

Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines

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British Standard

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Committees responsible for this British Standard

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- Association of Consulting Engineers
- Department of Trade and Industry (National Engineering Laboratory)
- Electricity Supply Industry in England and Wales
- Institution of Civil Engineers
- Institution of Electrical Engineers
- North of Scotland Hydro-electric Board
- Power Generation Association (BEAMA Ltd.)
- University of Southampton

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National foreword

This British Standard has been prepared under the direction of the Engineering Sector Board and is the English language version of EN 60041:1994, *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*, published by the European Committee for Electrotechnical Standardization (CENELEC). It was derived by CENELEC from IEC 41:1991 published by the International Electrotechnical Commission (IEC). Common modifications and editorial corrections are indicated by the presence of sidelines in the margins.

For graphical symbols, and letter symbols and signs approved by the IEC for general use, readers are referred to:

- IEC Publication 27: *Letter symbols to be used in electrical technology*
- IEC Publication 617: *Graphical symbols for diagrams*

The symbols and signs contained in the present publication have either been taken from IEC Publication 27 or 617, or have been specifically approved for the purpose of this publication.

For general terminology, readers are referred to IEC Publication 50: *International Electrotechnical Vocabulary* (IEV), which is issued in the form of separate chapters each dealing with a specific field, the General Index being published as a separate booklet. Full details of the IEV will be supplied on request¹⁾.

The terms and definitions contained in the present publication have been either taken from the IEV or specifically approved for the purpose of this publication.

Some Sections and Parts of BS 4727 are identical with or technically equivalent to IEC Publication 50. All Parts of BS 3939, except for Part 1, are identical with IEC Publication 617.

EN 60041 was produced as a result of international discussion in which the United Kingdom took an active part.

Cross-references

Publication referred to	Corresponding British Standard
	BS 4999 <i>General requirements for rotating electrical machines</i>
IEC 34-2A:1974	Part 102:1987 <i>Methods for determining losses and efficiency from tests (excluding machines for traction vehicles)</i>
IEC 185:1987	BS 7626:1993 <i>Specification for current transformers</i>
IEC 186:1987	BS 7625:1993 <i>Specification for voltage transformers</i>
IEC 545:1976	BS 5671:1979 <i>Guide for commissioning, operation and maintenance of hydraulic turbines</i>
	BS 3680 <i>Measurement of liquid flow in open channels</i>
	Part 3: <i>Stream flow measurement</i>
ISO 748:1979	Part 3A:1980 <i>Velocity-area methods</i>
	Part 4 <i>Weirs and flumes</i>
ISO 1438-1:1980	<i>Weirs and flumes</i>
	Part 4A:1981 <i>Method using thin-plate weirs</i>
	Part 8 <i>Measuring instruments and equipment</i>
ISO 2537:1988	Part 8A:1989 <i>Current meters incorporating a rotating element</i>
	BS 5857 <i>Methods for measurement of fluid flow in closed conduits, using tracers</i>
	Part 1 <i>Measurement of water flow</i>
ISO 2975-1:1974	Section 1.1:1980 <i>General</i>

¹⁾ Available from Sales Department, BSI, 389 Chiswick High Road, London W4 4AL.

Publication referred to	Corresponding British Standard
ISO 2975-2:1975	Section 1.2:1980 <i>Constant rate injection method using non-radioactive tracers</i>
ISO 2975-3:1976	Section 1.3:1980 <i>Constant rate injection method using radioactive tracers</i>
ISO 2975-6:1977	Section 1.4:1980 <i>Transit time method using non-radioactive tracers</i>
ISO 2975-7:1977	Section 1.5:1980 <i>Transit time method using radioactive tracers</i>
	BS 1042 <i>Measurement of fluid flow in closed conduits</i> Part 2 <i>Velocity area methods</i>
ISO 3354:1988	Section 2.4:1989 <i>Method of measurement of clean water flow using current meters in full conduits and under regular flow conditions</i>
	BS 3680 <i>Measurement of liquid flow in open channels</i> Part 8 <i>Measuring instruments and equipment</i>
ISO 3455:1976	Part 8C:1980 <i>Calibration of rotating-element current-meters in straight open tanks</i>
	BS 1042 <i>Measurement of fluid flow in closed conduits</i> Part 2 <i>Velocity area methods</i>
ISO 3966:1977	Section 2.1:1983 <i>Method using Pitot static tubes</i>
ISO 5168:1978	BS 5844:1980 <i>Methods of measurement of fluid flow: estimation of uncertainty of a flow-rate measurement</i>
	BS 7118 <i>Measurement of fluid flow: assessment of uncertainty in the calibration and use of flow measurement devices</i>
ISO 7066-1:1989	Part 1:1990 <i>Linear calibration relationships</i>
ISO 7066-2:1988	Part 2:1989 <i>Non-linear calibration relationships</i>

Additional information

The following ISO standards referred to in the text were earlier editions which have now been superseded by later editions. Where available the identical British Standard is cross-referenced.

ISO publication	Corresponding British Standard
ISO 31-3:1978	BS 5775 <i>Specification for quantities, units and symbols</i>
Superseded by ISO 31-3:1992	Part 3:1993 <i>Mechanics</i>
	BS 1042 <i>Measurement of fluid flow in closed conduits</i> Part 1: <i>Pressure differential devices</i>
ISO 5167:1980	Section 1.1:1992 <i>Specification for square-edged orifice plates, nozzles and Venturi tubes inserted in circular cross-section</i>
Superseded by ISO 5167-1:1991	<i>conduits running full</i>

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Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, the EN title page, pages 2 to 186, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

ICS 23.080:23.100.10

Descriptors: Turbine, hydraulic turbomachine, pump, pump-turbine, acceptance test, field test, hydraulic characteristics, measurement, test conditions, calculation

English version

Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines

(IEC 41:1991, modified)

Essais de réception sur place des turbines hydrauliques, pompes d'accumulation et pompes-turbines, en vue de la détermination de leurs performances hydrauliques
(CEI 41:1991, modifiée)

Abnahmeversuche zur Bestimmung der hydraulischen Eigenschaften von Wasserturbinen, Speicherpumpen und Pumpturbinen
(IEC 41:1991, modifiziert)

This European Standard was approved by CENELEC on 1994-03-08. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the Central Secretariat has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.

CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

Central Secretariat: rue de Stassart 35, B-1050 Brussels

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Foreword

The CENELEC questionnaire procedure, performed for finding out whether or not the International Standard IEC 41:1991 could be accepted without textual changes, has shown that one common modification was necessary for acceptance as a European Standard.

The reference document together with the common modifications prepared by the French National Committee was submitted to the CENELEC members for formal vote and was approved by CENELEC as EN 60041 on 1994-03-08.

The following dates were fixed:

- latest date of publication of an identical national standard (dop) 1995-03-15
- latest date of withdrawal of conflicting national standards (dow) 1995-03-15

Annexes designated “normative” are part of the body of the standard. In this standard, Annex ZA is normative.

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Section 1. General rules

1 Scope and object

1.1 Scope

1.1.1 This International Standard covers the arrangements for tests at the site to determine the extent to which the main contract guarantees (see **3.2**) have been satisfied. It contains the rules governing their conduct and prescribes measures to be taken if any phase of the tests is disputed. It deals with methods of computation of the results as well as the extent, content and style of the final report.

1.1.2 Model tests, when used for acceptance purposes, are dealt within IEC 193 with Amendment No. 1, first supplement 193 A, and in IEC 497.

1.1.3 Tests of speed governing systems are dealt with in IEC 308.

1.2 Object

The purpose of this standard for field acceptance tests of hydraulic turbines, storage pumps or pump-turbines, also called the machine, is:

- to define the terms and quantities which are used;
- to specify methods of testing and ways of measuring the quantities involved in order to ascertain the hydraulic performance of the machine;
- to determine if the contract guarantees which fall within the scope of this standard have been fulfilled.

The decision to perform field acceptance tests including the definition of their scope is the subject of an agreement between the purchaser and the supplier of the machine. For this, it has to be examined in each case, whether the measuring conditions recommended in this standard can be realized. The influence on the measuring uncertainties, due to hydraulic and civil conditions has to be taken into account.

If the actual conditions for field acceptance tests do not allow compliance with the guarantees to be proved, it is recommended that acceptance tests be performed on models (see **1.1.2**).

1.3 Types of machines

In general, this standard applies to any size and type of impulse or reaction turbine, storage pump or pump-turbine. In particular, it applies to machines coupled to electric generators, motors or motor-generators.

This standard applies to machines with unit power greater than 5 MW or with reference diameter greater than 3 m. Although the complex and detailed procedure involved is not generally justified for machines with smaller power and size, nevertheless this standard may be used for such machines by agreement between purchaser and supplier.

For the purpose of this standard the term turbine includes a pump-turbine functioning as a turbine and the term pump includes a pump-turbine functioning as a pump. The term generator includes a motor-generator functioning as a generator and the term motor includes a motor-generator functioning as a motor.

1.4 Reference to IEC and ISO Standards

IEC and ISO Standards referred to in this standard are listed in Annex ZA. If a contradiction is found between this standard and another IEC or ISO standard, this standard shall prevail.

1.5 Excluded topics

1.5.1 This standard excludes all matters of a purely commercial interest except those inextricably bound up with the conduct of the tests.

1.5.2 This standard is concerned neither with the structural details of the machines nor with the mechanical properties of their components.

2 Terms, definitions, symbols and units

2.1 General

The common terms, definitions, symbols and units used throughout the standard are listed in this clause. Specialised terms are explained where they appear.

The following terms are given in 5.1.2 and Figure 11:

- 1) A *run* comprises the readings and/or recordings sufficient to calculate the performance of the machine at one operating condition.
- 2) A *point* is established by one or more consecutive runs at the same operating conditions and unchanged settings.
- 3) A *test* comprises a collection of data and results adequate to establish the performance of the machine over the specified range of operating conditions.

The clarification of any contested term, definition or unit of measure shall be agreed to in writing by the contracting parties, in advance of the test.

2.2 Units

The International System of Units (SI) has been used throughout this standard²⁾.

All terms are given in SI base units or derived coherent units (e.g. N instead of $\text{kg} \cdot \text{m} \cdot \text{s}^{-2}$). The basic equations are valid using these units. This has to be taken into account, if other than coherent SI Units are used for certain data (e.g. kilowatt or megawatt instead of watt for power, kilopascal or bar ($= 10^5 \text{ Pa}$) instead of pascal for pressure, min^{-1} instead of s^{-1} for rotational speed, etc.). Temperatures may be given in degrees Celsius because thermodynamic (absolute) temperatures (in kelvins) are rarely required.

Any other system of units may be used but only if agreed to in writing by the contracting parties.

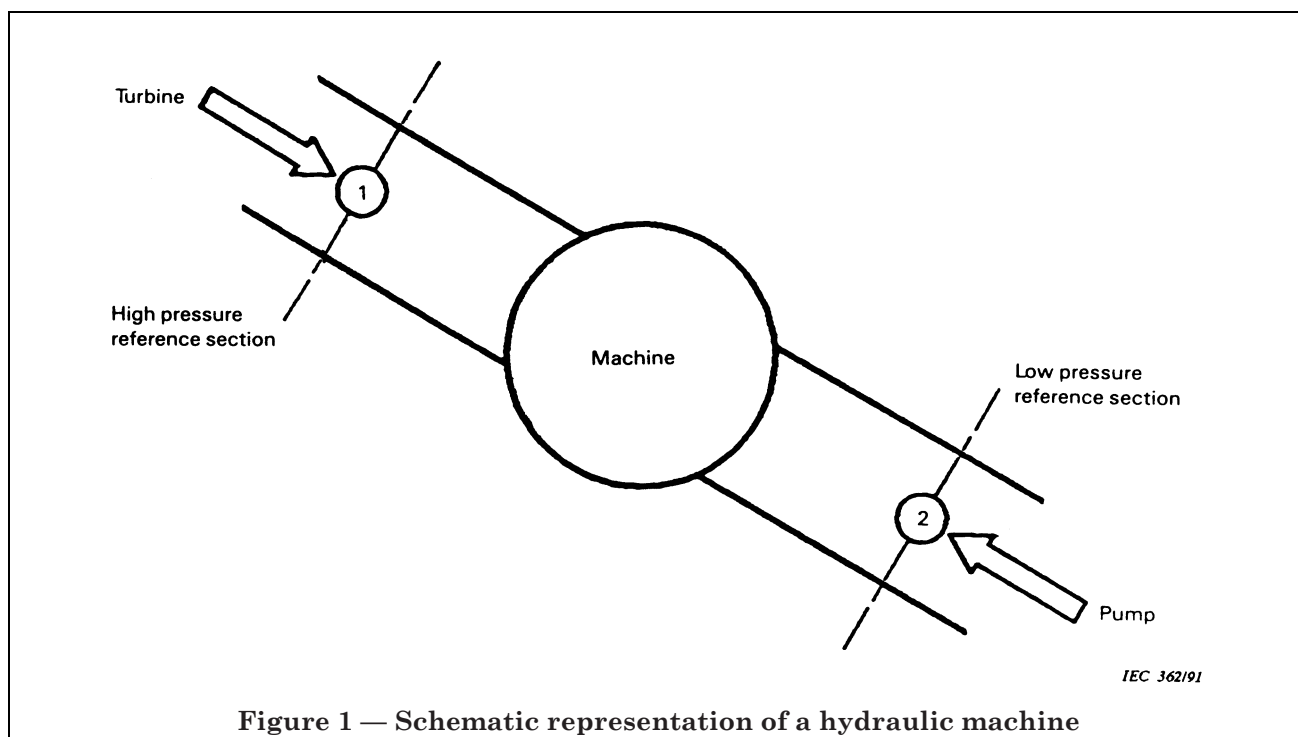
2.3 List of terms, definitions, symbols and units

2.3.1 Subscripts and symbols

The terms high pressure and low pressure define the two sides of the machine irrespective of the flow direction and therefore are independent of the mode of operation of the machine.

Sub-clause	Term	Definition	Subscript symbol
2.3.1.1	High pressure reference section	The high pressure section of the machine to which the performance guarantees (see Figure 1)	1
2.3.1.2	Low pressure reference section	The low pressure section of the machine to which the performance guarantees refer (see Figure 1)	2
2.3.1.3	High pressure measuring sections	Whenever possible these sections should coincide with section 1: otherwise the measured values shall be adjusted to section 1 (see 11.2.1)	1', 1'', ...
2.3.1.4	Low pressure measuring sections	Whenever possible these sections should coincide with section 2: otherwise the measured values shall be adjusted to section 2 (see 11.2.1)	2', 2'', ...
2.3.1.5	Specified	Subscript denoting values of quantities such as speed, discharge etc. for which other quantities are guaranteed	sp
2.3.1.6	Maximum Minimum	Subscripts denoting maximum or minimum values of any term	max min
2.3.1.7	Limits	Contractually defined values: — not to be exceeded — to be reached	 ○ or 
2.3.1.8	Ambient	Subscript referring to surrounding atmospheric conditions	amb

²⁾ See ISO 31-3.



2.3.2 Geometric terms

Sub-clause	Term	Definition	Symbol	Unit
2.3.2.1	Area	Net cross sectional area normal to general flow direction	A	m ²
2.3.2.2	Guide vane opening	Average vane angle measured from closed position ^a or average shortest distance between adjacent guide vanes (at a defined position, if necessary) (see Figure 2)	α a	degree m
2.3.2.3	Needle opening (impulse turbine)	Average needle stroke measured from closed position ^a	s	m
2.3.2.4	Runner blade opening	Average runner blade angle measured from a given position ^a	β	degree
2.3.2.5	Level	Elevation of a point in the system above the reference datum (usually mean sea level)	z	m
2.3.2.6	Difference of levels	Difference of elevation between any two points in the system	Z	m

^a Under normal working oil pressure.

