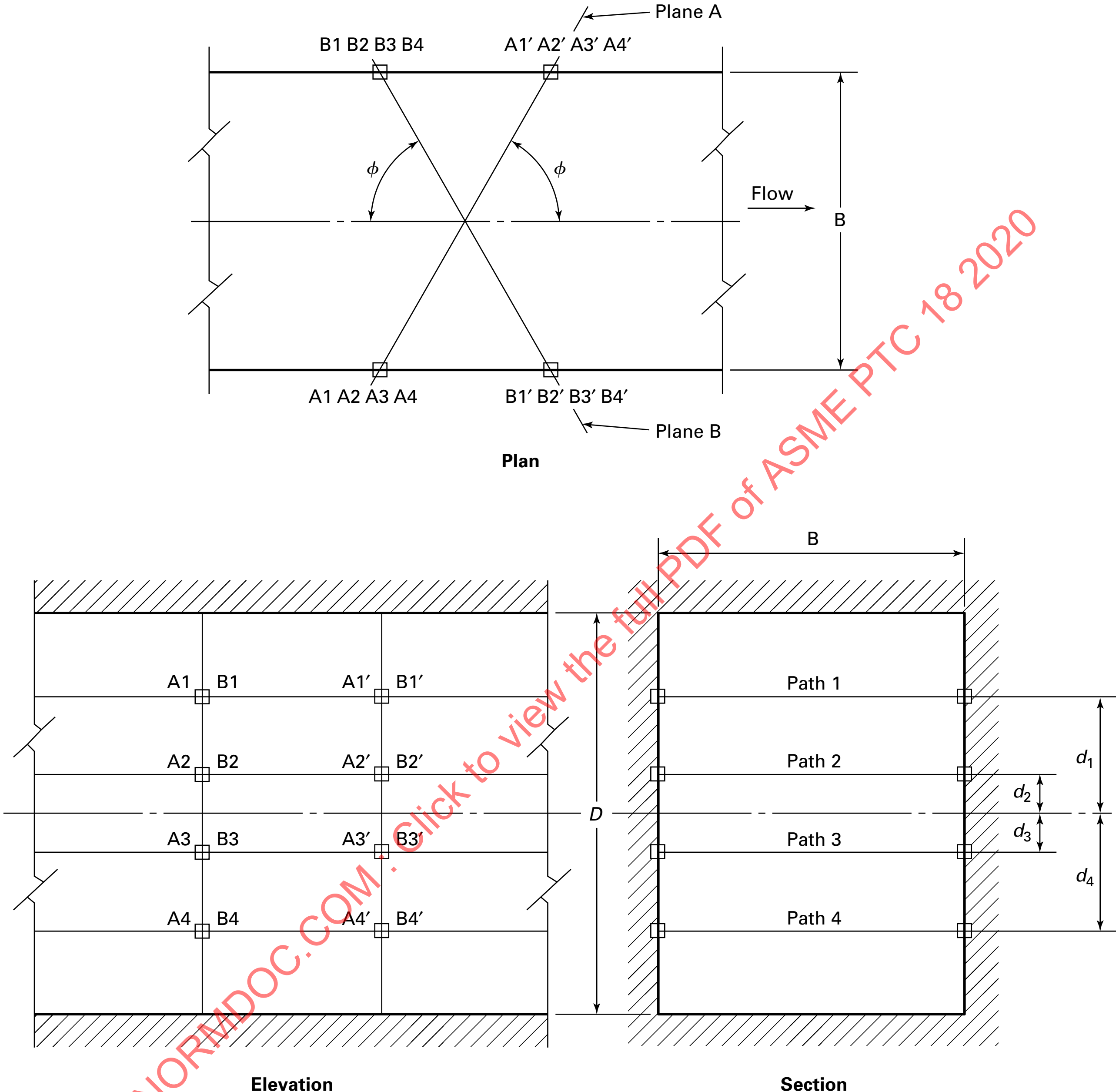
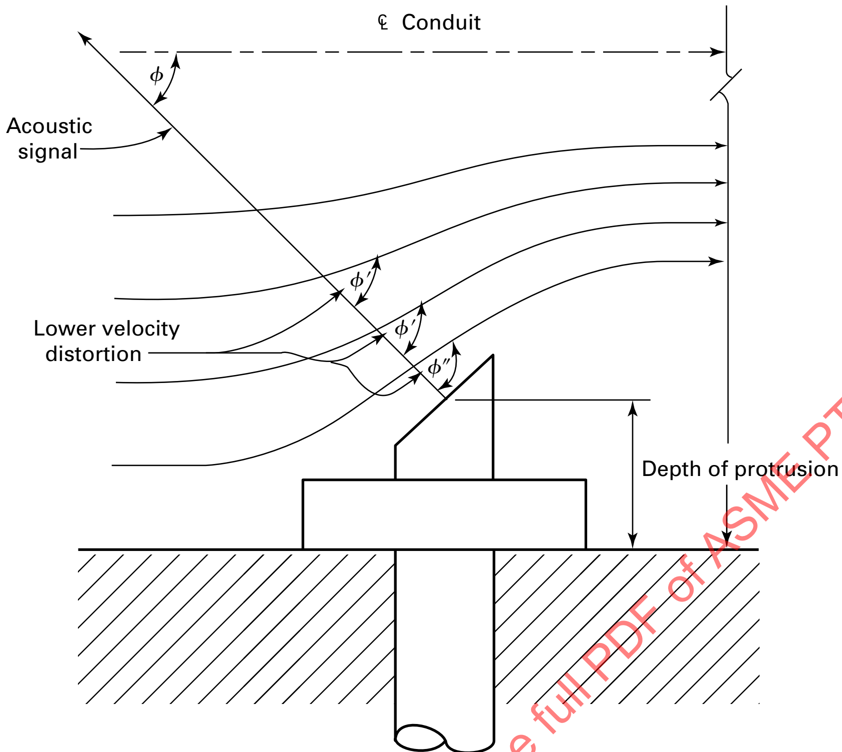


Figure 4-4.4.4-1 Distortion of the Velocity Profile Caused by Protruding Transducers



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

These effects [(a) and (b)] tend to be in opposite directions (undersampling of the velocity profile overestimates flow and velocity-path disturbance creates 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 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 conduit diameter to the piping diameter 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 Figure 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) are taken into account, the transit time of an ultrasonic pulse is given by

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

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 Plane B in Figure 4-4.4.1-2). For a given transverse flow component, Y = ±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 Figures 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 Figure 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.

NOTE: 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 para. 7-3.7 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 may 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-turbines operating in pumping mode

When the above conditions cannot be achieved, 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 Gauss–Jacobi quadrature methods for integration of the path averaged flow velocities meet the requirements of this Code, with the Gauss–Legendre method applicable to rectangular cross-sections and the Gauss–Jacobi method applicable to circular cross-sections. Use of weights based on either a uniform or logarithmic velocity profile (the latter technique based on a logarithmic velocity profile commonly referred to as the optimally weighted integration method for rectangular sections (OWIRS) and the optimally weighted integration method for circular sections (OWICS)) meet the requirements of this Code. At least four chordal paths in each plane shall be used for a determination of flow rate. For a four-path arrangement, the location of the paths and weighting coefficients for 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 conduit as described in para. 4-4.4.6, up to 18 acoustic paths in a cross plane arrangement can be used, using the path locations and weights shown in Table 4-4.4.6-1.

When the Gauss–Jacobi 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
$W'_1 = W'_9 = 0.0300$
$W'_2 = W'_8 = 0.10854$
$W'_3 = W'_7 = 0.20562$
$W'_4 = W'_6 = 0.28416$
$W'_5 = 0.31416$

$L_{wi} \sin \Phi = D \sin \alpha_i$ where α_i defines the angular location of path ends relative to the direction along which D is measured (see Figure 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

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

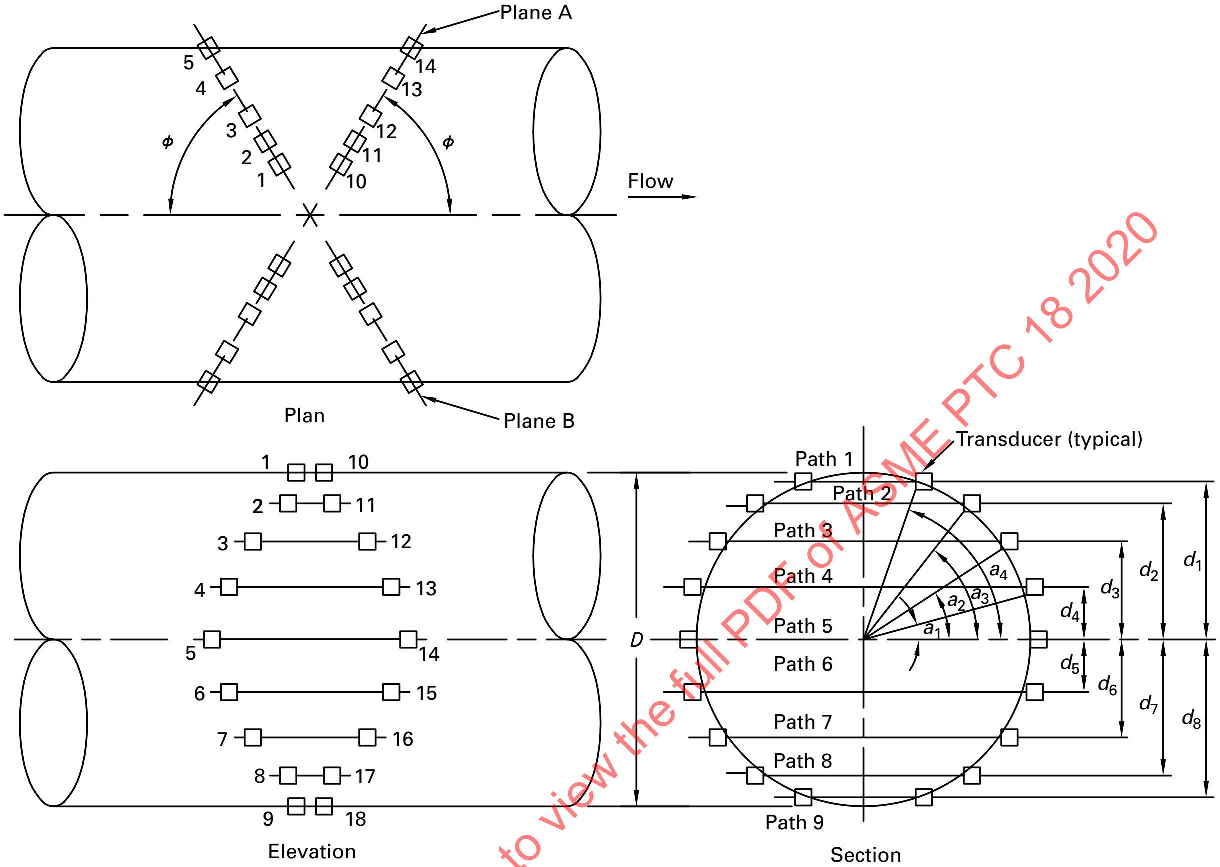


Figure 4-4.4.6-2 Ultrasonic Method: Typical Arrangement of Transducers for an 18-Path Flowmeter in a Rectangular Conduit

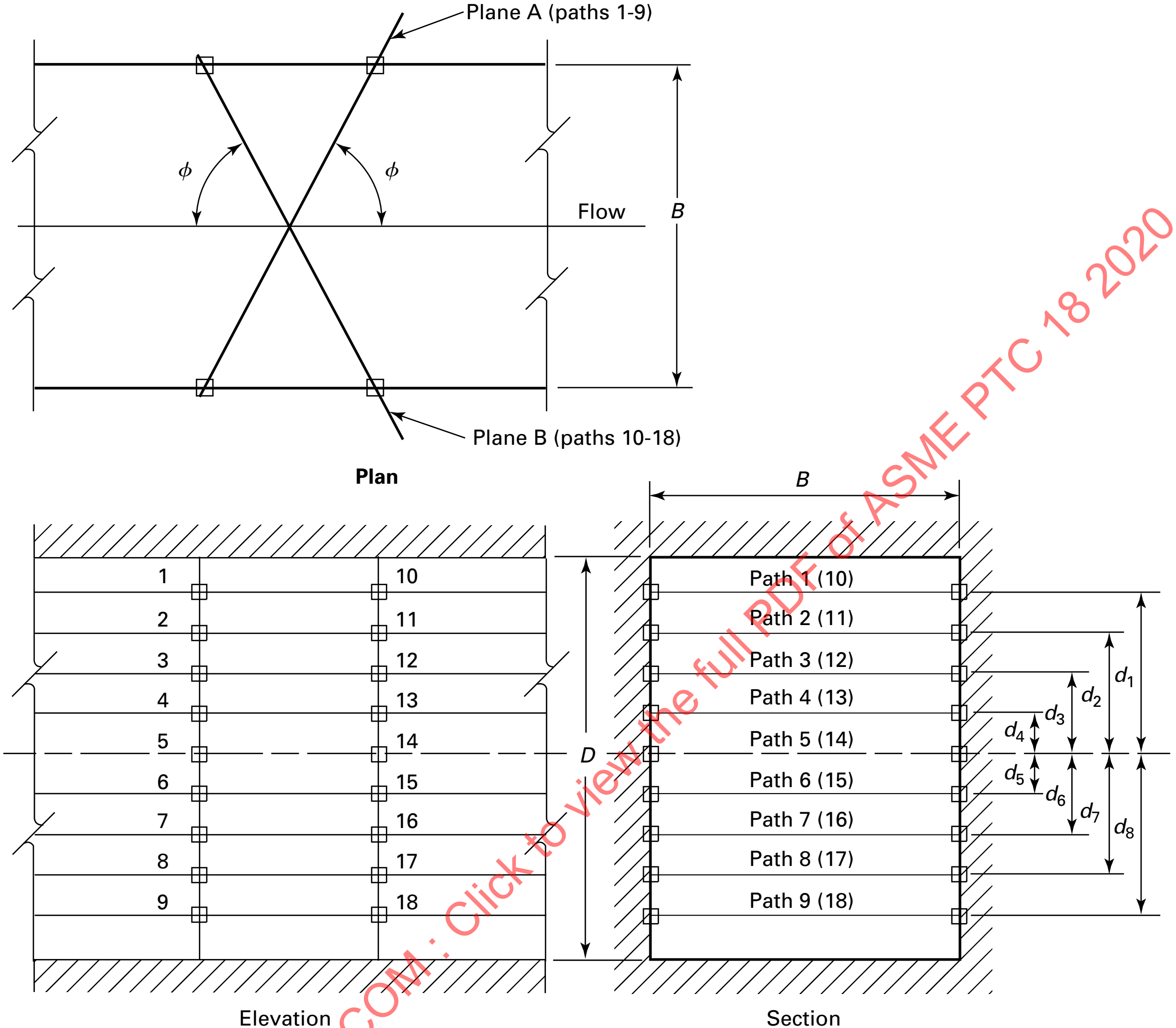
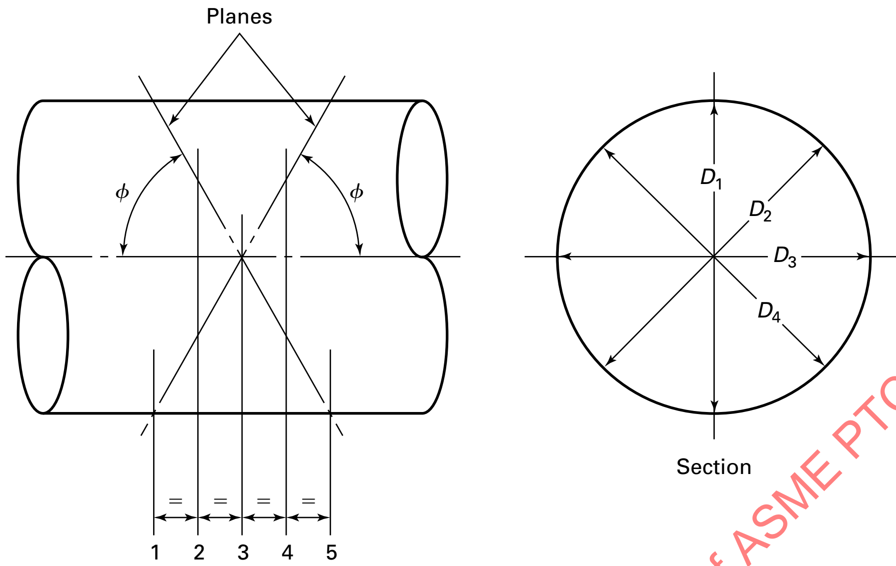


Table 4-4.4.6-1 Integration Parameters for Ultrasonic Method: Nine Paths in One Plane or 18 Paths in Two Planes

Gauss–Legendre Method			Gauss–Jacobi Method		
Chordal Path, i	**Weight, w_i**	**Position, d_i**	**Chordal Path, i**	**Weight, w_i**	**Position, d_i**
1	0.081274	0.968160	1	0.097081	0.951057
2	0.180648	0.836031	2	0.184658	0.809017
3	0.260611	0.613371	3	0.254160	0.587785
4	0.312347	0.324253	4	0.298783	0.309017
5	0.330239	0	5	0.314159	0.000000
6	0.312347	−0.324253	6	0.298783	−0.309017
7	0.260611	−0.613371	7	0.254160	−0.587785
8	0.180648	−0.836031	8	0.184658	−0.809017
9	0.081274	−0.968160	9	0.097081	−0.951057
Section Shape	**Shape Factor k**		**Section Shape**	**Shape Factor k**	
Circular	0.9994		Circular	1.000	
Rectangular	1.000		Rectangular	1.0083	
Gauss–Legendre Positions With OWIRS Weights			**Gauss–Jacobi Positions With OWICS Weights**		
Chordal Path, i	**Weight, w_i**	**Position, d_i**	**Chordal Path, i**	**Weight, w_i**	**Position, d_i**
1	0.078403	0.968160	1	0.095849	0.951057
2	0.182700	0.836031	2	0.185362	0.809017
3	0.258953	0.613371	3	0.253670	0.587785
4	0.313833	0.324253	4	0.299176	0.309017
5	0.328802	0	5	0.313796	0.000000
6	0.313833	−0.324253	6	0.299176	−0.309017
7	0.258953	−0.613371	7	0.253670	−0.587785
8	0.182700	−0.836031	8	0.185362	−0.809017
9	0.078403	−0.968160	9	0.095849	−0.951057
Section Shape	**Shape Factor k**		**Section Shape**	**Shape Factor k**	
Rectangular	1.000		Circular	1.000	

GENERAL NOTE: For the parameters in this table, 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 of height of the water passage channel ($D/2$).

Figure 4-4.4.11-1 Locations for Measurements of *D*



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 the measurement section, perpendicular to the direction of the measurement paths as shown in Figure 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 Figure 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 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 Section 7. 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. The systematic error for (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_0 = background concentration of dye in flow
C_1 = concentration of injected dye
C_2 = concentration of diluted 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 using distilled water 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

$$C_1 = D_s \times C_s$$

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

Determination of the exact concentrations of injection solution and samples are not necessary since the flow is proportionate to the dilution ratio.

