BS EN 62364:2013

BSI Standards Publication

Hydraulic machines — Guide for dealing with hydro-abrasive erosion in Kaplan, Francis, and Pelton turbines

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This British Standard is the UK implementation of EN 62364:2013. It is identical to IEC 62364:2013.

The UK participation in its preparation was entrusted to Technical Committee MCE/15, Hydraulic turbines.

A list of organizations represented on this committee can be obtained on request to its secretary.

Published by BSI Standards Limited 2013

ISBN 978 0 580 66842 5
ICS 23.100.10; 27.140

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 30 September 2013.

Amendments/corrigenda issued since publication

Date	Text affected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 62364

August 2013

ICS 23.100.10; 27.140

English version

Hydraulic machines - Guide for dealing with hydro-abrasive erosion in Kaplan, Francis, and Pelton turbines
(IEC 62364:2013)

Machines hydrauliques -
Guide relatif au traitement de l'érosion hydro-abrasive des turbines Kaplan, Francis et Pelton
(CEI 62364:2013)

Wasserturbinen -
Leitfaden für den Umgang mit hydroabrasiver Erosion in Kaplan-, Francis- und Pelton-Turbinen
(IEC 62364:2013)

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

CEN-CENELEC Management Centre: Avenue Marnix 17, B - 1000 Brussels

Ref. No. EN 62364:2013 E

Foreword

The text of document 4/279/FDIS, future edition 1 of IEC 62364, prepared by IEC TC 4 "Hydraulic turbines" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62364:2013.

The following dates are fixed:

– latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2014-05-01
– latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2016-08-01

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In the official version, for Bibliography, the following note has to be added for the standard indicated :

IEC 60193:1999 NOTE Harmonised as EN 60193:1999 (not modified).

CONTENTS

INTRODUCTION

Many owners of hydroelectric plants contend with the sometimes very aggressive deterioration of their machines due to particle abrasion. Such owners must find the means to communicate to potential suppliers of machines for their sites, their desire to have the particular attention of the designers at the turbine design phase, directed to the minimization of the severity and effects of particle abrasion.

Limited consensus and very little quantitative data exists on the steps which the designer could and should take to extend the useful life before major overhaul of the turbine components when they are operated under severe particle abrasion service. This has led some owners to write into their specifications, conditions which cannot be met with known methods and materials.

HYDRAULIC MACHINES – GUIDE FOR DEALING WITH HYDRO-ABRASIVE EROSION IN KAPLAN, FRANCIS, AND PELTON TURBINES

1 Scope

This Guide serves to:

a) present data on particle abrasion rates on several combinations of water quality, operating conditions, component materials, and component properties collected from a variety of hydro sites;

b) develop guidelines for the methods of minimizing particle abrasion by modifications to hydraulic design for clean water. These guidelines do not include details such as hydraulic profile shapes which should be determined by the hydraulic design experts for a given site;

c) develop guidelines based on “experience data” concerning the relative resistance of materials faced with particle abrasion problems;

d) develop guidelines concerning the maintainability of abrasion resistant materials and hard facing coatings;

e) develop guidelines on a recommended approach, which owners could and should take to ensure that specifications communicate the need for particular attention to this aspect of hydraulic design at their sites without establishing criteria which cannot be satisfied because the means are beyond the control of the manufacturers;

f) develop guidelines concerning operation mode of the hydro turbines in water with particle materials to increase the operation life;

It is assumed in this Guide that the water is not chemically aggressive. Since chemical aggressiveness is dependent upon so many possible chemical compositions, and the materials of the machine, it is beyond the scope of this Guide to address these issues.

It is assumed in this Guide that cavitation is not present in the turbine. Cavitation and abrasion may reinforce each other so that the resulting erosion is larger than the sum of cavitation erosion plus abrasion erosion. The quantitative relationship of the resulting abrasion is not known and it is beyond the scope of this guide to assess it, except to recommend that special efforts be made in the turbine design phase to minimize cavitation.

Large solids (e.g. stones, wood, ice, metal objects, etc.) traveling with the water may impact turbine components and produce damage. This damage may in turn increase the flow turbulence thereby accelerating wear by both cavitation and abrasion. Abrasion resistant coatings can also be damaged locally by impact of large solids. It is beyond the scope of this Guide to address these issues.

This guide focuses mainly on hydroelectric powerplant equipment. Certain portions may also be applicable to other hydraulic machines.

2 Terms, definitions and symbols

2.1 Units

The International System of Units (S.I.) is adopted throughout this guide but other systems are allowed.

2.2 Terms, definitions and symbols

For the purposes of this document, the following terms, definitions and symbols apply.

NOTE They are also based, where relevant, on IEC/TR 61364.

Sub-clause	Term	Definition	Symbol	Unit
2.2.1	specific hydraulic energy of a machine	specific energy of water available between the high and low pressure reference sections 1 and 2 of the machine Note 1 to entry: For full information, see IEC 60193.	E	J/kg
2.2.2	acceleration due to gravity	local value of gravitational acceleration at the place of testing Note 1 to entry: For full information, see IEC 60193.	g	m/s^2
2.2.3	turbine head pump head	available head at hydraulic machine terminal $H = E/g$	H	m
2.2.4	reference diameter	reference diameter of the hydraulic machine Note 1 to entry: For Pelton turbines this is the pitch diameter, for Kaplan turbines this is the runner chamber diameter and for Francis and Francis type pump turbines this is the blade low pressure section diameter at the band Note 2 to entry: See IEC 60193 for further information.	D	m
2.2.5	abrasion depth	depth of metal layer that has been removed from a component due to particle abrasion	S	mm
2.2.6	characteristic velocity	characteristic velocity defined for each machine component and used to quantify particle abrasion damage Note 1 to entry: See also 2.2.20 to 2.2.24.	W	m/s
2.2.7	particle concentration	the mass of all solid particles per m^3 of water solution Note 1 to entry: In case the particle concentration is expressed in ppm it is recommended to use the mass of particles per mass of water, so that 1 000 ppm approximately corresponds to 1 kg/m^3.	C	kg/m^3
2.2.8	particle load	the particle concentration integrated over the time, T, that is under consideration $PL = \int_0^T C(t) \times K_{\text{size}}(t) \times K_{\text{shape}}(t) \times K_{\text{hardness}}(t) dt$ $\left(\approx \sum_{n=1}^{N} C_n \times K_{\text{size},n} \times K_{\text{shape},n} \times K_{\text{hardness},n} \times T_{s,n} \right)$ $C(t)$ = 0 if no water is flowing through the turbine. If the unit is at standstill with pressurized spiral case then $C(t)$=0 when calculating PL for runner and labyrinth seals, but $C(t)$≠0 when calculating PL for guide vanes and facing plates.	PL	$\text{kg} \times \text{h/m}^3$
2.2.9	size factor	factor that characterizes how the abrasion relates to the size of the abrasive particles	K_{size}	
2.2.10	shape factor	factor that characterizes how the abrasion relates to the shape of the abrasive particles	K_{shape}	
2.2.11	hardness factor	factor that characterizes how the abrasion relates to the hardness of the abrasive particles	K_{hardness}	

Sub-clause	Term	Definition	Symbol	Unit
2.2.12	material factor	factor that characterizes how the abrasion relates to the material properties of the base material	K_m	
2.2.13	flow coefficient	coefficient that characterizes how the abrasion relates to the water flow around each component	K_f	$\frac{\mathrm{mm} \times \mathrm{s}^{3,4}}{\mathrm{kg} \times \mathrm{h} \times \mathrm{m}^{\alpha}}$
2.2.14	sampling interval	the time interval between two water samples taken to determine the concentration of abrasive particles in the water	T_s	h
2.2.15	yearly particle load	the total PL for 1 year of operation, i.e. PL for T = 8 760 h calculated in accordance with 2.2.8	PL_year	kg × h/m^3
2.2.16	maximum concentration	the maximum concentration of abrasive particles over a specified time interval	C_max	kg/m^3
2.2.17	particle median diameter	the median diameter of abrasive particles in a sample, i.e. such diameter that the particles with size smaller than the value under consideration represent 50 % of the total mass of particles in the sample	dP_{50}	mm
2.2.18	wear resistance index	abrasion depth or volume of a reference material (generally some version stainless steel) divided by the abrasion depth or volume of the material in question, tested under the same conditions	WRI	-
2.2.19	impingement angle	the angle between the particle trajectory and the surface of the substrate		°
2.2.20	characteristic velocity in Francis guide vanes characteristic velocity in Kaplan guide vanes	flow through unit divided by the minimum flow area at the guide vane apparatus estimated at best efficiency point $W_\mathrm{gv} = \frac{Q}{a \times Z_0 \times B_0}$	W_gv	m/s
2.2.21	characteristic velocity in guide vanes of Kaplan, Francis or tubular turbines	speed of the water flow at guide vane location $W_\mathrm{gv} = 0{,}5 \times \sqrt{2 \times E}$	W_gv	m/s
2.2.22	characteristic velocity in Pelton injector	speed of the water flow at injector location $W_\mathrm{inj} = \sqrt{2 \times E}$	W_inj	m/s
2.2.23	characteristic velocity in Kaplan or Francis tubular turbine runner	the relative velocity between the water and the runner blade estimated with below formulas at best efficiency point $W_\mathrm{run} = \sqrt{{u_2}^2 + {c_2}^2}$ $u_2 = n \times \pi \times D$ $c_2 = \frac{Q \times 4}{\pi \times D^2}$ Note 1 to entry: In calculation of c_2 for Kaplan turbines, the hub diameter has been neglected in the interest of simplicity.	W_run	m/s
2.2.24	characteristic velocity in Pelton runner	speed of the water flow at a Pelton runner $W_\mathrm{run} = 0{,}5 \times \sqrt{2 \times E}$	W_run	m/s
2.2.25	discharge (volume flow rate)	volume of water per unit time passing through any section in the system	Q	m^3/s
2.2.26	guide vane opening	average shortest distance between adjacent guide vanes (at a specified section if necessary)	A	m

Sub-clause	Term	Definition	Symbol	Unit
		Note 1 to entry: For further information, see IEC 60193.		
2.2.27	number of guide vanes	total number of guide vanes in a turbine	z_0	
2.2.28	distributor height	height of the distributor in a turbine	B_0	m
2.2.29	rotational speed	number of revolutions per unit time	n	1/s
2.2.30	specific speed	commonly used specific speed to of an hydraulic machine $n_\text{s} = \frac{60 \times n \times \sqrt{P}}{H^{5/4}}$ P and H are taken in the rated operating point and given in kW and m respectively	n_s	
2.2.31	output	output of the turbine in the rated operating point	P	kW
2.2.32	actual abrasion depth of target unit	the estimated depth of metal that will be removed from a component of the target turbine due to particle abrasion Note 1 to entry: For use with the Reference model.	$S_\text{target, actual}$	mm
2.2.33	actual abrasion depth of reference unit	the actual depth of metal that has been removed from a component of the reference turbine due to particle abrasion Note 1 to entry: For use with the Reference model.	$S_\text{ref, actual}$	mm
2.2.34	number of nozzles	number of nozzles in a Pelton turbine	z_0	
2.2.35	bucket width	bucket width in a Pelton runner	B_2	mm
2.2.36	number of buckets	number of buckets in a Pelton runner	z_2	
2.2.37	time between overhaul for target unit	time between overhaul for target unit Note 1 to entry: For use with the reference model.	TBO_target	h
2.2.38	time between overhaul for reference unit	time between overhaul for reference unit Note 1 to entry: For use with the reference model.	TBO_ref	h
2.2.39	turbine reference size	the reference size for calculation curvature dependent effects of erosion Note 1 to entry: For Francis turbines, it is the reference diameter, D (see 2.2.4). Note 2 to entry: For Pelton turbines it is the inner bucket width, B. Note 3 to entry: For further information in the inner bucket width, B, see IEC 60609-2.	RS	m
2.2.40	size exponent	exponent that describes the size dependant effects of erosion in evaluating RS	p	
2.2.41	exponent	numerical value of 0,4-p that balances units for K_f	α	

3 Abrasion rate

3.1 Theoretical model

In order to demonstrate how different critical aspects impact the particle abrasion rate in the turbine, the following formula is considered:

$dS/dt = f$(particle velocity, particle concentration, particle physical properties, flow pattern, turbine material properties, other factors)

However, this formula being of little practical use, several simplifications are introduced. The first simplification is to consider the several variables as independent as follows:

$dS/dt = f$(particle velocity) × f(particle concentration) × f(particle physical properties, turbine material properties) × f(particle physical properties) × f(flow pattern) × f(turbine material properties) × f(other factors)

This simplification is not proven. In fact, many examples can be found where this simplification was not strictly valid. Nevertheless, based on literature studies and experience, this simplification is considered to be justified for hydraulic machines.

The next simplification consists in assigning values to the functions. In the following equations the numerical values for the parameters, without units, have to be used. The units in which the values should be based are given below:

- f(particle velocity) = (particle velocity)^n. In the literature abrasion is often considered proportional to the velocity raised to an exponent, n. Most references give values of n between 2 and 4. In this guide we suggest to use $n = 3{,}4$. Particle velocity in m/s,
- f(particle concentration) = particle concentration in kg/m^3,
- f(particle physical properties, turbine material properties) = K_{hardness} = function of how hard the particles are in relation to the material at the surface. At the present stage we suggest to use K_{hardness} = fraction of particles harder than the material at the surface,
- f(flow pattern) = $K_{\text{f}}/RS^{\text{p}}$ (K_{f} = constant for each turbine component, RS = turbine reference size in m, p = exponent for each turbine component). K_{f} considers impingement angle and flow turbulence. RS^{p} considers part curvature radius,
- f(particle physical properties) = f(particle size, particle shape, particle hardness) = f(particle size) × f(particle shape) = $K_{\text{size}} \times K_{\text{shape}}$. Note that in this simplification it as assumed that there is no influence from the particle hardness for this function. The particle hardness is considered in the K_{hardness} factor,
- K_{size} = median diameter of particles in mm,
- $K_{\text{shape}} = f$(particle angularity). It is believed that K_{shape} will increase with the degree of irregularity of the particles. Specific data is not available at present but several literature references indicate that K_{shape} varies from 1 to 2 from round to sharp,
- f(turbine material properties) = K_{m}. In this guide we consider $K_{\text{m}} = 1$ for martensitic stainless steel with 13 % Cr and 4 % Ni and $K_{\text{m}} = 2$ for carbon steel. For coated components K_{m} should be smaller than 1,
- f(other factors) = 1.