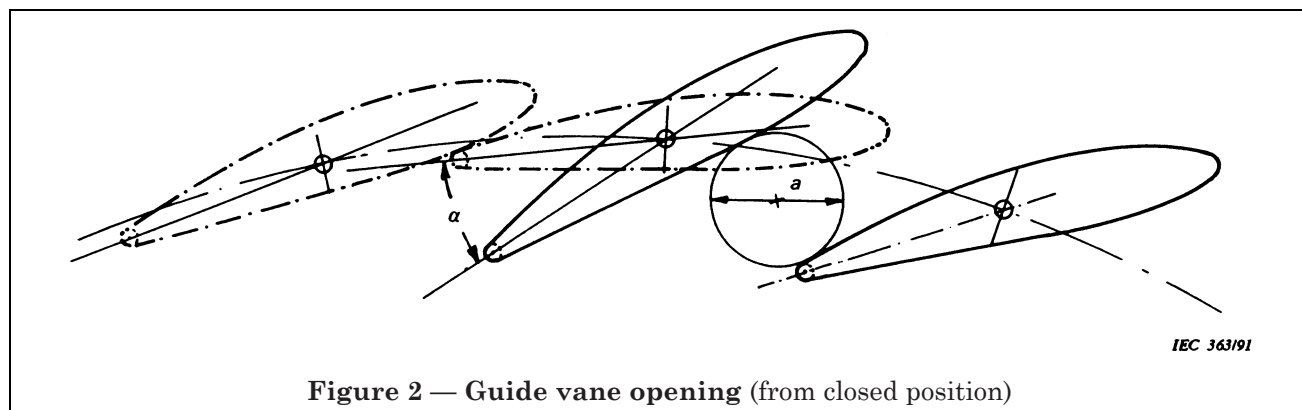


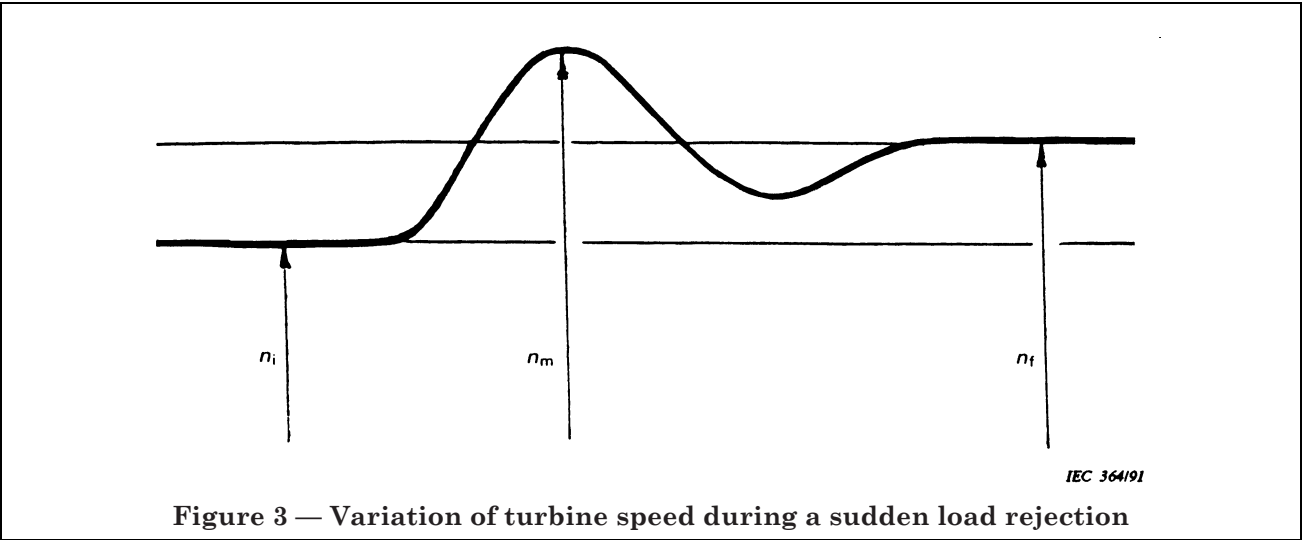
Figure 2 — Guide vane opening (from closed position)

2.3.3 Physical quantities and properties

Sub-clause	Term	Definition	Symbol	Unit
2.3.3.1	Acceleration due to gravity	Local value of g as a function of altitude and latitude of the place of testing (see Appendix E, Table EI)	g	$\text{m} \cdot \text{s}^{-2}$
2.3.3.2	Temperature	Thermodynamic temperature; Celsius temperature $\vartheta = \ominus - 273,15$	$\ominus$ ϑ	K $^{\circ}\text{C}$
2.3.3.3	Density	Mass per unit volume a) Values for water are given in Appendix E, Table EII (ρ is commonly used instead of ρ_w) b) Values for air are given in Appendix E, Table EIII. Usually the value of air density at the reference level of the machine (see 2.3.7.10) is used c) Values for mercury are given in Appendix E, Table EIV	ρ ρ_w ρ_a ρ_{Hg}	$\text{kg} \cdot \text{m}^{-3}$ $\text{kg} \cdot \text{m}^{-3}$ $\text{kg} \cdot \text{m}^{-3}$ $\text{kg} \cdot \text{m}^{-3}$
2.3.3.4	Specific volume	Volume per unit mass. Used only for water in this standard	$1/\rho$	$\text{m}^3 \cdot \text{kg}^{-1}$
2.3.3.5	Isothermal factor	Factor characterizing a thermodynamic property. Values for water are given in Appendix E, Table EV	α	$\text{m}^3 \cdot \text{kg}^{-1}$
2.3.3.6	Specific heat capacity	The rate of change of enthalpy per unit mass with change in temperature at constant pressure. Values for water are given in Appendix E, Table EVI	c_p	$\text{J} \cdot \text{kg}^{-1} \cdot ^{\circ}\text{C}^{-1}$ or $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$
2.3.3.7	Vapour pressure (absolute)	For purposes of this standard the absolute partial pressure of the vapour in the gas mixture over the liquid surface is the saturation vapour pressure corresponding to the temperature. Values for distilled water are given in Appendix E, Table EVII	p_{va}	Pa
2.3.3.8	Dynamic viscosity	A quantity characterising the mechanical behaviour of a fluid (see ISO 31-3)	μ	$\text{Pa} \cdot \text{s}$
2.3.3.9	Kinematic viscosity	Ratio of the dynamic viscosity to the density: $\nu = \frac{\mu}{\rho}$	ν	$\text{m}^2 \cdot \text{s}^{-1}$

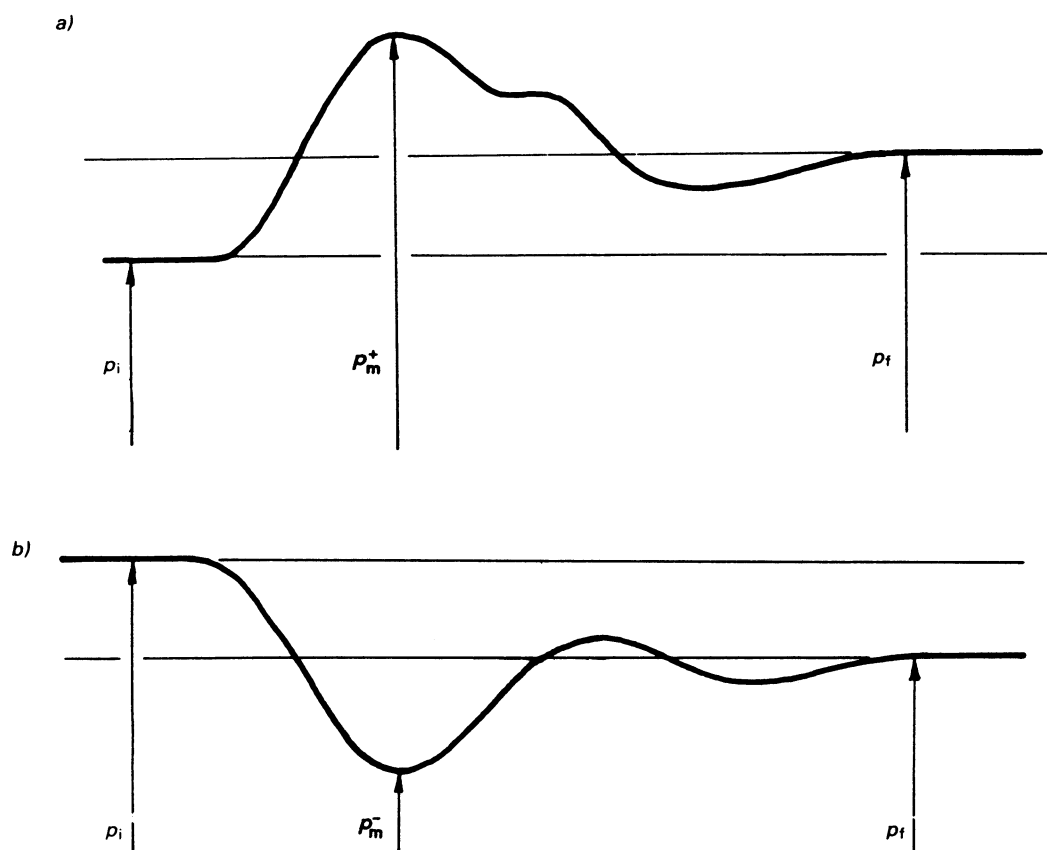
2.3.4 Discharge, velocity and speed terms

Sub-clause	Term	Definition	Symbol	Unit
2.3.4.1	Discharge (volume flow rate)	Volume of water per unit time flowing through any section in the system	Q	$\text{m}^3 \cdot \text{s}^{-1}$
2.3.4.2	Mass flow rate	Mass of water flowing through any section of the system per unit time. Both ρ and Q must be determined at the same section and at the conditions existing in that section NOTE The mass flow rate is constant between two sections if no water is added or removed.	(ρQ)	$\text{kg} \cdot \text{s}^{-1}$
2.3.4.3	Measured discharge	Volume of water per unit time flowing through any measuring section, for example 1' (see 2.3.1.3 and 2.3.1.4)	Q_1 or Q_2	$\text{m}^3 \cdot \text{s}^{-1}$
2.3.4.4	Discharge at reference section	Volume of water per unit time flowing through the reference section 1 or 2	Q_1 or Q_2	$\text{m}^3 \cdot \text{s}^{-1}$
2.3.4.5	Corrected discharge at reference section	Volume of water per unit time flowing through a reference section referred to the ambient pressure (see 2.3.5.2) e.g. $Q_{1c} = (\rho Q)_1 / \rho_{p_{\text{amb}}}$ (see 3.2.3) where $\rho_{p_{\text{amb}}}$ is the density at ambient pressure and the water temperature at the reference section	Q_{1c} or Q_{2c}	$\text{m}^3 \cdot \text{s}^{-1}$
2.3.4.6	No-load turbine discharge	Turbine discharge at no-load, at specified speed and specified specific hydraulic energy and generator not excited	Q_0	$\text{m}^3 \cdot \text{s}^{-1}$
2.3.4.7	Index discharge	Discharge given by relative (uncalibrated) flow measurement (see Clause 15)	Q_i	$\text{m}^3 \cdot \text{s}^{-1}$
2.3.4.8	Mean velocity	Discharge divided by the area A	v	$\text{m} \cdot \text{s}^{-1}$
2.3.4.9	Rotational speed	Number of revolutions per unit time	n	s^{-1}
2.3.4.10	No load turbine speed	The steady state turbine speed at no load with governor connected and generator not excited	n_0	s^{-1}
2.3.4.11	Initial speed	The steady state turbine speed just before a change in operating conditions is initiated (see Figure 3)	n_i	s^{-1}
2.3.4.12	Final speed	The steady state turbine speed after all transient waves have been dissipated (see Figure 3)	n_f	s^{-1}
2.3.4.13	Momentary overspeed of a turbine	The highest speed attained during a sudden specified load rejection from a specified governor setting (see Figure 3)	n_m	s^{-1}
2.3.4.14	Maximum momentary overspeed of a turbine	The momentary overspeed attained under the most unfavourable transient conditions (in some cases the maximum momentary overspeed can exceed the maximum steady state runaway speed)	$n_{m \text{ max}}$	s^{-1}
2.3.4.15	Maximum steady state runaway speed	The speed for that position of needles or guide vanes and/or runner/impeller blades which gives the highest value after all transient waves have been dissipated with electrical machine disconnected from load or network and not excited, under the maximum specific hydraulic energy (head). The runaway speed particularly of high specific speed machines may be influenced by cavitation and thus depends on the available NPSE (see 2.3.6.9)	$n_{R \text{ max}}$	s^{-1}



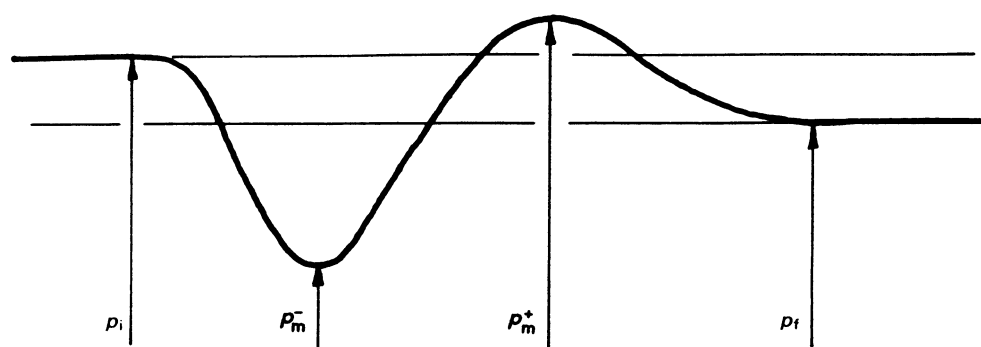
2.3.5 Pressure terms

Sub-Clause	Term	Definition	Symbol	Unit
2.3.5.1	Absolute pressure	The static pressure of a fluid measurement with reference to a perfect vacuum	p_{abs}	Pa
2.3.5.2	Ambient pressure	The absolute pressure of the ambient air	p_{amb}	Pa
2.3.5.3	Gauge pressure	The difference between the absolute pressure of a fluid and the ambient pressure at the place and time of measurement: $p = p_{abs} - p_{amb}$	p	Pa
2.3.5.4	Initial pressure	The steady state gauge pressure which occurs at a specified point of the system just before a change in operating conditions is initiated (see Figure 4)	p_i	Pa
2.3.5.5	Final pressure	The steady state gauge pressure which occurs at a specified point of the system after all transient waves have been dissipated (see Figure 4)	p_f	Pa
2.3.5.6	Momentary pressure	The highest/lowest gauge pressure which occurs at a specified point of the system under specified transient conditions (see Figure 4)	p_m^+ p_m^-	Pa Pa
2.3.5.7	Maximum/minimum momentary pressure	The momentary pressure under the most unfavourable transient conditions	$p_m^+ max$ $p_m^- min$	Pa Pa



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Figure 4a — Variation of pressure at the turbine high pressure reference section
 a) when a specified load is suddenly rejected
 b) when a specified load is suddenly accepted



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Figure 4b — Variation of pressure at the pump high pressure reference section during a power failure

2.3.6 Specific energy terms

In the International System of Units the mass (kg) is one of the base quantities. The energy per unit mass, known as specific energy, is used in this standard as a primary term instead of the energy per local unit weight which is called head and was exclusively used in the former IEC 41 and 198.

The latter term (head) has the disadvantage that the weight depends on the acceleration due to gravity g , which changes mainly with latitude but also with altitude. Nevertheless, the term head will still remain in use because it is very common. Therefore both related energy terms are listed, the specific energy terms in this sub-clause and the head terms in 2.3.7. They differ only by the factor g , which is the local value of acceleration due to gravity.

The symbol for specific energy at any section of flow is the small letter e ; the symbol for the difference of specific energies between any two sections is the capital letter E . The same applies to h and H .