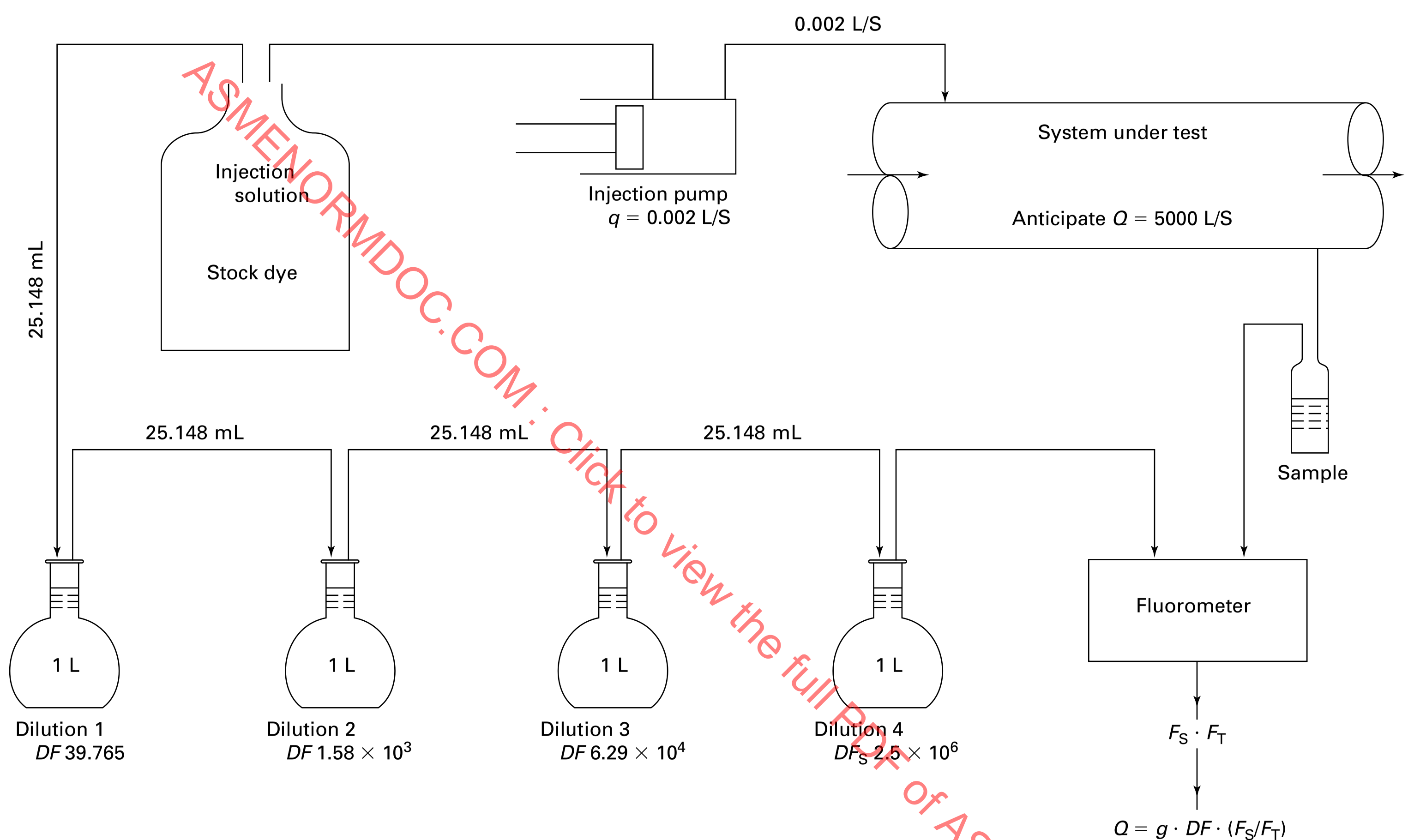
Figure 4-4.5.1-1 shows a schematic representation of the dye dilution technique.

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

Figure 4-4.5.1-1 Schematic Representation of Dye Dilution Technique



GENERAL NOTES:

(a) Example measured values:

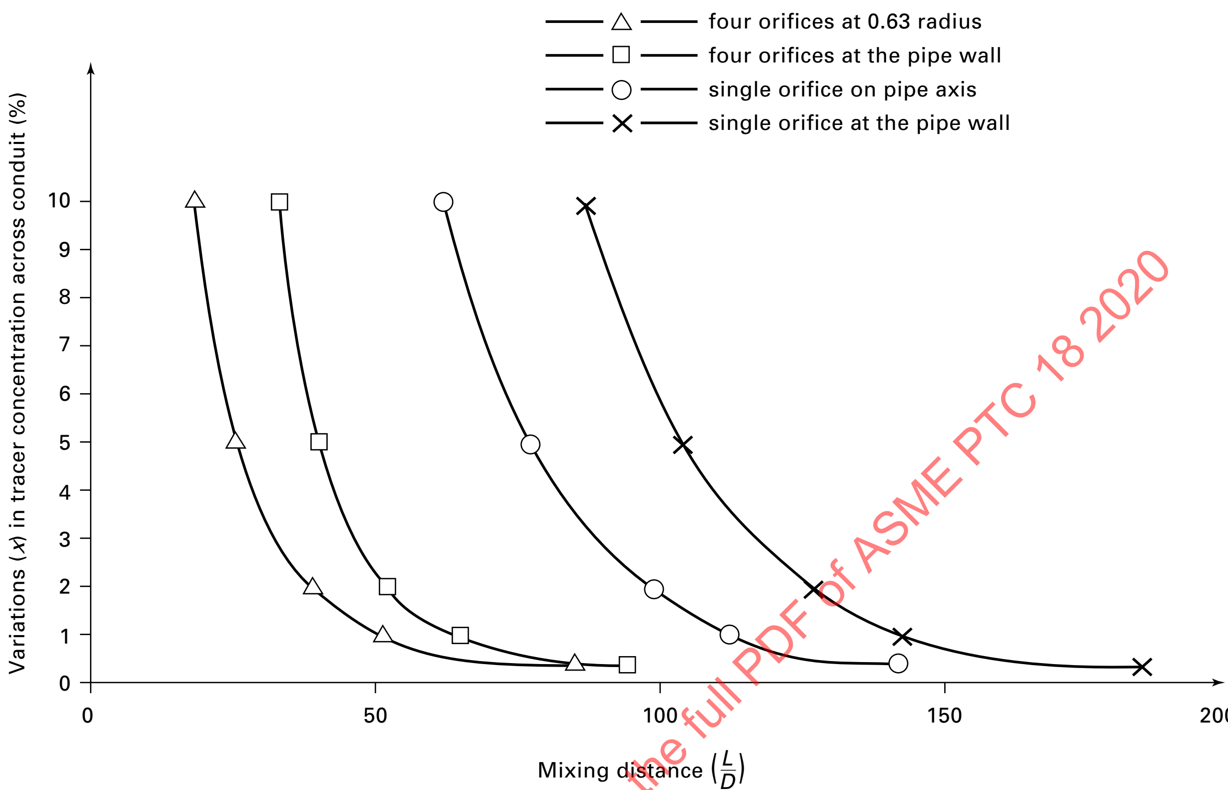
F_S = 500

F_T = 502

(b) $Q = 0.002 \text{ L/S} \cdot 2.5 \text{ x } 10_4 \cdot (500/502)$

$= 4980 \text{ L/S}$

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



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(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 Figure 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 predilution 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 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 $D_s = Q/q$. 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.

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 or equal to 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 4-4.5.2.4-1 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 bottles should be laboratory quality, clean, and opaque to light. For analysis by Method A described in para. 4-4.5.2.5.1, 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:

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

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

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

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.

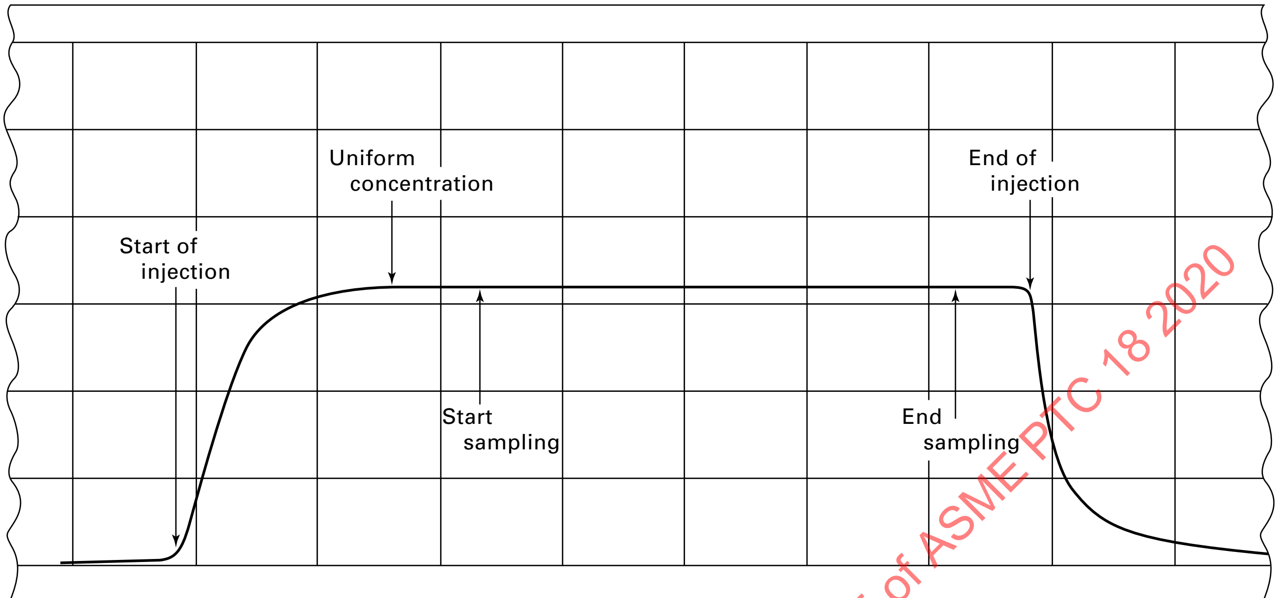
The temperature of the test sample and the standard solution should be within 0.2°C of the same temperature when each is analyzed. If it is not possible to achieve a temperature difference within 0.2°C, the fluorescence of the samples must be corrected to the same temperature before comparison.

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. Further repetition of analysis reduces the uncertainty in the estimate of the true dye

Figure 4-4.5.2.4-1 Typical Chart Recording During Sampling



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 THERMODYNAMIC METHOD FOR MEASURING EFFICIENCY

4-5.1 Principle of the Method

The thermodynamic method for efficiency determination is based on the law of conservation of energy. Energy losses generate an increase of the water temperature as it passes through the machine. The thermodynamic method is suitable for machines with heads in excess of 100 m.

The efficiency is obtained directly by measuring the difference of energy (potential, mechanical, thermal, kinetic) between the inlet and the outlet of the machine and comparing this difference to the available energy (specific energy or net head.[1] The flow is computed from the efficiency and other measured variables (head, power, density).

The efficiency is calculated as:

$$\eta = \eta_h \times \eta_m$$

where

η_h = hydraulic efficiency
η_m = mechanical efficiency

Any mechanical losses chargeable to the machine should be taken into account in the calculation of the efficiency.

For turbines

$$\eta_h = P_m/P_w = \frac{E_m}{E \pm \frac{\Delta P_h}{P_m} E_m}.\ \eta_m = P/P_m$$

For pumps

$$\eta_h = P_w/P_m = \frac{E \pm \frac{\Delta P_h}{P_m} E_m}{E_m} \cdot \eta_m = P_m/P$$

where

E = the specific energy (related to the net head)
E_m = the specific mechanical energy or the specific energy exchanged between the water and the machine[2]
P = Actual power
P_m = mechanical power

$$P_m = (\rho Q)_1 E_m$$

P_h = Correction term related to contractual definitions and local conditions (e.g., extraction of energy not involved in energy measurement and chargeable to the turbine)
P_w = Power from input

$$\begin{aligned} E_m &= E_{1-2} \\ &= \overline{\delta_T}(p_{abs1} - p_{abs2}) + \overline{c_p}(\Theta_1 - \Theta_2) \\ &+ \frac{v_1^2 - v_2^2}{2} + g(z_1 - z_2) \end{aligned}$$

where

$\overline{\delta_T}$ = isothermal throttling coefficient of water, $m^3 \cdot kg^{-1}$
p_{abs1}, p_{abs2} = absolute pressure, Pa
$\overline{c_p}$ = specific heat capacity of water, $J \cdot kg^{-1} \cdot K^{-1}$
Θ_1, Θ_2 = temperature, °C, K
v_1, v_2 = velocity, m/s

The properties of water (density, specific heat capacity and isothermal throttling coefficient) can be calculated using tables or formulas of Mandatory Appendix I. For sea water, "IOC, SCOR and AIAPSO, 2010: *The international thermodynamic equation of seawater – 2010: Calculation and use of thermodynamic properties*, International Oceanographic Manuals and Guides No. 56," can be used.

4-5.2 Specific Mechanical Energy, E_m

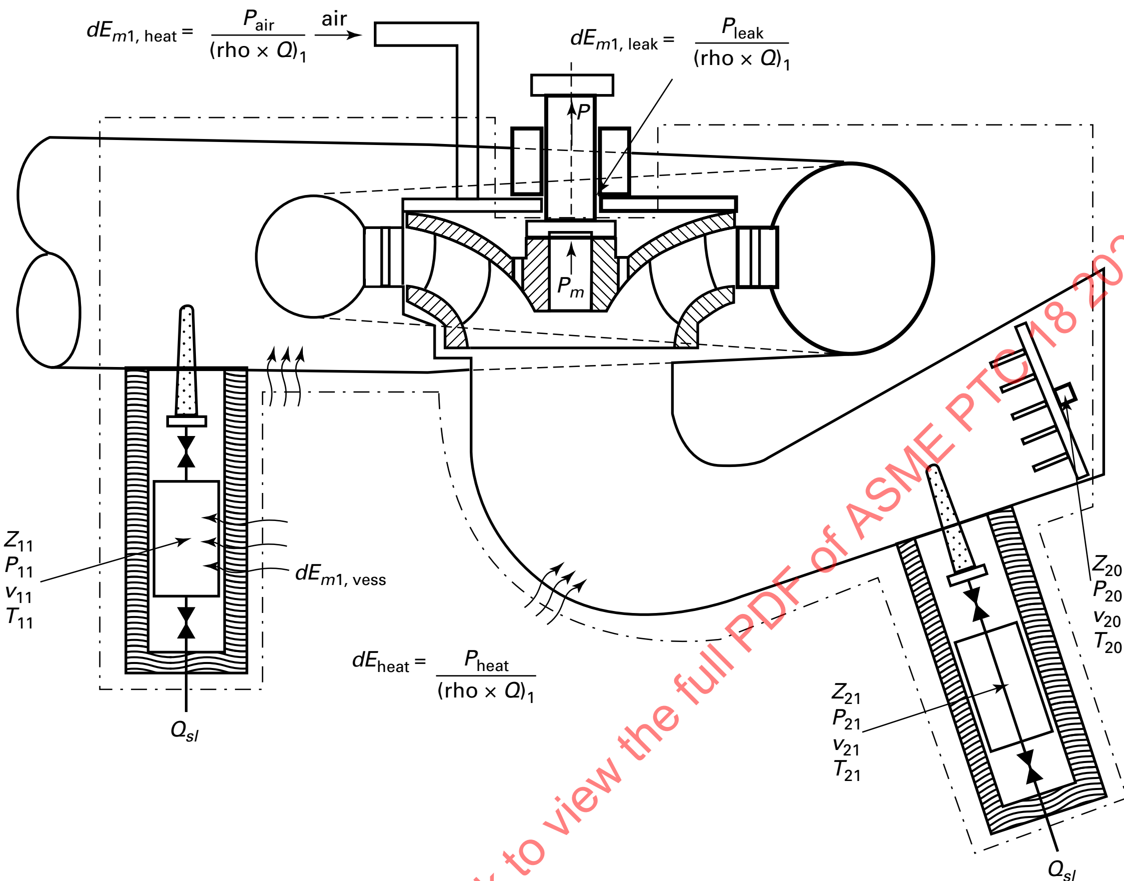
Due to high flow velocity, the mechanical energy is generally not measured directly in the flow but rather in specifically designed vessels (places marked 11, 20, and 21 in Figure 4-5.2-1), provided that there is no variation of the total energy between the machine and the sampling vessel. It is also not necessary that the sampling points coincide with the reference section of the net head (head losses will be transformed by heating, so the total energy is constant).

The practical expression of E_m is therefore:

[1] For the rest of the text, the specific energy E is used instead of the net head; both are related with the following relation $E = H_N{*}g$

[2] The theory of the thermodynamic method for measuring efficiency is based on the thermodynamic laws using the thermodynamic temperature Θ in kelvin (K). In the case of temperature differences the temperature can be directly expressed in degrees Celsius (°C) as $\vartheta_1 - \vartheta_2 = \Theta_1 - \Theta_2$ where ϑ_1 and ϑ_2 are the temperatures in °C.

Figure 4-5.2-1 General Schematic Diagram of Measuring Vessels and Balance of Energy for a Measurement With the Thermodynamic Method



$$E_m = E_{11-21}$$
$$= \overline{\delta_T}\left(p_{abs11} - p_{abs21}\right) + \overline{c_p}(\Theta_{11} - \Theta_{21}) + \frac{v_{11}^2 - v_{21}^2}{2} + g(z_{11} - z_{21}) + \sum_{i=1}^{n} \pm\delta E_{m,i}$$

(a) The mean values of δ_T and c_p are calculated for $(p_{abs11} + p_{abs21})/2$ and $(\Theta_{11} + \Theta_{21})/2$.

(b) Certain corrective terms (imperfect measurement conditions, secondary phenomena, etc.) must be taken into consideration. They are indicated by $\Sigma\delta E_{m,i}$ (see para. 4-5.3). The sign of $\delta E_{m,i}$ will depend on the machine mode (turbine or pump) and sign of the amount of energy transfer between the environment and the machine. Normally, an addition of energy for a turbine leads to a positive term.

(c) The values of $x1$ and $x2$ are those measured in the vessel.

If an auxiliary discharge is added or subtracted between the high and low pressure measuring sections which may be attributable or not to the machine, a balance of power, added or subtracted, allows the computation of the value of E_m in agreement with the general equation.

4-5.3 Correction of Specific Mechanical Energy

Any energy exchange (heat, mechanical, etc.) that is not due to the turbine (pump) must be corrected. Some corrections are due to heat exchange within the measurement circuit (vessels), others come from the variation of the water temperature. The general equation for the correction is as follows:

$$\delta E_m = \pm \frac{1}{(\rho Q)_1} \cdot P_{corr} \text{ (J/kg/)}$$

where

P_{corr} = rate of energy added to or subtracted from the machine

The most common sources of correction (see Figure 4-5.2-1, positive or negative) are listed below.

(a) heat exchange between machine wall and ambient air including condensation. For most of the case, i.e. the concrete wall or rock, the heat exchange is negligible.

(b) heat exchange between the water and the air entering the aeration system.

(c) heat exchange with the cooling circuit of the machine bearings and the generator.

(d) heat exchange in the measurement circuit (vessels) that is due to nonperfect heat insulation between the water and the air. When the temperature measurement is done in a vessel exposed to heat exchange, a correction must be calculated (para. 4-5.7.2).