Again, these functions are engineering approximations in order to obtain useful results for hydraulic machines. We then have the following formula

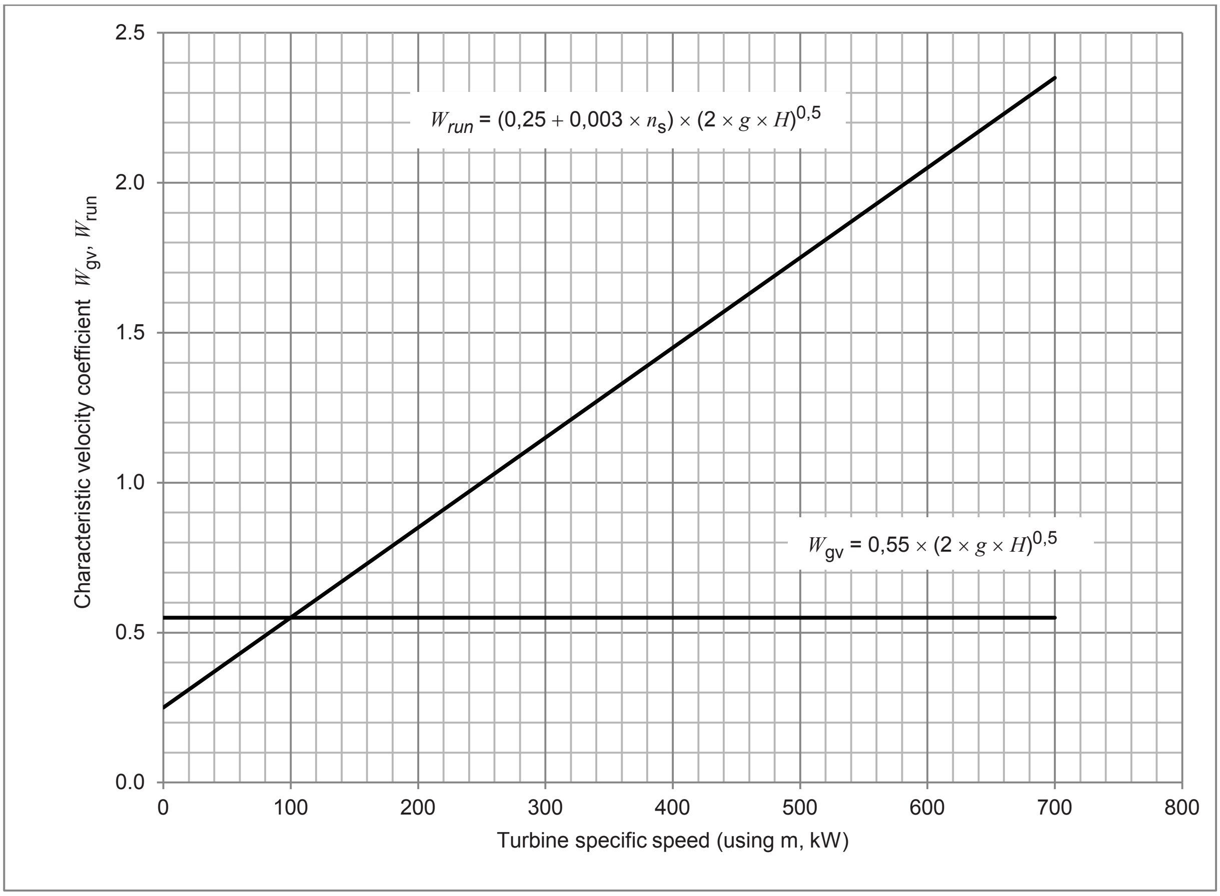
$$dS/dt = (\text{particle velocity})^{3,4} \times C \times K_{\text{hardness}} \times K_{\text{size}} \times K_{\text{shape}} \times K_{\text{f}} / RS^{\text{p}} \times K_{\text{m}}$$

The final step is to integrate this formula with respect to time. When we do this we find three distinct different types of variables with respect to their variations in time:

1) particle velocity and K_{f}: these variables vary with the water flow relative to the individual component, which in turn may vary with the head and flow;
2) C, K_{hardness}, K_{size} and K_{shape}: these variables vary with the particle properties. Integrated over time these variables become particle load, PL (see 2.2.8 for definition of PL and Annex A for a sample calculation);
3) RS, p and K_{m}: these variables are constant in time.

To find a simple and reasonably accurate estimate of the time integral, the *PL* variable (see 2.2.8) is introduced. *PL* integrates *C*, K_{hardness}, K_{size} and K_{shape} over time. When using *PL*, the particle velocity and K_{f} can be considered approximately constant over a limited variation of head and flow (see 3.2). Since these variables are considered constant, K_{f} and p were used as calibration factors to obtain good agreement between actual test data and the formula. The particle velocity can be replaced with the characteristic velocity, *W*, defined in 2.2.20 to 2.2.24.

W may be calculated for a specific turbine based on main data and dimensions. Since the effect of velocity on abrasion is proportional to the velocity raised to a power of 3,4 it is very important to estimate it accurately. For new turbines during design and bid stage, *W* for different components should be provided by the turbine manufacturer. When this is not possible, *W* can be estimated approximately from the diagram in Figure 1.



NOTE Values of *ns* and *H* in this figure refer to the rated operating point while the characteristic velocities are given for the points noted in 2.2.

Figure 1 – Estimation of the characteristic velocities in guide vanes, W_{gv}, and runner, W_{run}, as a function of turbine specific speed

So the final, time integrated formula becomes:

$$S = W^{3,4} \times PL \times K_{\mathrm{m}} \times K_{\mathrm{f}} / RS^{\mathrm{p}}$$

S is the numerical value of the abrasion depth in mm.

3.2 Introduction to the *PL* variable

In this code the *PL* variable has been introduced, which has not been widely used before. One common way to integrate abrasion over time has been to consider the total weight of particles that pass the turbine. However, this approach has usually not considered the effects from variation in flow or head in the turbine and could therefore lead to erroneous conclusions.

To illustrate this consider the following example. A Pelton injector (see Figure 2) operates for one day. Assume the head is 800 m and the abrasive particle concentration is 0,1 kg/m^3.

> Case 1: At full opening (top half of Figure 2) the water with particles flows over the seat ring with a velocity of $(2\times g\times H)^{0,5}$ = 125 m/s. In one day the amount of particles that pass the injector is 2 m^3/s × 3 600 s/h × 24 h/day × 0,1 kg/m^3 × 1 day = 17 tons.
>
> Case 2: At 10 % opening (bottom half of Figure 2) the water with particles flows over the seat ring with the same velocity as in case 1 (125 m/s). In one day the amount of particles that pass the injector is 0,2 × 3 600 × 24 × 0,1 × 1 = 1,7 tons.

In both cases the seat ring has been subject to abrasion with the same particle concentration, the same water velocity and the same amount of time. Therefore, the expected abrasion damage is the same. The PL variable also gives the same value in both cases. However, the total weight of particles that has passed the unit is 10 times higher in case 1 compared to case 2. So, PL is expected to correlate better with abrasion damage than the total weight of particles that has passed the seat ring.

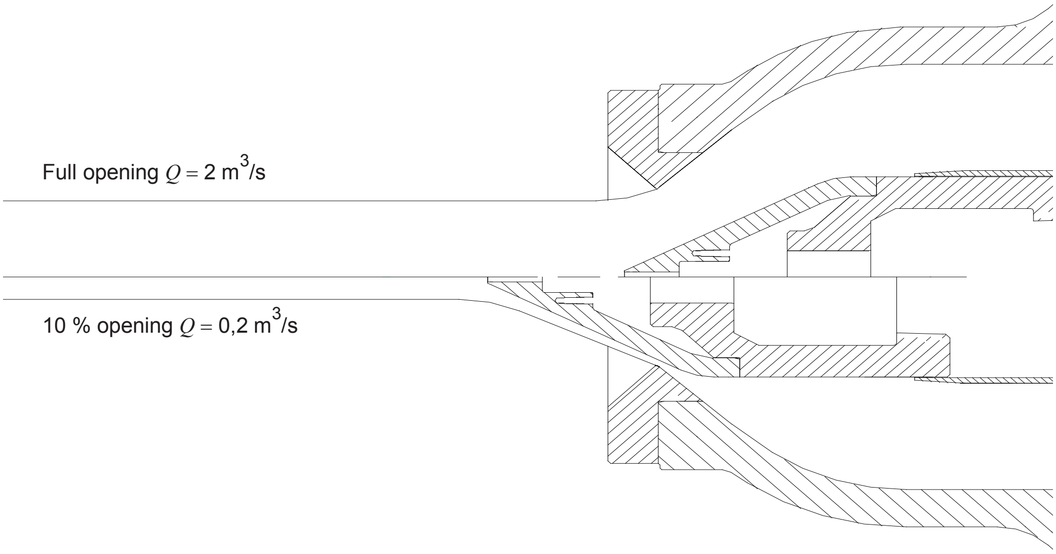


Figure 2 – Example of flow pattern in a Pelton injector at different load

The same type of reasoning can also be applied to other components subject to abrasion. In the following is a condensed summary of such analysis.

- Pelton needle tip

Very good correlation between PL and abrasion damage with minor influence of turbine discharge or head is expected. Some influence from the turbine flow since the water velocity is lower further inside the injector, where the needle is located at high flows. Some influence from turbine head since the water velocity is proportional to the square root of the head. With head and flow variations that are normal in Pelton projects this influence is disregarded in the interest of simplicity.

- Pelton runner

Good correlation between PL and abrasion damage with minor influence of turbine discharge or head is expected. Some influence from the turbine flow since the water film is thicker at higher flows and therefore more particles may be pressed towards the outside surface due to centrifugal forces. Some influence from turbine head since the relative water velocity in the runner depends on the head. With head and flow variations that are normal in Pelton projects, this influence is disregarded in the interest of simplicity.

- Francis and Kaplan guide vanes and covers / facing plates

Good correlation between PL and abrasion damage with minor influence of turbine discharge or head is expected. Some influence from the turbine flow since the water velocity is higher at low discharge and the pressure difference between the two sides of the guide vane varies with flow. In particular, if the unit is at standstill with pressurized spiral case the leakage flow through the guide vanes has high velocity. Some influence from the turbine head since the relative water velocity in the guide vanes depends on the head. With head and flow variations that are normal in Francis and Kaplan projects, this influence is disregarded in the interest of simplicity.

- Francis runner seals / labyrinths

Very good correlation between PL and abrasion damage with minor influence of turbine discharge or head is expected. Some influence is expected from the turbine flow and head since they influence the pressure before and after the seal and thus the leakage flow through the seal. With head and flow variations that are normal in Francis projects, this influence is disregarded in the interest of simplicity.

- Francis runner blade inlet

Good correlation between PL and abrasion damage with minor influence of turbine discharge or head is expected. Some influence from the turbine discharge is expected since the water velocity is higher at low discharge. Moreover, the pressure difference between the two sides of the guide vanes varies with opening, resulting in more leakage between the guide vanes and the covers which in turn results in more unfavourable flow conditions at the runner inlet. Also discharge and head variations from the optimum operating point, will result in more unfavourable flow conditions at the runner inlet. With head and flow variations that are normal in Francis projects this influence is disregarded, as long as inlet cavitation is not present, in the interest of simplicity.

- Francis runner blade outlet

Reasonable correlation between PL and abrasion damage with minor influence of turbine discharge or head is expected. At part load there are two main phenomena that influence the wear. One is that the average velocity (defined as the total flow divided by the flow passage area) will decrease with decreasing discharge. The other is that the degree of turbulence will increase and the flow distribution will lose uniformity at low discharge (typically below 50 % to 80 % of maximum discharge). These two phenomena influence the wear in opposite ways, but it is expected that the turbulence effect will dominate and thus that the wear will increase at partial load. However, due to lack of supporting data this influence is disregarded in the interest of simplicity.

- Kaplan runner blade

Very good correlation between PL and abrasion damage with minor influence of turbine discharge or head is expected. With head and flow variations that are normal in Kaplan projects this influence is disregarded in the interest of simplicity.

- Kaplan runner chamber

Good correlation between PL and abrasion damage with minor influence of turbine discharge or head is expected. With head and flow variations that are normal in Kaplan projects this influence is disregarded in the interest of simplicity.

3.3 Survey results

A questionnaire was sent to plant operators at sites known for their exposure to particle abrasion problems. The purpose of this questionnaire was to collect and analyse data on particle abrasion rates on as many combinations of water quality, operating conditions, component materials, and component properties as possible.

This data was analyzed and the factor K_f and the exponent p determined for each component to get the best possible correspondence between the calculated and observed amount of erosion. The average K_f was then determined for all observations with components of the same type. Table 1 below shows the resulting K_f and p for various components as well as the number of observations. The ratio between the measured and calculated values of the abrasion depth was determined and the standard deviation calculated.

Table 1 – Data analysis of the supplied questionnaire

Component	K_f	**Exponent p (for RS)**	**Number of observations**	**Standard deviation %**
Francis guide vanes	$1{,}06 \times 10^{-6}$	0,25	7	42
Francis facing plates	$0{,}86 \times 10^{-6}$	0,25	7	38
Francis labyrinth seals	$0{,}38 \times 10^{-6}$	0,75	7	30
Francis runner inlet	$0{,}90 \times 10^{-6}$	0,25	6	26
Francis runner outlet	$0{,}54 \times 10^{-6}$	0,75	6	41

Although the values of standard deviation in the table above shows that the formula gives reasonable accuracy, it should be kept in mind that the amount of observations is limited and that further observations may improve the formula.

It is only for Francis turbines that enough data has been available for a meaningful analysis. Not enough data is available for Kaplan and Pelton turbines to give detailed guidelines.

In general, it is challenging to obtain complete and unambiguous observations from existing measurements. It is hoped that additional observations can be made in the future to further calibrate and revise the erosion model.

3.4 Reference model

In the Reference model presented in this guide the TBO of two turbines are compared to each other. To do this the TBO of one turbine (here called reference turbine) and the differences in the influencing parameters to another turbine (here called target turbine) have to be known to calculate the TBO of the target turbine. Note that the same overhaul criteria have to be applied for both the target and reference turbines.

The aim of the Reference model is not to calculate the erosion depth (S). Therefore a calibrated model for the depth is not necessary. The criteria for the TBO can be the relative amount of damage, the efficiency loss or some other criteria but has to be the same for both turbines.

There are a few differences in the way the formula is built up between the Reference model and the absolute model as follows:

- since the Reference model does not calculate the erosion depth of individual components, constants valid for the whole turbine are used instead of different constants for different components;
- a larger turbine can normally withstand more abrasion depth than a small turbine before it needs overhaul. For this reason the exponent for turbine reference size, p, is chosen as 1 in the Reference model;
- for Pelton turbines it is assumed that the critical component for overhaul is the runner. In addition to the factors described above, the K_f for Pelton runners is assumed to be

proportional to the number of nozzles and the speed and inversely proportional to the number of buckets;
- for Pelton turbines the reference size is taken as the bucket width, B_2, instead of the runner diameter.

The *TBO* for the target turbine can be calculated as follows:

$$TBO_{\text{target}} / TBO_{\text{ref}} = W_{\text{ref}}^{3,4} / W_{\text{target}}^{3,4} \times PL_{\text{ref}} / PL_{\text{target}} \times K_{\text{m,ref}} / K_{\text{m,target}} \times K_{\text{f,ref}} / K_{\text{f,target}} \times RS_{\text{target}}^{\text{p}} / RS_{\text{ref}}^{\text{p}}$$

In this equation we use the following values for the relationships:

Pelton turbines: $K_{\text{f, ref}} / K_{\text{f, target}} = z_{0,\text{ref}} \times n_{\text{ref}} \times z_{2,\text{target}} / (z_{0,\text{target}} \times n_{\text{target}} \times z_{2,\text{ref}})$

Francis and Kaplan turbines: $K_{\text{f,ref}} / K_{\text{f,target}} = 1$

Size exponent: $p = 1$

The accuracy of the Reference model might decrease when the differences between the reference and target turbines become large.

The sensitivity of the calculated *TBO* value to variances in the input variables can also be studied with the same formula.

4 Design

4.1 General

The following guidelines explain some recommended methods to minimize particle abrasion and the effects thereof, by modifying the design for clean water.

It should be understood that every hydraulic powerplant is a compromise between several requirements. While it is possible to design a unit to be more resistant against particle abrasion this may adversely affect other aspects of the turbine. Some examples are:

- thicker runner blades may result in decreased efficiency and increased risk of vibrations from von Karman vortices,
- fewer runner blades (in order to improve the access to the blade surfaces for thermal spray surface treatment) may result in reduced cavitation performance,
- abrasion resistant coatings may initially result in increased surface roughness, which may reduce the efficiency,
- reduced runner blade overhang may result in reduced cavitation performance, which in turn may reduce the output that can be achieved for a turbine upgrade,
- many abrasion resistance design features will increase the total cost of the powerplant.