Sub-clause	Term	Definition	Symbol	Unit
2.3.6.1	Specific energy	The energy per unit mass of water at any section	e	$\text{J} \cdot \text{kg}^{-1}$
2.3.6.2	Specific hydraulic energy of machine	Specific energy of water available between the high and low pressure reference sections of the machine, taking into account the influence of the compressibility $E = \frac{p_{\text{abs1}} - p_{\text{abs2}}}{\bar{\rho}} + \frac{v_1^2 - v_2^2}{2} + \bar{g}(z_1 - z_2)$ with $\bar{\rho} = \frac{\rho_1 + \rho_2}{2}$ and $\bar{g} = \frac{g_1 + g_2}{2}$ a,b NOTE The value of gravity acceleration at the reference level of the machine (see 2.3.7.10) may be assumed as g. The values of ρ_1 and ρ_2 can be calculated from p_{abs1} and p_{abs2} respectively, taking into account v_1 or v_2 for both values, given the negligible influence of the difference of the temperature on ρ	E	$\text{J} \cdot \text{kg}^{-1}$ $(\text{m}^2 \cdot \text{s}^{-2})$ $\text{J} \cdot \text{kg}^{-1}$
2.3.6.3	Specific mechanical energy at runner(s)/impeller(s)	Mechanical power transmitted through the coupling of the runner(s)/impeller(s) and shaft (see Clause 14) divided by mass flow rate: $E_m = \frac{P_m}{(\rho Q)_1} \text{ (for } P_m, \text{ see 2.3.8.4)}$	E_m	$\text{J} \cdot \text{kg}^{-1}$
2.3.6.4	Specific hydraulic energy of the plant	Specific hydraulic energy available between head water level and tailwater level of the plant (see Figure 6) It is given by: $E_g = \frac{p_{\text{abs3}} - p_{\text{abs4}}}{\bar{\rho}} + \frac{v_3^2 - v_4^2}{2} + \bar{g}(z_3 - z_4)$ with $\bar{\rho} = \frac{\rho_3 + \rho_4}{2}$ and $\bar{g} = \frac{g_3 + g_4}{2}$ The water density at ambient pressure may be assumed as $\bar{\rho}$	E_g	$\text{J} \cdot \text{kg}^{-1}$

^a Figure 5a, Figure 5b (reaction machines) and Figure 5c (impulse turbines) illustrate some common cases of application of the basic formula for the specific hydraulic energy. The applicable simplified formula is given under each figure. Measurement methods for the evaluation of the specific hydraulic energy of the machine are described in detail in Clause 11.

^b See Appendix F.

Sub-clause	Term	Definition	Symbol	Unit
2.3.6.5	Zero-discharge (shut-off) specific hydraulic energy of the pump	Pump specific energy at specified speed and specified guide vane and runner/impeller blade settings with high pressure side shut-off	E_0	$\text{J} \cdot \text{kg}^{-1}$
2.3.6.6	Specific hydraulic energy loss	The specific hydraulic energy dissipated between any two sections	E_L	$\text{J} \cdot \text{kg}^{-1}$
2.3.6.7	Suction specific hydraulic energy loss	The specific hydraulic energy dissipated between the tailwater level and the low pressure reference section of the machine (see Figure 41)	E_{Ls}	$\text{J} \cdot \text{kg}^{-1}$
2.3.6.8	Suction specific potential energy of the machine	Specific potential energy corresponding to the difference between the reference level of the machine (see 2.3.7.10) and the piezometric level at section 2: $E_s = g_2(z_r - z_2') = g_2 Z_s$ (see Figure 7)	E_s	$\text{J} \cdot \text{kg}^{-1}$
2.3.6.9	Net positive suction specific energy	Absolute specific energy at section 2 minus the specific energy due to vapour pressure p_{va} ^a , referred to the reference level of the machine according to Figure 7 $NPSE = \frac{p_{abs2} - p_{va}}{\rho_2} + \frac{v_2^2}{2} - g_2(z_r - z_2)$ ^b	$NPSE$	$\text{J} \cdot \text{kg}^{-1}$

^a See 2.3.3.7 and Appendix E, Table EVII.

^b For definition of cavitation factor σ , see IEC 193A and 497.

2.3.7 Height and head terms

Sub-clause	Term	Definition	Symbol	Unit
2.3.7.1	Geodetic height of plant ^a	Difference in elevation between headwater level and tailwater level of plant (see Figure 6)	Z_g	m
2.3.7.2	Head	Energy per unit weight of water at any section $h = e/g$	h	m
2.3.7.3	Turbine or pump head	For definition of e , see 2.3.6.1 $H = E/\bar{g}$ For definition of E , see 2.3.6.2	H	m
2.3.7.4	Plant head ^a	$H_g = E_g/\bar{g}$ For definition of E_g , see 2.3.6.4	H_g	m
2.3.7.5	Zero-discharge (shut-off) head of pump	$H_0 = E_0/\bar{g}$ For definition of E_0 , see 2.3.6.5	H_0	m
2.3.7.6	Head loss	$H_L = E_L/\bar{g}$ For definition of E_L , see 2.3.6.6	H_L	m
2.3.7.7	Suction head loss	$H_{Ls} = \frac{E_{Ls}}{\bar{g}}$ For definition of E_{Ls} , see 2.3.6.7	H_{Ls}	m
2.3.7.8	Suction height	$Z_s = \frac{E_s}{g_2}$ (see Figure 7) For definition of E_s , see 2.3.6.8	Z_s	m
2.3.7.9	Net positive suction head	$NPSH = \frac{NPSE}{g_2}$ For definition of $NPSE$, see 2.3.6.9	$NPSH$	m
2.3.7.10	Reference level of the machine	Elevation of the point of the machine taken as reference for the setting of the machine as defined in Figure 8	z_r	m

^a Figure 6 shows the relationship between geodetic height of plant and plant head.

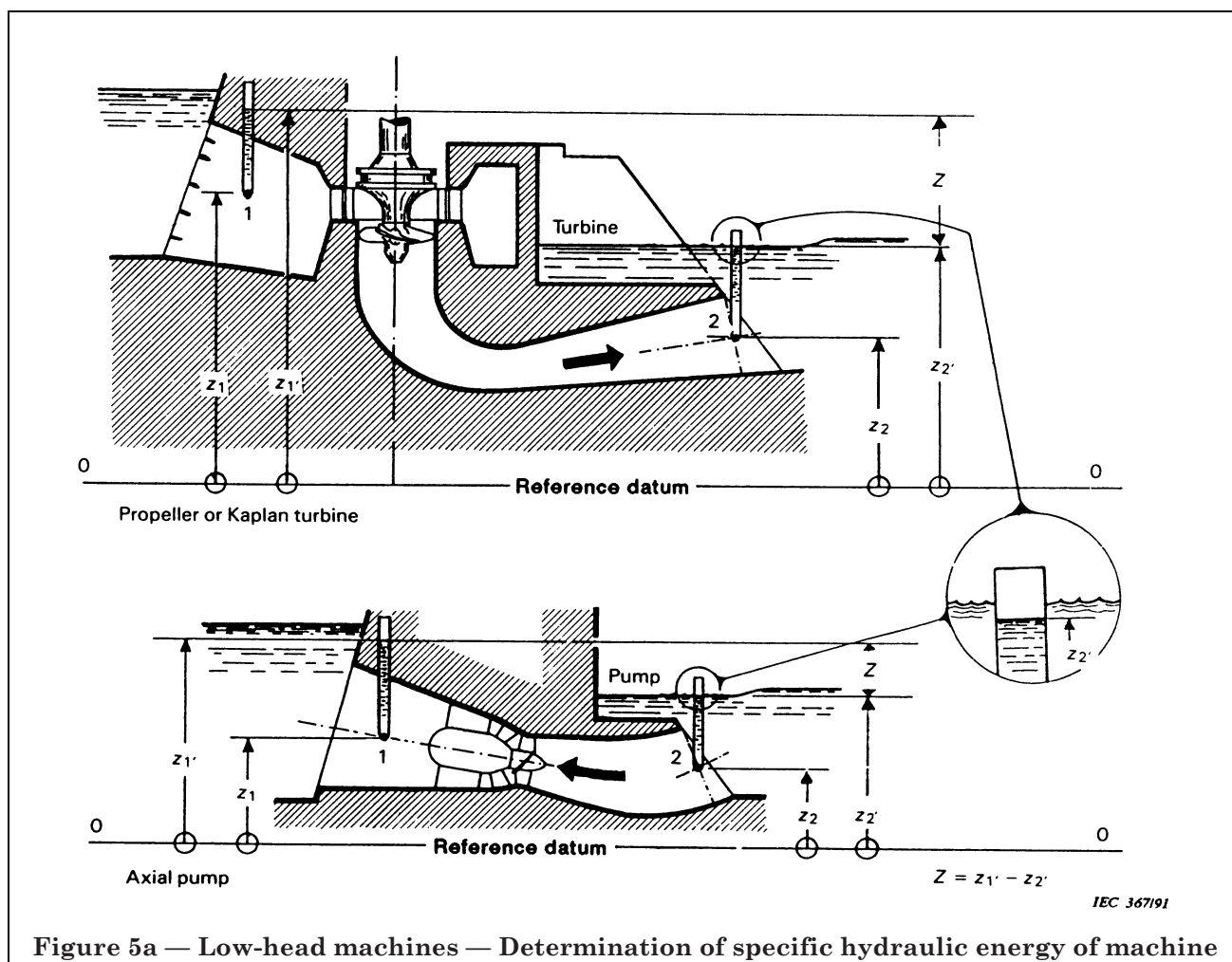


Figure 5a — Low-head machines — Determination of specific hydraulic energy of machine

Water column manometers are applied at point 1 and 2.

$$E = \bar{g}H = \frac{(p_{\text{abs}1} - p_{\text{abs}2})}{\bar{\rho}} + \frac{(v_1^2 - v_2^2)}{2} + \bar{g}(z_1 - z_2)$$

The compressibility of water is neglected because the difference of pressure between 1 and 2 is small therefore:

$$\rho_1 = \rho_2 = \bar{\rho}$$

Hence:

$$p_{\text{abs}1} = \bar{\rho} \cdot \bar{g}(z_{1'} - z_1) + p_{\text{amb}1'}$$

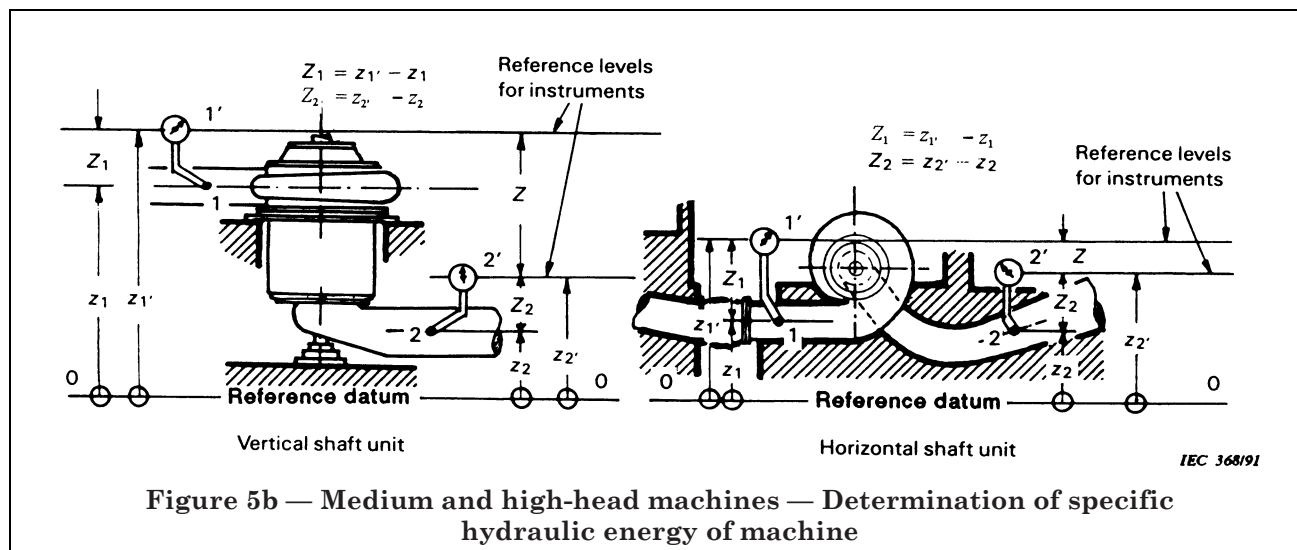
$$p_{\text{abs}2} = \bar{\rho} \cdot \bar{g}(z_{2'} - z_2) + p_{\text{amb}2'}$$

$$p_{\text{amb}1'} - p_{\text{amb}2'} = -\rho_a \cdot \bar{g}(z_{1'} - z_{2'})$$

and therefore the simplified formula is:

$$E = \bar{g} \cdot (z_{1'} - z_{2'}) \cdot \left(1 - \frac{\rho_a}{\bar{\rho}}\right) + \frac{(v_1^2 - v_2^2)}{2} = \bar{g} \cdot Z \left(1 - \frac{\rho_a}{\bar{\rho}}\right) + \frac{(v_1^2 - v_2^2)}{2}$$

The water density at ambient pressure may be assumed as $\bar{\rho}$.



Pressure gauges manometers are applied at points 1 and 2.

$$E = \bar{g}H = \frac{(p_{\text{abs}1} - p_{\text{abs}2})}{\bar{\rho}} + \frac{(v_1^2 - v_2^2)}{2} + \bar{g}(z_1 - z_2)$$

The difference in ambient pressure between 1' and 2' is neglected because Z is small compared to H , therefore:

$$p_{\text{amb}1'} = p_{\text{amb}2'} = p_{\text{amb}}$$

Since both Z_1 and Z_2 are small compared to H , it may be assumed that:

$$Z_1 \cdot \frac{\rho_1}{\bar{\rho}} = Z_1 \quad \text{and} \quad Z_2 \cdot \frac{\rho_2}{\bar{\rho}} = Z_2$$

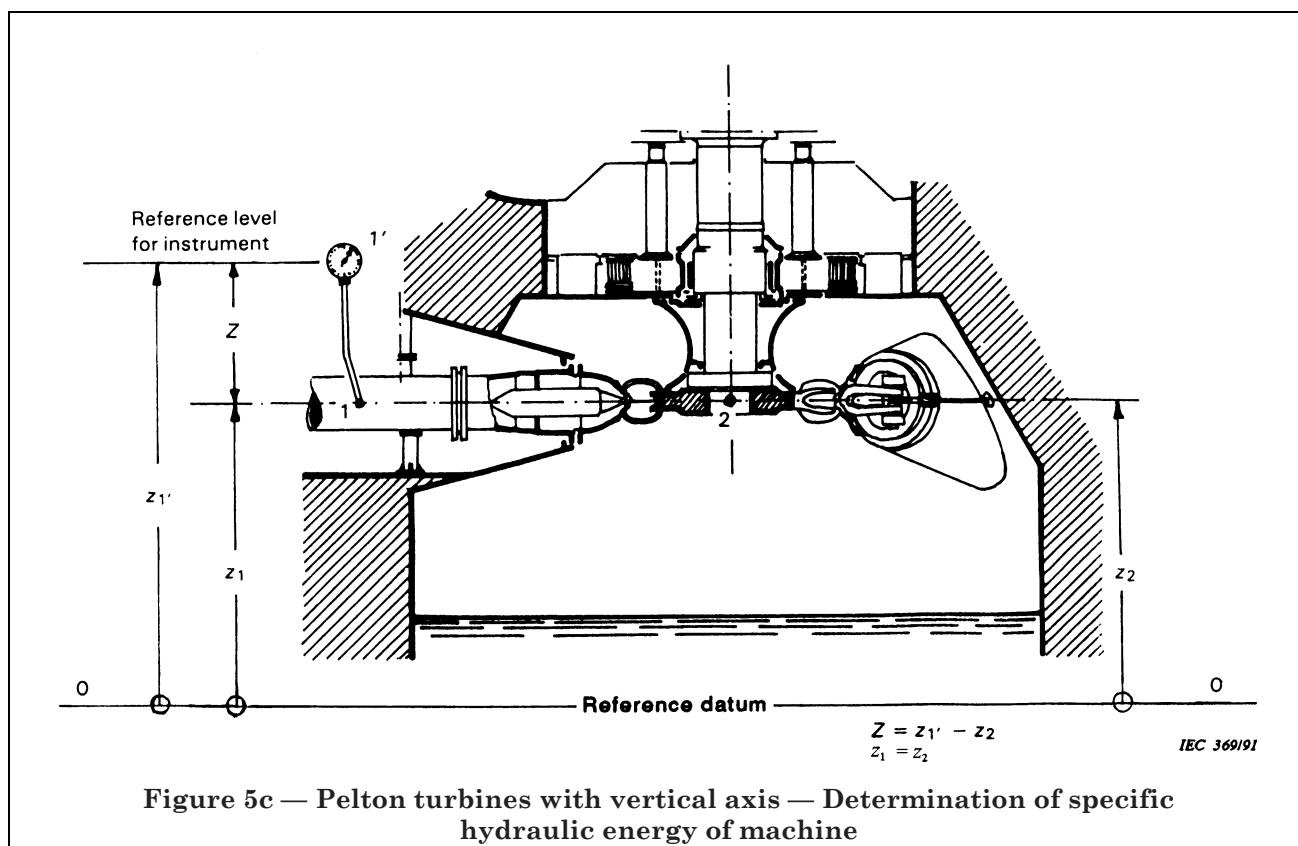
hence:

$$p_{\text{abs}1} = p_1' + Z_1 \cdot \rho_1 \cdot \bar{g} + p_{\text{amb}} \quad \text{where } p_1' \text{ is the gauge pressure measured at } 1'$$

$$p_{\text{abs}2} = p_2' + Z_2 \cdot \rho_2 \cdot \bar{g} + p_{\text{amb}} \quad \text{where } p_2' \text{ is the gauge pressure measured at } 2'$$

and therefore the simplified formula is:

$$E = \frac{(p_1' - p_2')}{\bar{\rho}} + \bar{g} \cdot (z_1' - z_2') + \frac{(v_1^2 - v_2^2)}{2} = \frac{(p_1' - p_2')}{\bar{\rho}} + \bar{g} \cdot Z + \frac{(v_1^2 - v_2^2)}{2}$$



Case of non-pressurised housing.