(e) When the temperature of the water flowing into the machine varies, a suitable correction shall be applied to E_m from the temperature variation $\Delta\Theta/\Delta t$ measured in Ks^{-1} and calculated as follows:

(1) for turbines

$$\delta E_m = \overline{c}_p \frac{\Delta\Theta}{\Delta t}(t_a - t - t_b)$$

(2) for pumps

$$\delta E_m = \overline{c}_p \frac{\Delta\Theta}{\Delta t}(t_a + t - t_b)$$

where

t = the time, in seconds, taken by the water to pass through the machine between the two measuring sections

t_a = the time, in seconds, taken by the water to pass from the high pressure tapping point to the corresponding measuring vessel

t_b = the time, in seconds, taken by the water to pass from the low pressure tapping point to the corresponding measuring vessel

4-5.4 Conditions and Limitations

For the present standard, the thermodynamic measurement method should not be used for machines with a net head lower than 100 m. For heads below 100 m, the nonuniformity of the measured parameters (mainly the temperature) could lead to a higher uncertainty. However, under very favorable conditions including a long penstock and draft tube outlet, the measurement can be done for machines with net heads as low as 80 m, provided that the energy distribution at the inlet and outlet is assessed carefully (i.e., increased number of sampling points). The measurement shall be done only by experienced people and agreement between all the parties prior to the test. The measurement uncertainty will generally be higher.

It is not recommended to use the thermodynamic method under unfavorable measuring conditions such as irregular temperature or velocity distribution (outlet of draft tube) in the measuring sections, unstable temperature etc., which may occur at some operating conditions (e.g., several turbines discharging into a common tailrace). Poor conditions will be more likely when back flow is present in the turbine (off peak efficiency operating condition).

The heat exchange between still water must be avoided. If this is a possibility, a physical separator shall be placed in these areas in order to avoid mixing of the flow with the still water areas which may be at a different temperature from that of the flowing water.

For these unfavorable operating conditions, it is strongly recommended to use index tests (Nonmandatory Appendix A) for which the relative discharge measurement must be calibrated by the thermodynamic method at favorable operating conditions.

If the low pressure side of the turbine or pump is very close to the ventilation duct of the electric machine, it is recommended to divert energy from the cooling circuit out of the main flow or to explore the temperature distribution in at least 12 points. A strong energy distribution gradient may require insulating the ventilation duct from the main flow.

The variation of the temperature entering the machine must be less than 0.005°C/min in one run. To limit the variation of the temperature, it is recommended to operate the unit during the night in order to keep the temperature of the conduit as constant as possible. Measurement during the day is not recommended when penstocks are directly exposed to sunlight. If a conduit supplies several units, the total discharge of the conduit should be maintained constant or the other units should be maintained at constant power.

For some types of sampling probes, the sensitive part of the temperature probe can be directly immersed in the sampling flow or main flow. In this case, caution is necessary not to increase the sampling discharge in order to prevent viscous heating on the probe. The velocity of the water directly in contact with the probe sensitive part must be limited to 2 m/s.

4-5.5 Measurement of Specific Mechanical Energy

The present standard recommends the measurement of the specific mechanical energy with the direct operating procedure. The partial expansion procedure is not considered in this Code. The direct operating procedure consists of extracting a sample discharge with a "total head" probe and bringing it to a vessel with a minimal head loss. If no energy is extracted or exchanged between the conduit and the measurement vessels, the total energy is constant and no correction is needed. Otherwise, the guidelines of the present standard must be followed.

4-5.6 Measuring Sections and Sampling Conditions

The high- and low-pressure measuring sections for E_m do not have to coincide exactly with the reference net head sections since the total energy is considered constant. The high and low pressure measuring sections must be chosen in order to have the best uniformity of flow and temperature. If the sections do not coincide, appropriate correction may be necessary to account for the difference in losses of the hydraulic circuit. In any case, the heat exchange must be taken into account.

Tables 4-5.6-1 and 4-5.6-2 give the minimum number of sampling points for the high and low pressure side in both turbine and pump mode.

When more than one measuring point is being used at any measuring section, the values of efficiency will be determined from individual connections and compared with the average of all points. If the difference exceeds 1,5%, the measurement is considered as an outlier and further investigation is required (see also para. 4-5.4, regarding poor/unfavorable measurement conditions).

4-5.7 Instrumentation

The thermometer must have a measurement uncertainty so that the temperature difference uncertainty is less than 1 mK. The instruments must be calibrated according to the recommendation of the present code (see subsection 4-1). If the thermometers show a high level of stability, the post-test calibration can be avoided by mutual agreement. Temperature probes must be verified (zero temperature difference) on site with an appropriate procedure over the whole range of expected water temperature during the test. It is important here to focus on the temperature difference.

The pressure transducer requirements must follow the same rules as for head measurement.

The sampling discharge which gives the velocity in the vessel must be measured with a measuring tank or flowmeter with an uncertainty of about ±5% or with an uncertainty of less than 0.1% on the efficiency.

The benchmark elevation for the measurement instrument must produce an uncertainty of less than ±0.1% on the efficiency.

Air flow, air temperature and humidity must be measured to determine heat exchange with the surrounding atmosphere when aeration of the machine is needed.

4-5.7.1 Apparatus. When the measuring sections are under pressure, the procedure consists of extracting a sample discharge, generally between 6 L/min and 30 L/min, by a "total head" probe. This is normally the case for the high pressure side of the machine.

The water extracted is normally led to the measuring external vessel. Probe, piping and vessel should be carefully insulated. The sampling probe may be designed to allow the installation of the thermometer directly in it.

For the case where the low pressure side section is at atmospheric pressure, the temperature sensor can be placed directly in the tailrace. If the velocity in this measurement section is higher than 2 m/s, the temperature probe should be placed in a measurement vessel in order to limit the viscous heating. The measurement vessel can be placed directly in the flow.

4-5.7.2 Sampling Probe or "Total Head Probe." Water samples from the conduit shall be taken by means of a probe fixed perpendicularly to the conduit and penetrating into the conduit (see Figure 4-5.7.2-1). This probe shall have a perfectly smooth orifice at its end, with a diameter equal to the internal diameter of the probe and pointing in an upstream direction.

The distance of this orifice from the internal wall of the conduit shall be at least 0.05 m.

The mechanical design of the probe must take into account the condition of the flow in the measuring section (vibration, etc.). The design must also take into account heat transfer of all the elements of the measuring setup.

The external diameter of the probe, in the vicinity of the sampling hole, may be in the range of 15 mm to 40 mm, the internal diameter being at least 8 mm. The measuring vessels shall be designed so that the flow velocity of the water inside is very low and good mixing occurs before the flow passes around the thermometer.

The sensitive element of the thermometer can be inserted in sampling water circuits where the flow traverses the conduit which will limit heat exchange with ambient air.

All parts of the water sampling circuit shall be carefully insulated. Three measurements of the sampling discharge should be done in order to evaluate possible heat exchange. A plot of the mechanical energy as function of the inverse of the sampling discharge will allow the determination of the correction value of E_m (see Figure 4-5.7.2-2) if the sampling discharge is large.

4-5.7.3 Tapping Device. For exploration of flow in an open channel section for example, a tapping device made of one or more tubes that collect water from several orifices positioned at equal intervals along the tubes can be used. If the energy of multiple orifices is measured by one thermometer, this is considered as a single sampling point no matter the number of orifices.

In any case, the total sampling discharge that passes through the tapping device should be recorded to assess the energy distribution, otherwise it will result in a higher uncertainty of the efficiency (see para. 4-5.11).

Table 4-5.6-1 Recommendations for the High Pressure Side Measuring Section

Measuring Section	Distance From Machine/Nozzle	Number of Sampling Points	Remarks
Francis (turbine)	As close as possible	$D \leq 5$ m: 2 points $D > 5$ m or length of penstock <150 m: 3 to 4 points	The sampling probe shall not be in the immediate wake of a butterfly valve.
Pelton	Greater than 4*D* pipe	Minimum 2 points	Any important disturbances upstream of the sampling points shall be avoided. If more than one jet, the sampling point can be just upstream of the first bifurcation.
Pump	5 times the diameter of the impeller from the machine	$D \leq 5$ m: 2 opposite tapping $D > 5$ m: 3 or 4 tappings	Different depths of penetration

Table 4-5.6-2 Recommendations for the Low Pressure Side Measuring Section

Measuring Section	Distance From Machine	Number of Sampling Points	Remarks
Open, turbine (Francis, Pelton)	4 to 10 runner diameters	A minimum of 6 points for temperatures/velocity	Adequate mixing is the main criteria, a greater distance than necessary may increase the heat exchange
Open, pump	As close as possible	6 points for temperatures/ velocity	Adequate mixing is the main criteria
Closed, turbine	>5 times the maximum runner diameters	6 points for temperatures/ velocity	Equal distance for circular section or in the middle of each side for rectangular section Several orifices for each of the sample tubes
Closed, pump	>3 times the maximum runner diameters		

Figure 4-5.7.2-1 Example of a Sampling Probe

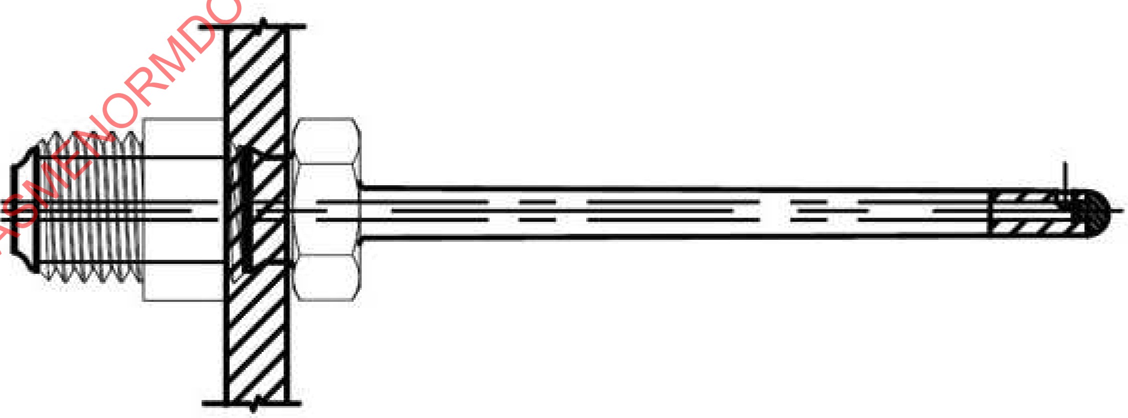
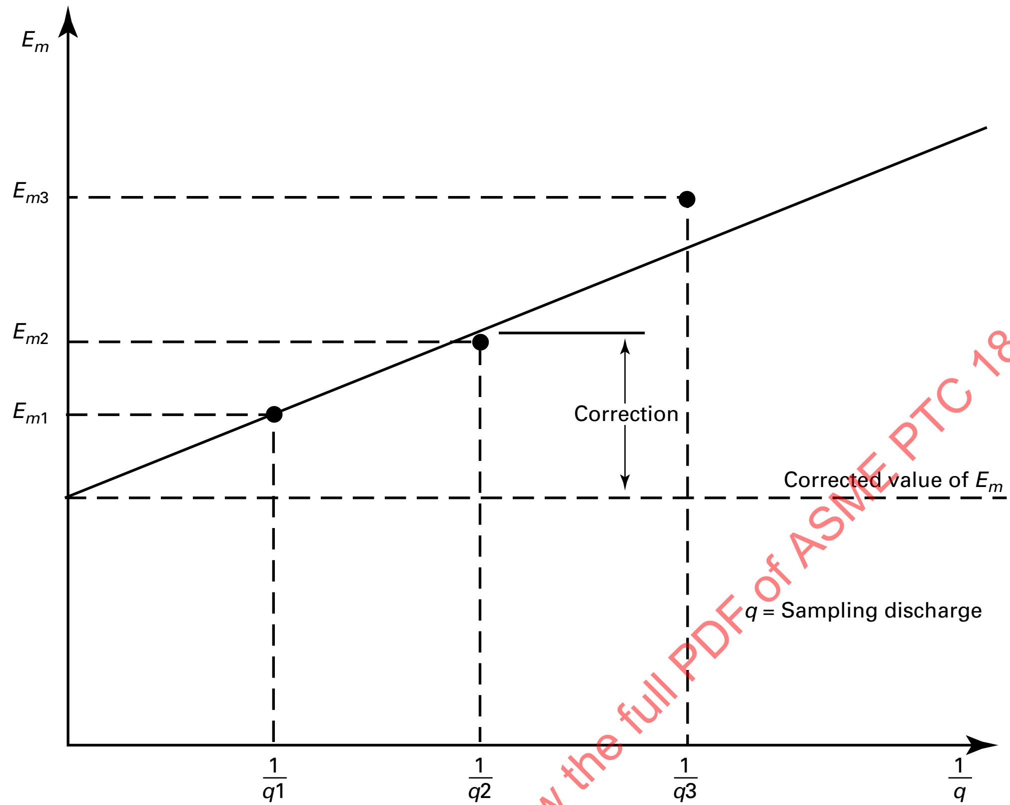


Figure 4-5.7.2-2 Determination of the Correction in E_m for Heat Transfer in the Water-Sampling Circuit



If the water is withdrawn outside of the main flow for measurement of its properties, all the elements of the sampling circuit shall be carefully insulated.

The tapping device should be designed so as to bring water into a measuring vessel with a low velocity and good mixing. The orifice will be around 7 mm in diameter with tubes of at least 30 mm. The head losses between the main flow and the measuring vessel should be measured.

The total sampling discharge should be about 5 L/s.

Other tapping device designs could be used, provided that the total energy is well measured. An agreement between the parties is needed before the test.

It may be difficult, in bad operating conditions (off-peak efficiency), to detect back flow in the measurement section with this device (see para. 4-5.4).

4-5.8 Repetition of Measurements

It is recommended to compute the efficiency for subsampling time intervals in order to assess the stability of the flow. The total sampling time will be dependent on the random uncertainty obtained for each individual run. Large fluctuations of measured efficiency (>1.5%) may be an indication of unfavorable conditions (i.e., back flow at the outlet of a turbine, see para. 4-5.4).

4-5.9 Particular Flow Arrangements

Inflow of auxiliary discharge between the high and low pressure sections, such as generator cooling water, should be avoided because the mixing of this water and the main discharge may not be complete.

In each case where auxiliary discharges are added or subtracted between the high pressure and low pressure measuring sections, a balance of power will allow the computation of E_m.

4-5.10 Limit of Corrections

Measurement shall not be considered valid whenever the corrections obtained from the measuring procedures or calculations given above exceed one of the following limits in relation to E_m:

(a) heat exchange between water in the sampling circuit and surroundings (see para. 4-5.3) at high pressure and low pressure measuring sections: 1%

(b) in the special case of extraction using pipes traversing concrete walls (see para. 4-5.3): 1.5%

(c) variation of temperature at inlet and correction resulting from external factors [see paras. 4-5.3(a) through 4-5.3(c)]: arithmetical sum of the corrections δE_m (detailed in para. 4-5.3): 2%

4-5.11 Uncertainty of Measurement

The total uncertainty in efficiency must be calculated according to the method presented in Section 7. The expected uncertainty highly depends on the measurement condition, head, instrument, corrective term, etc.

The uncertainty of the different parameters can be expected to be those listed below:

(a) Temperature difference : ±1 mK

(b) Pressure: ±0.2% of net head

(c) Elevation of transducers: 6 mm

(d) Velocity in discharge vessel: ±5%

(e) Density (pure water) ±0.1%

(f) Isothermal throttling coefficient δ_T (pure water): ±0.2%

(g) Specific heat capacity c_p (pure water): ±0.5%

(h) Correction due to secondary phenomenon δE_m: ±20% of correction

(i) Correction due to energy distribution at the inlet and outlet

(j) If the energy distribution is not measured and not proven to be homogenous, generally at the outlet of the machine (turbine), additional uncertainty must be added.

	High Pressure Side	Low Pressure Side
Turbine	±0.2%	±(120/H_n + 0.2)%, where H_n is given in m
Pump	±0.6%	±0.4%

4-6 POWER MEASUREMENT

4-6.1 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 IEEE 115-2009 shall be determined. The I^2R losses 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 terminals shall be made in accordance with PTC 19.6.

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 watt meters or watt-hour meters. Subsequent reference in this Code to watt meters 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 Figure 4-6.1-1 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 Figure 4-6.1-1 with the neutral connected to the potential transformer primary neutral, or the two-wattmeter connection for measuring three-phase power (Figure 4-6.1-2), 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 watt meters 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. In the two-wattmeter method, the phase angle shift from the meter transformers shall be taken into account when calculating power. The two-wattmeter method is more susceptible to phase angle shifts.

Proper corrections shall be made for temperature effects in the instruments, if the instruments are not temperature compensated. In cases of excessive temperature variation, an enclosure shall be used to ensure suitable temperatures for the instruments.

The indicating instruments shown in Figures 4-6.1-1 and 4-6.1-2 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.

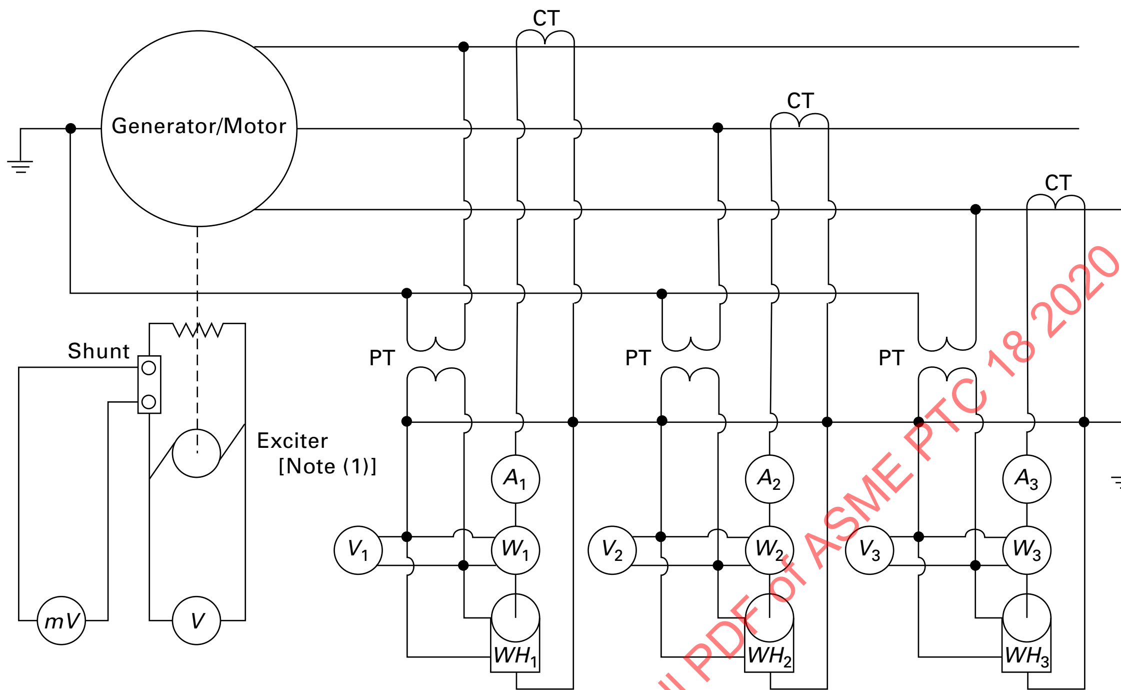
If the power output or input is measured by in-situ-indicating instruments, the number of readings shall depend upon the duration of the run and the load variations. Sufficient readings shall be taken to give a true average of the output or input during the run, and, in case of the pressure–time method 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 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 to ensure the burden, either in VA or impedance (Ω) is not exceeded. If the burden of the transformers is within 5% of their rated burden, then station metering circuits may be temporarily disconnected, and the burden shall be re-measured to ensure it is within acceptable levels. Once the test is concluded, the station metering circuits will need to be reconnected. The instrument transformers shall be tested to determine the ratio of transformation and of the phase angle deviations for secondary burdens. These phase angle deviations 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 voltage and current of the secondary loops 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 be placed on the source side of station instrumentation as shown on Figure 4-6.1-3. 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. Burden can be measured and recorded in either VA or impedance. V/I = VA/(I(nominal)^2) = Zb where Zb is the burden in impedance.