The optimum combination of abrasion resistant design features should be considered and selected for each site based on its specific conditions.

4.2 Water conveyance system

An important consideration for the water conveyance system is to remove as many particles as possible already before they enter the high velocity zones in the machinery. Large reservoirs may be very useful for this purpose. If a large reservoir is not available, so-called desilting chambers may be built. It appears that the minimum particle size that can be removed by desilting chambers is to the order of 0,1 mm to 0,3 mm unless the cost and size of the structures becomes prohibitive. The detailed design of desilting chambers is outside the scope of this Guide.

It is also important that any transient conditions that the powerplant may experience do not disturb the sand in sand traps, or other places where sand may accumulate, so that it is drawn into the turbine. Therefore, the design of sand traps should also consider possible transient conditions.

Even small amounts of large particles, such as stones, can cause severe damage since they may not be able to pass the turbine until they have been crushed into smaller pieces. This is due to the centrifugal force in the rotating water between runner and guide vanes. It is therefore important that tunnels and penstocks are clean and tidy at initial startup and after maintenance work.

Due to generally low velocity the water conveyance system itself seldom sees significant abrasion damage and normal coating paint is usually enough to protect it.

4.3 Valve

4.3.1 General

If solid particle abrasion is expected, as a general rule all mechanical disturbances in the flow are subject to high abrasive attack. Therefore a spherical valve should be preferred instead of a butterfly valve where the sealing disc is continuously exposed to the abrasive water flow.

As a general rule for the design, the area exposed to the abrasive water should be as small as possible. Discontinuities and sharp transitions or direction change of the flow should also be avoided.

The shape of the housing around the sealing of the rotor or disc shall be smooth without sharp edges and big changes in the flow direction.

In case of several units on a single penstock and with a spherical valve or a butterfly biplane valve as inlet valve, it is preferable to have a maintenance seal in addition to the service seal. This will make it possible to do maintenance of the downstream seal while the other units are in service.

A ring gate is a special type of valve and similar considerations apply to the ring gate and the main inlet valve.

4.3.2 Selection of abrasion resistant materials and coating

The selection of materials and possible abrasion resistant coatings for components which are subject to abrasive wear is important. See also Clause 5.

Because corrosion with simultaneously acting abrasion increases the wear rate, stainless steel is the preferred selection. Weldable stainless steel materials are preferred. On the basis of the larger hardness, martensitic steel is favored over austenitic steel. Weldability and erosion resistance are often contradictory and an optimum should be sought in each case.

The possibility to weld in situ is an advantage for future repair.

In case abrasion resistant coatings are not applied, it is recommended to make a mechanical component design where such coatings can easily be applied at a later stage.

The whole sealing area should be made of stainless steel and, if subject to abrasive wear, a coating should be applied.

4.3.3 Stainless steel overlays

Stainless steel welded overlays with sufficient thickness may be used instead of solid stainless components, if the abrasion area is not too large.

4.3.4 Protection (closing) of the gap between housing and trunnion

The area between trunnion and housing is especially susceptible for abrasive wear. Since the transition trunnion to the rotor is one of the highly stressed areas of the inlet valves this area has to be especially protected. Completely stainless or welded stainless overlay protected trunnions are recommended. Through a pre-labyrinth, the transitions can be protected against the direct attack of abrasive particles (see Figure 3).

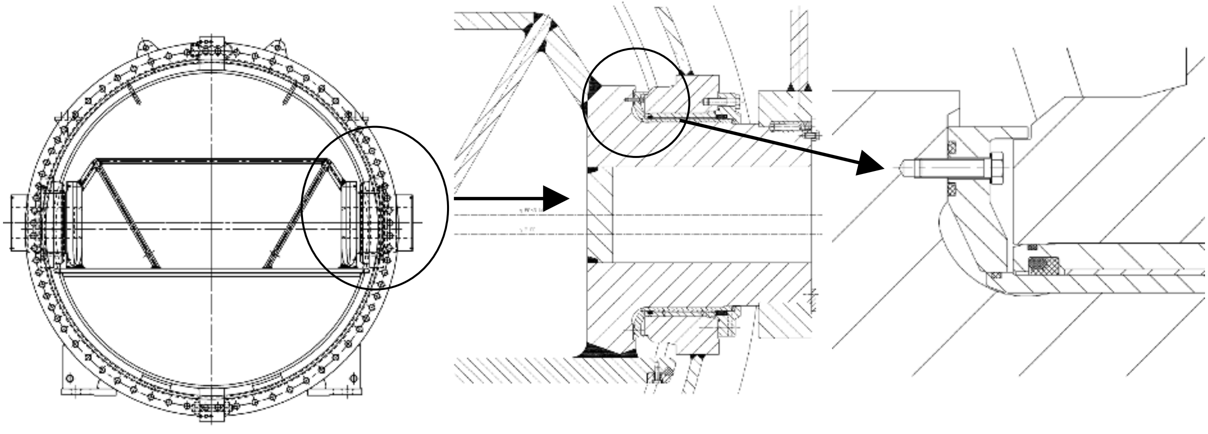


Figure 3 – Example of protection of transition area

4.3.5 Stops located outside the valve

In abrasive conditions, it is recommended that stops, which limit the angle of rotation of the rotor, are placed outside of the flow in the servomotor or adjacent to the lever.

4.3.6 Proper capacity of inlet valve operator

Normally inlet valves will be opened or closed with an approximately balanced pressure that is established by the bypass or the movable sealing rings.

If excessive abrasion occurs at the guide vanes, the differential pressure for the closing or opening of the inlet valve may be bigger than allowed or fixed in the layout. It is therefore recommended that the design takes into account a higher differential pressure for opening or closing. If the inlet valve is designed as an emergency shutoff valve it may already be able to open against a higher differential pressure.

Please see 5.2.2 for an example of how the pressurization of the spiral case can develop with abrasive wear in the guide vanes.

4.3.7 Increase bypass size to allow higher guide vane leakage

As already mentioned in 4.3.6 above, due to the excessive abrasion at the guide vanes the leakage water flow will increase to such an extent, that the balance water flow through the bypass of the inlet valve is not sufficient to achieve the pressure balance between the inlet pipe and spiral casing.

It is therefore recommended to increase the capacity of the bypass system.

4.3.8 Bypass system design

It is recommended to use an external bypass system instead of an internal one.

4.4 Turbine

4.4.1 General

These guidelines do not include details such as hydraulic profile shapes which should be determined by the hydraulic design experts for a given site.

4.4.2 Hydraulic design

4.4.2.1 Selection of type of machine

It is advantageous to select a type of machine that has low water velocity, that can easily be serviced and that can easily be coated with abrasion resistant coatings. Some general guidelines are as follows:

- in the choice between a vertical shaft Kaplan and a Bulb, the Kaplan will normally have lower velocity (see Figure 1). The serviceability and ease of coating is approximately equal between the two;
- in the choice between a Kaplan and a Francis, the Francis will normally have lower velocity. On the other hand, the Kaplan runner has better access for applying abrasion resistant coatings. The serviceability is approximately equal between the two;
- in the choice between a Francis and a Pelton the Francis will normally have lower maximum velocity. However, the parts in a Pelton turbine that are subject to the maximum velocity (i.e. the needle tips and seat rings) are small and have better access for applying abrasion resistant coatings. The Pelton turbine is also easier to service.

4.4.2.2 Specific speed

For the same plant lower specific speed machines are normally bigger and have lower water velocities in the runner outlet. However, the water velocities are not lower in the guide vanes and in the runner inlet. For Kaplan, Bulb and low head Francis turbines, most of the abrasion damage will be in the runner so the specific speed is important. For high head Francis turbines much of the abrasion damage will be in the guide vane apparatus, so the specific speed is not so important.

For Pelton turbines the water velocity does not depend on the specific speed. However, a lower number of jets is beneficial for a Pelton turbine since the buckets will be larger which in turn gives less water acceleration in the buckets and thus less abrasion damage. A lower number of jets will automatically result in a lower specific speed.

4.4.2.3 Variable speed

Even though variable speed machines are not frequent, they are less prone to cavitation, even under a wide head range operation. Due to this characteristic, the variable speed machine may better resist particle abrasion.

4.4.2.4 Turbine submergence

Cavitation and abrasion will mutually reinforce each other. For this reason it is recommended that the turbine submergence is higher for plants where abrasion is expected.

4.4.2.5 Runner blade overhang

During the refurbishment of a Francis turbine wheel it is sometimes necessary to significantly increase the turbine output. One way to do this is to extend the runner band inside the draft tube cone, in order to increase the blade area and therefore improve the cavitation performance, see Figure 4. However, this creates additional turbulences at the entrance of the draft tube cone that will increase metal removal if particles are present in the water. A secondary effect of the overhang blades is to create a lower pressure zone downstream of the runner band seal, thus creating higher seal leakage and more particle abrasion at the band seal.

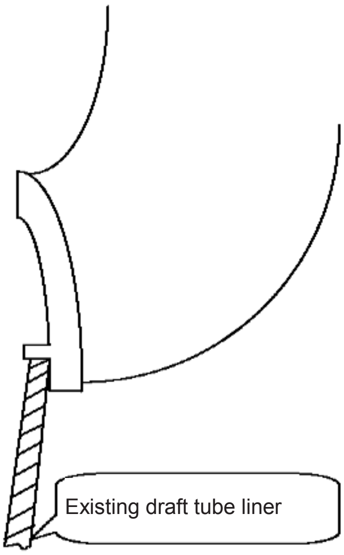


Figure 4 – Runner blade overhang in refurbishment project

4.4.2.6 Thicker runner blades and guide vanes

Increased runner blade thickness, particularly at the outflow edge, gives some extra margin before the removal of material on the runner blades becomes critical for the structural integrity of the runner. Designing a thicker blade should be done with care. A thicker blade may reduce the turbine efficiency and increase the risk for issues with von Karman vortices. Also, the risk of “mouse-ear” cavitation (cavitation damage on the runner band, downstream of the blade, see Figure 5) may increase. In this context it can be mentioned that abrasion resistant coatings may provide a means to design thin profiles with only a marginal increase in the thickness due to the coating.

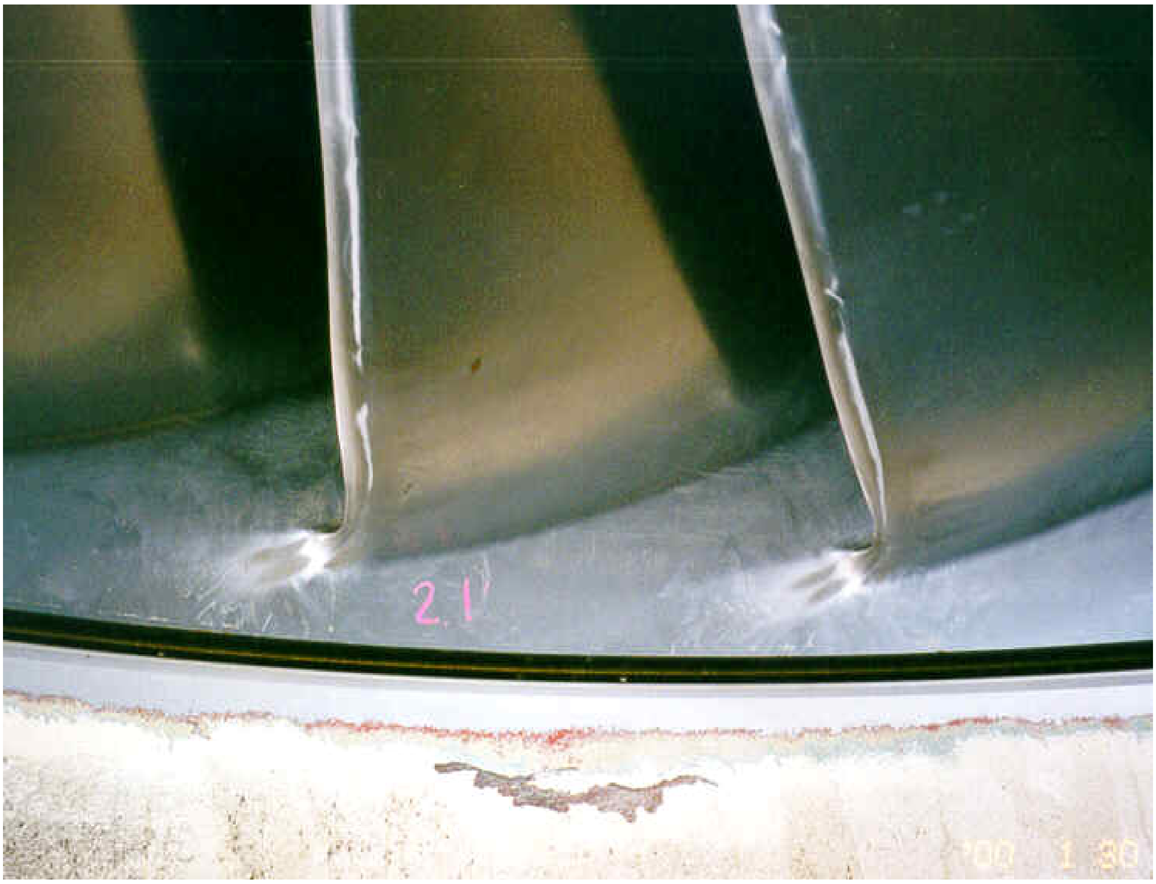


Figure 5 – Example of "mouse-ear" cavitation on runner band

Thicker guide vanes may also give an additional margin on abrasion, especially at the guide vane – trunnion area, although the critical areas in the guide vane apparatus are usually the guide vane end faces and the head covers and bottom rings, or facing plates.

4.4.2.7 Guide vane overhang

When guide vane overhang exists, the area underneath the guide vane will experience high turbulence and high recirculation and particle abrasion may be significant in that region. The high turbulence may also influence the runner inlet at the band. It is recommended to make the overhang as small as possible.

4.4.3 Mechanical design

4.4.3.1 General

If abrasion is expected and the turbine type is defined, not only the hydraulic design but also the mechanical design can take some precautions to reduce the abrasion rate and to allow easy maintenance or replacement of the abraded parts. In this subclause some features are mentioned.

If a special coating is foreseen, the design of the coated parts shall allow the type of application.

As a general rule for the design, the area exposed to the abrasive water should be as small as possible. As well, discontinuities and sharp transitions or direction change of the flow should be avoided.

The following subclauses are divided in direct measures to reduce abrasion and measures to allow an easy maintenance to dismantle the abraded components.

4.4.3.2 Direct measures to reduce abrasion or increase lifetime under abrasive attack

4.4.3.2.1 Guide vane seals

There are three different types of seals: end seals, seals between the inlet and trailing edge of the guide vanes, and seals between the trunnion of the guide vane and turbine head cover and bottom ring.

End seals may be provided in the end faces of the guide vanes. This type of seal is effective in all operation modes. Another type of end seal is located in the adjacent headcover and bottom ring. This type of seal is only effective if the guide vane is closed. Both seal types reduce the leakage water flow through the small end gaps and reduce the material abrasion of the adjacent components. However, the seals themselves are subject to attack by abrasion and the lifetime of these seals may be limited.

The use of guide vane end seals to avoid abrasion is only reasonable, if the seal lifetime extends over the time between overhaul or if it is possible to replace them easily. With seals located in the head cover and bottom ring, replacement is easier than with seals in the guide vane ends.