It is conventionally assumed that the low pressure reference section corresponds to the plane at elevation z_2 and that the pressure inside the housing is equal to the ambient pressure in the case of non-pressurised housing.

$$E = \bar{g} \cdot H = \frac{(p_{abs1} - p_{abs2})}{\bar{\rho}} + \frac{(v_1^2 - v_2^2)}{2} + \bar{g} \cdot (z_1 - z_2)$$

The difference in ambient pressure between 1' and 2 is neglected because Z is small compared to H , therefore:

$$p_{amb1'} = p_{amb2} = p_{amb}$$

For the same reason it is assumed that:

$$Z \cdot \frac{\bar{\rho}}{\bar{\rho}} = Z$$

hence:

$$p_{abs1} = p_{1'} + Z \cdot \bar{\rho} \cdot \bar{g} + p_{amb} \quad \text{where } p_{1'} \text{ is the gauge pressure measured at } 1'$$

$$p_{abs2} = p_{amb}$$

As $z_1 = z_2$ and assuming $v_2 = 0$, the simplified formula is:

$$E = \frac{p_{1'}}{\bar{\rho}} + \bar{g} \cdot (z_{1'} - z_2) + \frac{v_1^2}{2} = \frac{p_{1'}}{\bar{\rho}} + \bar{g} \cdot Z + \frac{v_1^2}{2}$$

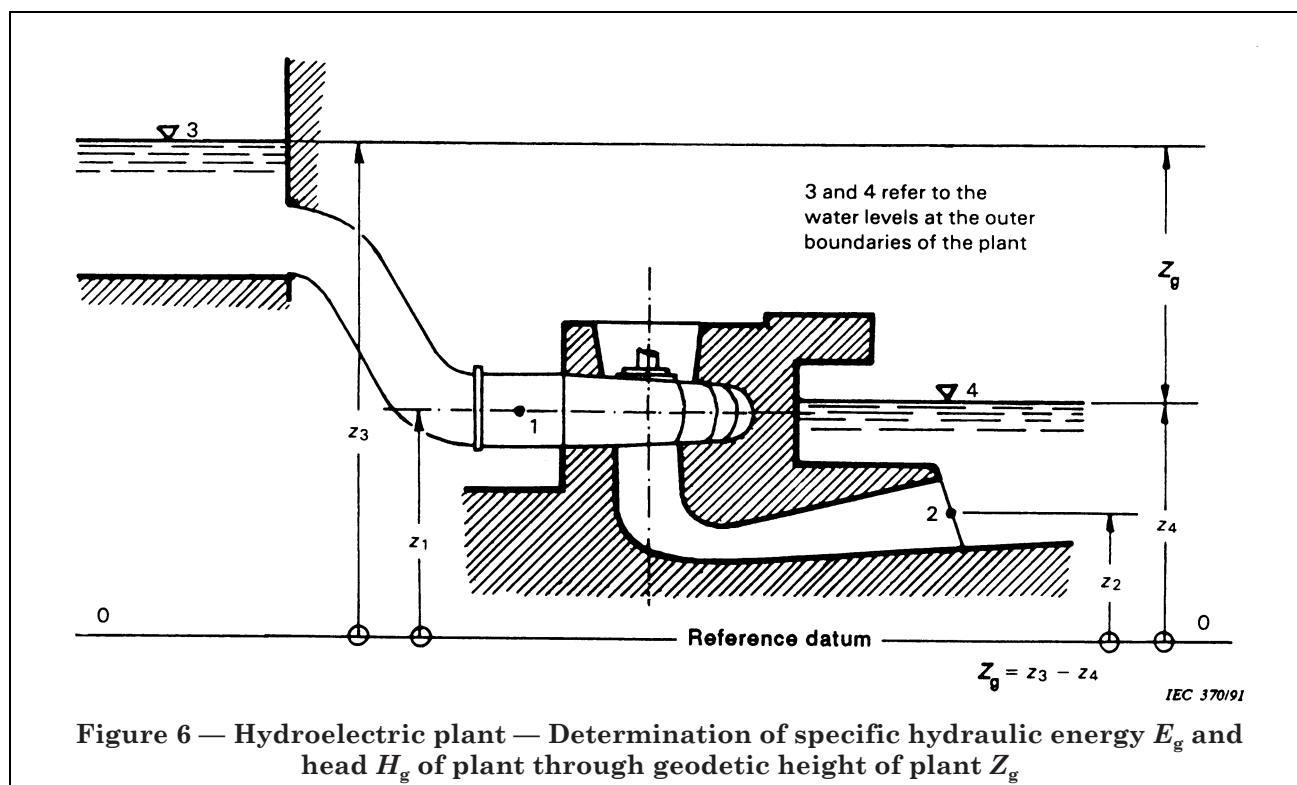


Figure 6 — Hydroelectric plant — Determination of specific hydraulic energy E_g and head H_g of plant through geodetic height of plant Z_g

The general formula is:

$$E_g = \bar{\gamma}_{3-4} \cdot H_g = \frac{(p_{\text{abs}3} - p_{\text{abs}4})}{\bar{\rho}_{3-4}} + \frac{(v_3^2 - v_4^2)}{2} + \bar{\gamma}_{3-4}(z_3 - z_4)$$

Assuming $\bar{g}_{3-4} = \frac{g_3 + g_4}{2} = \bar{g}$,

$$p_{\text{abs}3} - p_{\text{abs}4} = -\rho_a \cdot \bar{g} \cdot (z_3 - z_4);$$

assuming $v_3 = v_4 = 0$

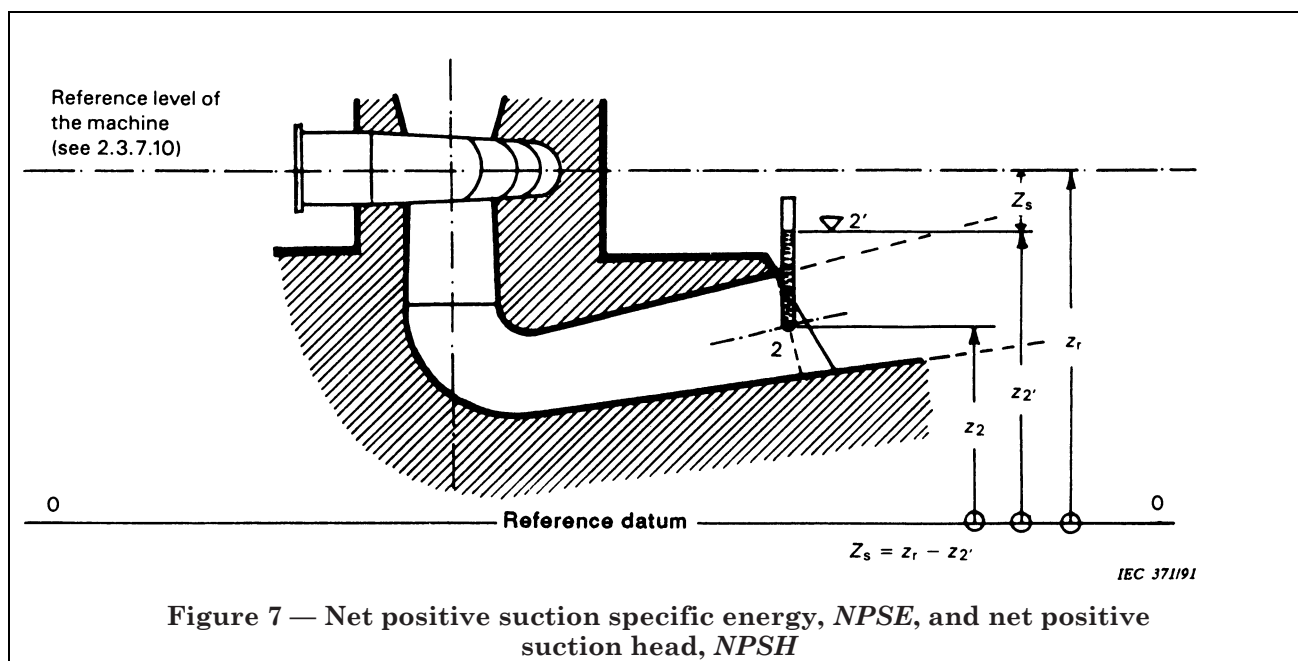
and $\bar{\rho}_{3-4} = \frac{\rho_3 + \rho_4}{2} = \bar{\rho}$ water density at the ambient pressure, the formula becomes:

$$E_g = \bar{\gamma} \cdot (z_3 - z_4) \cdot \left[1 - \frac{\rho_a}{\bar{\rho}} \right] = \bar{\gamma} \cdot Z_g \cdot \left[1 - \frac{\rho_a}{\bar{\rho}} \right]$$

where ρ_a is assumed equal to air density at the reference level of the machine.

Conversely:

$$E_g = E \pm \sum E_L \quad \text{where} \quad \begin{cases} + & \text{turbine} \\ - & \text{pump} \end{cases}$$



Water column manometer is applied at point 2.

$$NPSE = g_2 \cdot NPSH = \frac{(p_{abs_2} - p_{va})}{\rho_2} + \frac{v_2^2}{2} - g_2 \cdot (z_r - z_2)$$

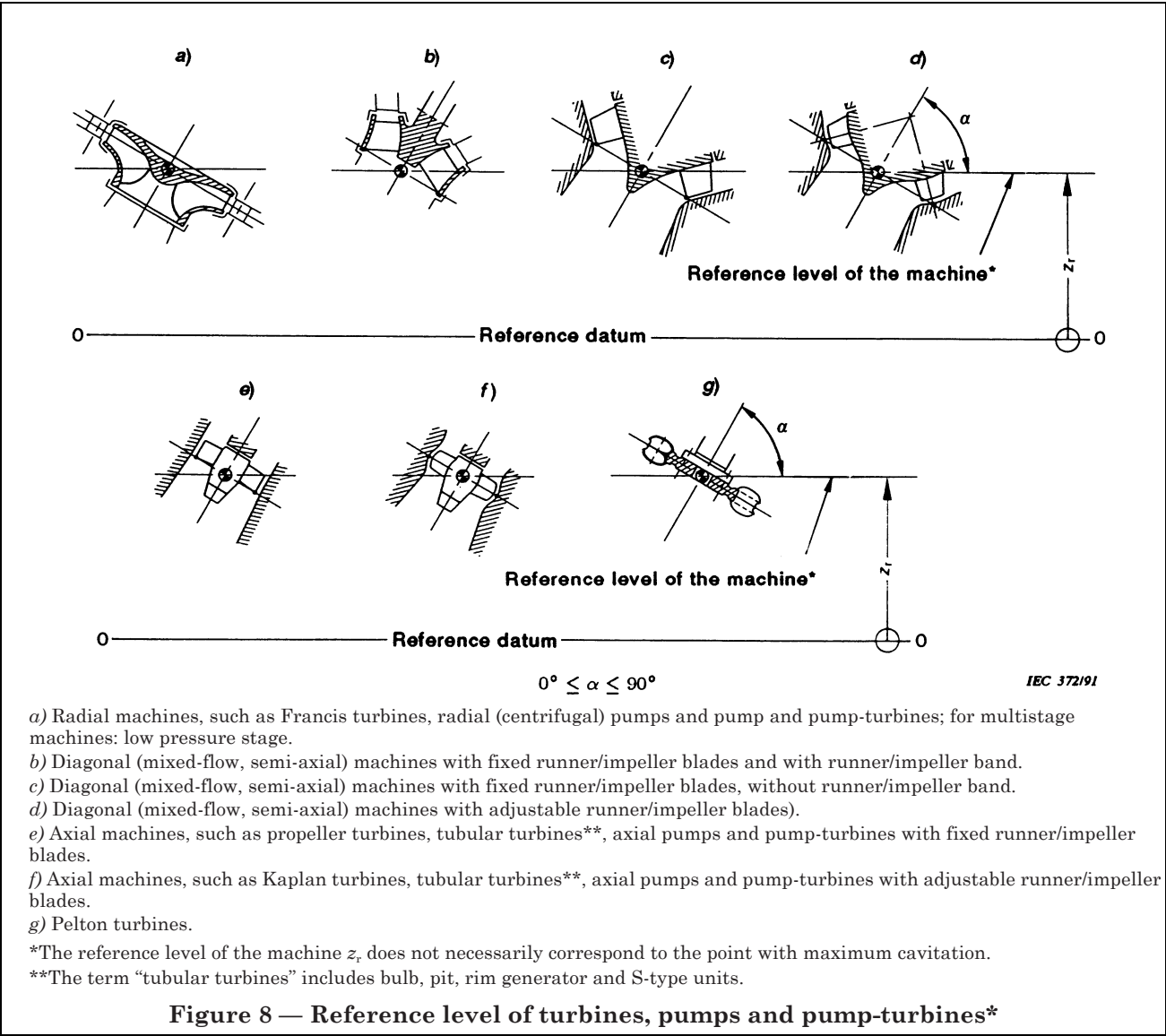
With:

$$p_{abs_2} = \rho_2 \cdot g_2 \cdot (z_{2'} - z_2) + p_{amb_{2'}}$$

the simplified formula becomes:

$$NPSE = \frac{(p_{amb_{2'}} - p_{va})}{\rho_2} + \frac{v_2^2}{2} - g_2 \cdot (z_r - z_{2'}) = \frac{(p_{amb_{2'}} - p_{va})}{\rho_2} + \frac{v_2^2}{2} - g_2 \cdot Z_s$$

where Z_s is positive if the level 2' is lower than the reference level of the machine and vice versa.



2.3.8 Power terms

NOTE All electrical power terms are defined in Clause 12.