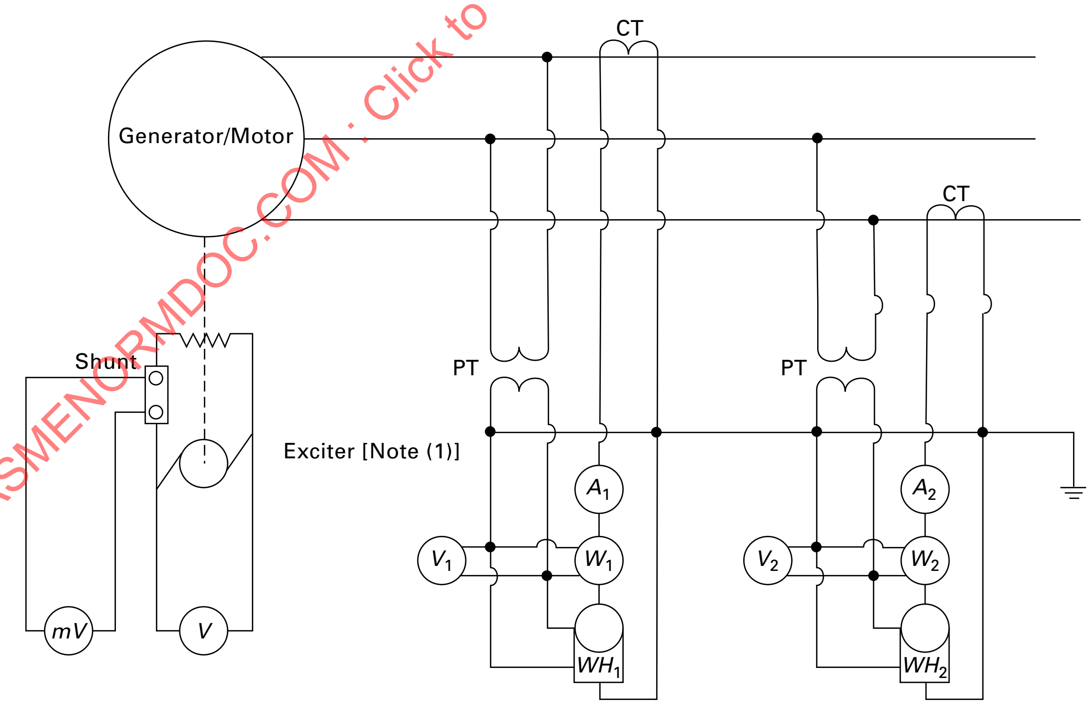
Turbine output is the sum of the generator output and generator losses. If possible, all auxiliaries driven from the machine being tested shall be disconnected during the test. If this is not possible, any power provided to shaft-driven auxiliaries not necessary for normal turbine operation shall be added to the turbine 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. If the generator is excited from a mechanically connected exciter, the calculated input to the exciter shall be added to the appropriate generator losses in determining the turbine output. 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.

Figure 4-6.1-1 Three-Wattmeter Connection Diagram



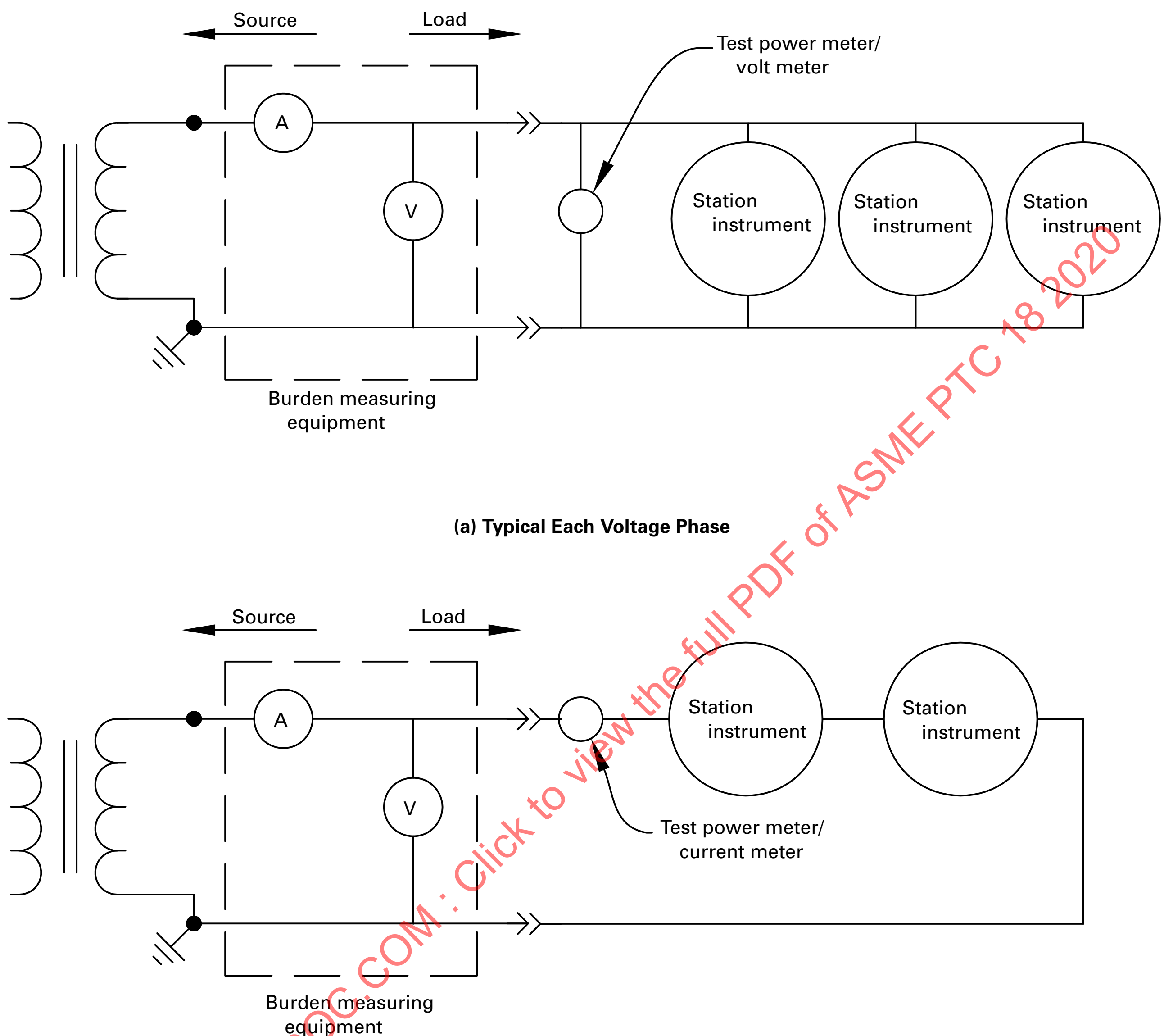
NOTE: (1) If mechanically connected exciter is used.

Figure 4-6.1-2 Two-Wattmeter Connection Diagram



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

Figure 4-6.1-3 Measuring Instrument Burden



(a) Typical Each Voltage Phase

(b) Typical Each Current Phase

Pump input shall be motor input plus electrical power input to auxiliaries necessary for normal continuous pump operation less all motor losses. If possible, all auxiliaries driven from the machine being tested shall be disconnected during the test. In this is not possible, any power input provided to shaft-driven auxiliaries not necessary for normal pump operation shall be deducted from the motor input. Motor losses obtained by shop tests may be used in this determination if corrected to pump test conditions and agreed upon by the parties to the test. If the motor is excited from a mechanically connected exciter, the calculated input to the exciter shall be added to the motor losses in determining 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 not directly connected to the pump necessary for proper operation and related to the performance of the pump.

4-6.2 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})
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 = speed of rotation, revolutions per second
N_p = number of runner blades
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. 4-6.2). 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.

4-6.3 Speed Increaser Losses

If the machine is connected to the generator or motor through a speed increaser, the speed increaser losses shall be added to the generator power or subtracted from the motor power. The speed increaser losses and the basis for their determination shall be documented. The uncertainty of their losses shall be factored into the overall uncertainty calculations.

4-7 SPEED MEASUREMENT

4-7.1 General

Accurate measurement of the rotational speed of a machine is essential when:

(a) Turbine power output is measured by a direct method such as a transmission dynamometer.

(b) Pump or turbine power is determined by an indirect method, but is a variable speed machine, or has an induction or a direct current motor or generator.

However, when the turbine power output or pump input is determined by an indirect method such as the measurement of the output of the synchronous generator or motor, the rotational speed can be computed from the system frequency.

4-7.2 A-C Interconnected Power Grid

The power systems in nearly all the 48 contiguous U.S. 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, U.S.A.

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 ±0.03% under normal operating conditions. For a Code test, the actual system frequency must be measured somewhere in the power system and its value recorded.

4-7.3 Isolated Alternating Current Systems, Variable Speed Machines 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.

4-7.4 Induction Generators and Motors or Direct Current System

A mechanically driven revolution counter using the same electronic equipment as above is preferred. 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.

4-8 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, before disconnecting any instruments, all test logs and records shall be completed and assembled, and then examined critically to determine whether or not the limits of permissible deviations from specified operating conditions have exceeded those given in subsection 3-5. 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.

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 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 Section 7. 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.

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 — Conversion to Specified Head

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)

$$\eta = \frac{\text{turbine power output }(P)}{\text{water power }(P_w)} = \frac{1000\,P}{\rho\, gQH_{spec}} = \frac{1000\,P_T}{\rho\, gQ_T H_T}$$

(U.S. Customary Units)

$$\eta = \frac{550\,P}{\rho\, gQH_{spec}}$$

Values of ρ and g are given in Tables I-1-3 and I-1-1, 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:

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

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

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

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:

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}

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

where

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

Step 3. Calculate flow rate and power at specified head.

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

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

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)

$$\eta' = \frac{1000P'}{\rho\, gQ'H_{\text{spec}}}$$

(U.S. Customary Units)

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

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

5-2.2 Pump Mode — Conversion to Specified Speed

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:

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

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

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

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

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)

$$\eta = \frac{\rho\, gQH}{1000P}$$

(U.S. Customary Units)

$$\eta = \frac{\rho\, gQH}{550P}$$

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 the characteristic curve of a 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}, and $P' = P + \Delta P$ at n_{spec} is given by:

(SI Units)

$$\eta' = \frac{\rho\, gQ'H'}{1000\, P'}$$

(U.S. Customary Units)

$$\eta' = \frac{\rho\, gQ'H'}{550\, P'}$$

Values of ρ and g are given in Tables I-1-3 and I-1-1, respectively.

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

5-2.3 Conversion to Specified Temperature

Guarantees are normally given for a specific water temperature, usually the average water temperature of the powerhouse. Water temperatures during the performance tests however may differ from the specified value due to factors such as the season at which the test is conducted or unexpected weather changes. It is recommended to correct the test results when they are performed at water temperatures which differ from the specified average value. The turbine efficiency correction, $\Delta\eta_t$, is calculated from the step-up formulae specified in the IEC 60193:2019, Annex D as follows:

$$\Delta\eta_t = \delta_{\text{ref}} \times \left[\left(\frac{Re_u\text{ref}}{Re_u\text{test}}\right)^{0.16} - \left(\frac{Re_u\text{ref}}{Re_u\text{spec}}\right)^{0.16}\right]$$

where

Re_u = Reynolds number and is defined as follows:

$$\text{Re}_u = \frac{D \times u}{\nu}, \text{ and } u = \frac{D \times \pi \times n}{60} \text{ then}$$

$$\text{Re}_u = \frac{D^2 \times \pi \times n}{60 \times \nu}$$

where

D = turbine runner reference diameter, m
N = turbine rotational speed, rpm
u = peripheral velocity, m/s
ν = kinematic viscosity, m^2/s

and,

$\text{Re}_{u,\text{ref}}$ = Reynolds number for the reference condition = 7.00×10^6
$\text{Re}_{u,\text{spec}}$ = Reynolds number calculated with the specified water temperature
$\text{Re}_{u,\text{test}}$ = Reynolds number calculated with the tested water temperature
δ_{ref} = relative scalable losses at $\text{Re}_{u,\text{ref}}$, and is defined as follows:

$$\delta_{\text{ref}} = \frac{1 - \eta_{h,\text{opt}}}{\left(\frac{\text{Re}_u\text{ref}}{\text{Re}_u\text{opt}}\right)^{0.16} + \left(\frac{1 - V_{\text{ref}}}{V_{\text{ref}}}\right)}$$

where

$\text{Re}_{u,\text{opt}}$ = Reynolds number of the optimum efficiency of the hill chart (usually taken from the homologous model test report)
V_{ref} = loss distribution coefficient = 0.6 for pumps, 0.7 for radial turbine and axial fixed blade turbine, 0.8 for for axial or turbine with adjustable blades
= 0.6 for pumps (radial or axial), 0.7 for radial and axial with fixed blade turbine and 0.8 for axial turbine with movable blades
$\eta_{h,\text{opt}}$ = turbine peak hill chart efficiency (usually taken from the homologous model test report)

This turbine efficiency correction, $\Delta\eta_t$, is then added to the efficiency calculated in para. 5-2.1.1 or para. 5-2.2.1 before comparison to the guarantee as follows:

$$\eta \text{ corrected} = \eta + \Delta\eta_t$$

If the temperature of the entire test is constant within 1°C, a constant correction can be applied on the entire test. If the water temperature varies by more than 1°C during the test, then a correction shall be calculated for each test point.

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 Section 7.

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 flow rates. 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 Section 7.

Section 6
Final Report

6-1 Components of the Final Report

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

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

(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, etc.

(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 and speed increaser efficiency curves.

(n) copies of instrumentation calibration documentation.

(o) corrections for deviations from specified conditions, including water temperature.

(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, illustrations, and photos 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 among the parties to the test.

Section 7
Uncertainty

7-1 BASIS FOR UNCERTAINTY CALCULATION

Regardless of the care taken in their design and implementation, all tests yield measurements and results that are different from the true values which would have been determined with perfect methods and perfect measurements. This results in uncertainty as to what the "true" or "exact" result is. The objective of an uncertainty analysis is to rationally quantify the uncertainty in the test results (e.g., hydroturbine efficiency). Uncertainty analysis is a required part of the code-accepted test.

ASME PTC19.1-2013 describes a comprehensive methodology for performing an uncertainty analysis under many scenarios and conditions. This Section presents a summary of some of the key concepts of ASME PTC 19.1, with emphasis on applicability to hydroturbines, and closely follows the methodology presented in ASME PTC 19.1. The most significant deviation from the standard methodology presented in ASME PTC 19.1 is the retention of Student's t statistic for small sample sizes. Because hydroturbine efficiency measurements often have small sample size, the ASME PTC 19.1 approach that the approximation that the Student's t statistic = 2 is valid (large degrees of freedom) is not always justified. In the case of large sample sizes, the two approaches yield nearly identical results. In the case of small sample sizes, the use of the actual Student's t statistic will generally yield larger uncertainties.

In all cases, ASME PTC 19.1 should be consulted for a more comprehensive development of an uncertainty analysis.

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 of the measured result 95% of the time. Conversely, the true result will not be within the uncertainty of the measured result 5% of the time.

Before performing an uncertainty analysis, the data and results should be examined for outliers, i.e., data points that are apparently so far from the trend of the data as to likely be in error. Outliers are further discussed in para. 7-3.6.

7-2 SUMMARY OF METHODOLOGY

The methodology presented here uses turbine efficiency as an example. This 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, including the final results, are the following:

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

(b) Identify which uncertainties are "systematic" and which are "random."

(c) Using the defining equation(s), determine how sensitive the result is to changes in the parameters from which it is computed.

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

(e) Determine the "standard" uncertainty in these parameters.

(f) Determine the uncertainty at the 95% confidence level.

(g) Combine these individual uncertainties to determine the overall uncertainty of the final result.

7-3 GENERAL APPROACH WITH TURBINE EFFICIENCY EXAMPLE

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

The equation which defines turbine efficiency is:

$$\eta_T = \frac{p_T}{\rho g Q H} \tag{1}$$

NOTE: The above equation assumes dimensionally homogeneous units, e.g., the SI system of units. Conversion factors may be required for other systems of units, such as the U.S. Customary System.

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

The uncertainty in a parameter (such as turbine efficiency or net head) is a combination of "systematic" uncertainties, which are generally due to uncertainty in instrumentation accuracy and calibrations, geometric measurements, etc., and "random" uncertainties, which generally arise from variations in the quantities being measured or in the repeatability of the measurement systems.

The systematic uncertainty is determined from analysis of calibration equipment, calibration history, measuring equipment, manufacturer's specifications, published guidelines, engineering judgement, etc.

The random uncertainty is generally determined from the statistics of the measurement record.

Given a set of N measurements of parameter X, the sample mean $\overline{X}$ is an estimate of the true mean and is given by

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i \tag{2}$$

where X_i is the value of an individual measurement in the sample.

The sample standard deviation s_X is given by

$$s_X = \left(\frac{1}{N-1}\sum_{i}^{n}\left(X_i - \overline{X}\right)^2\right)^{\frac{1}{2}} \tag{3}$$

The random *standard* uncertainty of actual value of the mean $s_{\overline{X}}$ is given by

$$s_{\overline{X}} = \frac{s_X}{\sqrt{N}} \tag{4}$$

For a normally distributed population the interval $\overline{X} \pm s_{\overline{X}}$ is expected to contain the true population mean about 68% of the time. With a large number of samples (N > 30), the interval $2s_{\overline{X}}$ is expected to contain the true population mean 95% of the time.

This equation for $s_{\overline{X}}$ shows that the random standard uncertainty in the mean value can be reduced by taking more measurements (i.e., increasing N), with the caveat that the measurements be spaced far enough apart in time that there is no correlation of the random component between the individual measurements.

For a normally distributed population with a small number of samples ($N \leq 30$), the factor of 2 in the 95% confidence interval given above is replaced by Student's t statistic, which is tabulated in Table 7-3-1. The 95% confidence interval is then expressed as $\overline{X} \pm ts_{\overline{X}}$ rather than $\overline{X} \pm 2s_{\overline{X}}$.

Student's t statistic can be interpreted as a correction factor, recognizing that as N becomes small, the uncertainty in the mean becomes larger, because the computation of the sample standard deviation relies on fewer measurements. In effect, it accounts for the uncertainty in the computed sample standard deviation. For large N, the approximation that t = 2 is adequate for practical applications, simplifying the analyses with no significant loss of accuracy.

As discussed above, systematic uncertainty can be determined from published information, special data, and engineering judgment. It is often the case that the uncertainty for a single (elemental) parameter is specified at the 95% confidence level. For example, a voltmeter may be specified by the manufacturer to have an accuracy of ± 0.02% of reading at the 95% confidence level. In this case the systematic "standard" uncertainty in the voltage, $b_{\overline{V}}$, would be expressed by

$$b_{\overline{V}} = \frac{B_{\overline{V}}}{2} \tag{5}$$

where $B_{\overline{V}}$ is the systematic uncertainty at the 95% confidence level.

Thus, the systematic *standard* uncertainty for the voltage measurement would be 0.02%/2 = 0.01%.

Note that in the above equation, the denominator of 2 expresses the assumption that t = 2. In many, if not most, cases there is no way of determining the value of t for a systematic uncertainty, so the assumption that t = 2 may be the only practical approach.