Seals between the inlet and trailing edge of the guide vane will reduce the leakage of the closed distributor. The principle here is the same as for the end seals. This type of seal is effective when the unit is closed without a closed inlet valve.

Figure 6 shows seals between the guide vane trunnion and head cover and bottom ring. These seals reduce the leakage water in open as well as in closed position of the guide vanes and have a positive effect on the abrasion rate. The material of the seal rings should be solid wear resistant stainless steel or coated stainless steel.

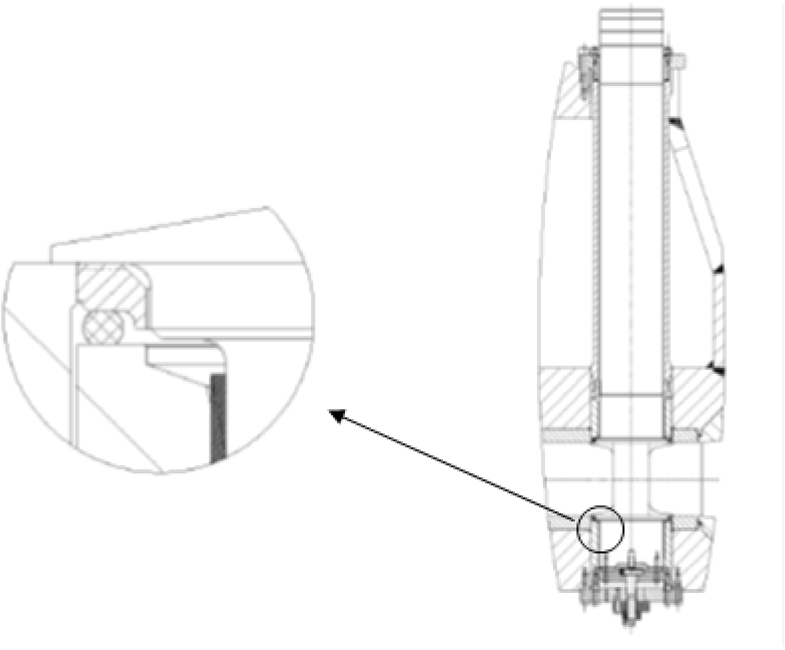


Figure 6 – Detailed design of guide vane trunnion seals

All seals should have a stainless steel or a wear resistant coating counterpart.

A more effective method for reducing leakage at standstill is prestressing the guide vanes in closed position. In addition, the trailing edge could be manufactured in a cambered shape, to compensate for the guide vane deformation under pressure that results in a closed gap even with the headwater pressure acting on the closed guide vanes.

4.4.3.2.2 Location of runner seals

The right location of the labyrinth rings in Francis turbines could also reduce the abrasive attack on the labyrinth rings. Collecting abrasive particles in front of the labyrinth rings and an increase in particle concentration should be avoided.

For medium and high specific speed turbines, the labyrinth rings could preferably be located directly at the transition between the head cover and bottom ring and the outer rim of the runner crown or band.

If, due to this position of the labyrinth rings, unbalanced axial forces occur, this shall be compensated in the layout of the balancing pipes or thrustbearing.

4.4.3.2.3 Protection of concrete with longer steel lining

In normal operating conditions, without abrasive particles, a steel lining or other additional protection should be provided if the flow velocity is higher than 6 m/s to 7 m/s. If the water contains abrasive particles the protection should be extended to protect the concrete surface against abrasion. In this case the limit of the flow velocity is recommended to be 4 m/s to 5 m/s.

4.4.3.2.4 Material selection

The material selection for components which are subject to abrasive wear is an important criterion. In Clause 5, examples of abrasion ratings of different materials are given.

Weldable stainless steel materials are preferred. The possibility to weld in situ is an advantage for future repair. A retroactive coating of the materials should be possible.

If both corrosive and abrasive attack occurs, stainless steel is preferred. Given its higher hardness, martensitic steel is preferred over austenitic steel.

4.4.3.2.5 Shaft seal with clean sealing water

Shaft seals in units which are operated with water which contains abrasive particles have to be fed with clean sealing water. It should be avoided that the contact surface or wearing surface comes into contact with abrasive particles.

The water has to be cleaned by applicable filters or cyclones which can sometimes be a challenge.

A standstill seal is recommended to protect the seal at standstill against the ingression of water containing abrasive particles. If no standstill seal is provided and the tailwater pressure is acting on the shaft seal, the shaft seal should be fed with clean sealing water also during standstill.

The shaft seal should also be easy to replace without having to dismantle other parts.

4.4.3.2.6 Facing plates on the head cover and bottom ring

Facing plates on the head cover and bottom ring at the ends of the guide vanes are effective to reduce the abrasive wear. They are fixed on the head cover and bottom ring and are removable. Use of martensitic steel or coated plates instead of austenitic steel will increase the protection.

If the expected abrasion wear is high and the facing plates have to be changed often it is recommended to fix the facing plates with bolts from the dry side of the head cover or bottom ring. The bolts have to be sealed accordingly.

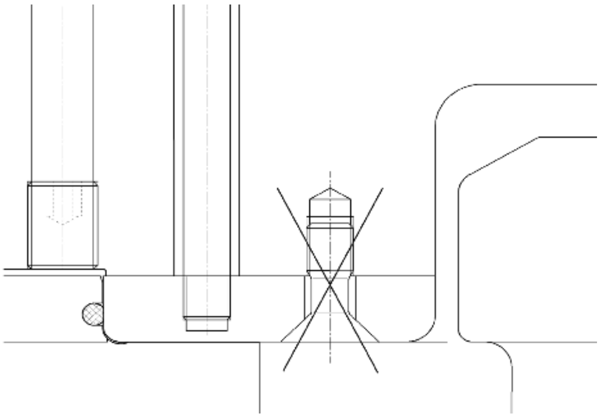


Figure 7 – Example of fixing of facing plates from the dry side

Normally the facing plates are bolted to the head cover or bottom ring with stainless steel bolts from the water side. The bolt heads have to be machined flush with the surface of the facing plates and a gap should be avoided. Changing this type of facing plates takes more time than changing the facing plates from the dry side and is also more complicated if the facing plates are coated. Please refer to Figure 7.

According to the expected wear rate an alternative is possible. Instead of removable facing plates a stainless steel overlay may also be used. If the guide vanes are large enough to access the stainless steel overlay the repair could also be done in situ.

4.4.3.2.7 Stainless steel overlay in throat rings

In Kaplan and tubular turbines, it is recommended that the runner chamber is made either from complete stainless steel or protected with thick stainless steel overlay. This will increase the lifetime of the runner chamber. The repair of any abraded surface can be done by a new welded stainless steel overlay, welding on of stainless steel tiles or a thermal spray coating.

4.4.3.2.8 Stainless steel overlay in areas adjacent to runner band and crown

Applying a stainless steel overlay or stainless steel protection plates is recommended in areas of Francis turbines behind the runner crown or band, especially in areas of discontinuities or flow changes. Repair of abraded stainless steel overlay can be done by new welded stainless steel overlay, welding on stainless steel tiles or a thermal spray coating.

4.4.3.2.9 Increase of wall thickness

Increasing the wall thickness is one of the methods to increase the time between the overhaul of a component due to abrasion. Increasing the thickness of hydraulic components such as runner blades, is discussed in 4.4.2.6.

For structural components, which do not influence the efficiency, the wall thickness can be increased in critical areas to avoid early failure of the component due to higher stresses. Typical components are guide vane trunnions, increased wall thickness at discontinuities in head covers, bottom rings, guide vanes and stay vanes.

One important item is to have enough wall thickness in embedded steel pipes – especially if pressure relief or balancing pipes from head covers are used. The bends of these pipes are particularly subject to strong abrasive attack due to sudden changes in water flow direction. Therefore these pipes should have increased wall thickness, and pipe bends with a greater radius should be used. Please see Figure 8 for typical balancing pipes.

When such balancing pipes are used, they should also be designed for low water velocity, taking into account any increased leakage of the labyrinth seals. It is, of course, also possible to accomplish the balancing with holes in the runner instead of separate balancing pipes.

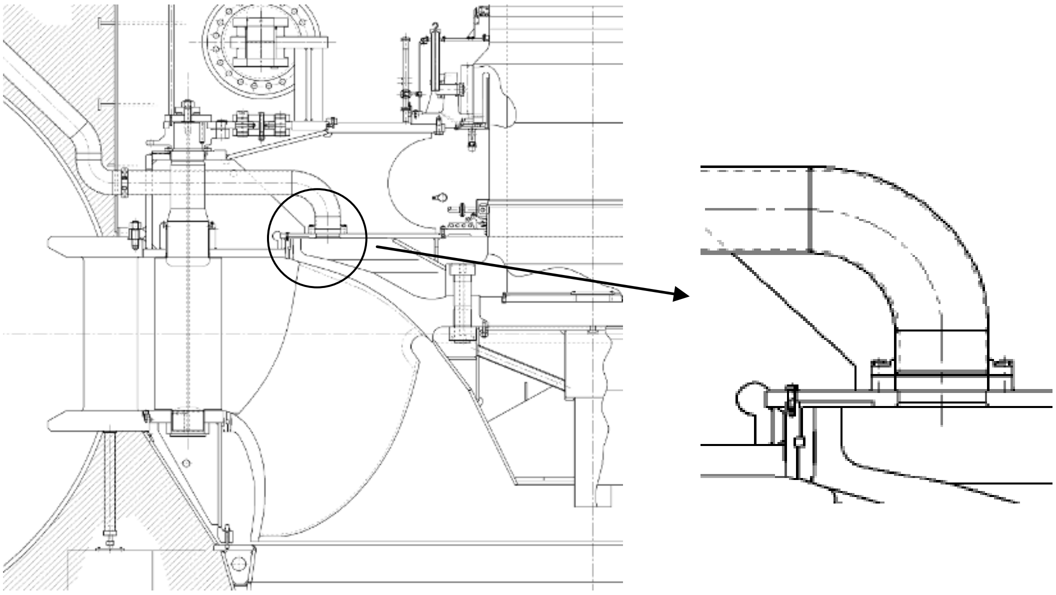


Figure 8 – Head cover balancing pipes with bends

4.4.3.2.10 Thrust bearing

In Francis turbines, the axial thrust may depend on the amount of leakage over the labyrinth seals and therefore the clearance of the labyrinth seals. If particle abrasion is present, the thrust bearing may be designed to handle additional load so that the unit can be operated with some wear of the labyrinth seals.

4.4.3.3 Design concepts to allow easy maintenance or replacement

4.4.3.3.1 General

If the components are damaged by abrasion and have to be replaced, it is very important that the replacement or repair can be carried out quickly and easily to reduce downtime and operation interruption. This should already be taken into consideration during the concept stage of planning of the powerplant and the design has to be take this into account.

4.4.3.3.2 Component removal

The main components which have to be replaced or dismantled for repair in Francis turbines are the runner, the guide vanes and the facing plates. The removal of the runner and lower cover from the bottom enables a quick dismantling without removing the generator, operating mechanism and headcover.

If, for of specific reasons, the dismantling from the bottom of the unit is not possible, a “dismantling from the middle” in the direction of the turbine floor also makes the removal of the runner easier because the generator could remain in place. However, the headcover and operating mechanism have to be removed.

To facilitate the dismantling of the runner, the coupling between the runner and turbine shaft should be easy to assemble and disassemble. Friction type couplings are recommended since joint machining of the runner and shaft or joint reaming and new fitting of shear bolts is not necessary.

4.4.3.3.3 Appropriate design for coating

The resistance of the components against abrasion can be considerably improved through appropriate abrasion resistant coating. The extension of the service life of a coated component which can be achieved depends on several factors, for example:

- component and turbine type;
- head and discharge;
- particle concentration and composition;
- flow conditions around the component.

Abrasion resistant coatings are usually not effective against cavitation. Depending upon the intensity of cavitation, the coating may be locally destroyed already after a brief period.

The following main components, classified according to the type of turbine, can at present be considered for coating, either fully or partially according to the present status of technology. Specific coating schemes should be decided based on the necessity for abrasion protection, accessibility and economy:

Francis turbine, pump, pump turbine:

- Runner
  - labyrinth seals
  - if possible the entire flow tunnel (if access for coating is difficult the coated areas may be limited to the runner blade outlet and runner blade inlet)
  - runner crown and band
- Guide vanes – complete blade, trunnion seal rings
- Headcover – labyrinth seals, facing plates
- Bottom ring – labyrinth seals, facing plates

Pelton turbine:

- Runner – internal surface of the bucket, except root area if NDT inspection is required
- Needle tip
- Nozzle seat ring
- Nozzle head (beak)
- Deflector (if used for long time)

Kaplan, Propeller and Bulb turbines:

- Runner hub
- Runner blades
- Runner chamber

The application of thermal spray should be carefully considered for components, which are subjected to greater expansions conditioned by their function. In the case of a nozzle seat ring, at head greater than 1 000 m, the expansion of the seat ring can lead to cracks in the coating and thus the failure of the component.

The coating layer thickness and the tolerance of the coating layer thickness should be taken into consideration in all the components, whose function places high requirements on strict tolerances. This is, for example, the case for labyrinth seals, as well as between facing plates and guide vanes.

The residual stresses in thermal spray layers may lead to chipping off and cracks at sharp edges or pointed corners. For example for thermal spray coatings, the radius on the edges is recommended to be minimum 0,5 mm and in corners minimum 1 mm at present status of technology.

4.4.3.3.4 Exceptional use of carbon steel as base material

In general, stainless steel is recommended as small damages to the coating will result in less corrosion and abrasion with stainless steel. However, the use carbon steel can also be considered for economic reasons (with possible increased risk of corrosion, abrasion and cavitation).

4.4.3.3.5 Accessibility for thermal spray coating

A minimum space is required for the application of a thermal spray coating. This issue should be taken into consideration in particular for Francis runners with an external diameter under 4 m, where partial coating may be the only feasible solution.

Step-labyrinths have small space between the fingers thus special solutions may be adopted such as concentrically split seals. For straight labyrinths it is recommended to use a straight gap or to optimize the shape of the step, see Figure 9 below.

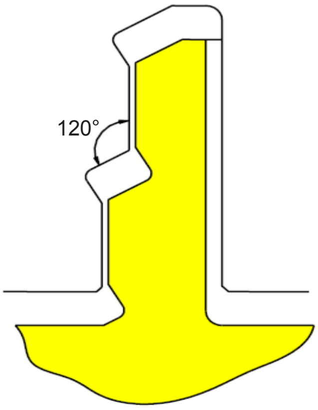


Figure 9 – Step labyrinth with optimized shape for hard coating

4.4.4 Operation

The following actions are recommended for consideration during operation of the units.

- Shut down the units at higher particle concentration periods. This may prevent excessive wear on the unit for a small amount of production loss. This strategy can be particularly useful for run of river schemes, where a significant variation in particle concentration can happen occur very quickly. It is recommended to install an early warning system to measure the upstream particle concentration manually or automatically, and to stop the unit before the water with large particle concentration reaches the intake.
- In case water with high particle concentration has been standing in the penstock for a long time, particles may deposit at the bottom of the penstock. It may then be difficult to open the inlet valve. In this case it may be possible to inject compressed air and open the penstock drainage valve to flush out particles immediately in front of the inlet valve.
- Minimize the amount of debris passing through unit. Large solid items, for example logs, gravel (larger than 2 mm), etc. may damage the hydraulic surfaces and any abrasion resistant coatings. Damage to hydraulic surfaces may increase the turbulence of the flow, which will, in turn, increase the abrasion damage. This is especially important for high head Francis and Pelton units, since the water velocities are very high and these units rely on smooth hydraulic surfaces to keep the turbulence low.