Sub-clause	Term	Definition	Symbol	Unit
2.3.8.1	Hydraulic power	The hydraulic power available for producing power (turbine) or imparted to the water (pump) $P_h = E(\rho Q)_1 \pm \Delta P_h$	P_h	W
2.3.8.2	Hydraulic power correction	Correction term to be evaluated after a relevant analysis according to contractual definitions and local conditions ^a (see 9.2.3)	ΔP_h	W

^a Example: if a small discharge q is taken from the system upstream of section 1 in a turbine and this water is contractually chargeable to the hydraulic machine, the hydraulic power is: $P_h = E(\rho Q)_1 + E(\rho q)$

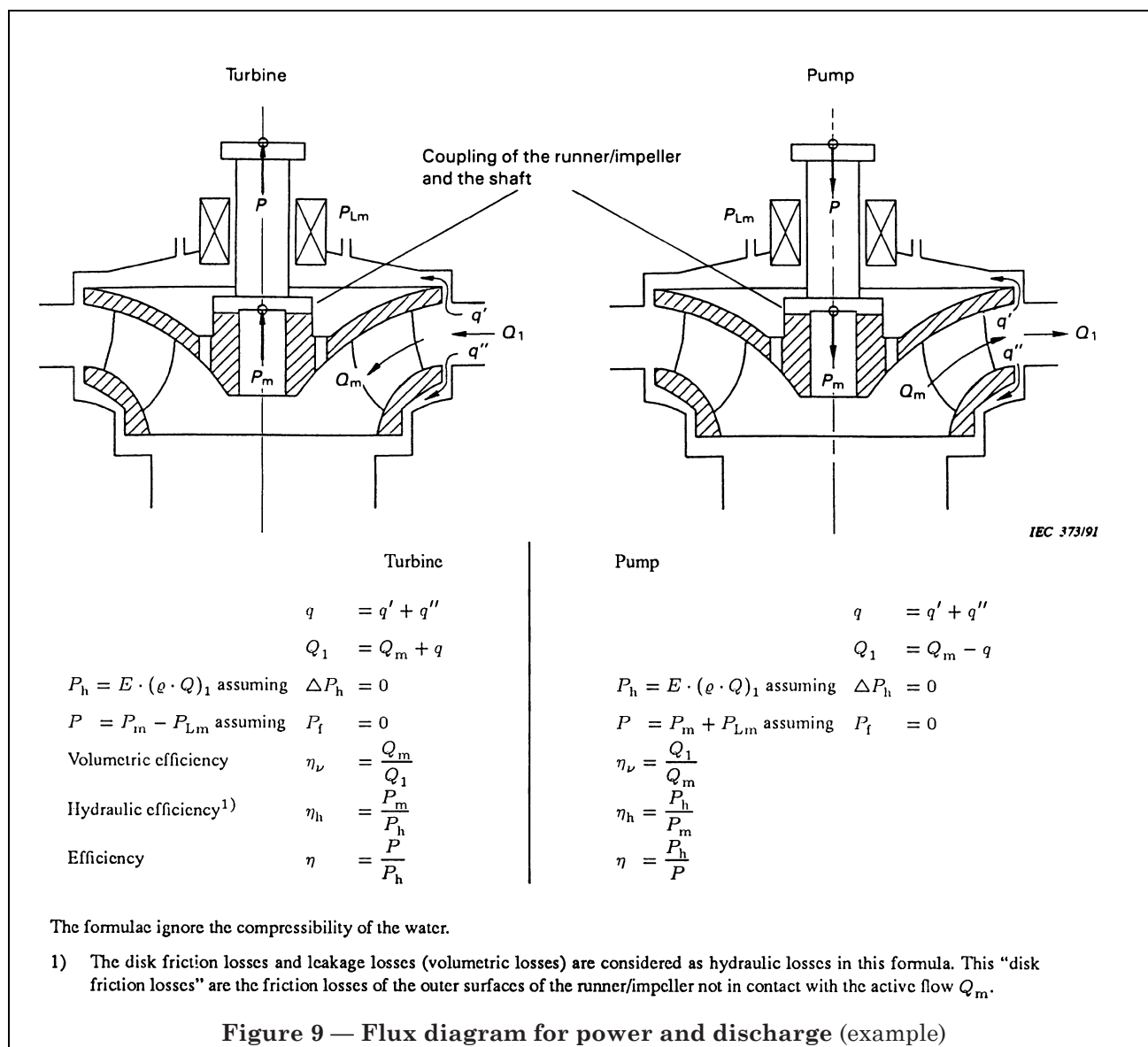
Sub-clause	Term	Definition	Symbol	Unit
2.3.8.3	Mechanical power of the machine (Power)	The mechanical power delivered by the turbine shaft or to the pump shaft, assigning to the hydraulic machine the mechanical losses of the relevant bearings (see Figure 9)	P	W
		— For a turbine:		
		$P = P_a + P_b + P_c + P_d + P_e - P_f$		
		where:		
		P_a is the generator power as measured at the generator terminals	P_a	W
		P_b are the mechanical and electric losses in the generator, including windage losses (see 12.1.2.1)	P_b	W
		P_c are the thrust bearing losses due to generator. In the case of a common thrust bearing, the bearing losses shall be attributed to the turbine and generator in proportion to the thrust of each on the bearing (see 12.1.2.2)	P_c	W
		P_d are the losses in all rotating elements external to the turbine and to the generator, such as flywheel, if any, gear, pump impeller in air, if any, etc. (see 12.1.2.3)	P_d	W
		P_e is the power supplied to any directly driven auxiliary machine (see 12.1.2.4)	P_e	W
		P_f is the electric power supplied to the auxiliary equipment of the turbine (e.g. for the governor) if the contract specifies this to be chargeable to the turbine	P_f	W
		— For a pump:		
		$P = P_a - (P_b + P_c + P_d + P_e) + P_f$		
		where:		
		P_a is the power to the motor as measured at the motor terminals	P_a	W
		P_b are the mechanical and electric losses in the motor, including windage losses (see 12.1.2.1)	P_b	W
		P_c are the thrust bearing losses due to the motor. In the case of a common thrust bearing, the bearing losses shall be attributed to the pump and motor in proportion to the thrust of each on the bearing (see 12.1.2.2)	P_c	W
		P_d are the losses in all rotating elements external to the pump and to the motor, such as flywheel, if any, gear, starting turbine runner, turbine runner rotating in air, etc. (see 12.1.2.3)	P_d	W

Sub-clause	Term	Definition	Symbol	Unit
2.3.8.4	Mechanical power of runner(s)/impeller(s)	P_e is the power supplied to any directly driven auxiliary machine (see 12.1.2.4)	P_e	W
		P_f is the electric power supplied to the auxiliary equipment of the pump (e.g. for the governor) if the contract specifies this to be chargeable to the pump	P_f	W
		Mechanical power transmitted through the coupling of the runner(s)/impeller(s) and the shaft (see demonstrative sketch Figure 9): — in the case of a turbine: $P_m = P + P_{Lm} + P_f$ — in the case of a pump: $P_m = P - P_{Lm} + P_f$	P_m	W
2.3.8.5	Mechanical power losses	Mechanical power dissipated in guide bearings, thrust bearing and shaft seals of the hydraulic machine. See also 2.3.8.3 (P_j)	P_{Lm}	W
2.3.8.6	Zero-discharge (shut-off) power of the pump	Pump power at specified speed and at specified guide vane and impeller settings with high pressure side shut-off	P_0	W

2.3.9 Efficiency terms

Sub-clause	Term	Definition	Symbol	Unit
2.3.9.1	Hydraulic efficiency ^a	— For a turbine: $\eta_h = \frac{P_m}{P_h} = \frac{E_m}{E \pm \frac{\Delta P_h}{P_m} E_m}$ — For a pump: $\eta_h = \frac{P_h}{P_m} = \frac{E \pm \frac{\Delta P_h}{P_m} E_m}{E_m}$	η_h	—
2.3.9.2	Mechanical efficiency	— For a turbine: $\eta_m = \frac{P}{P_m}$ — For a pump: $\eta_m = \frac{P_m}{P}$	η_m	—
2.3.9.3	Efficiency	— For a turbine: $\eta = \frac{P}{P_h} = \eta_h \cdot \eta_m$ For a pump: $\eta = \frac{P_h}{P} = \eta_h \cdot \eta_m$	η	—
2.3.9.4	Relative efficiency	Ratio of the efficiency at any given operating condition to a reference value	η_{rel}	—
2.3.9.5	Weighted average efficiency	The efficiency calculated from the formula: $\eta_w = \frac{w_1 \eta_1 + w_2 \eta_2 + w_3 \eta_3 + \dots}{w_1 + w_2 + w_3 + \dots}$ where $\eta_1, \eta_2, \eta_3, \dots$ are the values of efficiency at specified operating conditions and $w_1, w_2, w_3, \dots$ are their agreed weighting factors respectively	η_w	—
2.3.9.6	Arithmetic average efficiency	The weighted average efficiency (2.3.9.5) with $w_1 = w_2 = w_3 = \dots$	η_a	—

^a The disk friction losses and leakage losses (volumetric losses) are considered as hydraulic losses in the formulae in 2.3.9.1. The “disk friction losses” are the friction losses of the outer surfaces of the runner/impeller not in contact with the active flow.



3 Nature and extent of hydraulic performance guarantees

3.1 General

3.1.1 A contract for a regulated or non-regulated³⁾ machine should contain guarantees covering at least power, discharge, efficiency (see 3.2.5), maximum momentary overspeed and maximum/minimum momentary pressure, maximum steady state runaway speed (reverse runaway speed in case of a pump).

In the case of a pump the guarantees may also cover the maximum zero-discharge specific hydraulic energy (head) and the zero-discharge power, the latter one with impeller rotating in water and/or in air, for the specified speed.

These guarantees are considered as main hydraulic guarantees (see 3.2) and fall within the scope of this standard. Other guarantees (see 3.3) are not covered by this standard.

³⁾ A regulated machine is a machine in which the flow is controlled by a flow-controlling device such as guide vanes, needle(s), and/or runner/impeller blades. A single regulated machine is a regulated machine with one flow-controlling device; a double regulated machine is a regulated machine with two flow-controlling devices. A non-regulated machine is a machine in which no flow-controlling device is provided.

3.1.2 The purchaser shall arrange for the supplier of the machine to be provided with true, full and acceptable data covering all basins, inlet and outlet structures, waterways between the points of intake and discharge and all parts and equipment relating thereto, all the driven or driving machinery whether electric or not and the revolving parts thereof, and all governors, valves, gates and allied mechanisms.

3.1.3 The purchaser shall be responsible for specifying the values of all the parameters on which guarantees are based, including water quality and temperature⁴⁾, specific hydraulic energies of the plant (see **2.3.6.4**) and specific hydraulic energy losses (see **2.3.6.6**), for the study of the plant, particularly the correct inlet and outlet conditions of the machine and for the co-ordination of what concerns the interaction between the machine and the waterways. Should the operational and guaranteed ranges differ, he shall indicate the limits of the operation.

3.1.4 If the electric generator or motor is to be used for measuring turbine or pump power (see **2.3.8.3**), such electric generator or motor and its auxiliaries shall be given appropriate tests. It should be a condition of the contract that the supplier of the hydraulic unit or his representative shall have the right to be present at such tests. A certified copy of the generator or motor test calculations and results shall be given to the supplier of the hydraulic machine.

3.2 Main guarantees

3.2.1 Practical plant operation

Practical plant operation usually involves some variation in specific hydraulic energy (head). Therefore specifications shall state the specific hydraulic energies to which guarantees shall apply.

For practical reasons a transient test may not be conducted at the same time as a steady-state performance test.

3.2.2 Power

Power guarantees may be required at one or more specified speeds for:

- a) a regulated turbine: power to be reached at one or more specified specific hydraulic energies (see Figure 10a);
- b) a non-regulated turbine: power to be reached and power not to be exceeded over a specified specific hydraulic energy range⁵⁾ (see Figure 10b);
- c) a non-regulated/regulated pump: power not to be exceeded over a specified specific hydraulic energy range (see Figure 10c).

3.2.3 Discharge

Discharge guarantees may be required at one or more specified speeds for:

- a) a regulated turbine: discharge to be reached at one or more specified specific hydraulic energies (see Figure 10a);
- b) a non-regulated turbine: discharge to be reached over a specified specific energy range (this guarantee is usually replaced by the corresponding power guarantee, see **3.2.2 b**) and discharge not to be exceeded (see Figure 10b);
- c) a non-regulated/regulated pump: discharge over a specified specific hydraulic energy range, including values to be reached or not to be exceeded⁶⁾ (see Figure 10c).

The guaranteed discharge may be referred to the ambient pressure (see **2.3.4.5**).

3.2.4 Efficiency

3.2.4.1 Regulated turbine efficiency guarantees may be required at one or more specified speeds and specific hydraulic energies:

- a) at one or more individual specified powers or discharges or as a curve (see Figure 10a);
- b) as weighted average efficiencies⁷⁾ over a range of power or discharge;
- c) as arithmetic average efficiencies⁷⁾ over a range of power or discharge.

⁴⁾ If the water temperature during the acceptance test is significantly different from the specified value (e.g. more than 10 °C), the relevant scale effect should be taken into account.

⁵⁾ For the contractual limits of the power corresponding to the specified specific hydraulic energies, see **6.3.1**.

⁶⁾ For the contractual limits of the discharge corresponding to the specified specific hydraulic energies, see **6.3.2**.

⁷⁾ Weighted or arithmetic average efficiencies and a series of individual efficiencies shall not normally be guaranteed simultaneously.

3.2.4.2 Non-regulated turbine or non-regulated/regulated pump efficiency guarantees may be required at one or more specified speeds:

- a) at one or more individual specified specific hydraulic energies or as a curve (see Figure 10b and Figure 10c);
- b) as weighted average efficiencies⁸⁾ over a specified range of specific hydraulic energies;
- c) as arithmetic average efficiencies⁸⁾ over a specified range of specific hydraulic energies.

3.2.5 Choice of power, discharge and efficiency guarantees

It is recommended that the contractual agreements avoid fixing more than one guarantee for correlated quantities; for instance, in the case of a regulated turbine efficiency shall be guaranteed versus discharge or power, but not versus discharge and power.

3.2.6 Maximum momentary overspeed and maximum/minimum momentary pressure^{9),10)} (see 2.3.4.14 and 2.3.5.7)

Maximum or minimum momentary pressure and maximum momentary overspeed should be guaranteed over the whole operating range, generally in accordance with IEC 308.

Since the characteristics of the hydraulic and electric machines, the governor and all or part of the conduit system may be involved in the determination of the maximum overspeed and maximum/minimum momentary pressure, manufacturers shall be supplied with all relevant information.

3.2.7 Maximum steady state runaway speed (see 2.3.4.15)

Guarantees should be given that the maximum steady state runaway speed (maximum reverse runaway speed in case of a pump) will not exceed specified values under conditions to be specified in the contract (e.g. specific hydraulic energy, net positive suction specific energy, etc).

It is generally recommended to avoid this test (see 7.1.2.2).

3.2.8 Maximum zero-discharge specific hydraulic energy and zero-discharge (shut-off) power of a pump (see 2.3.6.5 and 2.3.8.6)

In the case of a pump a guarantee should be given that the zero-discharge power — with watered and de-watered impeller — and the maximum specific hydraulic energy will not exceed a specified value for the specified speed.

3.3 Other guarantees

Additional guarantees may be given; the following are guarantees covered by other IEC publications.

3.3.1 Speed governing systems

Acceptance of speed governing systems should be carried out in accordance with IEC 308.

3.3.2 Cavitation pitting

The amount of cavitation pitting should be guaranteed subject to the limitation that the unit will be operated only within the prescribed ranges of power, discharge, speed, duration, water temperature and net positive suction specific energy (*NPSE*). Recommendations on this subject are dealt with in IEC 609.

⁸⁾ Weighted or arithmetic average efficiencies and a series of individual efficiencies shall not normally be guaranteed simultaneously.

⁹⁾ This standard deals only with speed and pressure variations associated with specified sudden load rejection (turbine) or power failure (pump). The most unfavourable transient conditions appearing in the definitions at 2.3.4.14 and 2.3.5.7 shall be specified in the contract.

¹⁰⁾ For superimposed pressure fluctuations, if any, see 7.1.1 and 8.2.2.