The total standard uncertainty, including systematic and random uncertainty, in a measurement $u_{\overline{X}}$ is given by

$$u_{\overline{X}} = \sqrt{b_{\overline{X}}^2 + s_{\overline{X}}^2} \tag{6}$$

In the case of large N (i.e., N > 30, t = 2), the uncertainty at the 95% confidence level is then given by

$$U_{\overline{X}} = 2u_{\overline{X}} \tag{7}$$

However, if N is small (N < 30), then the random uncertainty should be modified by Student's t statistic. In this case, the total standard uncertainty at the 95% confidence level is given by

$$\begin{aligned} U_{\overline{X}} &= \sqrt{(2b_{\overline{X}})^2 + (ts_{\overline{X}})^2} \\ &= 2\sqrt{(b_{\overline{X}})^2 + \left(\frac{t}{2}s_{\overline{X}}\right)^2} \end{aligned} \tag{8}$$

For elemental random standard uncertainties, i.e., the uncertainty associated with a single measurement, the degrees of freedom, ν, is defined by

$$\nu = N - 1 \tag{9}$$

Table 7-3-1 Two-Tailed Student's *t* Table for the 95% Confidence Level

Degrees of Freedom ν	*t*	Degrees of Freedom ν	*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:

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

7-3.1 Correlated Uncertainties

The relationships given above for combining individual uncertainties assume that these uncertainties are uncorrelated. This may not always be the case. Take for example, flow measurement of the total discharge from three pipes carrying approximately equal loads by an acoustic time-of-flight method. The total flow is the sum of the flows from the three pipes.

If three separate flowmeters calibrated using different standards are used, then the systematic calibration errors of the flowmeters may be considered uncorrelated. When the total relative flow uncertainty is computed, the uncertainty due to the flowmeter calibration is reduced by a factor of $\sqrt{3}$, because the sign of the errors is not correlated (this is shown later in this Section).

If, however, the same instrument is used to measure the individual pipe discharges, then the sign of the systematic calibration error is clearly correlated, and the systematic uncertainty in the total flow due to flowmeter calibration is not reduced by a factor of $\sqrt{3}$. Some degree of correlation may also exist if the same standard is used to calibrate the three flowmeters.

The possibility that measurement errors may be correlated should be carefully considered when combining uncertainties. ASME PTC 19.1 should be consulted for further guidance on how to handle correlated errors under various circumstances.

7-3.2 Sensitivity Coefficients

The relative sensitivity of a result (dependent parameter), R, due to changes in a particular independent parameter, X_i, is given by using a Taylor series approximation to define a sensitivity coefficient for the parameter, θ_i:

$$\theta_i = \frac{\partial R}{\partial X_i} \quad (10)$$

The error in the result, δR_i, due to an error in the parameter, δX_i, is then approximated by

$$\delta R_i = \theta_i \cdot \delta X_i \quad (11)$$

Thus an error in a parameter with a large sensitivity coefficient will have a proportionally larger contribution to the overall error in the result than one with a small sensitivity coefficient. The same will be true of uncertainties, as is discussed in the next subsection.

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

$$\begin{aligned} \theta_P &= \left(\frac{\partial \eta_T}{\partial X_P}\right) = \frac{1}{\rho g H Q} \\ \theta_H &= \left(\frac{\partial \eta_T}{\partial X_H}\right) = -\frac{P_T}{\rho g H^2 Q} \\ \theta_Q &= \left(\frac{\partial \eta_T}{\partial X_Q}\right) = -\frac{P_T}{\rho g H Q^2} \\ \theta_g &= \left(\frac{\partial \eta_T}{\partial X_g}\right) = -\frac{P_T}{\rho g^2 H Q} \\ \theta_\rho &= \left(\frac{\partial \eta_T}{\partial X_\rho}\right) = -\frac{P_T}{\rho^2 g H Q} \end{aligned} \quad (12)$$

Dividing each coefficient by η_T (the result R in this case) leads to the following simple relationships for computing relative uncertainties

$$\begin{aligned} \frac{\theta_P}{\eta_T} &= \frac{1}{P_T} \\ \frac{\theta_H}{\eta_T} &= -\frac{1}{H} \\ \frac{\theta_Q}{\eta_T} &= -\frac{1}{Q} \\ \frac{\theta_g}{\eta_T} &= -\frac{1}{g} \\ \frac{\theta_\rho}{\eta_T} &= -\frac{1}{\rho} \end{aligned} \quad (13)$$

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 usually be neglected. A similar line of reasoning applies to the determination of g.

7-3.3 Uncertainty of a Result

The absolute standard random uncertainty of a result, s_R, is given by

$$s_R = \left[\sum_{i=1}^{m} (\theta_i s_{\overline{X}_i})^2 \right]^{1/2} \tag{14}$$

Where m is the number of parameters that contribute to the uncertainty in the result and $s_{\overline{X}i}$ is the standard random uncertainty of the mean for parameter i.

The relative standard random uncertainty of a result is given by

$$\frac{s_R}{R} = \left[\sum_{i=1}^{m} (\theta_i \frac{s_{\overline{X}_i}}{R})^2 \right]^{1/2} \tag{15}$$

The absolute standard systematic uncertainty of a result b_R is given by

$$b_R = \left[\sum_{i=1}^{m} (\theta_i b_{\overline{X}_i})^2 \right]^{1/2} \tag{16}$$

The relative standard systematic uncertainty of a result is given by

$$\frac{b_R}{R} = \left[\sum_{i=1}^{m} \left(\theta_i \frac{b_{\overline{X}_i}}{R}\right)^2 \right]^{1/2} \tag{17}$$

For the computation the relative uncertainties in turbine efficiency, the terms $\frac{\theta_i}{R}$ in the above equations can be replaced by the simple relations given by eq. (13).

In the case of a large number degrees of freedom ($\nu > 30$; $t = 2$), the overall standard uncertainty in a result is given by

$$u_R = \sqrt{b_R^2 + s_R^2} \tag{18}$$

The uncertainty at the 95% confidence level is $U_R = 2u_R$.

In the case of a small number of degrees of freedom, Student's t static can be obtained from Table 7-3-1, and the 95% level uncertainty is given by

$$\begin{aligned} U_R &= \sqrt{(2b_R)^2 + (ts_R)^2} \\ &= 2\sqrt{b_R^2 + \left(\frac{t}{2}s_R\right)^2} \text{ f} \end{aligned} \tag{19}$$

The degrees of freedom nu in this case can be estimated from the Welch-Satterthwaite formula

$$nu = \frac{\left(\sum_{k=1}^{K} (s_{\overline{X}k})^2\right)^2}{\sum_{k=1}^{K} \frac{(s_{\overline{X}k})^4}{\nu_k}} \tag{20}$$

where

K = the number of parameters used to compute the random standard uncertainty

ν_k = the appropriate degrees of freedom for $s_{\overline{X}k}$

7-3.4 Combining Uncertainties for Common Mathematical Operations

Several useful specific forms for propagation of uncertainties are given below.

(a) Sum or Difference of Two Parameters. If a result is computed as the sum or difference of two parameters

$$R = x \pm y \tag{21}$$

then the absolute uncertainty in the result is given by

$$\begin{aligned} \delta R &= \left[\left(\frac{\partial R}{\partial x}\delta x\right)^2 + \left(\frac{\partial R}{\partial y}\delta y\right)^2 \right]^{1/2} \\ &= \left[\delta x^2 + \delta y^2\right]^{1/2} \end{aligned} \tag{22}$$

and the relative uncertainty is given by

$$U_R = \frac{\delta R}{R} = \left[\left(\frac{\delta x}{x+y}\right)^2 + \left(\frac{\delta y}{x+y}\right)^2 \right]^{1/2} \tag{23}$$

(b) Special Case: Uncorrelated Parameters of Approximately Equal Value. Suppose that x and y are approximately equal and that δx and δy are approximately equal and are uncorrelated, as might be the case for the random uncertainties in a flow measurement in a two-bay intake, where x and y are the flows in the two intakes.

In this case, we have

$$U_R = \frac{\delta R}{R} \cong \left[\left(\frac{\delta x}{2x}\right)^2 + \left(\frac{\delta x}{2x}\right)^2 \right]^{1/2} = \frac{1}{\sqrt{2}}\left(\frac{\delta x}{x}\right) \tag{24}$$

Thus the uncertainty in the overall result is less than the uncertainty in the parameter. For example, if the flow rate in each individual bay has an uncertainty of 2%, the combined uncertainty would be $2/\sqrt{2} = 1.41\%$. This result assumes that the uncertainties are uncorrelated.

(c) Average of Two Parameters. If a result is computed as an average of two parameters

$$R = \frac{1}{2}(x + y) \tag{25}$$

then the absolute uncertainty in the result is given by

$$\delta R = \left[\left(\frac{\partial R}{\partial x}\delta x\right)^2 + \left(\frac{\partial R}{\partial y}\delta y\right)^2\right]^{1/2} = \left[\left(\frac{1}{2}\delta x\right)^2 + \left(\frac{1}{2}\delta y\right)^2\right]^{1/2} = \frac{1}{2}\left[(\delta x)^2 + (\delta y)^2\right]^{1/2} \tag{26}$$

and the relative uncertainty is given by

$$U_R = \frac{\delta R}{R} = \frac{1}{2}\left[\left(\frac{\delta x}{x+y}\right)^2 + \left(\frac{\delta y}{x+y}\right)^2\right]^{1/2} \tag{27}$$

(d) Product of Two Parameters. For a result computed as a product of two parameters:

$$R = x \cdot y \tag{28}$$

The absolute uncertainty in the result is given by

$$\delta R = \left[\left(\frac{\partial R}{\partial x}\delta x\right)^2 + \left(\frac{\partial R}{\partial y}\delta y\right)^2\right]^{1/2} = \left[(y\delta x)^2 + (x\delta y)^2\right]^{1/2} \tag{29}$$

and the relative uncertainty is given by

$$UR = \frac{\delta R}{R} = \left[\left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2\right]^{1/2} \tag{30}$$

Note that in the case of a product, the overall relative uncertainty is the RSS of the individual relative uncertainties.

(e) Quotient of Two Parameters. For a result computed as a quotient of two parameters:

$$R = \frac{x}{y} \tag{31}$$

The absolute uncertainty in the result is given by

$$\delta R = \left[\left(\frac{\partial R}{\partial x}\delta x\right)^2 + \left(\frac{\partial R}{\partial y}\delta y\right)^2\right]^{1/2} = \left[\left(\frac{\delta x}{y}\right)^2 + \left(-\frac{x}{y^2}\delta y\right)^2\right]^{1/2} \tag{32}$$

and the relative uncertainty is given by

$$U_R = \frac{\delta R}{R} = \left[\left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2\right]^{1/2} \tag{33}$$

Thus the relative uncertainty for the quotient of two parameters is the same as for the product of two parameters.

7-3.5 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 usually 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 example, 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:

$$\hat{\eta} = c_o + c_1 P + c_2 P^2 + c_3 P^3 + c_4 P^4 + c_5 P^5 \tag{34}$$

where 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

$$S_\eta = \left(\frac{1}{N - M - 1}\sum_{i=1}^{N}(\eta_i - \hat{\eta})^2\right)^{1/2} \tag{35}$$

where η_i are the individual efficiencies, $\hat{\eta}$ is the curve fit of the efficiency as a function of power, N is the number of measurements, and M is the number of coefficients to be determined (the polynomial coefficients in the example above, for which $M = 6$).

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

$$S_{\overline{\eta}} = S_\eta / \sqrt{N} \tag{36}$$

Table 7-3.6-1 Modified Thompson τ (at the 5% Significance Level)

N	τ	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

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 graphed as a function of power output, a second-order polynomial will generally not follow the "true" curve very well. This will lead to an artificially 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 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 curves fits greater than fifth order often yield unsuitable curves. Such unreasonableness can often be detected by simply plotting and inspecting the derived curve fit.

7-3.6 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 or the system being measured. 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 ASME PTC 19.1.

Let y_i be the value of the observation y that is most remote from $\widehat{Y}$, 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 of $d = \left| y_i - \widehat{Y} \right|$ is greater than the product τS, the value y_i is rejected as an outlier. The value of τ is obtained from Table 7-3.6-1.

After rejecting an outlier, $\widehat{Y}$ 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 η should be tested for outliers. The test should also be applied to curves fit to test data over a range of operating conditions.

7-3.7 Typical Values of Uncertainty

The following paragraphs present typical uncertainties (including both systematic and random errors) which may be attainable with calibrated instrumentation and normal test conditions. The values listed below for specific measurements are for general guidance only, and do not take the place of a full uncertainty analysis applied to each parameter. This general list is not comprehensive, and all uncertainties associated with each test measurement should be identified and separately addressed.

7-3.7.1 Flow Rate Uncertainty

(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%
- *(3)* In an intake, ±1.75%

(b) Pressure–time method, ±1.0%

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

(d) Dye dilution method, ±1.5%

7-3.7.2 Head Uncertainty

(a) Measurement of free water level difference, h
- *(1)* Point gauge, hook gauge, or float gauge
  - *(-a)* ±(1/h)% (SI units)
  - *(-b)* ±(3.2/h)% (U.S. Customary units)
- *(2)* Plate gauge, fixed
  - *(-a)* ±(5/h)% (SI units)
  - *(-b)* ±(16.4/h)% (U.S. Customary units)

(b) Pressure uncertainty

(1) Deadweight gauge, ±0.1%
(2) Height of mercury, h
(-a) ±(0.1/h′)% (SI units)
(-b) ±(0.32/h′)% (U.S. Customary units)
(3) Spring pressure gauge, ±0.5%
(4) Transducers, ±(0.1 to 0.5)%

7-3.7.3 Power Uncertainty. When using the generator as a dynamometer, with meter class instrument transformers, ±0.5%.

7-3.7.4 Speed Uncertainty. Electric counter and other precision speed-measuring devices = ±0.1%.

7-3.7.5 Efficiency Uncertainty for the Thermodynamic Method

(a) gross head from 100 m to 200 m (328 ft to 656 ft), ±1.3%
(b) gross head from 200 m to 500 m (656 ft to 1,640 ft), ±1.0%
(c) gross head >500 m (>1,640 ft), ±0.7%

MANDATORY APPENDIX I
TABLES OF PHYSICAL PROPERTIES

I-1 PHYSICAL PROPERTIES

This Appendix provides tables of physical properties for use in the equations in this Code. The values to be used are those corresponding to the site specific test conditions. See Tables I-1-1 through I-1-9 (Tables I-1-1C through I-1-8C).

Table I-1-1 Acceleration of Gravity as a Function of Latitude and Elevation, SI Units (m/s²)

	Altitude Above Mean Sea Level, Z, m							
Latitude, ϕ, deg	**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

GENERAL NOTES:

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

(b) Gravitational acceleration equation given in the reference noted in General Note (a) above is

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

where

g = acceleration, m/s²

Z = elevation, m

ϕ = latitude, deg

(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/s² (32.17405 ft/sec²).

Table I-1-1C Acceleration of Gravity as a Function of Latitude and Elevation, U.S. Customary Units (ft/sec^2)

	Altitude Above Mean Sea Level, Z, ft						
Latitude, 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 equation given in the reference noted in General Note (a) above is

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

where

g = acceleration, m/s^2

Z = elevation, m

ϕ = latitude, deg

(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 (32.17405 ft/sec^2).

Table I-1-2 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	21	2.488
1	0.6571	22	2.645
2	0.7060	23	2.811
3	0.7581	24	2.986
4	0.8135	25	3.170
5	0.8726	26	3.364
6	0.9354	27	3.568
7	1.002	28	3.783
8	1.073	29	4.009
9	1.148	30	4.247
10	1.228	31	4.497
11	1.313	32	4.759
12	1.403	33	5.035
13	1.498	34	5.325
14	1.599	35	5.629
15	1.706	36	5.947
16	1.819	37	6.282
17	1.938	38	6.632
18	2.065	39	7.000
19	2.198	40	7.384
20	2.339		

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 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:

$$T(°F) = T(°C) \times 1.8 + 32$$

$$P_{vp}\left(\text{lbf/in.}^2\right) = P_{vp}(\text{kPa}) \times 1000 \times (0.3048/12)^2 / (0.45359237 \times 9.80665)$$

Table I-1-2C 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	74	0.41599
34	0.09607	76	0.44473
36	0.10403	78	0.47518
38	0.11258	80	0.50744
40	0.12173	82	0.54159
42	0.13155	84	0.57772
44	0.14205	86	0.61593
46	0.15328	88	0.65632
48	0.16530	90	0.69899
50	0.17813	92	0.74405
52	0.19184	94	0.79161
54	0.20646	96	0.84178
56	0.22206	98	0.89468
58	0.23868	100	0.95044
60	0.25639	102	1.0092
62	0.27524	104	1.0710
64	0.29529	106	1.1361
66	0.31662	108	1.2046
68	0.33927	110	1.2766
70	0.36334	112	1.3523
72	0.38889		

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 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:

$$T(°F) = T(°C) \times 1.8 + 32$$

$$P_{vp}\left(\text{lbf/in.}^2\right) = P_{vp}(\text{kPa}) \times 1000 \times (0.3048/12)^2 / (0.45359237 \times 9.80665)$$

Table I-1-3 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 (8°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

$$\rho_a = \frac{352.9838}{(273.15 + T)}(1 - 2.2558 \times 10^{-5}Z)^{5.2559}$$

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 I-1-3C 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 (8°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

$$\rho_a = \frac{352.9838}{(273.15 + T)}(1 - 2.2558 \times 10^{-5}Z)^{5.2559}$$

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 I-1-4 Density of Mercury, SI Units (kg/m^3)

Temperature, *T*, °C	Density, ρ, kg/m^3	Temperature, *T*, °C	Density, ρ, kg/m^3
−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 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.
(c) Conversion factors from U.S. Customary Units:

$$T(°C) = (T(°F) - 32)/1.8$$

$$\rho a(kg/m^3) = \rho a(slug/ft^3) \times (0.45359237/9.80665)/(0.3048)^4$$

Table I-1-4C Density of Mercury, U.S. Customary Units (slugs/ft^3)

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

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

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

where
ρ = density, slugs/ft^3
T = temperature, °F

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.

Table I-1-5 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

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

(c) The use of geometric elevation Z instead of the geopotential elevation specified in the reference produces pressures accurate to within ±0.033%
(d) Conversion factor: p_a (lbf/in.^{2}) = p_a (kPa) × 1000 × $(0.3048/12)^2$/(0.45359237 × 9.80665)

Table I-1-5C Atmospheric Pressure, U.S. Customary Units (lbf/in.^{2})

Altitude, Z, ft	Atmospheric Pressure, p_a, lbf/in.^{2}
0	14.6959
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 (lbf/in.^{2}) = p_a (kPa) × 1000 × $(0.3048/12)^2$/(0.45359237 × 9.80665)

Table I-1-6 Density of Water as Function of Temperature and Pressure, SI Units (kg/m³)

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	999.84	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	999.97	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	998.94	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	992.22	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:

$$\rho = \frac{p^*}{R(T + 273.15)} \left[\sum_{i=1}^{34} - n_i I_i \left(7.1 - \frac{p}{p^*}\right)^{I_i - 1} \left(\frac{T^*}{(T + 273.15)} - 1.222 \right) \right]^{-1}$$

where

p = absolute pressure, kPa

T = water temperature, °C

ρ = density of water, kg/m³

Constants:

p^* = 16,530 kPa

R = 0.461526 kJ/kg K

T^* = 1,386 K

Refer to Table I-1-6.1 for the coefficients I_i, J_i, and n_i.