- Do not operate the unit in case the abrasion damage jeopardizes the safety of operation. As the abrasion damage progresses the unit will eventually become unsafe to operate. This could for example be due to the seal leakage increasing so much that the axial thrust exceeds allowable limits or that the remaining material thickness of some component falls below acceptable minimum thickness. Regular inspections of critical components should be made at least every year and inspection results compared to predefined acceptance criteria.
- For Pelton turbines the best ratio of produced electricity to abrasive wear is at full opening of one or more nozzles. Contrary to other turbine types, Pelton turbines allow for reducing the wear with reduced load by full closing individual nozzles, if allowed by the mechanical design of the turbine.
- For other types of turbines the best ratio of produced electricity to abrasive wear is obtained at the largest opening. Avoid no load or low load operation as much as possible. No load and low load operation are the worst operating conditions with respect to abrasion for most components and turbine types.
- Close inlet valve at shutdown. With a turbine at standstill and the water shut off only by the guide vanes, the water leaking past the guide vane clearances will have very high velocity, close to the free spouting velocity. This will cause abrasion wear in the guide vane apparatus. By closing the inlet valve this abrasion is eliminated. Closing the inlet valve is especially important for high head units.
- Hard coatings are very sensitive to cavitation. Thus, in machines with such coatings all operating conditions that lead to cavitation should be avoided:
  - Strictly stick to the recommended operating range for the turbine;
  - Pelton turbines: Watch for good condition of the interior surface of the nozzle, including nozzle tip and seat and for proper alignment.

See comment in Clause 6 regarding cavitation requirements.

4.4.5 Spares and regular inspections

- Keep additional spares in stock for parts subject to abrasion. In case of severe abrasion a complete set of exchangeable parts (for example guide vanes, head covers, bottom rings and runner) may be kept and exchanged at regular intervals. The parts taken out can then be repaired without influence on the downtime.
- Inspect critical components at least once per year and compare inspection results to predefined acceptance criteria. Keep adequate records of the amount of abrasion damage for each component. It is recommended that the depth of maximum metal loss be measured and recorded together with pictures of each component subject to abrasion damage.

4.4.6 Particle sampling and monitoring

It is important to keep permanent records of the concentration and properties of abrasive particles in the water. Water samples can be taken at predetermined intervals and analyzed in a laboratory. In addition, there are now several types of equipment for continuous monitoring of particle concentration in the water. They can be used for making operation decisions to avoid periods with extreme high particle concentrations. If it is to be used for this purpose the measuring station should be carefully selected to give sufficient warning to stop the unit before the high particle concentration reaches the intake.

It is important to distinguish between the particle load in the river and the particle load in the water that passes the turbine. At many sites, especially if there is a large reservoir, there can be a significant difference between the two. This can in some cases make it necessary to install two different sampling systems.

In the case where the concentration measurement system is based on discrete samples, and not continuous monitoring, the issue of the time interval between two samples will soon arise. Measurement intervals should be small enough to capture all the significant fluctuations in concentration of particles with a minimum threshold of inaccuracy. The duration of the sampling interval can be different in periods of high particle concentration and periods of low concentration. A rule of thumb estimate of a reasonable sample interval is:

$$T_\mathrm{s} = 0{,}01 \times PL_\mathrm{year}/C_\mathrm{max}$$

As a practical example this formula could give the following sample intervals

- "High particle" period:

  $PL_\mathrm{year} = 2\ 352\ \mathrm{kg} \times \mathrm{h/m^3}$

  $C_\mathrm{max} = 26\ \mathrm{kg/m^3}$

  then:

  $T_\mathrm{s} = 0{,}01 \times 2\ 352\ /\ 26 = 1\ \mathrm{h}$ for "high particle" period
- "Low particle" period:

  $PL_\mathrm{year} = 2\ 352\ \mathrm{kg} \times \mathrm{h/m^3}$

  $C_\mathrm{max} = 0{,}05\ \mathrm{kg/m^3}$

  then:

  $T_\mathrm{s} = 0{,}01 \times 2\ 352\ /\ 0{,}05 = 470\ \mathrm{h}$ (20 days) for "low particle" period

For practical reasons it is recommended to use the following sampling intervals; once per hour, once per day, once per week, once every two weeks and once per month. Select the next lower interval compared to the calculation.

For the measurement of shape, hardness and size it is recommended to take at least one sample per month for the first year of operation. If the variation of the K_hardness, K_shape and K_size is less than 10 % the sampling interval can be doubled after the first year. If the variation of the K_hardness, K_shape and K_size is more than 20 % the sampling interval should be halved as soon as this variation is detected.

It is also recommended to keep continuous records of operating parameters of each unit. At a minimum the following parameters should be recorded:

- output;
- hydraulic specific energy (or head);
- tailwater level elevation (TWL);
- guide vane angle or servomotor stroke;
- runner blade angle (if applicable);
- number of nozzles in operation (for Pelton units);
- water pressure on the head cover (for Francis units).This gives an indication of the wear of the labyrinths.

It should be able to relate the above records to the records of particle concentration and particle properties, so that it is possible, for example, to find out how much the unit output was at a time when water with high particle concentration passed the site.

5 Abrasion resistant materials

5.1 Guidelines concerning relative abrasion resistance of materials including abrasion resistant coatings

5.1.1 General

Annex F shows the results of several comparative abrasion tests on various materials. Since abrasion test results depend very much on the test setup, each test is presented as a relative comparison of abrasion resistance, the individual “wear resistance index”. In general, a higher wear resistance index means that the material is more resistant against abrasion within the same test. Note that wear resistance indices are not comparable between different tests.

Experience shows that abrasion tests give widely varying results depending on parameters such as velocity, impact angle, composition, concentration and size of particles, etc. Also, the relative wear resistance of different materials may vary under varying test conditions. Therefore the wear resistance index and even the relative order of the materials, obtained in different tests8, may vary. For this reason it is recommended to choose a test method that resembles the conditions expected in a prototype as closely as possible. Also, experience from actual applications in powerplants should be considered.

In addition to the wear resistance index several other factors should be considered when selecting an abrasion resistant coating, such as:

- how easy it is to apply the coating;
- how easy it is to remove and/or repair the coating;
- how thick is the coating layer. A thick layer of a material with a lower wear resistance index may have longer lifetime than a very thin layer of a material with a high wear resistance index.

5.1.2 Discussion and conclusions

Protection of hydro power plant equipment by using abrasion resistant materials or abrasion resistant coatings can often increase the lifetime between major overhauls.

At present, the most common abrasion resistant coating materials in hydraulic machines is thermal sprayed tungsten carbide held in a matrix of cobalt chromium, WCCoCr or various types of polymer coatings (sometimes referred to as “soft coatings").

The thermal spray coating, often referred to as “hard coating”, can be applied to most abrasion prone components. One important exception is small and medium size Francis runners, where it cannot be applied to certain surfaces due to access limitations. This coating shows very good abrasion resistance, if applied properly. It is worth to note that substantial variations in abrasion resistance are present between different thermal spray versions. This is due to variations in powder composition, environmental conditions during application and spray parameters.

Some polymer type and nanomaterial coatings show better abrasion resistance than hard coating, but substantial variations between different polymer coatings are reported. Polymer coatings are primarily applied on surfaces not requiring small tolerances to adjacent surfaces. These coatings are thus primarily used on water passages in Francis and Kaplan turbines. The variation of adhesion of polymer coatings to the base material is high and has to be high enough not to peel off. There are less geometrical access restrictions compared to hard coatings. Polymer coatings are relatively easy to repair.

Stainless steel facing plates or stainless steel overlay welds can also be considered a coating. It is common to protect, for example, carbon steel head covers and bottom rings with stainless steel at sensitive locations. Stainless steel has better abrasion resistance than carbon steel, although it is far from the level of thermal spray or polymer coating. Abraded stainless steel facing plates are also relatively easy and quick to replace. Martensitic stainless steel (e.g. 13 % Cr, 4 % Ni) has, in general, better abrasion resistance than austenitic stainless steel (e.g. 18 % Cr, 8 % Ni). Further improvement in abrasion resistance is achieved by special hard overlay weld electrodes, such as Co-Cr-C alloys.

Other coating materials different from those reported in this clause have been applied to hydro turbine components, but are less common.

5.2 Guidelines concerning maintainability of abrasion resistant coating materials

5.2.1 Definition of terms used in this subclause

1) *Overhaul*: Restoration of entire part to the original geometry and quality level including restoration of protective coating.
2) *Repair*: *Local* treatment of parts *at worn areas* to the following extent:
   - *Repair A*: Improve hydraulic shape just by grinding
   - *Repair B*: Restore hydraulic shape by welding and grinding
   - *Repair C*: Re-apply coating on prepared surface, after possible repair A or B.

5.2.2 Time between overhaul for protective coatings

Protective coatings that have been deposited onto part surfaces will also be subject to wear but at a considerably lower rate than the underlying steel. After a certain period of operation the coating will be worn out and the underlying steel will appear. From this moment on, the wear progresses at a higher rate on such stripped areas, leading to a modification of the geometry of the hydraulic profile. Such alterations are not detected during operation unless a visual inspection takes place. In severe cases a drop of power may be observed which should be taken as an alert for a visual inspection. At a certain stage of damage, the owner has to stop the production and replace the worn parts by new or overhauled ones.

The level of wear at which the overhaul is necessary is basically the same as for unprotected hydraulic parts and given by the following points:

1) As soon as safe operation is no longer possible, the overhaul has to be carried out: for example, when the wall thickness of a part is reduced to a level where mechanical stability of the part can no longer be assured and injury to people or substantial damage to the entire turbine is possible.
2) Provided safety is still intact, the economical optimum interval between overhaul/repairs has to be found. Delaying the overhaul/repair will result in
   - additional risk for unplanned stops and related production loss;
   - reduced efficiency;
   - increased overhaul cost and overhaul time because of accelerated base-material loss.

These items should be balanced against the cost of the overhaul / repair.

Proper planning of repair and overhaul will help the owner to avoid unplanned stops and thus optimize production. Before the powerplant is built the optimum time between overhaul may be estimated using the wear model cited in 3.1 and the data in Clause 5 considering the yearly PL value and the main characteristics of the turbine equipment.

Once the plant has been operated for some time a more refined estimate can be made considering additional data such as:

- Former experience including inspection reports with pictures of damage after different PL values.
- Continuous measurement of particle concentration and discharge for each turbine during operation. This makes it possible to assess the part of PL actually “used” and the time remaining before overhaul. The continuous measurement of the concentration of particles can also trigger an alarm to stop the turbine if a predetermined concentration is exceeded.
- The measurements of the pressure in the head cover to detect wear in the labyrinth seals for Francis turbines.
- A very effective judgment of whether the abrasion of the guide apparatus has passed a certain point, is the pressure differential across the main inlet valve after opening the

bypass during startups. When the head losses through the bypass exceed the head losses through the worn guide vane apparatus the pressure in the spiral case will drop significantly. This drop in pressure will indicate that the guide vane apparatus has been worn out to certain point. A reference pressure drop can be set beyond which overhaul of the guide vane apparatus has to be undertaken. An example of how this pressure differential develops over time for a high head Francis power plant is shown in Figure 10, which shows the development of the spiral case pressure with closed guide vanes and valve, but with open bypass line. Units 1, 2 and 3 have no coating while units 4, 5 and 6 have guide vanes, head covers and bottom rings coated by thermal spray. For increased accuracy, the flow in the bypass line can also be measured.

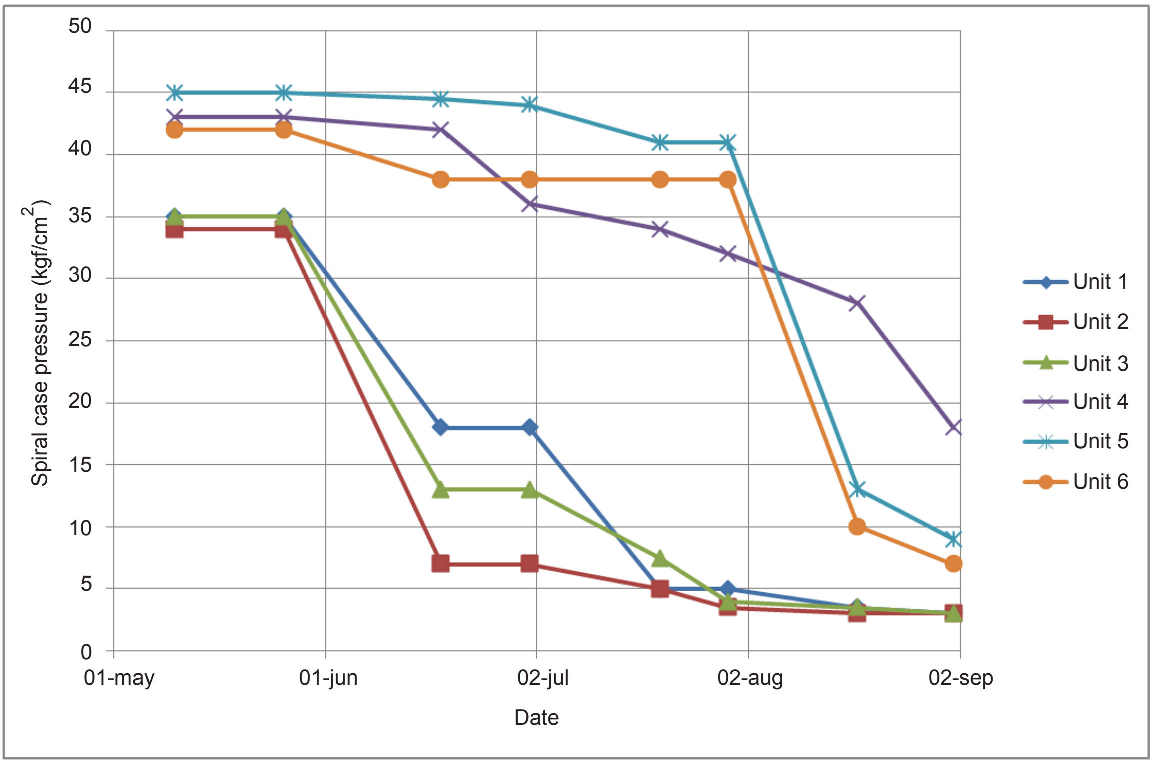


Figure 10 – Development of spiral pressure over time

5.2.3 Maintenance of protective coatings

In order to achieve best quality it is recommended to execute overhauls and repairs in a dedicated shop with the necessary equipment and the space for clean, safe and accurate access to all areas of the part.

During short standstill periods in-situ repairs of types A and B may be envisaged in order to extend the time between overhauls. In-situ repair means treating the part without withdrawing it from the turbine. However, as shown in Table 2, in-situ repair of type C is not always possible or recommended.

Table 2 – Overview over the feasibility for repair C

Coating type	Feasibility	Remarks
Hard coating	Possible, but poor quality	Poor bond strength on remaining coating. Poor operator safety if manual spray in narrow spaces (e.g. in Francis).
Polymer coating	Possible	Clean and humidity controlled environment necessary to achieve good quality.
Weld overlays	Possible for easily accessible locations	Pre-heating may be required. No stress relief heat treatment possible and thus, for certain alloys, risk of cracking.

In-situ repairs of type B and C are particularly recommended for Pelton runners in order to reduce unwanted flow turbulence due to abrasion induced shape changes of the cutting edge and the inlet edges. In addition, a special challenge refers to in situ HVOF coating, which might not be allowed in some countries.