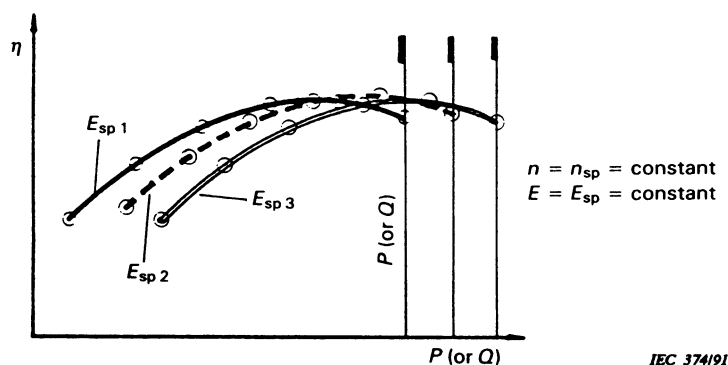


Figure 10a — Regulated turbine

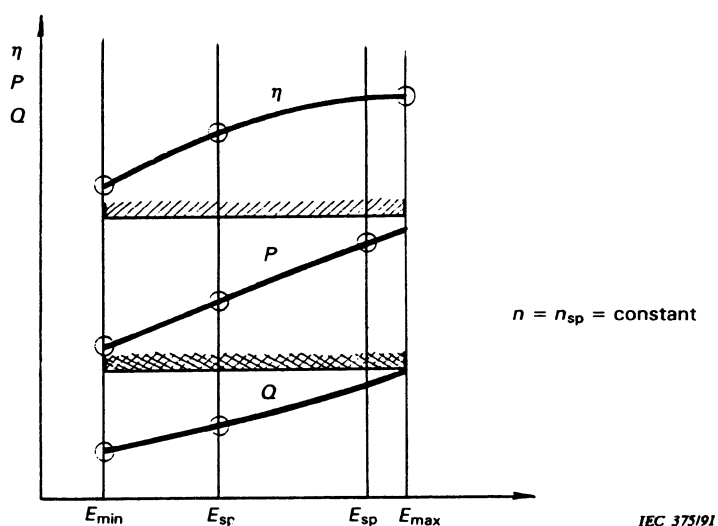


Figure 10b — Non-regulated turbine

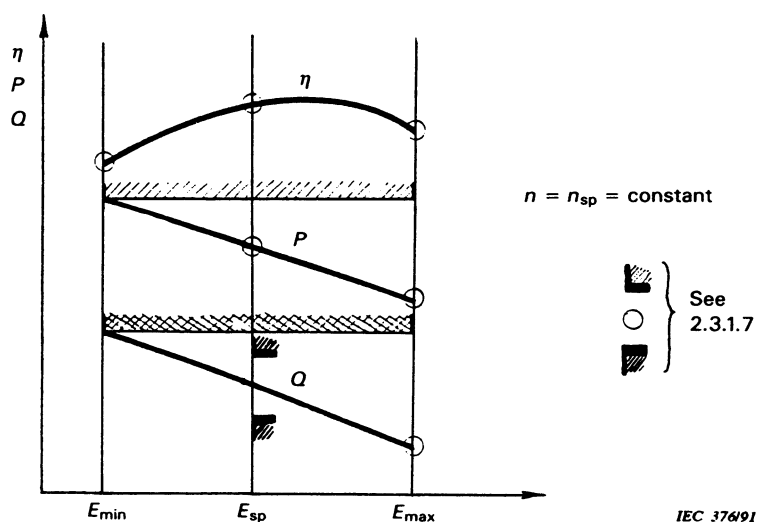


Figure 10c — Pump

NOTE Usually only a part of the guarantees here described are required.

Figure 10 — Guarantee curves

4 Organisation of test

4.1 Adequate provision for test

It is recommended that attention should be given to provisions for testing when the plant is being designed. This applies particularly to the arrangements for measuring discharge and specific hydraulic energy. It is suggested that during the design stage of the plant and the machines to be tested, provision is made for more than one method of measuring discharge and pressure (or free water level). The methods of measurement should be fully covered in the specifications and in the contracts.

The conditions should also be considered when a prospective purchaser, or the engineers, submit an enquiry to possible suppliers. It should be stated at this time that the acceptance tests shall be performed in accordance with all applicable requirements of this standard. Any anticipated deviation from this standard should be clearly stated.

4.2 Authority for test

Subject to the provisions of the contract, both parties shall have equal rights in determining the test methods and procedures and in selecting all test personnel. The test may be entrusted to experts who hold independent positions with respect to both parties. If so, they and the Chief of test together with the contracting parties shall have final authority in selecting all other test personnel.

4.3 Personnel

The selection of personnel to conduct the test and procedures in connection therewith are matters of prime importance.

4.3.1 *Chief of test*

A Chief of test shall be appointed by agreement between the two parties. He should be competent to supervise all of the calibrations, measurements and calculations necessary to determine the performance of the machine. He shall exercise authority over all observers. He shall supervise the conduct of the test in accordance with this standard and any written agreement made prior to the test by the contracting parties. He shall be responsible for the calibration of all test instruments and for all test measurements. He shall report on test conditions and be responsible for the computation of results including the determination of the measurement uncertainties and the preparation of the final report. On any question pertaining to the test his decision, subject to the provisions of 4.5.1, 4.7.6 and 4.9.1, shall be final.

4.3.2 *Choice of personnel*

The testing team shall have the necessary competence and experience for the correct installation and utilization of the measuring equipment.

4.3.3 *Presence at test*

Both purchaser and supplier of the machine shall be entitled to have representatives present at all tests in order to verify that they are performed in accordance with this standard and any prior written agreements.

4.4 Preparation for test

4.4.1 *Submission of drawings and relevant data*

All drawings of importance for the test and all relevant data, documents, specifications, certificates and reports on operating conditions shall be placed at the disposal of the Chief of test.

4.4.2 *Inspection on site*

Shortly before the start of the test, the unit and all test equipment shall be subjected to thorough inspection by representatives of both parties and the Chief of test to ensure that conditions are such that the performance of the machine may be judged equitably (see also 4.8). It shall be verified that:

- a) all machinery is complete and according to specifications;
- b) the scales indicating the opening of the guide vanes and/or runner/impeller blades, where applicable, or the opening of nozzles and deflectors are calibrated and the relationship between openings is correct. The scales shall have sufficient resolution and will be accessible throughout the test. Provisions shall exist to block effectively the guide vane or nozzle openings during each point to promote stability and accurate repetition of openings;
- c) no water passages are obstructed or restricted by any foreign matter;

d) no wear has taken place on vital parts, particularly in the form of cavitation damage to runners/impellers, guide vanes, nozzles or other water passage components and/or damage to wearing rings or labyrinths, that could have a significant effect on efficiency;

e) all pressure taps, piezometric tubes and connecting pipes have been properly formed and located and are clear of obstruction.

4.4.3 Measurements before test

The dimensions of the conduit at and between measurement sections, when required, shall be measured accurately before the unit is operated.

A main bench mark for levels shall be established. All secondary bench marks (levelling reference points) in the specific hydraulic energy measuring system shall be referred to it. All bench marks shall be retained undisturbed until the final report has been accepted.

When the indirect method of power measurement is used, the results of the generator/motor efficiency test should preferably be available prior to the hydraulic machine performance test. In case such information is missing the guaranteed values of generator/motor for losses may be used for preliminary computation of the results.

4.5 Agreement on test procedure

4.5.1 Approval of procedure

The test programme and procedure shall be prepared by the Chief of test, taking into consideration the plans previously prepared according to 4.1. All arrangements and plans shall be submitted to both purchaser and supplier in ample time for consideration and agreement. Approval or objection shall be given in writing.

4.5.2 Date of test

The acceptance test shall not take place until the commissioning tests, including speed and pressure variation trials, have been conducted. See also IEC 545 and 805.

It is for the purchaser to decide, with respect to plant operation and flow conditions, on the date of the acceptance test. This shall be within the contract guarantee period and preferably within six months after the machine has been handed over to the purchaser, unless otherwise agreed by both parties in writing.

4.5.3 General programme

The general programme shall be drafted by the Chief of test and shall include particulars concerning the following items:

4.5.3.1 Specific hydraulic energy for acceptance test

In those cases where guarantees are given for more than one specific hydraulic energy the general programme shall state at which value or values of specific hydraulic energy the acceptance test shall be carried out, on the basis of the purchaser's instructions.

4.5.3.2 Machines to be tested for efficiency

The contract shall specify whether several or only one of a group of identical machines are to be tested with regard to efficiency. The general programme shall specify the actual machine or machines to be tested. If only one is to be tested, it is recommended that the machine shall be chosen by mutual agreement between purchaser and supplier.

4.5.3.3 Extent and duration of test

The general programme shall include a statement on the number of points to be taken and the corresponding operating conditions. The number of points to be obtained depends on the nature and extent of the guarantees and shall be decided by the Chief of test. Prescriptions on the number of points, the mode of machine operation and other related items which shall be included in the general programme are detailed in 5.1 for the steady state performance test and in 7.1 for the transient operation test.

4.6 Instruments

4.6.1 Identification of instruments

The maker, serial number or other identification, and owner of each instrument shall be stated in the final report.

4.6.2 Calibration of instruments

All instruments, including electrical instrument transformers, shall be calibrated before the test and both purchaser and supplier may witness their calibration. Whether calibrated on or off site, the validity of all calibrations shall be verified by the Chief of test. In the case of an off-site calibration, a valid certificate, acceptable to both the purchaser and the supplier, shall be provided. All necessary correction and pre-test calibration curves of the instruments to be employed shall be available before any test is carried out.

Unless omitted by agreement, all calibrations shall be repeated after completion of the test. The dates and places of all calibrations shall be stated in the final report. The institutions that have performed the calibrations shall state in writing whether the variations between pre- and post-test calibrations are within acceptable limits. If such is the case, their arithmetical means shall be used in the computation of the final results. If not, either a special agreement shall be made as to how any disputed values shall be used or the test shall be repeated.

4.7 Observations

4.7.1 Observation sheets

Observation sheets which clearly indicate the items to be measured shall be prepared for use at each of the various stations. A sufficient number of copies of the observation sheets shall be prepared and each party to the test shall immediately be handed a complete set. These observation sheets shall:

- a) record the power plant designation and the serial number of each machine to be tested and the serial numbers of the instruments as well as any other essential information to identify all instruments and their location;
- b) record the positions of all nozzles needles, runner/impeller blades, and/or adjustable guide vanes;
- c) record all readings made at each observation station and the time at which each reading was taken, together with any circumstances deserving attention;
- d) be signed by the particular observer;
- e) provide for other necessary signatures (see 4.7.5);
- f) be examined by, and copies given to, all parties before the end of the test.

4.7.2 Instrument readings

All readings of direct-reading instruments shall be taken during the same period of time and the frequency of the reading shall be decided by the Chief of test. Care shall be taken that the time interval between readings does not coincide with the period, or any multiple thereof, of any steady state oscillations in the instrumentation or machine under test. Visual averaging is to be avoided, if possible, because this inevitably introduces some personal bias (see also 5.2.1). All readings for the preliminary test (5.1.3) shall be taken with the same care and accuracy as for the acceptance test.

4.7.3 Instrument recordings

Instrument recordings (analog or digital) may be used provided that the accuracy and resolution of the records are comparable to or better than instantaneous readings of direct reading test instruments. All recordings shall be averaged or interpreted under the direct supervision of the Chief of test, using the most suitable and accurate techniques.

4.7.4 Preliminary calculation

After completion of the test, the readings and recordings shall be examined by both parties and representative results shall be provisionally computed on site using the pre-test calibrations. All errors or inconsistencies thereby discovered shall be eliminated or taken into account. Only on this basis may the test be terminated and the test instruments removed (see 4.6.2).

4.7.5 Signing of readings and recordings

The test recordings shall be signed by the Chief of test and by representatives of both parties.

4.7.6 Procedure in case of dispute or repetition

If there is any dissatisfaction with the test for clearly explained reasons stated in writing, the dissatisfied party shall have the right to demand additional tests. Agreement at this stage shall not preclude either party from expressing dissatisfaction with the test when the final results are available. In such case, either party and/or the Chief of test may demand a repeat test. If final agreement as to the conduct of such a test cannot be reached, the matter shall be referred to an independent arbitrator acceptable to all parties.

The contract should fix the responsibility for the cost of any repeat test.

4.8 Inspection after test

If requested by either party or the Chief of test, the unit and all test equipment shall be available for inspection within two days after completion of the test. A request for this inspection should be made as early as possible and, in any case, before the completion of testing.

4.9 Final report

4.9.1 Preparation of final report

The Chief of test shall be responsible for the preparation of the final report. A draft form of the report shall be submitted to both the purchaser and supplier to obtain the approval of both parties on all items including calculations and presentation of results. Any dissatisfaction shall be resolved by both parties with each having equal rights in determining the final contents of the report. In case of lack of agreement, the matter shall be referred to an independent arbitrator acceptable to all parties.

4.9.2 Content

The final report shall include at least all the topics listed below but not necessarily in this order.

- a) Object of test.
- b) Records of all preliminary agreements pertinent to the test.
- c) Personnel taking part in the test.
- d) Identification, characteristics and description of the machine.
- e) Description of associated equipment or works, for example pipelines, valves, gates, intake and outlet passages, and their condition, with drawings where appropriate.
- f) Particulars concerning service conditions of the machine, for example operating hours, power, discharge and water levels from commissioning date up to the beginning of the acceptance test.
- g) Comments on inspection of machine.
- h) Details of performance guarantees.
- i) Description of all test equipment including serial numbers, calibrations, and all checks made pertaining to the test (see 4.7.1).
- j) Test procedures.
- k) Detailed calculations, preferably tabulated, from the original rough data to the final curves for at least one point. All diagrams or their copies used, such as Gibson pressure-time diagram, salt-velocity curves, current-meter velocity distribution, etc. shall be included.
- l) Daily log of the events of the test.
- m) The tabulated results of all measurements including necessary intermediate data, the results of calculations for the specific hydraulic energy, discharge and power, the conversion of the values measured to the specified conditions E_{sp} and n_{sp} , the determination of the efficiency of the generator or motor and the calculation of turbine or pump efficiency.
- n) An evaluation of the random and systematic uncertainties of each measured quantity and a calculation of the total uncertainty of data derived from combined measurements.
- o) Graphs showing the principal results.
- p) Discussion of the test results on the basis of the test graphs:
 - 1) for regulated turbines at specified speed and at each specified specific hydraulic energy:
 - efficiency-power or efficiency-discharge;
 - power-discharge;
 - discharge and power-guide vane or needle opening.

2) for non-regulated turbines or pumps at specified speed:

- efficiency-specific hydraulic energy;
- discharge-specific hydraulic energy (pumps) or power-specific hydraulic energy (non-regulated turbines).

In the case of machines with adjustable runner/impeller blades and adjustable guide vanes, curves shall be drawn for different blade/vane settings to indicate how the cam control for the optimum relationship was determined.

q) Comparison with guaranteed values and conclusions: unfavourable influences during the test shall be reported.