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

(c) Standard atmospheric pressure is 101.325 kPa [refer to Table I-1-5 (Table I-1-5C)]

Table I-1-6C Density of Water as Function of Temperature and Pressure, U.S. Customary Units (slug/ft^3)

	Absolute Pressure, p_{abs}, lbf/in.^{3}									
Temperature, T, °F	**14**	**14,696**	**15**	**25**	**50**	**100**	**200**	**500**	**1000**	**2000**
32,036	1.94002	1.94002	1.94002	1.94009	1.94026	1.94060	1.94128	1.94331	1.94667	1.95332
34	1.94014	1.94014	1.94014	1.94021	1.94038	1.94072	1.94139	1.94341	1.94674	1.95334
36	1.94022	1.94022	1.94023	1.94029	1.94046	1.94080	1.94146	1.94346	1.94677	1.95332
38	1.94026	1.94027	1.94027	1.94033	1.94050	1.94083	1.94150	1.94348	1.94677	1.95327
40	1.94026	1.94027	1.94027	1.94034	1.94050	1.94083	1.94149	1.94346	1.94672	1.95318
42	1.94023	1.94023	1.94024	1.94030	1.94047	1.94079	1.94145	1.94340	1.94664	1.95305
44	1.94016	1.94016	1.94016	1.94023	1.94039	1.94072	1.94137	1.94331	1.94653	1.95290
46	1.94005	1.94006	1.94006	1.94012	1.94028	1.94061	1.94125	1.94318	1.94638	1.95271
48	1.93991	1.93992	1.93992	1.93998	1.94014	1.94046	1.94110	1.94302	1.94620	1.95249
50	1.93974	1.93974	1.93974	1.93981	1.93997	1.94029	1.94092	1.94283	1.94599	1.95225
55	1.93916	1.93917	1.93917	1.93923	1.93939	1.93971	1.94034	1.94222	1.94534	1.95151
60	1.93841	1.93841	1.93841	1.93847	1.93863	1.93894	1.93956	1.94142	1.94450	1.95060
65	1.93747	1.93748	1.93748	1.93754	1.93770	1.93800	1.93862	1.94046	1.94350	1.94953
70	1.93638	1.93638	1.93638	1.93645	1.93660	1.93690	1.93751	1.93933	1.94235	1.94832
75	1.93513	1.93513	1.93514	1.93520	1.93535	1.93565	1.93625	1.93806	1.94105	1.94697
80	1.93373	1.93374	1.93374	1.93380	1.93395	1.93425	1.93485	1.93664	1.93961	1.94548
85	1.93220	1.93221	1.93221	1.93227	1.93242	1.93271	1.93331	1.93509	1.93804	1.94387
90	1.93054	1.93054	1.93054	1.93060	1.93075	1.93105	1.93164	1.93341	1.93634	1.94214
95	1.92875	1.92875	1.92875	1.92881	1.92896	1.92926	1.92984	1.93160	1.93452	1.94029
100	1.92684	1.92684	1.92685	1.92690	1.92705	1.92734	1.92793	1.92968	1.93259	1.93834
105	1.92481	1.92482	1.92482	1.92488	1.92503	1.92532	1.92590	1.92765	1.93054	1.93628
110	1.92268	1.92268	1.92269	1.92274	1.92289	1.92318	1.92376	1.92551	1.92839	1.93411

GENERAL NOTES:

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

$$\rho = \frac{p^*}{R(T + 273.15)}\left[\sum_{i=1}^{34} - n_i I_i \left(7.1 - \frac{p}{p^*}\right)^{I_i - 1}\left(\frac{T^*}{(T + 273.15)} - 1.222\right)^{J_i}\right]^{-1}$$

where

p = absolute pressure, kPa
T = water temperature, °C
ρ = density of water, kg/m^3

Constants:

p^* = 16,530 kPa
T^* = 1,386 K
R = 0.461526 kJ/kg K

Refer to Table I-1-6.1 for the coefficients I_i, J_i, and n_i.

(b) Intermediate values may be interpolated or calculated from the equation given 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) × 1000 × (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 14.696 lbf/in.^{2} [refer to Table I-1-5 (Table I-1-5C)]

Table I-1-6.1 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 I-1-7 Specific Heat Capacity of Water, c_p (J/kg K), SI Units

Temperature, T, °C	Absolute Pressure, p_{abs}									
	100	**101.325**	**500**	**1 000**	**2 000**	**3 000**	**4 000**	**5 000**	**10 000**	**15 000**
0	4 219.44	4 219.43	4 217.44	4 214.96	4 210.03	4 205.15	4 200.32	4 195.53	4 172.28	4 150.12
1	4 216.02	4 216.01	4 214.09	4 211.68	4 206.91	4 202.18	4 197.50	4 192.86	4 170.32	4 148.84
2	4 212.89	4 212.88	4 211.01	4 208.68	4 204.05	4 199.47	4 194.92	4 190.42	4 168.55	4 147.70
3	4 210.01	4210.01	4 208.19	4 205.93	4 201.44	4 196.99	4 192.58	4 188.21	4 166.97	4 146.71
4	4 207.38	4 207.37	4 205.61	4 203.41	4 199.04	4 194.72	4 190.43	4 186.19	4 165.54	4 145.83
5	4 204.95	4 204.95	4 203.24	4201.10	4 196.85	4 192.64	4 188.48	4 184.34	4 164.25	4 145.07
6	4 202.73	4 202.72	4 201.05	4 198.97	4 194.84	4 190.74	4 186.69	4 182.66	4 163.09	4 144.40
7	4 200.68	4 200.67	4 199.05	4 197.02	4 192.99	4 189.00	4 185.05	4 181.13	4 162.05	4 143.82
8	4 198.79	4 198.79	4 197.20	4 195.23	4 191.30	4 187.41	4 183.55	4 179.73	4 161.11	4 143.32
9	4 197.05	4 197.05	4 195.50	4 193.58	4 189.74	4 185.94	4 182.18	4 178.44	4 160.27	4 142.88
10	4 195.45	4 195.45	4 193.94	4 192.05	4 188.31	4 184.60	4 180.92	4 177.27	4 159.51	4 142.51
12	4 192.61	4 192.60	4 191.16	4 189.36	4 185.78	4 182.23	4 178.71	4 175.22	4 158.21	4 141.92
14	4 190.18	4 190.17	4 188.79	4 187.06	4 183.63	4 180.22	4 176.84	4 173.50	4 157.16	4 141.50
16	4 188.10	4 188.10	4 186.77	4 185.10	4 181.80	4 178.52	4 175.27	4 172.05	4 156.32	4 141.23
18	4 186.32	4 186.32	4 185.03	4 183.43	4 180.25	4 177.09	4 173.95	4 170.84	4 155.66	4 141.07
20	4 184.80	4 184.79	4 183.55	4 182.01	4 178.92	4 175.87	4 172.84	4 169.83	4 155.13	4 141.01
22	4 183.50	4 183.49	4 182.29	4 180.79	4 177.81	4 174.84	4 171.90	4 168.99	4 154.73	4 141.02
24	4 182.39	4 182.38	4 181.22	4 179.76	4 176.86	4 173.98	4 171.13	4 168.29	4 154.44	4 141.09
26	4 181.45	4 181.45	4 180.31	4 178.90	4 176.07	4 173.27	4 170.49	4 167.73	4 154.24	4 141.23
28	4 180.67	4 180.66	4 179.56	4 178.18	4 175.43	4 172.69	4 169.98	4 167.29	4 154.12	4 141.42
30	4 180.02	4 180.02	4 178.94	4 177.59	4 174.90	4 172.24	4169.59	4 166.96	4 154.08	4 141.66
32	4 179.51	4 179.50	4 178.45	4 177.13	4 174.50	4 171.89	4 169.29	4 166.72	4 154.12	4 141.94
34	4 179.11	4 179.10	4 178.07	4 176.77	4 174.20	4 171.64	4 169.10	4 166.58	4 154.22	4 142.27
36	4 178.82	4 178.82	4 177.80	4 176.53	4 174.00	4 171.49	4 169.00	4 166.52	4 154.38	4 142.64
38	4 178.64	4 178.63	4 177.64	4 176.39	4 173.90	4 171.44	4 168.98	4166.55	4 154.61	4 143.06
40	4 178.56	4 178.55	4 177.57	4 176.34	4 173.90	4 171.47	4 169.06	4 166.66	4 154.90	4 143.52

GENERAL NOTES:

(a) The specific heat capacity at constant pressure given above were computed from the following equation:

$$c_p = -R\left(\frac{T^*}{(T+273.15)}\right)^2 \sum_{i=1}^{34} n_i\left(7.1 - \frac{p}{p^*}\right)^{I_i} J_i(J_i - 1)\left(\frac{T^*}{(T+273.15)} - 1.222\right)^{J_i-2}$$

where

c_p = specific heat of water, J/kg K
p = absolute pressure, kPa
T = water temperature, °C

Constants:

p^* = 16,530 kPa
R = 0.461526 kJ/kg K
T^* = 1,386 K

Refer to Table I-1-9 for the coefficients I_i, J_i , and n_i.

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

(c) Standard atmospheric pressure is 101.325 kPa [refer to Table I-1-5 (Table I-1-5C)

Table I-1-7C Specific Heat Capacity of Water, c_p, (Btu/lbm °F), U.S. Customary Units

Temperature, *T*, °F	Absolute Pressure, p_{abs}, lbf/in.^{2}									
	14	14.696	15	25	50	100	200	500	1000	2000
32,036	1.007782	1.007776	1.007774	1.007692	1.007487	1.007077	1.006263	1.003851	0.999937	0.992490
34	1.006896	1.006891	1.006888	1.006809	1.006611	1.006215	1.005428	1.003098	0.999316	0.992116
36	1.006076	1.006071	1.006069	1.005992	1.005801	1.005418	1.004658	1.002405	0.998748	0.991783
38	1.005332	1.005327	1.005324	1.005250	1.005065	1.004695	1.003959	1.001779	0.998238	0.991491
40	1.004655	1.004650	1.004647	1.004575	1.004396	1.004038	1.003325	1.001212	0.997780	0.991237
42	1.004038	1.004033	1.004031	1.003961	1.003787	1.003440	1.002748	1.000699	0.997368	0.991015
44	1.003477	1.003472	1.003470	1.003402	1.003233	1.002895	1.002224	1.000233	0.996998	0.990823
46	1.002964	1.002960	1.002958	1.002892	1.002727	1.002399	1.001746	0.999811	0.996665	0.990656
48	1.002497	1.002492	1.002490	1.002426	1.002266	1.001947	1.001312	0.999428	0.996365	0.990512
50	1.002069	1.002065	1.002063	1.002001	1.001845	1.001534	1.000915	0.999080	0.996094	0.990387
55	1.001153	1.001149	1.001147	1.001089	1.000942	1.000650	1.000067	0.998341	0.995530	0.990150
60	1.000417	1.000413	1.000411	1.000356	1.000217	0.999941	0.999390	0.997757	0.995095	0.989994
65	0.999824	0.999820	0.999818	0.999766	0.999634	0.999371	0.998847	0.997294	0.994761	0.989900
70	0.999346	0.999342	0.999340	0.999290	0.999164	0.998913	0.998413	0.996929	0.994507	0.989853
75	0.998962	0.998959	0.998957	0.998909	0.998788	0.998548	0.998068	0.996643	0.994318	0.989844
80	0.998659	0.998655	0.998654	0.998607	0.998491	0.998259	0.997797	0.996425	0.994183	0.989865
85	0.998423	0.998420	0.998419	0.998374	0.998262	0.998037	0.997591	0.996264	0.994095	0.989914
90	0.998248	0.998245	0.998244	0.998200	0.998091	0.997874	0.997441	0.996153	0.994048	0.989987
95	0.998127	0.998124	0.998123	0.998081	0.997975	0.997763	0.997342	0.996089	0.994040	0.990083
100	0.998056	0.998053	0.998052	0.998011	0.997907	0.997701	0.997290	0.996068	0.994068	0.990202
105	0.998032	0.998029	0.998028	0.997987	0.997886	0.997684	0.997282	0.996087	0.994130	0.990343
110	0.998052	0.998049	0.998048	0.998008	0.997909	0.997711	0.997317	0.996145	0.994225	0.990509

GENERAL NOTES:

(a) The specific heat capacity at constant pressure given above were computed from the following equation:

$$c_p = -R\left(\frac{T^*}{(T+273.15)}\right)^2 n_i\left(7.1-\frac{p}{p^*}\right)^{I_i} J_i(J_i -)1\left(\frac{T^*}{(T+273.15)}-1.222\right)^{J_i-2}$$

where

c_p = specific heat of water, J/kg K
p = absolute pressure, kPa
T = water temperature, °C

Constants:

p^* = 16,530 kPa
R = 0.461526 kJ/kg K
T^* = 1,386 K

Refer to Table I-1-9 for the coefficients I_i, J_i , and n_i.

(b) Intermediate values may be interpolated or calculated from the equation given 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 14.696 lbf/in.^{2} [refer to Table I-1-5 (Table I-1-5C)]

Table I-1-8 Isothermal Throttling Coefficient of Water δ_T (10^{-3} m^3/kg), SI Units

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	1.01865	1.01865	1.01803	1.01725	1.01570	1.01416	1.01264	1.01112	1.00365	0.99641
1	1.01373	1.01373	1.01313	1.01238	1.01088	1.00938	1.00790	1.00643	0.99919	0.99216
2	1.00897	1.00897	1.00838	1.00765	1.00620	1.00475	1.00331	1.00188	0.99485	0.98803
3	1.00435	1.00435	1.00378	1.00307	1.00166	1.00025	0.99886	0.99747	0.99064	0.98401
4	0.99986	0.99986	0.99931	0.99862	0.99725	0.99589	0.99453	0.99318	0.98655	0.98011
5	0.99550	0.99550	0.99497	0.99430	0.99296	0.99164	0.99032	0.98901	0.98257	0.97631
6	0.99126	0.99126	0.99074	0.99009	0.98879	0.98751	0.98623	0.98495	0.97870	0.97261
7	0.98713	0.98713	0.98662	0.98599	0.98473	0.98348	0.98224	0.98100	0.97492	0.96900
8	0.98310	0.98310	0.98261	0.98199	0.98077	0.97956	0.97835	0.97715	0.97123	0.96548
9	0.97917	0.97917	0.97869	0.97810	0.97691	0.97573	0.97455	0.97339	0.96764	0.96204
10	0.97534	0.97534	0.97487	0.97429	0.97314	0.97199	0.97085	0.96971	0.96412	0.95868
12	0.96793	0.96793	0.96749	0.96694	0.96585	0.96476	0.96368	0.96261	0.95732	0.95216
14	0.96083	0.96083	0.96042	0.95990	0.95887	0.95784	0.95682	0.95580	0.95080	0.94591
16	0.95402	0.95402	0.95363	0.95314	0.95216	0.95119	0.95022	0.94926	0.94452	0.93989
18	0.94746	0.94745	0.94708	0.94662	0.94570	0.94478	0.94386	0.94295	0.93846	0.93408
20	0.94112	0.94112	0.94077	0.94033	0.93946	0.93859	0.93772	0.93686	0.93261	0.92845
22	0.93499	0.93499	0.93466	0.93424	0.93342	0.93260	0.93178	0.93096	0.92693	0.92299
24	0.92905	0.92905	0.92873	0.92834	0.92756	0.92678	0.92600	0.92523	0.92142	0.91768
26	0.92327	0.92327	0.92297	0.92260	0.92186	0.92112	0.92039	0.91966	0.91605	0.91251
28	0.91764	0.91764	0.91736	0.91701	0.91631	0.91562	0.91492	0.91423	0.91081	0.90746
30	0.91215	0.91215	0.91188	0.91155	0.91089	0.91024	0.90958	0.90893	0.90570	0.90252
32	0.90678	0.90678	0.90653	0.90622	0.90560	0.90498	0.90436	0.90374	0.90069	0.89769
34	0.90153	0.90153	0.90129	0.90100	0.90041	0.89983	0.89925	0.89867	0.89578	0.89295
36	0.89638	0.89638	0.89616	0.89588	0.89533	0.89478	0.89423	0.89368	0.89097	0.88829
38	0.89132	0.89132	0.89111	0.89085	0.89033	0.88982	0.88930	0.88879	0.88623	0.88371
40	0.88635	0.88635	0.88615	0.88591	0.88542	0.88494	0.88445	0.88397	0.88157	0.87919

GENERAL NOTES:

(a) The isothermal throttling coefficient given above were computed from the following equation:

$$\delta_T = \frac{RT^*}{p^*} \sum_{i=1}^{i=34} - n_i I_i J_i \left(7.1 - \frac{p}{p^*}\right)^{I_i - 1} \left(\frac{T^*}{(T + 273.15)} - 1.222\right)^{J_i - 1}$$

where

p = absolute pressure, kPa
T = water temperature, °C
δ_T = isothermal throttling coefficient of water (10^{-3} m^3/kg)

Constants:

p^* = 16,530 kPa
R = 0.461526 kJ/kg K
T^* = 1,386 K

Refer to Table I-1-9 for the coefficients I_i, J_i, and n_i.

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

(c) Standard atmospheric pressure is 101.325 kPa [refer to Table I-1-5 (Table I-1-5C)].

Table I-1-8C Isothermal Throttling Coefficient of Water δ_T (10^{-3} ft^3/lbm), U.S. Customary Units

Temperature, T, °F	Absolute Pressure, p_{abs}, lbf/in.^{2}									
	14	14.696	15	25	50	100	200	500	1000	2000
32,036	0.0163157	0.0163156	0.0163155	0.0163138	0.0163095	0.0163009	0.0162838	0.0162328	0.0161493	0.0159874
34	0.0162300	0.0162298	0.0162298	0.0162281	0.0162240	0.0162157	0.0161991	0.0161498	0.0160690	0.0159122
36	0.0161456	0.0161455	0.0161454	0.0161438	0.0161398	0.0161318	0.0161158	0.0160681	0.0159899	0.0158382
38	0.0160640	0.0160639	0.0160639	0.0160623	0.0160584	0.0160507	0.0160352	0.0159890	0.0159134	0.0157665
40	0.0159851	0.0159849	0.0159849	0.0159834	0.0159796	0.0159721	0.0159571	0.0159125	0.0158392	0.0156970
42	0.0159085	0.0159084	0.0159083	0.0159069	0.0159032	0.0158960	0.0158814	0.0158382	0.0157673	0.0156295
44	0.0158342	0.0158341	0.0158341	0.0158326	0.0158291	0.0158221	0.0158080	0.0157662	0.0156975	0.0155640
46	0.0157620	0.0157619	0.0157619	0.0157605	0.0157571	0.0157503	0.0157367	0.0156961	0.0156296	0.0155002
48	0.0156918	0.0156917	0.0156917	0.0156904	0.0156870	0.0156804	0.0156672	0.0156280	0.0155635	0.0154380
50	0.0156235	0.0156234	0.0156233	0.0156221	0.0156188	0.0156124	0.0155997	0.0155616	0.0154991	0.0153774
55	0.0154600	0.0154599	0.0154599	0.0154587	0.0154557	0.0154498	0.0154380	0.0154028	0.0153449	0.0152322
60	0.0153058	0.0153058	0.0153057	0.0153046	0.0153019	0.0152964	0.0152855	0.0152529	0.0151993	0.0150947
65	0.0151597	0.0151596	0.0151596	0.0151586	0.0151560	0.0151510	0.0151408	0.0151107	0.0150610	0.0149639
70	0.0150204	0.0150204	0.0150203	0.0150194	0.0150170	0.0150124	0.0150030	0.0149750	0.0149290	0.0148389
75	0.0148872	0.0148871	0.0148871	0.0148862	0.0148840	0.0148797	0.0148710	0.0148451	0.0148025	0.0147189
80	0.0147591	0.0147590	0.0147590	0.0147582	0.0147562	0.0147521	0.0147441	0.0147202	0.0146807	0.0146032
85	0.0146355	0.0146354	0.0146354	0.0146347	0.0146328	0.0146291	0.0146217	0.0145996	0.0145630	0.0144912
90	0.0145159	0.0145158	0.0145158	0.0145151	0.0145134	0.0145100	0.0145031	0.0144827	0.0144490	0.0143826
95	0.0143997	0.0143996	0.0143996	0.0143990	0.0143974	0.0143943	0.0143880	0.0143692	0.0143381	0.0142768
100	0.0142865	0.0142865	0.0142865	0.0142859	0.0142845	0.0142816	0.0142758	0.0142585	0.0142300	0.0141735
105	0.0141760	0.0141760	0.0141760	0.0141754	0.0141741	0.0141715	0.0141662	0.0141504	0.0141243	0.0140725

GENERAL NOTES:

(a) The isothermal throttling coefficient given above were computed from the following equation:

$$\delta_T = \frac{RT^*}{p^*} \sum_{i=1}^{i=34} -n_i I_i J_i \left(7.1 - \frac{p}{p^*}\right)^{I_i - 1} \left(\frac{T^*}{(T + 273.15)} - 1.222\right)^{J_i - 1}$$

where

p = absolute pressure, kPa
T = water temperature, °C
δ_T = isothermal throttling coefficient of water (10^{-3} m^3/kg)

Constants:

p^* = 16,530 kPa
R = 0.461526 kJ/kg K
T^* = 1,386 K

Refer to Table I-1-9 for the coefficients I_i, J_i, and n_i.