6 Guidelines on insertions into specifications

6.1 General

This clause presents a recommended approach which owners could and should take to ensure that specifications communicate the need for particular attention to different aspects such as machine type, hydraulic design, mechanical design, etc. at their sites without establishing criteria which cannot be satisfied because the means are beyond the control of the manufacturers.

Cavitation and abrasion may mutually reinforce each other as explained in Clause 4. Also some popular abrasion resistant coatings are more sensitive to cavitation damage than stainless steel. For this reason it is recommended that more stringent cavitation requirements are used for plants where abrasion is expected. This can, for example, mean that for a Francis unit the runner submergence and the runner design should be such that there is a margin to incipient cavitation in normal operating range and that the plant should be operated accordingly. Also inlet cavitation should be considered and the unit operating range may have to be limited to allow this.

The foreseen philosophy for overhaul and repair / replacement of abraded parts should be communicated. A suggestion for how to define criteria for overhauls is in Annex G. The time of year and duration when maintenance is allowed should be stated.

Desired design features (see Clause 4) should be specified.

It is important to clearly communicate the data on particles expected to pass through the turbine (which may be different from the particles in the river) at different periods of the year and the corresponding operating conditions of the turbine. It shall be possible to calculate PL based on this data. The following Tables 3 to 5 are a recommended format. The time periods in the tables should be chosen to give the most representative picture of the particle contents and operation. Special attention should be paid to periods with high particle concentration.

The specification should require the supplier to provide a report, based on the data provided in the specification. The report should estimate the expected erosion, in accordance with the guidelines in this guide, and estimate the TBO and overhaul scope for safe operation of the unit.

6.2 Properties of particles going through the turbine

The properties of the particles going through the turbine over time have to be recorded. Table 3 offers a form to do so.

Table 3 – Form for properties of particles going through the turbine

Period[a] Month	PL kg×h/m^3	**Average particle concent ration** kg/m^3	**Particle size,** dP_{50} mm	**Fraction of hard particles** Mohs>5 %	**Typical shape of hard particle**[b]	**Opera-ting net head** m	**Opera-ting tailwater elevation** m.a.s.l.	**Operating time at 80 % to 110 % of rated output** h	**Operating time at 60 % to 80 % of rated output** h	**Operating time at 50 % to 60 % of rated output** h	**Operating time at 20 % to 50 % of rated output** h	**Operating time at 0 % to 20 % of rated output** h	**Operating time at speed no load** h
Jan – April													
May – Sept													
Oct – Dec													

[a] In column "Period" select the appropriate interval.

[b] Refer to Annex D for further details.

6.3 Size distribution of particles

The size distribution of particles going through the turbine over time has to be recorded. Table 4 offers a form to do so.

Table 4 – Form for size distribution of particles

Relevant period	Fraction 0 μm to 63μm >Mesh 230[a]	Fraction 63 μm to 125 μm Mesh 230 to 120[a]	Fraction 125 μm to 250 μm Mesh 120 to 60[a]	Fraction > 250 μm < Mesh 60[a]	Total
Jan – April					
May – Sept					
Oct – Dec					

[a] Mesh sizes according to ASTM.

NOTE 1 Other methods of grading particle size can also be used.

In case of high contents of smaller particles (dP_{50} < 0,063 mm) further grading will be required.

6.4 Mineral composition of particles for each of the above mentioned periods

The hardness of the particles has of large influence on the abrasion process, thus mineral composition has to be recorded. Table 5 offers a form to do so.

Table 5 – Form for mineral composition of particles for each of the above mentioned periods

Mineral name	Mohs hardness	Fraction 0 μm to 63 μm >Mesh 230	Fraction 63 μm to125 μm Mesh 230 to 120	Fraction 125 μm to 250 μm Mesh 120 to 60	Fraction > 250 μm <Mesh 60
Quartz					
Feldspar					
….					
Total					

It is only an example that the particles can be divided according to this table. Suitable format for the actual particle analysis should be used.

Annex A
(informative)

PL calculation example

This annex gives an example of how to calculate *PL*. In order to illustrate the process we consider only a short time duration and a small number of particle measurements.

Assume that we have a turbine that started operation on May 5 at 22 h and stopped on May 10 at 15 h. During this time 8 water samples were taken and analyzed for particle concentration. One of the samples was in addition analyzed for particle size and particle hardness. The results were as shown in Table A.1.

Table A.1 – Example of documenting sample tests

ID	Date, Time	Event	Particle concentration kg/m^3	Particle size, dP_{50} mm	Fraction harder than Mohs number > 4,5 %
0	May 5, 22:00	Start turbine	-	-	-
1	May 6, 06:00	Sample taken	4,5	-	-
2	May 6, 10:30	Sample taken	4,9	-	-
3	May 7, 04:30	Sample taken	4,7	-	-
4	May 7, 16:30	Sample taken	4,1	-	-
5	May 8, 08:00	Sample taken	3,8	-	-
6	May 9, 01:00	Sample taken	4,4	0,069	73
7	May 9, 14:00	Sample taken	4,6	-	-
8	May 10, 00:30	Sample taken	4,9	-	-
9	May 10, 15:00	Stop turbine	-	-	-

The formula to calculate *PL* with discrete samples is:

$$PL = \sum_{n=1}^{N} C_{\mathrm{n}} \times K_{\mathrm{size,n}} \times K_{\mathrm{shape,n}} \times K_{\mathrm{hardness,n}} \times T_{\mathrm{s,n}}$$

where

C_{n}	is the particle concentration in kg/m^3 for each sample;
K_{size}	is the same numerical value as the median particle size, dP_{50}, in mm. Since only one sample was analysed for particle size we use this value for all samples;
K_{shape} =	1,5;
K_{hardness}	is the same numerical value as the fraction of particles harder than Mohs 4,5. For components in 13Cr4Ni stainless steel this will be the hardness of the steel on the Mohs scale. Note that the value should be the fraction, not the number of

percent. Since only one sample was analyzed for particle hardness we use this value for all samples;

$T_{s,n}$ is the time interval to consider for each sample. For n=1 we use the time from turbine start until half the time between the first and second sample. Likewise, for n=8 we use the time from half the time between the seventh and eigth sample until turbine stop. For n=2 to n=7 we use the time from half the time between samples (n-1) and n to half the time between samples n and (n+1);

N is the number of samples = 8.

On the basis of this data we can now establish the following Table A.2.

Table A.2 – Example of documenting sample results

n	C_n kg/m^3	$K_{size,n}$	$K_{shape,n}$	$K_{hardness,n}$	$T_{s,n}$ h	PL_n kg×h/m^3
1	4,5	0,069	1,5	0,73	10,25	3,48
2	4,9	0,069	1,5	0,73	11,25	4,16
3	4,7	0,069	1,5	0,73	15	5,33
4	4,1	0,069	1,5	0,73	13,75	4,26
5	3,8	0,069	1,5	0,73	16,25	4,67
6	4,4	0,069	1,5	0,73	15	4,99
7	4,6	0,069	1,5	0,73	11,75	4,08
8	4,9	0,069	1,5	0,73	19,75	7,31
Total					**113**	**38,28**

This shows that during the 113 h of operation this turbine was exposed to a PL = 38,28 kg × h/m^3.

Annex B
(informative)

Measuring and recording abrasion damages

B.1 Recording abrasion damage

The following is a guideline to measure the wear of the individual parts of machines.

The goal of this guideline is to get reliable results of the erosion rate of different power plants in such a way that the measurement is always the same so that they can be compared to each other. Based on this hydro-abrasive erosion damage, together with measurements of the particle load, the goal is to get reliable predictions of safe operation and inspection intervals for the future.

During an inspection of the parts, it is important to gather as much information as possible and the following should give a guideline for the minimum requirements during an inspection for hydro-abrasive erosion damages.

In general, parts should be marked so that they can easily be identified before being photographed. The project name, blade / bucket number, date of inspection and number of operating hours should be written on the component. In the case of a picture series (e.g. all buckets of a runner) this information should be written at least on the first bucket and the other buckets have to be numbered. In this case the pictures should be named in such a way that a series can be identified. The pictures should be taken electronically with at least with a 5 megapixel camera, so that details can be seen.

For each component a log book should be made, starting with its commissioning and ending with its disposal. The following items should be noted in the log book:

- part number (individual number stamped into the part, e.g. runner number). This is to clearly identify the part during its operation and to avoid mix-up of earlier collected data;
- date of commissioning, including the meter reading of the total unit operating hours;
- date of inspection, including the meter reading inspection of the total unit operating hours and the status of the part after inspection, for example
  – continue in operation,
  – extracted for repair,
  – extracted for standby,
  – extracted for disposal,
  – etc.,
- observations and measurements made during inspection, in accordance with the following clauses.

In addition it should be possible to find the output of the unit for each hour of each day.

B.2 Pelton runner without coating

At first, photos of all buckets should be taken in such a way that both halves can be seen. Camera position shall be in the centre of the bucket. Sketches of the erosion damages or any other noticeable features like impact damages of stones should be made in parallel, marking certain features on the bucket and photographing them.

The bucket number has to be seen in every photo. In addition, the first bucket should have the following information: project, hours, date of inspection.

At least four buckets, randomly selected, have to be examined as described below:

– Measure the bucket wear from original profile by using templates at minimum 5 points per half bucket and at least 3 locations (front, middle back). The gap between runner and template has to be measured and also a sketch of the section showing the measured points should be made.
– While the template is being held in the bucket, photos should be taken so that the gap between template and bucket can be seen and a ruler should be held in such a way that the dimensions of the gap can also be seen. This should be at least done for one bucket, e.g. the one with the highest erosion rate.
– The splitter width on top has to be measured at the position of the 3 templates. Additional photos to show special features should also be taken with a ruler held next to the features to see the dimensions.

B.3 Needle and mouth piece without coating

Photos should be taken in closed needle position to see any gaps between needle and seat ring; use ruler to document dimensions as described earlier for the runner.

If the pieces are disassembled, individual photos of parts should be taken. In both cases any defects should be photographed individually.

If possible a measurement of the leakage with closed injectors should also be noted in the log book.

Visualize photos, overview of parts (if taken apart) and in closed position to see gaps between the parts. If possible, a measurement of the leakage should be done.

B.4 Pelton runner with hard coating

All buckets have to be photographed. The procedure is the same as for uncoated runners with the following exceptions:

Templates are not needed for the wear measurement as in most cases there is enough coating left so that the original contour is still visible. It is thus advisable, to map major defects and make individual depth measurements along with pictures of typical local defects.

B.5 Needle, seat ring and nozzle housing with coating

The procedure is the same as for uncoated runners with the following exceptions:

Measurement of areas where coating failed with a sketch, a depth measurement and photos should be included. The transition from coated to uncoated areas should be photographed and eventual height of steps as well as eventual width of gaps between the seat ring and nozzle housing should be recorded in the log book.

B.6 Francis runner and stationary labyrinth without coating

The measurement of the erosion should be done as follows:

1) the trailing edge thickness should be measured at 8 points equally spaced over the length of the trailing edge. This should be recorded together with a sketch with exact location descriptions;
2) the thickness at template points of at least 3 templates equally spaced over the trailing edge with at least 3 points per template (2 templates near the transition to the band and the crown) should be measured;
3) the thickness of the blade at the transition to the band at the entrance edge should be measured.

At least three blades should be measured e.g. the most worn, the least worn and an average blade.

In addition to the overview photos, photos of areas with erosion in addition to a sketch of the location of photos should be supplied in the report. At least all areas with major damages have to be photographed. The transition area band-blade and the blade near the band is where the highest abrasion usually occurs and should be given special attention.

On areas of major erosion damage the depth of erosion should be measured and photos taken to see how it was measured. A description of the measurement technique should be given.

In the dismantled condition photos of the whole runner, the complete outside of the runner and the rotary and stationary labyrinth, as overview and details should be photographed and recorded in sketches.

The gap between the runner and the bottom facing plate should be measured and photographed.

B.7 Francis runner with coating and stationary labyrinth

The blade number should be seen in every photo. In addition the first blade should have the following information: project, hours, date of inspection. The pictures should be taken electronically with at least with a 5 megapixel camera, so that details can be seen.

Depending on the size of the blades one or more pictures have to be taken to give an overview of each blade. On every picture the number of the blade should be seen.

For all blades a sketch should be made of the areas with damaged coating where the location of the damages and also the size of the areas are reported.

The depth of the eroded areas on the blades should be measured and the maximum values should be recorded. The method of the measurement (e.g. with curved ruler/template) should be explained, if possible with a sketch. Photos of the measurements should also be included. Detailed pictures where more information is gained may be added.

If the coating is gone at the trailing edge: see measurements for Francis without coating.

The gap between the runner and the bottom facing plate should be measured and photographed.

B.8 Guide vanes and facing plates without coating

Overview photos and detail photos should be taken and their location indicated in a sketch.

If the damage is so high that no reference point exists anymore only pictures to show damages may to be taken.

If a reference points still exists the abrasion measurements on facing plates (maximum) consist of measuring the gaps between guide vanes and facing plates at minimum 4 vanes.

An additional indication of the abrasion damage to the guide vane apparatus consists of measuring the spiral case pressure at standstill with closed guide vanes and MIV but open MIV bypass valve. This should be measured as often as possible with the exact information indicating the time and parameters when the measurement took place.

B.9 Guide vanes and facing plates with coating

Overview photos and detail photos should be taken and the location marked in a sketch. Each guide vane should be photographed and all damages recorded together with a sketch showing the exact location and extent of each damage.

The depth of erosion for every case of damage should be measured and the maximum value for each case recorded. The way of measuring should be explained and some photos given (e.g. curved ruler, template). The vanes should be labelled as explained above for the blades of a Francis runner.

Detailed pictures where more information is gained should be given.

B.10 Kaplan uncoated

The measurement of the erosion should be done as follows:

The trailing edge thickness should be measured at 5 points equally spaced over the length of the trailing edge. This should be recorded together with a sketch with exact location descriptions.

At least three arbitrarily selected blades have to be inspected.

A report with several kinds of photos should be made. In addition to the overview photos, photos of areas with erosion in addition to a sketch of the location of photos should be supplied in the report. At least all areas with major wear have to be photographed.

On areas of major erosion damage the depth of erosion should be measured and photos taken to see how it was measured. A description of the measurement technique should be given.

Additionally the gaps between the outer diameter of the blade and the discharge ring have to be documented.

B.11 Kaplan coated

The blade number should be seen in every photo. In addition, the first blade should have the following information: project, hours, date of inspection.

Depending on the size of the blades one or more pictures have to be taken to give an overview of each blade. On every picture the number of the blade should be seen.

For all blades a sketch should be made of the areas with damaged coating where the location of the damages and also the size of the areas are reported.

The depth of the eroded areas on the blades should be measured and the maximum values should be recorded. The method of the measurement (e.g. with curved ruler/template) should be explained, if possible with a sketch. Photos of the measurement should also be included. Detailed pictures where more information is gained may be added.

If the coating is gone at the trailing edge: see measurements for Kaplan without coating.

Additionally the gap between the outer diameter of the blade and the discharge ring should be documented.

B.12 Sample data sheets

The data sheets for recording abrasion damage shall necessarily be specific to each project, taking into account the specific design of the unit, the actual abrasion pattern and what measurements are easily accessible.

If possible the records should directly show the abrasion depth of the parts in mm. Sometimes this is not possible since there is no convenient undamaged surface to use as a reference to measure from. In such cases other measurements can be taken from which abrasion depth can be calculated with help from the turbine design drawings. Sketches that explain the measurements should be included in the data sheets.