Section 2. Execution of test for the determination of the steady state performance of the machine

5 Test conditions and procedure

5.1 General test procedure

5.1.1 *Methods of measurement*

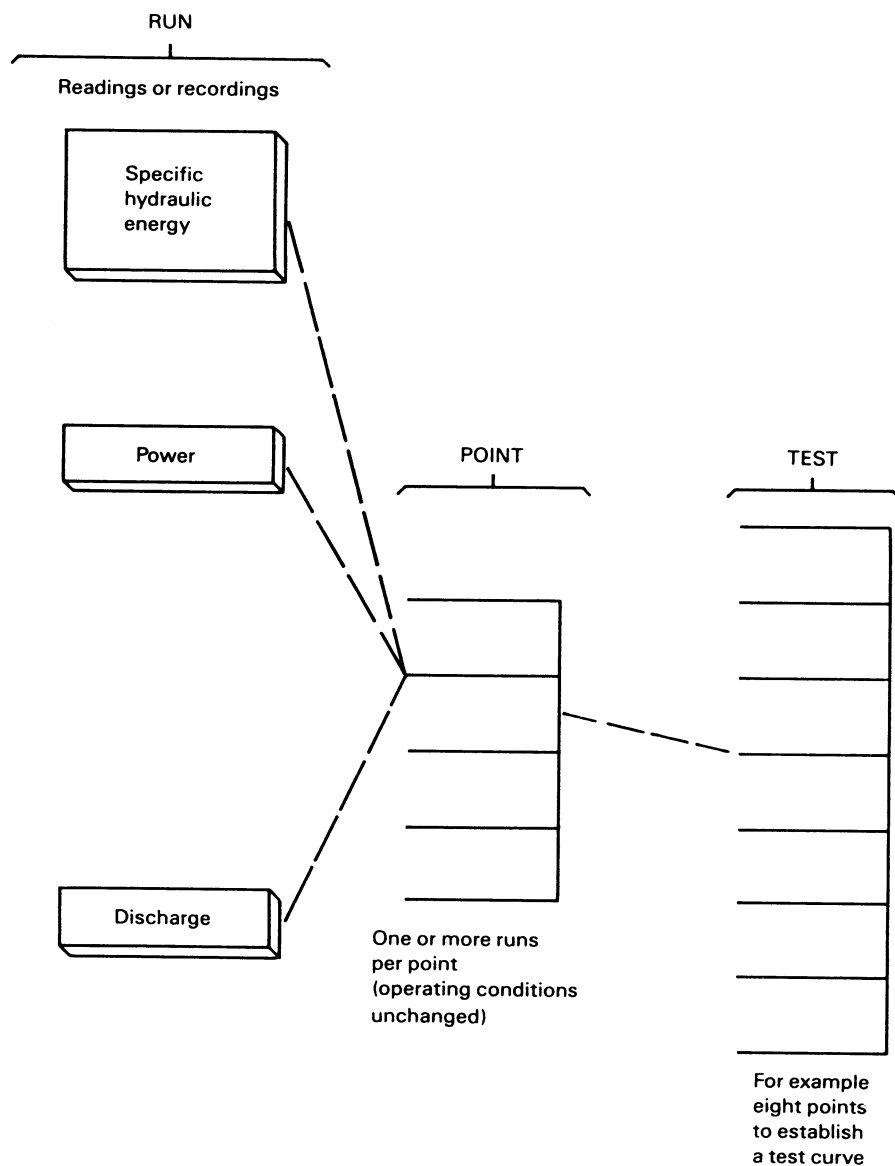
The methods to be used for the measurement or computation of discharge, power, specific hydraulic energy, efficiency, speed and losses shall be stated in the general programme. They are described in Clauses 9 to 14.

An additional index discharge measurement is recommended to overcome any difficulties that may arise from the chosen method. The index test methods are described in Clause 15.

5.1.2 *Number of points, runs and readings*

A performance curve such as that illustrated by Figure 10a requires a minimum of six and preferably eight or ten points. Each point will be obtained from one or more runs (see 2.1 and 5.1.3). The number of measurements taken during a run depends upon the methods of measurement used, but for a statistical treatment (see Appendix C and Appendix D) at least five readings of direct-reading instruments per run are to be taken over an agreed time or over the duration of any time-based measurements. Figure 11 shows an example of a test schedule.

The interval of time during which all instantaneous readings and instrument recordings are made for each run shall generally be the same for each point. For some types of measurement such as the transit time method of discharge measurement, the time necessary to complete a run may vary significantly with discharge. It may then be appropriate to adjust the time interval between instantaneous readings so that each run contains the same number of readings or at least an agreed minimum number of readings. The sole exception is for any pressure-time method diagrams which shall be started within approximately 15 s after the last instantaneous reading or the end of recording of the other quantities.



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NOTE The number of points to establish a curve, the number of runs per point and the number of readings per run depend on many factors (test methods, local conditions, type of machine, etc.) and shall be decided by the Chief of test. When Method A (see 5.1.3.1) is used, one run is sufficient for one point.

Figure 11 — Example of a test schedule

5.1.3 Recommended test procedures

Two procedures are recommended. The first (Method A) consists of testing a number of points over a range of operating conditions and drawing performance curves through them. The second (Method B) is based on testing several times one or a few specified operating points. Both methods may be supplemented as necessary by index tests.

For Method A, the quality of the measurements is judged by the deviations of the points from the best smooth mean curve drawn through them. For Method B, not applicable when test conditions can be maintained constant for a short time only, the quality of the measurements is judged by the deviations of the results of the individual runs from their arithmetical mean value at the operating point considered.

If a guarantee is given for peak efficiency, but the corresponding operating conditions are unknown or unspecified, a preliminary index test shall be carried out to determine these operating conditions, after which the necessary complete runs shall be made (see also 5.1.4).

A preliminary test should be carried out to instruct all participants in their respective duties and to verify satisfactory operation of all test equipment or to correct or improve it, if necessary. During both the preliminary and acceptance tests, all possible cross-checks of data and results should be carried out to reduce or eliminate errors. Provisional results should be calculated and plotted as fast as the data are gathered. These running plots of discharge and power versus gate opening for turbines or discharge and power versus specific hydraulic energy for pumps may reveal testing errors or abnormalities in the operating characteristics of the machine which require further investigation. It may not be practicable to include all of the instrument corrections in the provisional results.

5.1.3.1 *Method A*

This method shall be used when performance curves over a range of operating conditions must be obtained (see also Appendix D) or when the test conditions can be maintained constant (see 5.2.1) only for a short time. The test programme shall define:

- a) the range of operating conditions to be covered by the test;
- b) the number and sequence of operating points to be tested;
- c) the guide vane/needle, runner/impeller blade and speed settings;
- d) any supplementary index test to be made.

5.1.3.2 *Method B*

This method may be used only if the operating conditions can be maintained constant (5.2.1) over the whole test time necessary to establish the machine performance at the operating point specified (see also Appendix C).

The test programme shall define the minimum number of runs, but in no case shall the number be less than five at the same operating conditions. If tests at more than one operating condition are required, each of them shall have the same number of runs.

The test programme shall also define:

- a) the number and sequence of operating points to be tested;
- b) the guide vane/needle, runner/impeller blade and speed settings;
- c) any supplementary index test to be made.

5.1.4 *Particular procedure for double regulated turbines*

Efficiency and power tests shall be made with the optimum relationship between guide vane and runner blade openings.

The optimum relationship can be established either during acceptance test or by previous index test. In this case, the optimum relationship must be established under the same hydraulic conditions as for the acceptance test, using for each of at least five blade openings, at least five different guide vane openings.

5.1.5 *Particular procedure for single regulated or double regulated pumps*

If possible, tests of these machines shall be carried out over the specified range of specific hydraulic energy and discharge. Efficiency and power tests shall be made with the openings of guide vanes and/or runner/impeller blades adequate to check the contract guarantees. These openings must be established under the same hydraulic conditions as for the acceptance test. In the case of a double regulated pump the relationship between guide vane and impeller blade openings can be established during the acceptance test or by a previous index test.

When adequate changes in water levels are not possible, discharge throttling and/or speed variation, if possible, may be used to obtain the necessary range of specific hydraulic energy.

5.2 Test conditions to be fulfilled

A run is considered valid if the following test conditions are fulfilled.

5.2.1 *Fluctuations and variations during a run* (see 2.1)

Fluctuations are defined as high frequency (more than 1 Hz) changes in the values of specific hydraulic energy, rotational speed, discharge or power about average values.

Some form of linear damping should be employed to eliminate the fluctuations and to read longer period changes (variations), which constitute the proper readings for the determination of the average value. In the case of sudden changes, the run cannot be considered valid. Variations of specific hydraulic energy, rotational speed and generator/motor power shall be such that the readings lie within the following limits during a run:

- a) the variations of power shall not exceed $\pm 1,5$ % of the average value of power;
- b) the variations of specific hydraulic energy shall not exceed ± 1 % of the average value of specific hydraulic energy;
- c) the variations of rotational speed shall not exceed $\pm 0,5$ % of the average value of rotational speed.

5.2.2 *Deviations of average specific hydraulic energy and rotational speed from specified values during a run* (see 2.1)

A departure of the average values of specific hydraulic energy E and rotational speed n measured during a run from their specified values E_{sp} , n_{sp} is defined as deviation.

In all cases the deviations must lie within the limits defined under a) and b) below:

$$\text{a) } 0,97 \leq \frac{n/\sqrt{E}}{n_{sp}/\sqrt{E_{sp}}} \leq 1,03$$

In no case shall the values of $\frac{n}{\sqrt{E}}$ fall outside the values defining the operating range.

$$\text{b) } 0,80 \leq \frac{E}{E_{sp}} \leq 1,20$$

and $0,90 \leq \frac{n}{n_{sp}} \leq 1,10$

For conversion of test results to specified conditions see 6.1.2.

5.2.3 *Net positive suction specific energy* (see 2.3.6.9) *and tailwater level during the measurement of a point* (see 2.1)

5.2.3.1 For a reaction machine the net positive suction specific energy, $NPSE$, shall not fall below the value specified in the contract.

If the actual average specific hydraulic energy and/or speed deviate from the specified values, it is necessary to have the curve of minimum guaranteed value of $NPSE/E$ as a function of E . The actual value of $NPSE/E$ shall not fall below the curve (see Figure 12).

5.2.3.2 For impulse turbines, the highest tailwater level shall not exceed the maximum level specified in the contract.

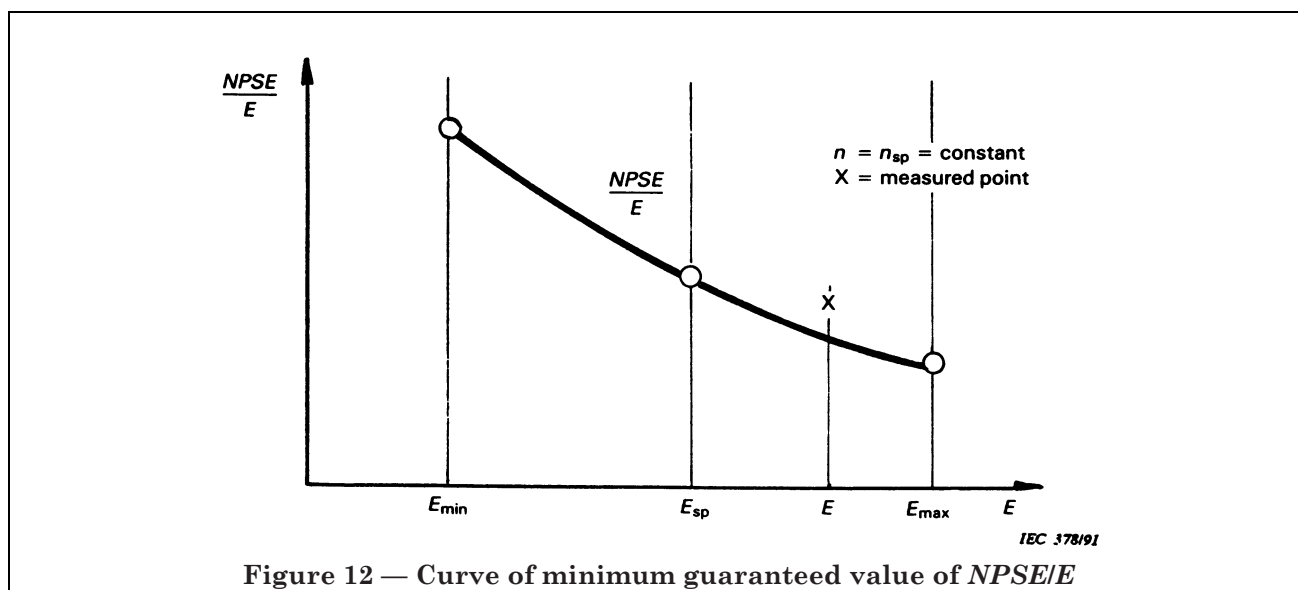


Figure 12 — Curve of minimum guaranteed value of $NPSE/E$

6 Computation and analysis of results

6.1 Computation of test results

6.1.1 Computation of a point

For each run the arithmetic average value of the readings and recordings is computed for each measured quantity (n , Q , E , P); on the basis of these values the performance is calculated applying the necessary conversions and corrections (see 6.1.2).

In the case of multiple runs the performance results, obtained as indicated above, are averaged to establish the point.

6.1.2 Conversion and correction of test results to specified conditions

Figure 10 shows the guarantee curves. For the regulated turbine a guarantee curve is usually given for each specified specific hydraulic energy (Figure 10a); on the contrary, for the non-regulated turbine and for the pump only a value for guaranteed quantities (efficiency for instance) is given for each specified specific hydraulic energy (Figure 10b and Figure 10c). Provided that the conditions described at 5.2 are fulfilled, test results are valid. The method to calculate a point is explained at 6.1.1.

If the guaranteed discharge is referred to the ambient pressure (see 3.2.3), the measured value must be converted to this condition (see 2.3.4.5). If the average specific hydraulic energy E_n and/or rotational speed n deviate from specified values E_{sp} and n_{sp} during a run, a conversion must be made using affinity laws, assuming that the conditions of these laws are fulfilled. The following formulae and procedures can be adopted:

6.1.2.1 Non-regulated turbine and pump; if $n \neq n_{sp}$:

$$\frac{Q_{n_{sp}}}{Q_n} = \frac{n_{sp}}{n}; \quad \frac{E_{n_{sp}}}{E_n} = \left(\frac{n_{sp}}{n}\right)^2; \quad \frac{P_{n_{sp}}}{P_n} = \left(\frac{n_{sp}}{n}\right)^3; \quad \eta_{n_{sp}} = \eta_n$$

Figure 13 a) and Figure 13 b) represent the guarantee curves and the shifting of measured quantities Q , P , converted to n_{sp} .

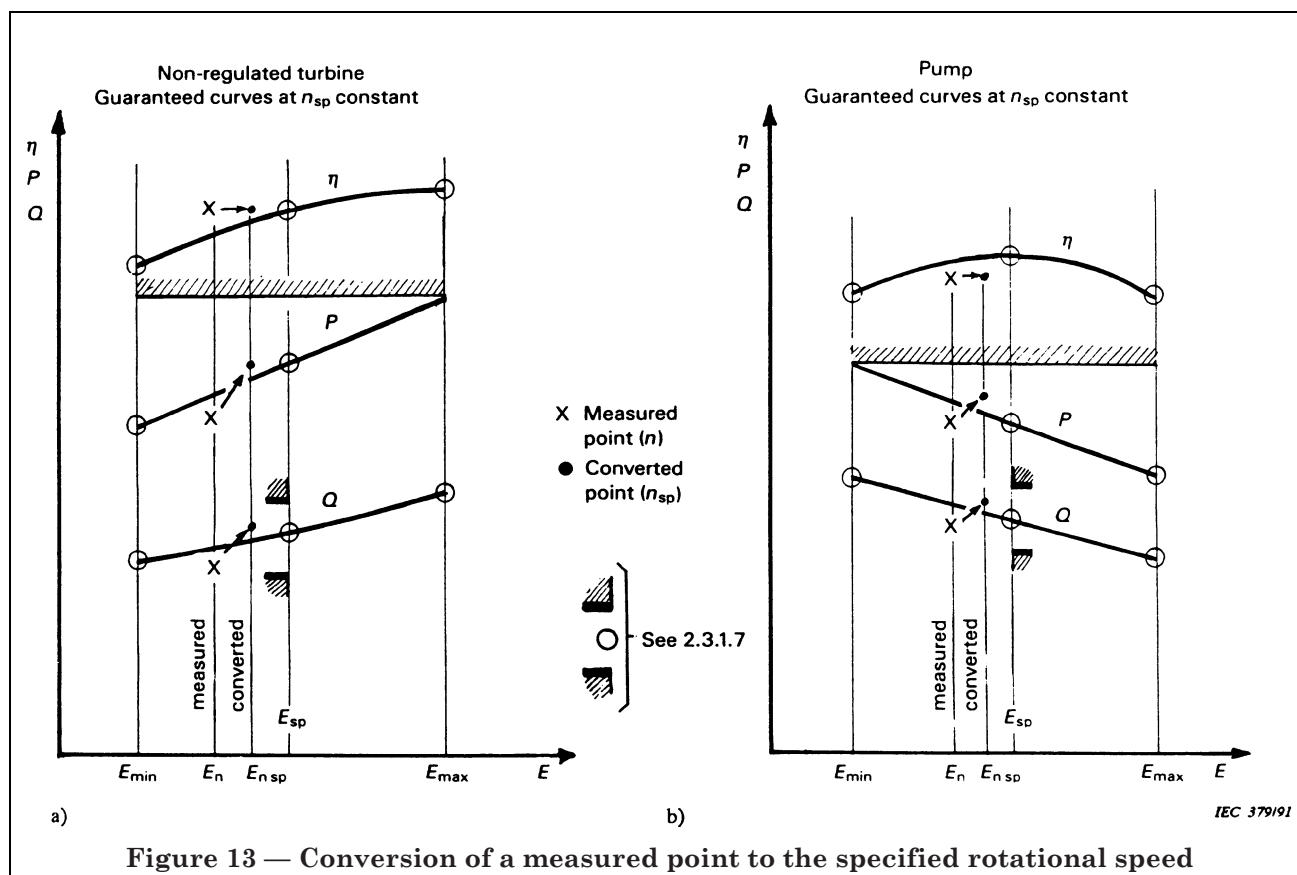


Figure 13 — Conversion of a measured point to the specified rotational speed

6.1.2.2 Regulated turbine: if $E_n \neq E_{sp}$ and/or $n \neq n_{sp}$, there are three possible cases:

- a) in some rare cases it is possible to meet the relation $\frac{n}{\sqrt{E}} = \frac{n_{sp}}{\sqrt{E_{sp}}}$ and to avoid corrections outlined under c) by adjusting the speed if $E \neq E_{sp}$ and/or the specific hydraulic energy if $n \neq n_{sp}$.