(b) Intermediate values may be interpolated or calculated from the equation given 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 14.696 lbf/in.^{2} [refer to Table I-1-5 (Table I-1-5C)].

Table I-1-9 Coefficients I_i, J_i, and n_i

i	I_i	J_i	n_i	i	I_i	J_i	n_i
1	0	−2	0.14632971213167	18	2	3	$-0.44141845330846 \times 10^{-5}$
2	0	−1	−0.84548187169114	19	2	17	$-0.72694996297594 \times 10^{-15}$
3	0	0	$-0.37563603672040 \times 10^{1}$	20	3	−4	$-0.31679644845054 \times 10^{-4}$
4	0	1	$0.33855169168385 \times 10^{1}$	21	3	0	$-0.28270797985312 \times 10^{-5}$
5	0	2	−0.95791963387872	22	3	6	$-0.85205128120103 \times 10^{-9}$
6	0	3	0.15772038513228	23	4	−5	$-0.22425281908000 \times 10^{-5}$
7	0	4	$-0.16616417199501 \times 10^{-1}$	24	4	−2	$-0.65171222895601 \times 10^{-6}$
8	0	5	$0.81214629983568 \times 10^{-3}$	25	4	10	$-0.14341729937924 \times 10^{-12}$
9	1	−9	$0.28319080123804 \times 10^{-3}$	26	5	−8	$-0.40516996860117 \times 10^{-6}$
10	1	−7	$-0.60706301565874 \times 10^{-3}$	27	8	−11	$-0.12734301741641 \times 10^{-8}$
11	1	−1	$-0.18990068218419 \times 10^{-1}$	28	8	−6	$-0.17424871230634 \times 10^{-9}$
12	1	0	$-0.32529748770505 \times 10^{-1}$	29	21	−29	$-0.68762131295531 \times 10^{-18}$
13	1	1	$-0.21841717175414 \times 10^{-1}$	30	23	−31	$0.14478307828521 \times 10^{-19}$
14	1	3	$-0.52838357969930 \times 10^{-4}$	31	29	−38	$0.26335781662795 \times 10^{-22}$
15	2	−3	$-0.47184321073267 \times 10^{-3}$	32	30	−39	$-0.11947622640071 \times 10^{-22}$
16	2	0	$-0.30001780793026 \times 10^{-3}$	33	31	−40	$0.18228094581404 \times 10^{-23}$
17	2	1	$0.47661393906987 \times 10^{-4}$	34	32	−41	$-0.93537087292458 \times 10^{-25}$

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 IAPWS Industrial Formulation 1997.

(c) The above coefficients are the complete set of coefficients of the full Region 1 formulation defined in the reference.

NONMANDATORY APPENDIX A RELATIVE FLOW MEASUREMENT — INDEX TEST

A-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 along a tapered section of penstock or across Winter-Kennedy taps. Relative efficiency is expressed as a proportion of peak index efficiency.

A-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.

(i) to check the power guarantee of the machine, with agreement of the parties to the test.

(j) to check as part of aeration tests for DO increase on an aerating turbine.

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.

A-3 RELATIVE FLOW RATE

A-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. A-3.2). This is the Winter–Kennedy method, described in “Improved Type of Flow Meter for Hydraulic Turbines.” Winter, I.SA. ASCE. April 1933. This method is not suitable for relative flow measurement for pump operation.

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

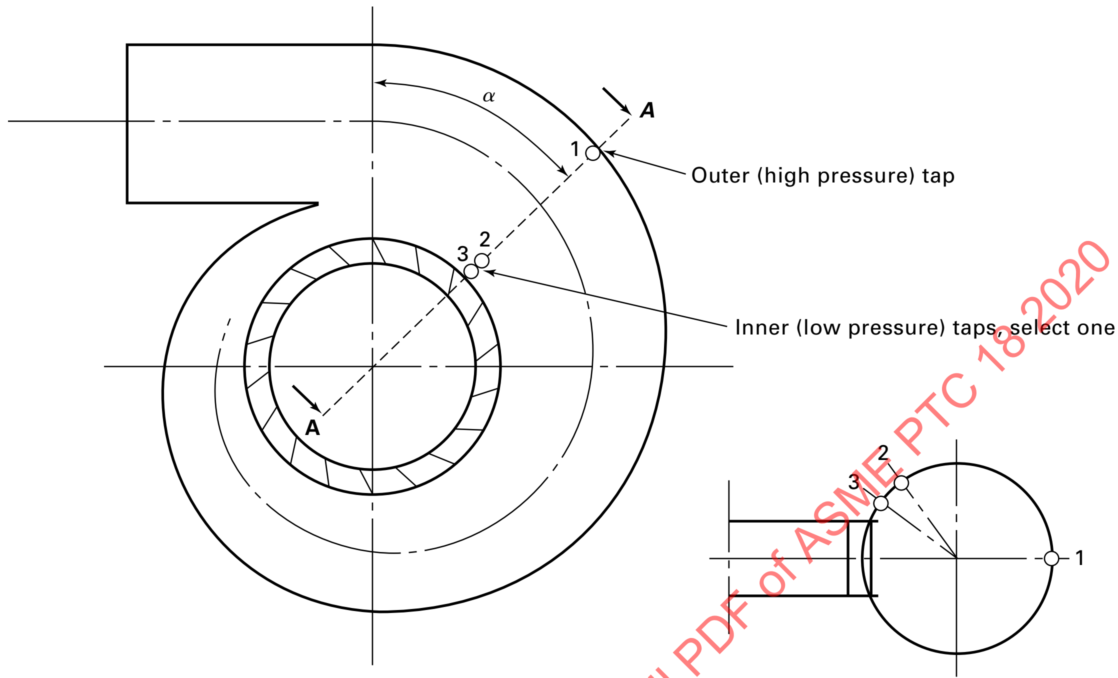
(c) measurement of the difference between the elevation of water in the inlet pool and the inlet section of the machine (see para. A-3.4).

(d) measurement of differential pressure between two piezometers located on a conduit elbow (see para. A-3.5).

(e) measurement of differential pressure between suitably located taps on a bulb or tubular turbine (see para. A-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.

Figure A-3.2-1 Location of Winter–Kennedy Pressure Taps in Spiral Case



α = 15 to 90 deg

Section ***A–A***

Flow rate is taken as proportional to the nth exponent of the differential-pressure head [i.e., $Q_{\text{rel}} = k(\Delta h)^n$]. 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 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-vs-discharge characteristic shape has been checked by tests on a homologous model of the turbine needle valve. Care shall be taken to assure that the needle, nozzle, and support vanes are clean and in good order during the test.

A-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 semi-spiral case. See Figures A-3.2-1 and A-3.2-2. One tap is located at the outer radius of the spiral or semi-spiral 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 semi-spiral case section. The inner taps shall lie on a flow line between stay vanes.

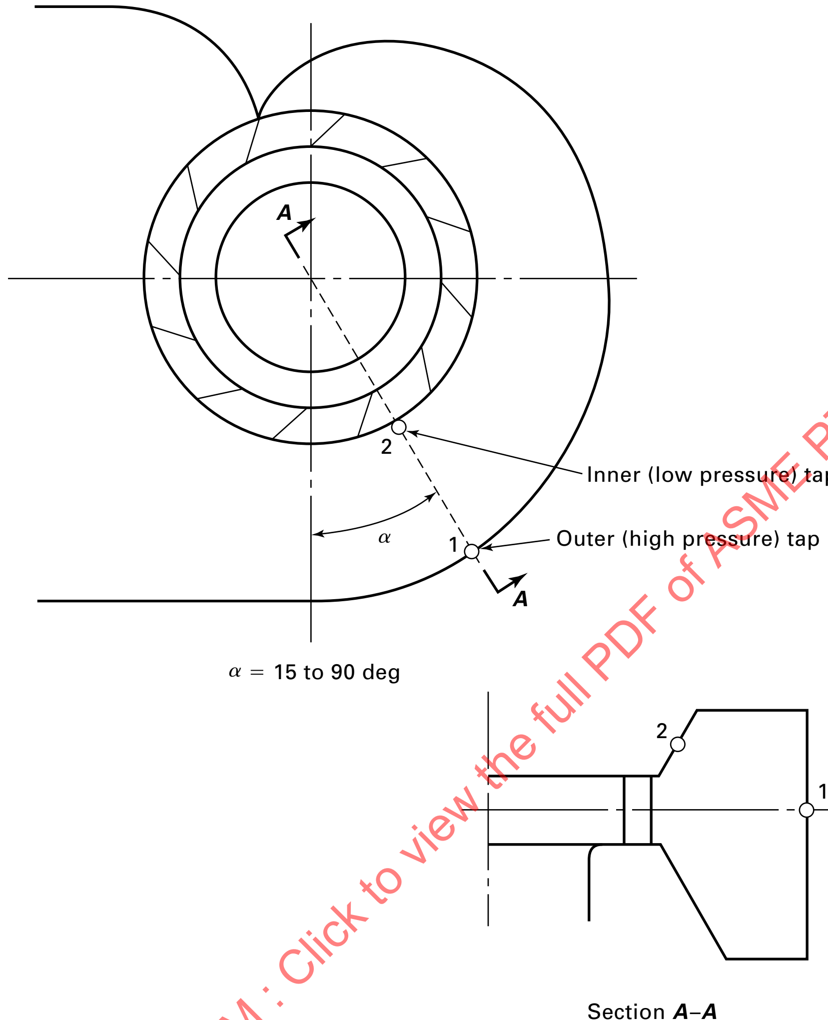
A-3.3 Relative Flow Measurement by the Converging Taper Method

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.

A-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.

Figure A-3.2-2 Location of Winter–Kennedy Pressure Taps in Semi-Spiral Case



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 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 may 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.

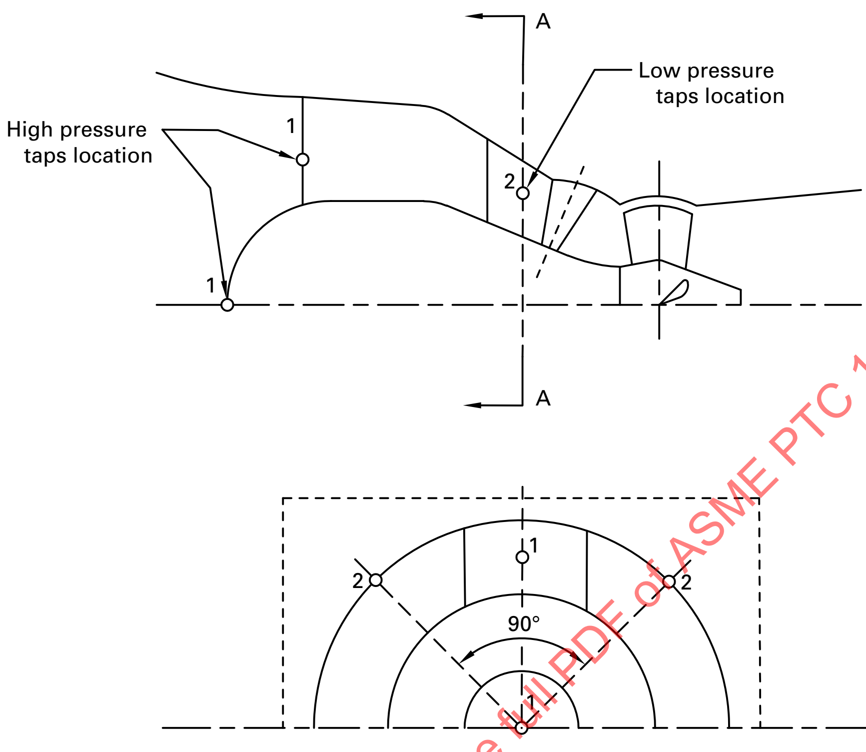
A-3.5 Relative Flow Measurement as a Differential at an Elbow

The differential pressure readings between two pressure taps located on the inside and outside radius of a penstock elbow may be used to determine relative flow rate.

A-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

Figure A-3.6-1 Location of Differential Pressure Taps in Bulb Turbine



casing upstream of the wicket gates. See Figure A-3.6-1. 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.

A-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. For separate comparative tests the pressure taps and area around the taps should be inspected and their condition documented prior to each test. This applies to the pressure taps used for head measurement as well as those used for relative flow measurement. However, the error associated with changes to the pressure taps for head measurement is usually much smaller than the error in relative flow measurement.

When the pressure taps are calibrated using a Code-approved method of measuring flow rate (subsection A-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 at plants where the pressure taps are relatively close to racks, as the pressure profile at the pressure-tap plane may be affected by wakes or turbulence resulting from different levels of trash.

A-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. In order 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. However, if the purpose of the index test is to check power guarantee, the error in flow can result in an error in velocity head and therefore in net head. In this case the uncertainty in flow must be included in the overall uncertainty analysis.

Depending on the purpose of the index test and the configuration on the plant, an index test may be conducted by measuring only the gross head.

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.

A-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 Figure A-3.9-1. A change in exponent n will rotate the relative efficiency curve about the reference or stipulated point, whereas a change of the coefficient k will increase or decrease the relative flow by a constant percentage. 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. Consistency in indicated flow rate Q_i, within ±0.5% over the range of Q_{rel} = 0.5 to Q_{rel} = 1, may be taken as confirmation of the correctness of the 0.5 exponent.

A-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 panel instrumentation, but with less accuracy, provided that relatively small changes in power can still be measured.

A-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.

A-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 $P_e/[(\Delta h^{0.5})(H)]$-vs-$P_e$ 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

Δh = differential-pressure head
k = coefficient
n = exponent
Q_{rel} = relative flow rate

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 an estimate of maximum turbine or pump efficiency at the test head. The corresponding flow rate, Q, is then as follows:

(a) For Turbine

(SI Units)

$$Q = \frac{1000P}{\eta \rho g H} (\mathrm{m^3/s})$$

(U.S. Customary Units)

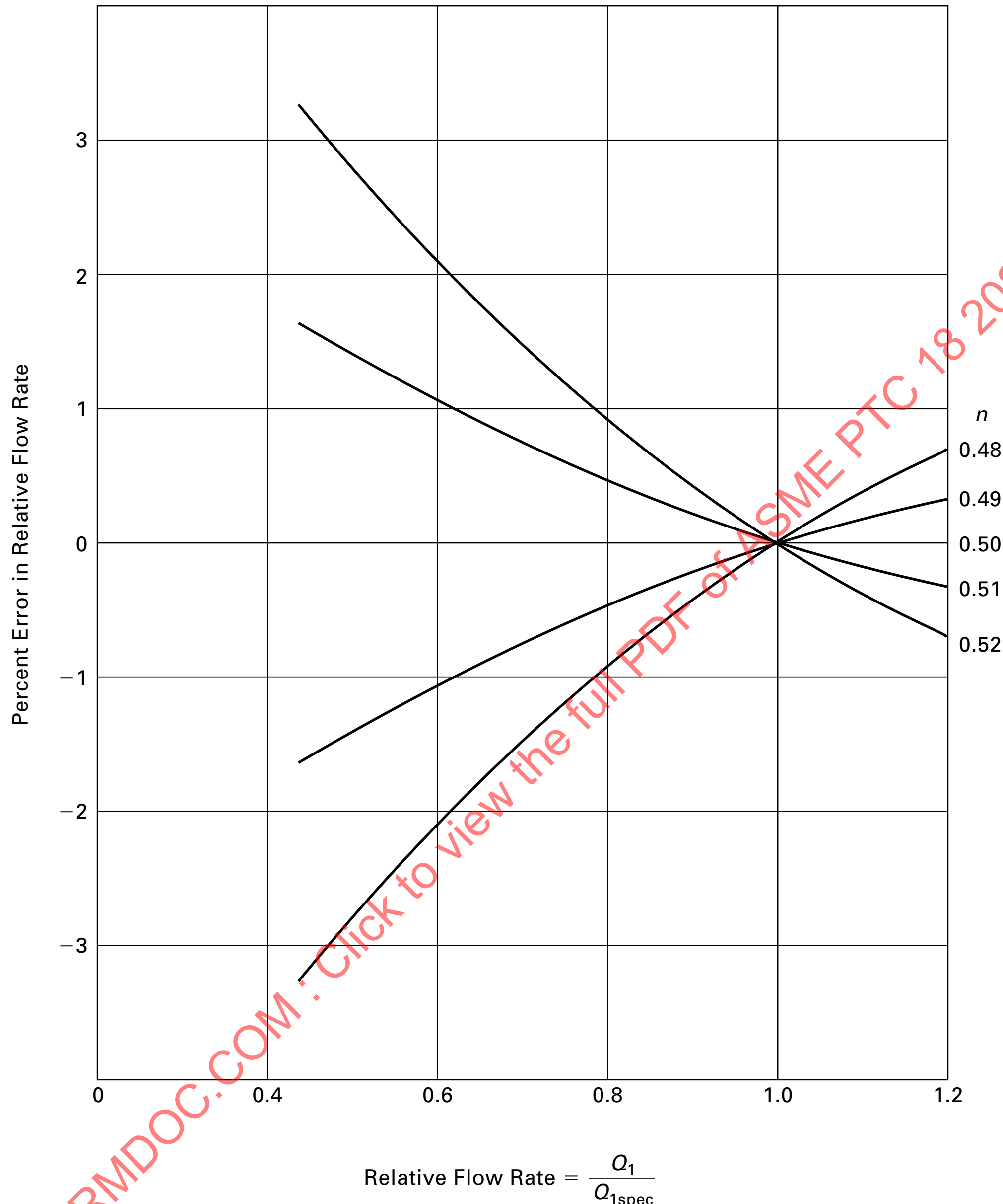
$$Q = \frac{550P}{\eta \rho g H} (\mathrm{ft^3/s})$$

(b) For Pump

(SI Units)

$$Q = \frac{1000\eta P}{\rho g H} (\mathrm{m^3/s})$$

Figure A-3.9-1 Effect of Variations in Exponent on Relative Flow Rate



GENERAL NOTE: Relative flow rate = Qi/Q_P
where
$Q_i = k\Delta h^n$ = indicated flow rate, where h is the differential pressure across the taps
Q_P = flow rate at estimated maximum efficiency

The error arises from assuming n = 0.5 when the true value can be, for instance, 0.48 or 0.52.