Hydraulic machines often contain several design elements with multiple components of exactly the same shape. Examples are runner blades and guide vanes. As explained above the abrasion depth and location in the turbine of several individual components should be recorded in such cases. It is normal for the abrasion depth to vary significantly between the individual components.

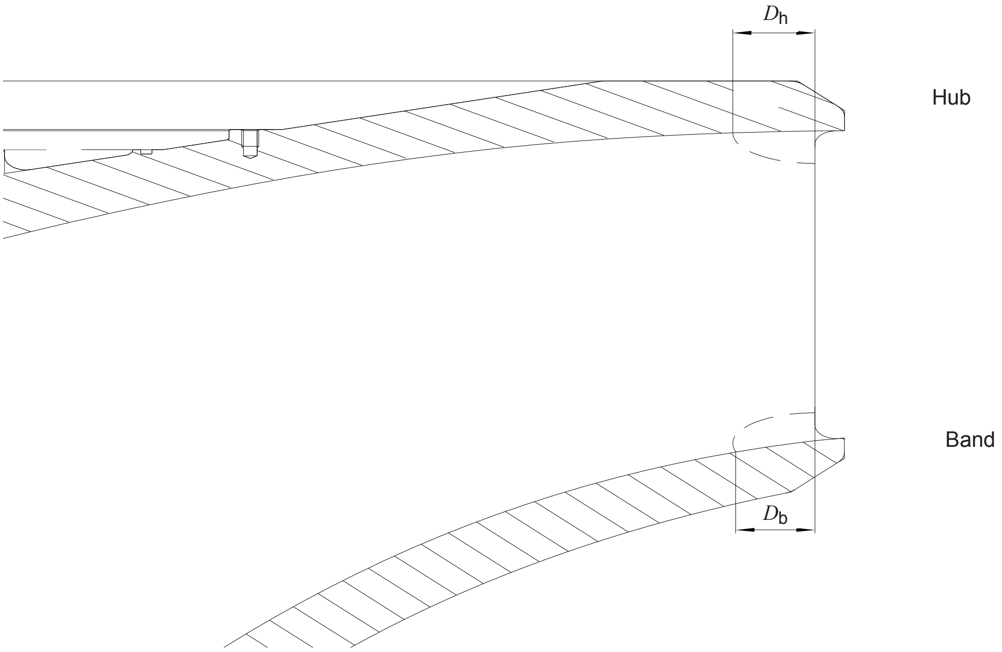
The abrasion depth on the same component usually varies with location on the component. It is recommended to record abrasion depth in a few typical locations on the component. In each location the maximum abrasion depth should be considered.

Enclosed below, are a set of sample data sheets for recording damage in a high head Francis turbine, see Tables B.1 to B.21. The data sheets may need to be modified to fit the actual damage and component shape. Inspection records should be suitable for the areas with maximum abrasion and areas that may affect the safe operation of the unit.

B.13 Inspection record, runner blade inlet

Table B.1 – Inspection record, runner blade inlet form

Plant	Unit Nb	Date	Sign	

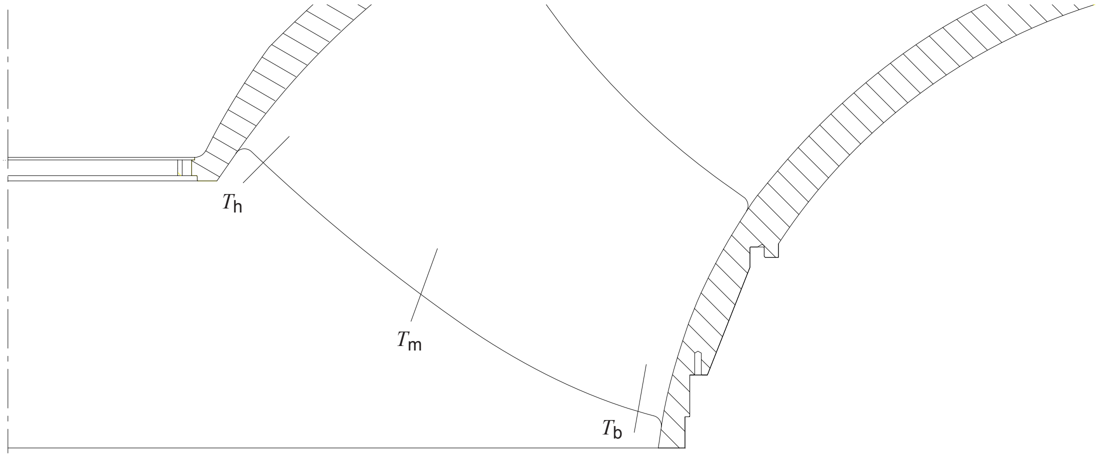


Blade Nb	Hub erosion depth, D_h	Band erosion depth, D_b
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		

B.14 Inspection record, runner blade outlet

Table B.2 – Inspection record, runner blade outlet form

Plant	Unit Nb	Date	Sign	



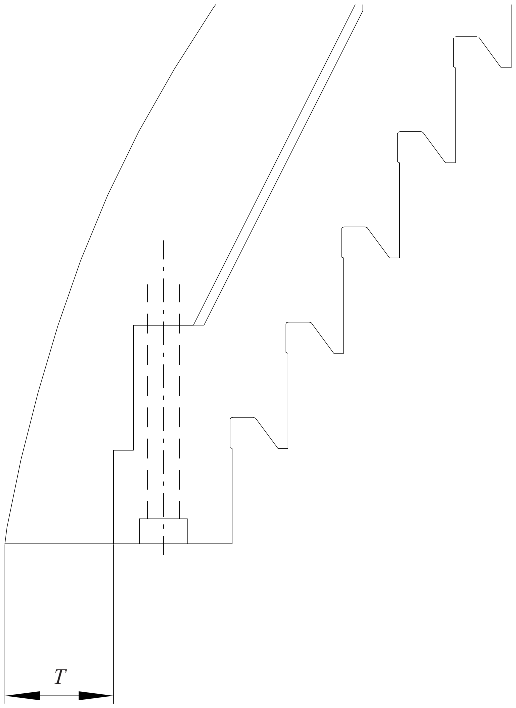
Blade Nb	Thickness at hub, T_h	Thickness at middle, T_m	Thickness at band, T_b
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			

NOTE Template locations T_h, T_m and T_b can be taken at the same locations as existing runner blade templates.

B.15 Inspection record, runner band

Table B.3 – Inspection record, runner band form

Plant	Unit Nb	Date	Sign	



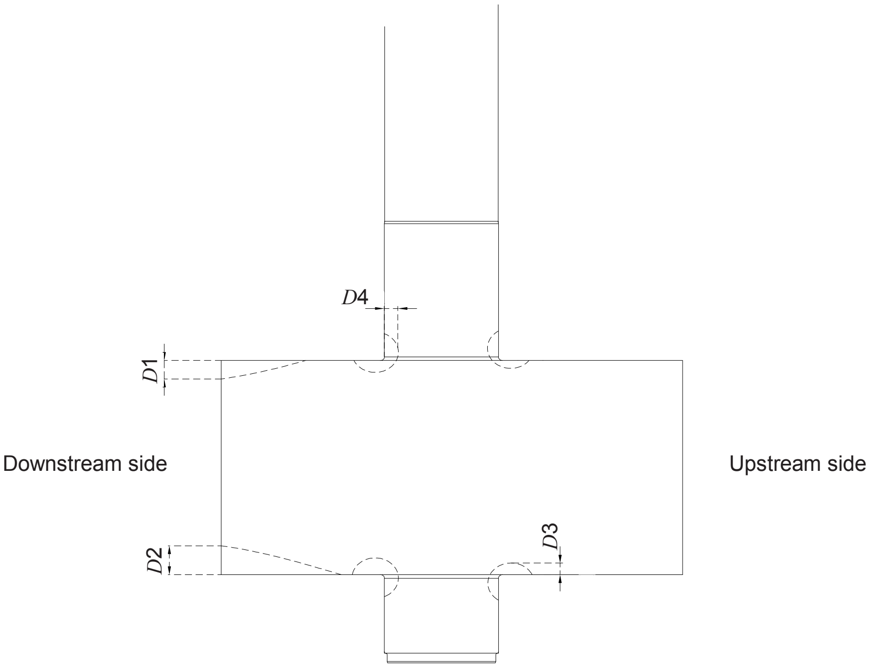
Measuring point	Thickness, T
1	
2	
3	
4	

NOTE Measuring points are 90 degrees apart.

B.16 Inspection record, guide vanes

Table B.4 – Inspection record, guide vanes form

Plant	**Unit Nb**	**Date**	**Sign**	

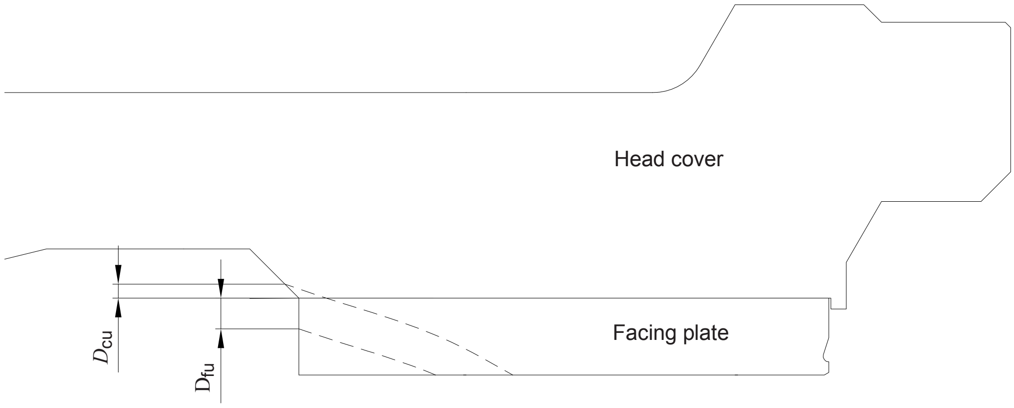


Guide vane Nb	**Face towards head cover, *D*1**	**Face towards bottom cover, *D*2**	**Face around bottom stem, *D*3**	**Guide vane top stem, *D*4**
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				

B.17 Inspection record, facing plates and covers

Table B.5 – Inspection record, facing plates and covers form

Plant	Unit Nb	Date	Sign	



Measuring point Nb	Upper facing plate, D_{fu}	Head cover, D_{cu}	Lower facing plate, D_{fl}	Lower cover, D_{cl}
1				
2				
3				
4				

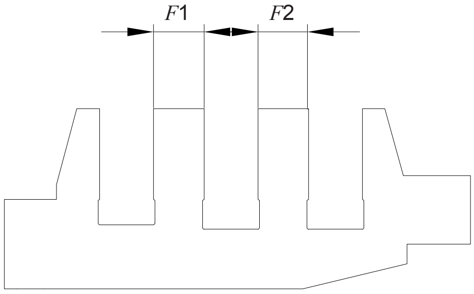
NOTE 1 Dc is only measured in case there is no more facing plate material remaining.

NOTE 2 Measuring points are 90° apart.

B.18 Inspection record, upper stationary seal

Table B.6 – Inspection record, upper stationary seal form

Plant	Unit Nb	Date	Sign	

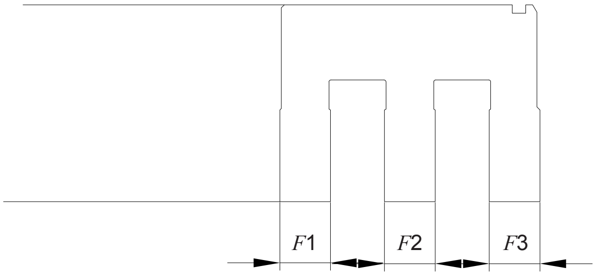


	Location 1	Location 2	Location 3	Location 4
Finger 1, $F1$				
Finger 2, $F2$				
NOTE Measuring points are 90 degrees apart.				

B.19 Inspection record, upper rotating seal

Table B.7 – Inspection record, upper rotating seal form

Plant	Unit Nb	Date	Sign	

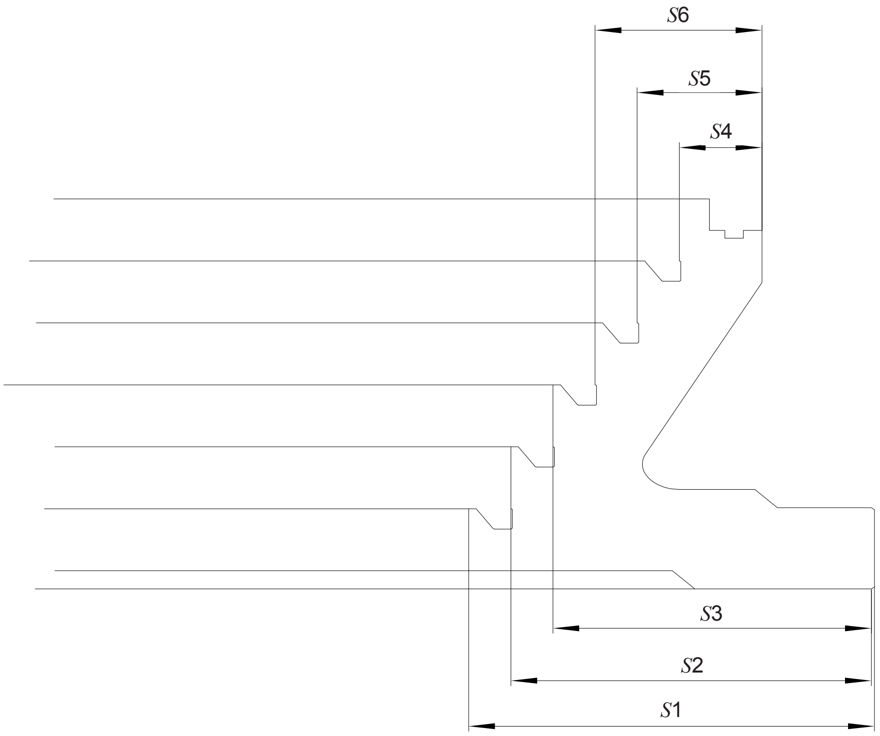


	Location 1	Location 2	Location 3	Location 4
Finger 1, $F1$				
Finger 2, $F2$				
Finger 3, $F3$				
NOTE Measuring points are 90° apart.				

B.20 Inspection record, lower stationary seal

Table B.8 – Inspection record, lower stationary seal form

Plant	Unit Nb	Date	Sign	

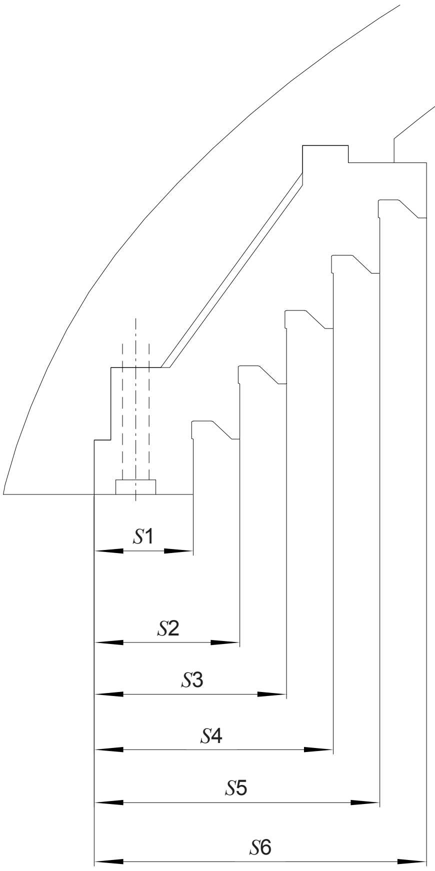


	Location 1	Location 2	Location 3	Location 4
Surface 1, $S1$				
Surface 2, $S2$				
Surface 3, $S3$				
Surface 4, $S4$				
Surface 5, $S5$				
Surface 6, $S6$				
NOTE Measuring points are 90° apart.				