Conversion formulae are:

$$\frac{Q_{E_{sp}}}{Q_E} = \left(\frac{E_{sp}}{E} \right)^{1/2}$$

$$\frac{P_{E_{sp}}}{P_E} = \left(\frac{E_{sp}}{E} \right)^{3/2}$$

$$\eta_{E_{sp}, n_{sp}} = \eta_{E, n}$$

- b) when the adjustment described above is not possible, and if $0,99 \leq \frac{n/\sqrt{E}}{n_{sp}/\sqrt{E_{sp}}} \leq 1,01$, no correction [see c)] is necessary and the conversion formulae given at a) are used.

- c) when the adjustment described at a) is not possible and if $\frac{n/\sqrt{E}}{n_{sp}/\sqrt{E_{sp}}}$ is outside the range given at b), it is necessary to make — in addition to conversion — a correction.

For this purpose it is necessary to have — in addition to the efficiency guaranteed curves corresponding to the different specified specific hydraulic energies — the relevant portion of the efficiency hill diagram (see Figure 14). In the case where the efficiency guarantees are given only for a specified specific hydraulic energy, it is necessary to have the portion of the efficiency hill diagram included between maximum and minimum specific hydraulic energies of the operational range. A previous agreement should be reached between purchaser and supplier on this matter.

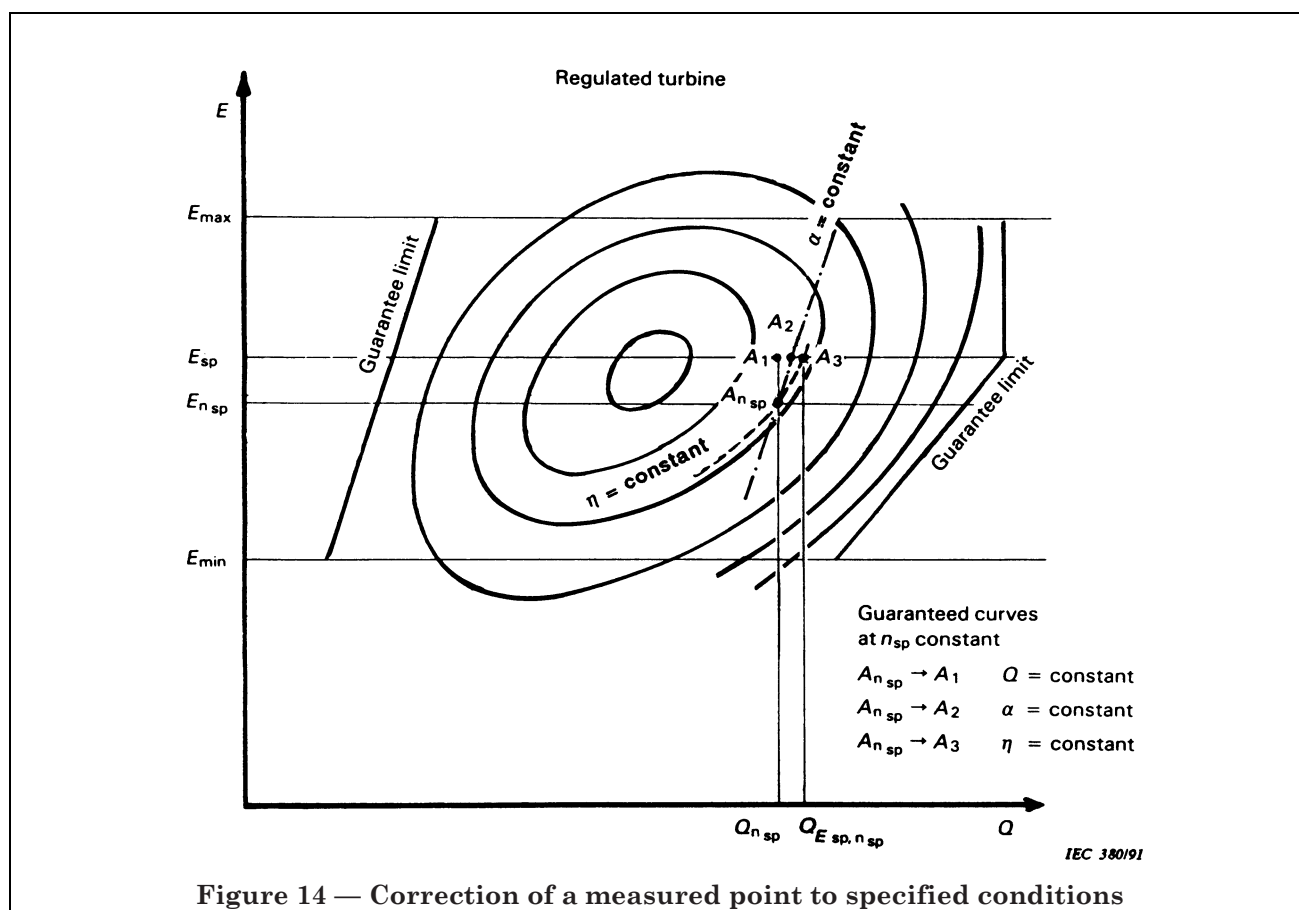
If $n \neq n_{sp}$ and $E \neq E_{sp}$, the first thing to do is to convert point A_n into $A_{n_{sp}}$ using the formulae described in 6.1.2.1. As $E_{n_{sp}} \neq E_{sp}$, the next step is to shift $A_{n_{sp}}$ to the line corresponding to E_{sp} in Figure 14, following a constant opening method (A_2). Other modes of shifting (i.e. at constant discharge A_1 , or at constant efficiency, A_3) may be agreed upon between the parties.

Efficiency shall be corrected by the formula:

$$\eta_{E_{sp}, n_{sp}} = \eta + \Delta\eta$$

where η = measured value and $\Delta\eta$ = difference between efficiency in A_2 for instance, and efficiency in $A_{n_{sp}}$ according to efficiency hill diagram.

E_{sp} is known, $Q_{E_{sp}, n_{sp}}$ and $\eta_{E_{sp}, n_{sp}}$ are determined as explained before, $P_{E_{sp}, n_{sp}}$ is consequently calculated.



6.1.3 Test curves

— For regulated turbines:

values of η shall be plotted against $P_{E_{sp}, n_{sp}}$ or $Q_{E_{sp}, n_{sp}}$; values of $P_{n_{sp}}$ shall be plotted against $E_{n_{sp}}$.

— For non-regulated turbines and for pumps:

values of $Q_{n_{sp}}$, $P_{n_{sp}}$ and η shall be plotted against $E_{n_{sp}}$.

Conversion to specified values is given in 6.1.2.

6.2 Uncertainties in measurements¹¹⁾ and presentation of results

6.2.1 Definition of error

The error in the measurement of a quantity is the difference between that measurement and the true value of the quantity.

No measurement of a physical quantity is free from uncertainties arising from systematic errors and random errors. Systematic errors cannot be reduced by repeating measurement since they arise from the characteristics of the measuring apparatus, the installation, and the operation conditions. However, a reduction in the random error may be achieved by repetition of measurements since the random error of the mean of n independent measurements is $\sqrt{n}$ times smaller than the random error of an individual measurement (see Appendix C).

6.2.2 Definition of uncertainty

The range within which the true value of a measured quantity can be expected to lie with a suitably high probability is termed the “uncertainty of the measurement”. For the purposes of this standard, the probability to be used shall be 95 % level.

6.2.3 Types of errors

There are three types of error which must be considered:

- spurious errors;
- random errors;
- systematic errors.

6.2.3.1 Spurious errors

These are errors such as human errors, or instrument malfunction, which invalidate a measurement: for example, the transposing of numbers in recording data or the presence of pockets of air in leads from a water line to a manometer. Such errors should not be incorporated into any statistical analysis and the measurement must be discarded. Where the error is not large enough to make the result obviously invalid, some rejection criteria should be applied to decide whether the data point should be rejected or retained.

Unless otherwise agreed, the Grubbs test described in Appendix B is recommended for testing possible outliers; other tests, such as the Dixon test given in ISO 5168, may be used by agreement.

It is necessary to recalculate the standard deviation of the distribution of results after applying the outlier test if any data points are discarded. It should also be emphasized that outlier tests may be applied only if there is an independent technical reason for believing that spurious errors may exist: data should not be thrown away lightly.

6.2.3.2 Random errors

Random errors are caused by numerous, small, independent influences which prevent a measurement system from delivering the same reading when supplied with the same input value of the quantity being measured.

The measurements deviate from the mean in accordance with the laws of chance, such that the distribution usually approaches a normal distribution as the number of measurements is increased.

The random error is influenced by the care taken during measurements, the number of measurements and the operating conditions. The scatter of readings observed during a point results from the combination of the random error arising from the instrumentation and of the influence of the operating conditions.

¹¹⁾ See ISO 5168.

6.2.3.3 Estimation of the uncertainty associated with random error

Statistical methods for estimating the uncertainty associated with random error are discussed in Appendix C and Appendix D.

When the sample size is small, it is necessary to correct the statistical results that are based on a normal distribution by means of Student's t values, as explained in these appendices. Student's t is a factor which compensates for the uncertainty in the standard deviation increasing as the sample size is reduced.

The uncertainty corresponding to a level of 95 % is written $(f_r)_{95}$.

An agreement prior to the test shall specify the maximum permissible value $\pm f_r$ of the uncertainty bandwidth due to random errors. If more than 5 % of the results are outside this range, an accurate analysis will be made and the measurements will be repeated or a new value of the uncertainty bandwidth due to random errors will be agreed.

6.2.3.4 Systematic errors

Systematic errors are those which cannot be reduced by increasing the number of measurements if the equipment and conditions of measurements remain unchanged.

The systematic error of a measurement depends partly on the residual error in the instrument or measuring system at the start of the test. At that time, all removable errors will have been eliminated by calibration, careful measurement of dimensions, proper installation, etc. The error still remaining is called systematic error (bias) and always exists, however small.

The systematic error is largely controlled by the choice of measuring method, and the operating conditions; for example, the value of the kinetic energy calculated with the mean velocity can differ from its true value if the velocity distribution at the measuring section is not sufficiently regular. Systematic errors do not affect the repeatability of measurements during a test.

Prior to any test, an agreement should be reached on an expected band of systematic uncertainty within the range given in the first column of Table AI, Appendix A. It must be emphasised that the values for systematic uncertainties listed in the second column are expected uncertainties when the measurements are made in normal conditions by experienced personnel with an apparatus of high quality, in accordance with the provisions of the standard. The actual value of systematic uncertainty usually depends on many factors, some of which can only be evaluated after the test. A review of these factors shall be made and an agreement between the parties concerned established whether the expected uncertainties have to be changed on technical grounds or not.

6.2.3.5 Estimation of the uncertainty associated with systematic errors

The uncertainty associated with systematic errors cannot be assessed experimentally without changing the equipment or conditions of measurement. This change can indicate an order of magnitude of the systematic error and should be applied whenever possible. The alternative is to make a subjective judgement on the basis of experience and consideration of the equipment involved.

The first step in the estimation of this uncertainty is to identify those aspects of the measurement that can affect its value; the second step is to allocate uncertainty limits to allow for each of these effects. This may be done, in part at least, by statistical analysis¹²⁾.

If the error has a unique known value then this shall be added to (or subtracted from) the result of the measurement and the uncertainty in the measurement due to this source is then taken as zero. If the systematic error of a measuring device is unknown but its error limits (class of accuracy) are specified, the interval between them may be assumed as the systematic uncertainty of that device with a confidence level better than 95 %.

Systematic errors usually are considerably larger than random errors for the highest quality field test.

Actually, notwithstanding the difference exposed above between systematic and random uncertainties, the probability distribution of the possible values of each systematic component is essentially gaussian and the systematic uncertainty f_s is computed from the individual systematic uncertainties by the root-sum-squares method; for example, the systematic uncertainty of efficiency $(f_\eta)_s$ is computed from the individual systematic uncertainties in discharge $(f_Q)_s$, specific hydraulic energy $(f_E)_s$ and power $(f_P)_s$ by:

$$(f_\eta)_s = \pm [(f_Q)_s^2 + (f_E)_s^2 + (f_P)_s^2]^{1/2}$$

See also Clause A.2 of Appendix A.

¹²⁾ See for example ISO 5168.

6.2.4 Total uncertainty

The total uncertainty in a measurement (f_t) is obtained by combining the systematic (f_s) and random (f_r) uncertainties (see 6.2.3.3 and 6.2.3.5). It defines a range within which the true value is assumed to have a probability of 95 % to lie, and any point in this range is equally valid.

Given the same type of probability distribution of the systematic and random uncertainties (see 6.2.3.5), they can be combined by the root-sum-squares method. The total uncertainty is thus given by:

$$f_t = \pm (f_s^2 + f_r^2)^{1/2}$$

6.2.5 Analysis of results

The method of analysis and presentation of results described hereafter with particular reference to comparison with guarantees is recommended. Appendix A contains estimates of systematic uncertainties; Appendix C and Appendix D provide enough information to make simple estimates of random uncertainties; Appendix B describes a method for rejecting outliers.

6.2.6 Presentation of results

Taking into account the total uncertainties calculated as explained in 6.2.4, each measured point should be represented on a diagram by an ellipse. The axes of this ellipse represent the total uncertainty, at a confidence level of 95 %, in the two quantities chosen as coordinates of the diagram. Any point within this ellipse is equally valid.

If a curve is guaranteed (guarantee given within a range of powers, for instance), an uncertainty band corresponding to the upper and lower envelopes of these ellipses is superimposed to the best fitted curve drawn through the test points (see Appendix D). All the points within this band are equally valid and thus this band constitutes an acceptable bandwidth for comparison with guarantees.

In some cases, for example, when the guarantee curve is plotted against specific hydraulic energy, the limits of the total uncertainty bandwidth can be obtained by reducing the ellipses to their principal axis.

6.3 Comparison with guarantees

The comparison with guarantees shall be made by the following methods using the total uncertainty bandwidth (see 6.2.6) and taking into account the contractual limits (see Figure 10a, Figure 10b and Figure 10c).

6.3.1 Power (see 3.2.2)

6.3.1.1 Regulated turbine

Figure 15 shows the guaranteed curve of the power to be reached against the specified specific hydraulic energy. In this example, the guarantee for power is not fulfilled in the range A.