(U.S. Customary Units)

$$Q = \frac{550\eta P}{\rho g H}\,(\text{ft}^3/\text{s})$$

and

$$k = \frac{Q_{\text{rel}}}{(\Delta h)^{0.5}}$$

where

η = the estimated maximum efficiency

Whenever possible 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.

A-5 ASSESSMENT OF INDEX TEST ERRORS

The methods for uncertainty analysis described in Section 7 to account for errors in the measurements also apply to index tests.

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 Section 7, does not exceed ±0.5% at 95% confidence limits. If the test conditions are such that this uncertainty level 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. For a comparative test to assess the change in performance of the machine, the random uncertainty for both tests must be summed using the methods described in Section 7.

Systematic errors in head or power measurement are constant percentage errors that have unknown magnitude. The degree that these systematic errors affect the index test results will depend on the purpose of the test. For example, if the test is conducted to determine the optimum relationship of runner blade angle and wicket gate opening, the systematic uncertainty in power measurement is of no importance, and the uncertainty in head generally has minimal effect on the results. The same is true for tests to check the general shape of the efficiency curve of the machine.

Systematic errors can be important for an index test where results are compared to homologous model tests, where the test is used to verify guaranteed power, or for a comparative test to assess the change in performance of the machine.

When comparative tests are made the systematic uncertainties for both tests must be summed using the methods described in Section 7, except for those features or measurement methods that are unchanged for the two tests. If the two tests are made using unchanged current transformers, potential transformers and power meter, the systematic uncertainty in power measurement can be neglected unless there is a possibility of instrument calibration drift. This also applies to head measurement.

Possible errors due to changes in the relative flow measurement must be carefully assessed for comparative tests. The requirement for pressure taps for relative flow measurement to remain unchanged is addressed in para. A-3.7. Other factors can affect the velocity profile at the location of relative flow measurement, and therefore the magnitude of the relative flow. This can include water level at the intake, trash-rack cleaning, operation of adjacent generating or pumping units and flow at a nearby spillway. To the extent practical these site conditions should be same for both tests. Use of two methods for relative flow measurement will help reduce uncertainty. The uncertainty in changes in relative flow measurement for two tests should be agreed to by the parties to the test.

NONMANDATORY APPENDIX B NET HEAD AND NPSH DETERMINATION IN SPECIAL CASES

B-1 PURPOSE

Calculation of net head (H_N) during a performance test requires measurement of pressure head (h) and calculation of total head (H) at the high and low pressure section of the machine. These sections are illustrated in Figures 2-3-1 to 2-3-3, and accurate measurement of h is typically made using pressure taps at the respective sections. Where it is not possible to measure h at the specified high or low pressure measurement sections due to absence of pressure taps at these locations, this Appendix provides guidelines for determining the total head at these locations.

While pressure taps could be added specifically for the performance test, such installation may not be technically or economically feasible.

Reliable calculation of turbine net head (H_N), is important for accurate determination of power output and efficiency. Reliable estimate of the total head at the low pressure section is also essential for calculation of NPSH.

B-2 APPLICATION

This Appendix is applicable to all reaction machines, regardless of head with no pressure taps installed in the high pressure section and/or low pressure section. The language of this Appendix is generally for a turbine; however, the same principles can be applied to a pump-turbine operating as a pump.

B-3 VARIABLES

The variables relative to the turbine net head, head loss, and NPSH determination, which are used in this Appendix, are defined in Table 2-3-1 and on Figures 2-3-1 through 2-3-3.

B-4 FLOW RATE, Q

Flow rate (Q) needs to be measured or calculated/estimated to determine a velocity head (h_v). The accuracy with which the flow rate is established, has a secondary effect on the accuracy of the net head determination. The significance of overstating or understating of flow rate is greater for low head machines because velocity head (h_{v2}) is generally a higher percentage of net head.

For example, with a net head of 25 m (82 ft) and velocity of v_2 = 2.3 m/s (7.5 ft/sec), the velocity head (h_{v2}) is equal to 0.27 m (0.88 ft) or 1.08% of net head. If the flow rate is overstated in this example by 5%, the velocity head (h_{v2}) increases to 0.30 m (0.98 ft) or 1.20% of net head, resulting in a 0.12-percentage point difference in net head and efficiency.

B-5 TOTAL HEAD OF HIGH PRESSURE SECTION, H_1

The common practice for total head (H_1) determination in most types of intakes (including multibay intakes) with pressure taps installed in the high pressure section, is to manifold the tubing from all of the taps and directly measure the average pressure head (h_1) in the manifold. The total head (H_1) is the sum of average potential head, pressure head, and velocity head:

$$H_1 = Z_1 + h_1 + h_{v1}$$

The velocity head (h_{v1}) is based on velocity (v_1), which is typically calculated from the total measured or estimated flow rate divided by the total area of high pressure section (A_1).

For tests of machines with multi-bay intakes where the flow rates (Q_X) are measured individually in each bay, pressure heads (h_{1X}) should be measured individually for each bay and the individual total heads (H_{1X}) calculated by adding the actual velocity heads (h_{v1X}) and the potential head (Z_1). The overall total head (H_1) will then be a weighted average calculated for the individual total heads (H_{1X}), using the respective individual flow rates (Q_X) as weighing factors.

For installations with no pressure taps in the high pressure section, pressure head in a bulkhead or intake gate slot could be measured using a suitable method (laser, bubbler system, float, etc.). The total head in such gate slot could be determined as the measured pressure head plus the calculated velocity head just downstream from the gate slot. This total head could then be assumed to be the total head (H_1) and the head loss (H_{L1}) calculated in accordance with the equation in Table 2-3-1. If the gate slot where the measurement is made is at a significant distance from the true high pressure section, then by agreement between parties to the test, a correction can be made for head losses between the gate slot and the high pressure section. The correction would typically be determined by analytical methods, and, if appropriate, additional uncertainty in net head be included in the uncertainty calculations for the test.

B-6 TOTAL HEAD OF LOW PRESSURE SECTION, H_2

With no pressure taps installed in the low pressure section, the total head (H_2) can be calculated as the water level in an "hydraulically isolated" draft tube gate slot plus the velocity head just downstream of the gate slot plus head loss between the low pressure section and the gate slot (similarly as discussed above for the high pressure section). For a draft tube gate slot to be "hydraulically isolated" from the tailrace, there must be a physical separation between the draft tube gate slot and the tailrace. When the draft tube gate slot is not "hydraulically isolated," the total head (H_2) is determined by measuring the TWL and adding the head loss (H_{L2}).

For most projects, the low pressure section is defined and is located upstream from the actual exit of the draft tube, or "Draft Tube Exit Section (e)" as defined in Figure B-6-1. Pressure taps, if used, would normally be installed in the low pressure section. If the low pressure section is not defined it could be assumed to be the draft tube exit section.

For convenience, the head loss (H_{L2}) is divided into two parts

(a) Head loss ($H_{L2\text{-}e}$) between low pressure section and the draft tube exit section

(b) Head loss (H_{Le}) between the draft tube exit section and the tailrace

In many cases the head loss ($H_{L2\text{-}e}$) will be insignificant and could be assumed equal to zero, as its magnitude is typically much less than the uncertainty of the total head determination. If the draft tube exit section is at a considerable distance from the defined low pressure section, or for any other reason, then by agreement between parties to the test, a calculation of head loss ($H_{L2\text{-}e}$) can be performed using analytical methods.

Determining the head loss (H_{Le}) between the draft tube exit section and the TWL is based on an assumption that high percentage of the draft tube exit velocity head is lost and the remainder is recovered. A limiting or simplified case would be a sudden, very large expansion at the draft tube exit, where the head loss would be essentially equal to the exit velocity head $v_e^2/2g$. However, a sudden very large expansion is usually not the case, and, some of the exit velocity energy may be recovered in the tailrace, resulting in lower pressure at the draft tube exit than would occur if no exit energy were recovered. The effect will be that the true static pressure at the draft tube exit will be lower than the measured TWL.

The percentage of energy recovered in the tailrace is site specific and can vary significantly. It can depend on the tailrace design and configuration, the type of the turbine, load on the turbine, draft tube design, the flow velocity profile in the draft tube and tailrace, the presence and load on the adjacent units, and the location where the TWL is measured. For projects with a favorable tailrace design/configuration, test data suggests recoveries can be up to 50%. A "recovery factor" R can be defined as the fraction of the exit velocity head (h_{ve}) that is recovered downstream of the draft tube exit section.

The head loss on low pressure side (H_{L2}) is then given by

$$H_{L2} = H_{L2-e} + (1 - R) \times v_e^2/2g$$

and total head H_2 = TWL + H_{L2} if the correction factor $[1 - (\rho_a/\rho)] = 1.0$ is assumed.

Velocity (v_e) is the flow rate divided by the cross-sectional area of the draft tube exit section (A_e).

Parties to the test need to take into consideration the above circumstances and agree upon the value of the recovery factor R and upon the location where the TWL will be measured. Experience has shown that where TWL is measured close to the end of the draft tube, the value of R may typically range from 0.0 to 0.4.

In the example in subsection B-4, the exit velocity head was h_{v2} = 0.27 m. If a recovery factor of 0.2 is used, the recovered velocity head is 0.2 × 0.27 = 0.054 m. Thus the pressure at the draft tube exit will be lower by 0.054 m of water. The relative increase in the net head would then be 0.054/25 = 0.0022, or 0.22%.

B-7 DETERMINATION OF NET HEAD, H_N

Synthesizing the equation presented in Table 2-3-1 with the above considerations, net head could be calculated according to the following equation:

$$H_N = (Z_1 + h_1 - \mathrm{TWL})[1 - (\rho_a/\rho)] + h_{v1} - H_{L2}$$

B-8 DETERMINATION OF NET POSITIVE SUCTION HEAD (NPSH)

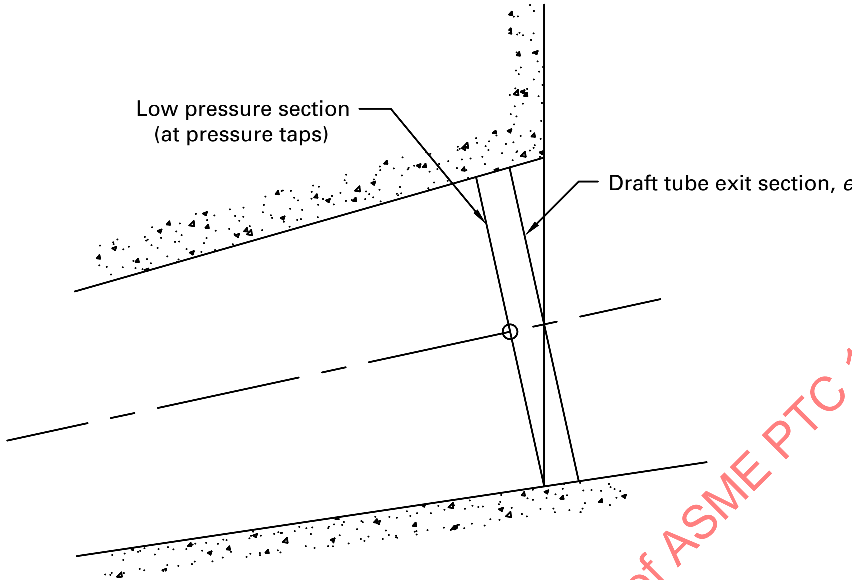
The velocity head recovery can also affect the calculated NPSH. Similarly to net head, the formula for NPSH could be written as follows:

$$\mathrm{NPSH} = h_{\mathrm{atm2}} + H_2 - h_{vp} - Z_c$$

As noted in Table 2-3-1, the parties to the test may also opt for using the traditional formula for NPSH as follows:

$$\mathrm{NPSH} = h_{\mathrm{atm}} - h_{vp} + \mathrm{TWL} - Z_c$$

Figure B-6.1 Low Pressure and Draft Tube Exit Sections



NONMANDATORY APPENDIX C ACOUSTIC SCINTILLATION METHOD OF DISCHARGE MEASUREMENT

C-1 GENERAL

The use of the acoustic scintillation method (ASM) is restricted to rectangular conduits flowing full with adequate turbulence present (usually produced by trash racks). ASM has been developed specifically for the short, rectangular converging intakes typically found in plants with heads of 35 m or less and without penstocks in which measurements with other methods can be made. However, the ASM may be used at higher head plants or for other flow measurement applications with rectangular intake sections. The configuration of the intake and the nature of the approach flow impose some limitations on the use of the ASM; these limitations are described in para. C-3.1. This method has yet to be accepted as a code method under the terms of para. 4-4.1. Its application is permissible by mutual agreement by parties to the test or in conjunction with a flow measurement code method under the terms of para. 4-4.1, in which case the latter method will prevail in comparison with the guarantees.

C-2 PRINCIPLES OF MEASUREMENT

The ASM utilizes the natural turbulence embedded in the flow, as shown in Figure C-2-1. In its simplest form, two transmitters are placed on one side of the measurement section, two receivers at the other. The signal transmissions are not continuous, but are sent as a series of individual pulses. The signal amplitude at the receivers varies randomly as the turbulence along the propagation paths changes with time and the flow. If the two paths are sufficiently close (Δx), the turbulence remains embedded in the flow, and the pattern of the amplitude variations at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay, Δt. This time delay corresponds to the peak in the time-lagged cross-correlation function calculated for Signal 1 and Signal 2. The mean velocity perpendicular to the acoustic paths is then $\Delta x/\Delta t$. Three transmitters and three receivers are needed at each measurement level for the average inclination of the velocity to be obtained. Both Δx and Δt are required for an accurate calculation of the horizontal component of the velocity.

For discharge measurements that meet the requirements of this Code, measurements are taken at a number of pre-selected measurement levels representing the total cross-sectional area. Unstable inflow velocities and/or divergent approach angles will likely exist in most intakes. Both the magnitude and the inclination of the flow velocity as measured by the ASM shall be therefore considered in the calculation of discharge. Each measurement level shall have three acoustic paths with accurately known spacing and the ability to measure the time-lagged cross-covariance from which the magnitude and angular inclination of the resultant velocity vector shall be calculated. The discharge for the measurement section (intake bay) shall be calculated by integrating the average horizontal component of the velocity measured at each level over the cross sectional area of the intake.

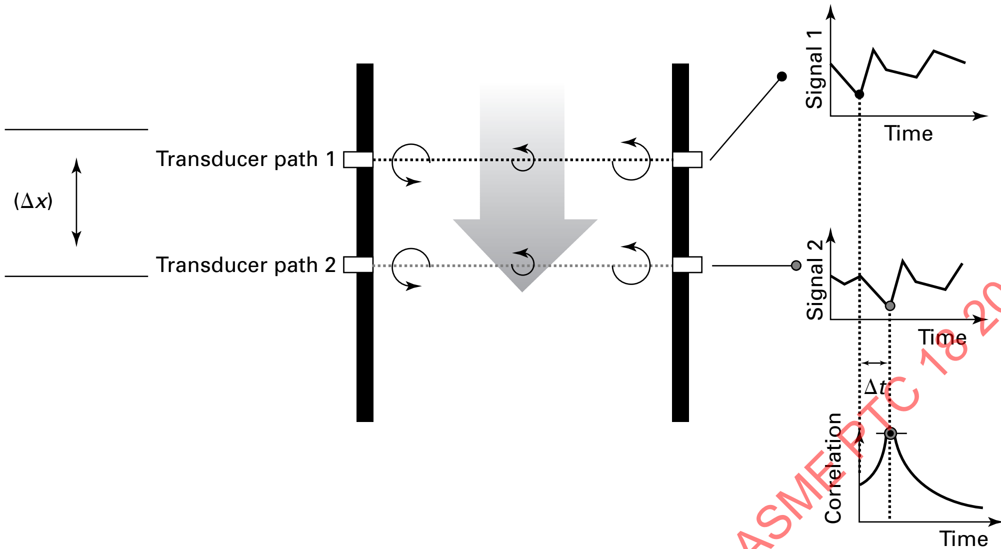
Where there is more than one intake bay, the discharge through each intake bay shall be measured by installing instrumentation in each bay. The discharge in all intake bays shall then be added to obtain total discharge, provided the flow condition remains constant and the entire data set for total discharge is obtained within a mutually agreed time period.

C-2.1 Measurement Levels

The individual measurement levels are selected to optimally sample the vertical structure of the flow in the measurement section. As a minimum, 10 measurement levels, uniformly spaced by not more than 1/10 of the intake height shall be used. Only for intakes with very low heights may the number of measurement levels be reduced below 10. In regions of the measurement section where large variations in velocity are expected closer spacing will be beneficial and additional measurement levels should be added. The integration algorithm used for computations shall not require regular spacing of the sampling levels.

Uncertainties are reduced when the number of measurement levels is increased from the required minimum of 10 up to 20 or even 30, depending on the measurement section structural configuration and the desired measurement accuracy. For all ASM

Figure C-2-1 Schematic Representation of ASM Operation



measurements the number of measurement levels shall be established by mutual agreement.

There are two basic approaches to installing the equipment and measuring the flow at each level: sensor paths are installed at fixed elevations (each measurement level) on a fixed frame spanning the full height of the measurement section (Figure C-2.1-1), or one or more sensor paths are mounted on a smaller profiling frame that is moved through a series of elevations to sample the full height of the measurement section (Figure C-2.1-2).

In general, profiling frames allow more flexibility in measurement level locations, but at the disadvantage of having cross-members in the flow. For both the fixed frame and profiling frame, the frame is typically installed in an existing slot. It is also possible to attach the transducers directly to the intake side walls, but that would normally only be done if a permanent installation is intended.

C-2.2 Sequence of Measurements

The ASM typically measures the flow velocity at one measurement level at a time. After sampling at the first measurement level is complete, the ASM computes the flow velocity for that level and then switches to the next measurement level. The process is repeated until all levels have been sampled. The typical sequence is from the floor to the roof and shall be mutually agreed between all parties to the test. It is possible to sample two measurement levels simultaneously provided that the levels are sufficiently separated to prevent interference. Once sampling is completed, the discharge shall be computed for the operating condition being measured. The preliminary results (discharges and the flow velocities and inclinations) shall be written to an electronic file, and the ASM equipment is ready for a new measurement.

As a statistical measurement, ASM requires a minimum sample size to produce a meaningful measurement. The sampling period for each run shall be of sufficient duration to average out large-scale turbulent fluctuations (a minimum of 30 s per run). At least three or four runs at each measurement level are recommended to permit calculation of an average discharge and standard deviation. Subsection 3-5 provides further details.

Profiling frames (Figure C-2.1-2) may be either stopped at each measurement level for the duration of the measurement or, if using very slow (not more than 5% of average flow velocity) and constant travel speed, may be swept continuously over the total vertical dimension of the measurement section. If a continuous sweep is used, the position of the frame as a function of time shall be recorded electronically.

C-2.3 Boundary Conditions

The measurement levels shall not be placed too close to boundaries, such as the roof and floor, because of interfering echoes. The limit of approach depends on the width of the measurement section. To ensure proper sampling near these boundaries, the uppermost and lowermost measurement levels shall be positioned at the distance D, given by the equation

$$D = (Wc\tau/2)^{1/2}$$

where

W = the width of the measurement section
c = the speed of sound
τ = the duration of the acoustic pulse

Figure C-2.1-1 ASM Typical Arrangement — Fixed Frame in a Three-Bay Application