B.21 Inspection record, lower rotating seal

Table B.9 – Inspection record, lower rotating seal form

Plant	Unit Nb	Date	Sign	



	Location 1	Location 2	Location 3	Location 4
Surface 1, *S*1				
Surface 2, *S*2				
Surface 3, *S*3				
Surface 4, *S*4				
Surface 5, *S*5				
Surface 6, *S*6				
NOTE Measuring points are 90° apart.				

Annex C
(informative)

Water sampling procedure

The sampling should be carried out at a point where the particle content going through the turbine is measured. The flow at the sampling location should result in homogenous particle distribution at this point. Suitable locations are in the water conveyance system from the intake to the tailrace close to the runner. During the design of a new powerhouse, suitable sampling points should be planned.

During the design stage, when historical data is not yet available, water samples are often taken directly from the river. The location of sample taking does not depend on whether a continuous or discrete sampling method is used, but it should be in a place of medium flow. Note that considerable sedimentation may take place in the reservoir and this shall also be taken into consideration.

The best way for recording particle concentration is a continuous online measurement system, so that the concentration changes can be seen in great detail and used for further calculations.

If the measurement is not done continuously, the measurement frequency depends on the change of particle load over time as explained in this guide.

When recording the measurement, the location of measurement has to be given in addition to an exact description of how the data was obtained.

Annex D
(informative)

Procedures for analysis of particle concentration, size, hardness and shape

D.1 General

The analysis of the abrasive particles in the water going through the turbine should include all parameters, which are necessary to evaluate the hydro-abrasive erosion action the particles in the water can have on the turbine parts. The particle analysis should include:

- particle concentration;
- particles size distribution;
- mineralogical composition of sediment;
- particle geometry.

D.2 Particle concentration

Particle concentration is non-dissolved particles in the water. Particle content should be given in kg/m^3 and may be analyzed in accordance with ISO 4365: 2005.

D.3 Particle size distribution

As different particle sizes have a different behaviour in the flow of water this also has an impact on their type of damage on the turbine parts. Due to this particle size distributions should be made regularly. Also here the method of measurement should be given with the data.

Sieving is a good way to determine the particle size distribution when the proportion of small particles is low (samples containing mostly particles with diameters > 0,05 mm). The sieving fractions can be used also for the following determination of the mineral composition.

Size distribution may also be analysed in accordance with ISO 4365:2005.

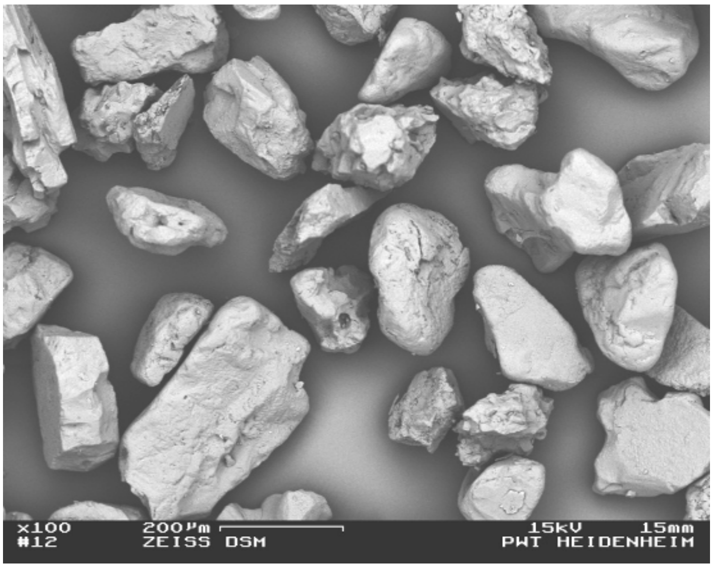
D.4 Mineral composition of the particles

Using the different particle size fractions from the particle size distribution an analysis of each fraction should be made to determine the mineralogical composition, as due to the different hardness of minerals the impact on erosion differs considerably.

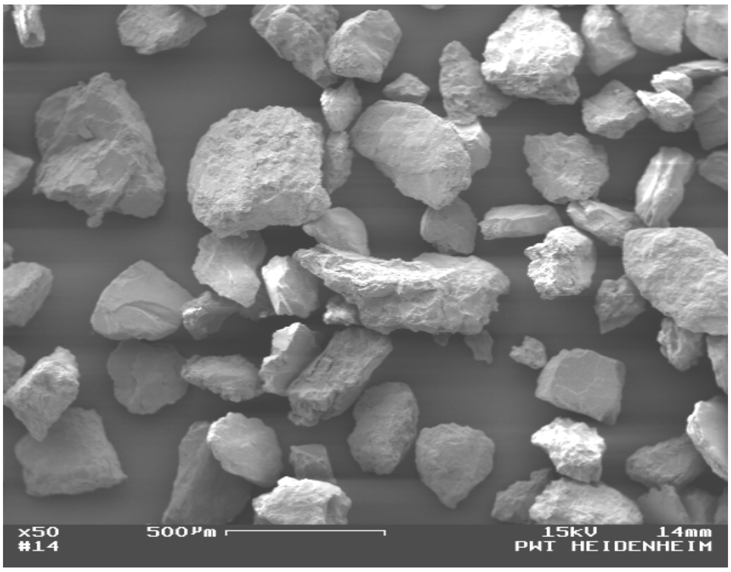
D.5 Particle geometry

Pictures of the different fractions should be taken and added to the report so that the form of typical particles can be seen. The aim is to see if either rounded particles or particles with sharp edges mainly are present in the sediment.

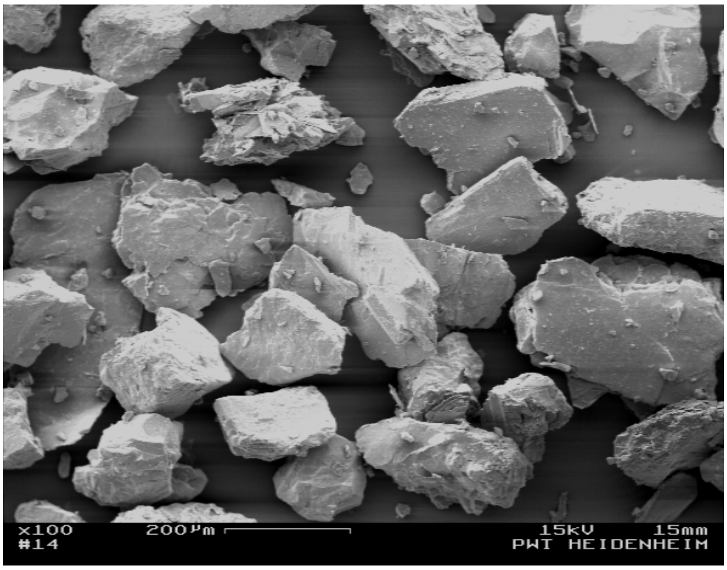
The following Figure D.1 gives three typical examples of such images, designated round, sub-angular and angular from top to bottom. Please note that the magnification is not the same in each picture. It should be chosen in such a way that a representative choice of particles can be clearly seen.



a) – Round particle geometry



b) – Subangular particle geometry



c) – Angular particle geometry

Figure D.1 – Typical examples of particle geometry

Annex E
(informative)

Tests of abrasion resistant materials

E.1 General

This annex contains examples of laboratory erosion tests and corresponding wear resistance index. Since abrasion test results highly depend on the test setup, each test is presented as a relative comparison of abrasion resistance, the individual “wear resistance index". It is not intended as a definite grading of materials or coatings or as a complete listing of testing methods. Also see 5.1.

Special attention must be paid to the following:

a) the “wear resistance indices” in the tests below are normally not the same as in a turbine. There may be a factor 100 difference between laboratory tested wear resistance indices and actual wear improvement in turbines;

b) the reference material in each table has the wear index of “1” (one). Wear resistance indices from different test rigs are not comparable.

E.2 Test 1

Figure E.1 shows the design of test rig number 1 and Table E.1 shows the results.

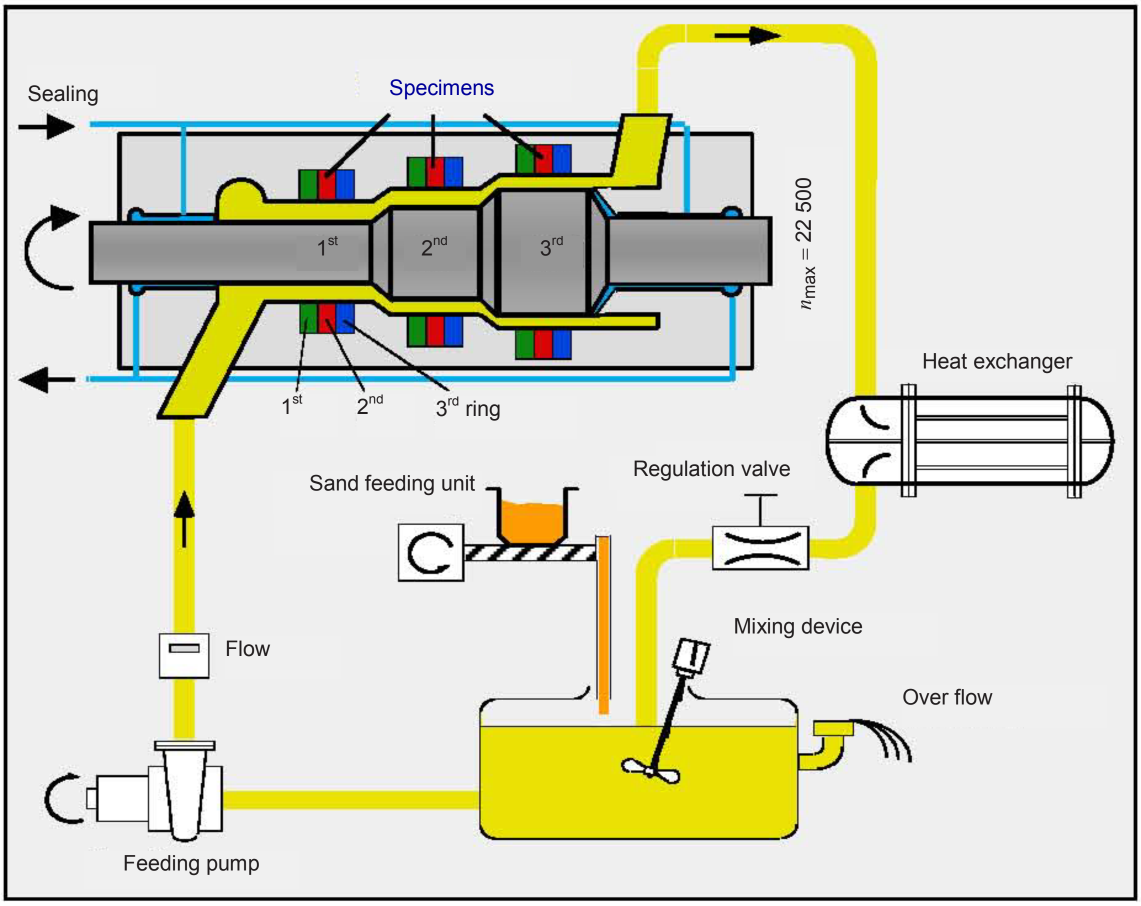


Figure E.1 – Schematic of test rig used for test 1

Table E.1 – Relative wear resistance in laboratory test 1

Material	Deposition method	Brand	Wear resistance index from	Wear resistance index to
Steel X5CrNi13 4	Solid body	n.a.	1	1
Co-base	Overlay weld	Cavitec Castolin	1,4	1,6
Steel X5CrNi13 4	Flame sprayed	Metcolloy 2	2	2,3
Nitrided steel X5CrNi13 4	Plasma nitrided	n.a.	5	6,5
Co-Cr-C	Overlay weld	Stellite 6	4	7,3
Cr	Electroplated	n.a.	25	36
Alumina/zirconia	Plasma sprayed	n.a.	30	59
Chrinium-oxide	Plasma sprayed	n.a.	30	80
NiCrBSi	Overlay weld	Nicrobor 60	60	110
WCCoCr	HVOF version 1	n.a.	70	115
WCCoCr	HVOF version 2	SXH70	150	315

E.3 Test 2

At this test rig, specimens are positioned along the inner wall of a cylindrical container. A rotating tube continuously delivers particles with high speed to the surface of the specimens at a given impact angle. The loss of weight is measured after the throughput of a certain mass of particles. In these tests quartz particles with a size of 80 μm 120 μm and an impingement speed of 115 m/s were used. Table E.2 shows the wear resistance index with duplex steel at 30 degrees impact angle taken as the reference.

Table E.2 – Relative wear resistance in laboratory test 2

Material	Deposition method	Wear resistance index			
Impingement angle (°)		12	30	60	90
DUPLEX steel	Solid	1,5	1,0	1,1	1,6
STELLITE 6	Cast	2,3	1,1	1,0	1,5
WC	Solid	178	222	296	74
WCCoCr	HVOF	52	7,4	4,3	6,3
NICROBOR 60	Weld overlay	5,8	1,6	1,0	1,0

E.4 Test 3

This test is a dry abrasion test based on the Standard Test Method of ASTM G 76 - 95. The apparatus consists of a nozzle tube, which is perfused with gas-entrained solid particles. The dimensions of the nozzle are defined. The outcoming stream impinges on the surface of the rectangle specimen. The velocity of the gas and the particles, the particle feed rate and the impingement angle are adjustable as well as the testing time. At the end of the test the amount of coating loss per weight of erodent (cc/kg) is measured. See IEC 60193 in Bibliography. Table E.3 shows the results of this test and Figure E.2 shows a schematic of the test apparatus.

Table E.3 – Relative wear resistance in laboratory test 3

Material	Deposition method	Brand	Wear resistance index
Polymer coating	Paintbrush	Ceramalloy	0,07
Polymer coating	Paintbrush	Duratough	0,13
Polymer coating	Paintbrush	CIBA	0,36
Stainless steel	Solid	N/a	1,00
WCCoCr	HVOF	Version 4	1,21
Diamond composite	Settling	Version 5	1,33
Chromium carbide	Brazed tape	N/a	1,93
WCCoCr	HVOF	Version 2	4,73
WCCoCr	HVOF	Version 1	5,20
Polymer coating	Spray paint	ErodeTek	>10

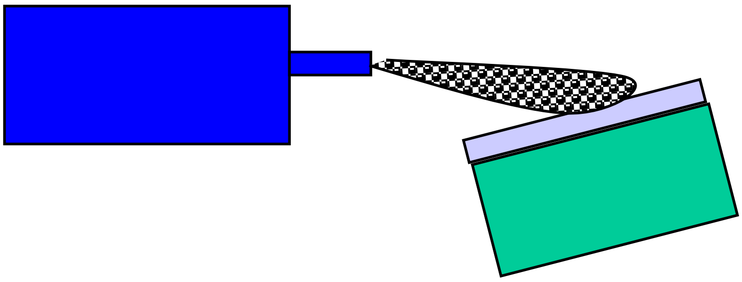


Figure E.2 – ASTM test apparatus

E.5 Test 4

This test is a field test with test coupons having various coatings welded into the draft tube cone of a hydro turbine. See Figure E.3. After operating the turbine for one season the coupons were taken out and the thickness loss of the coating was measured.

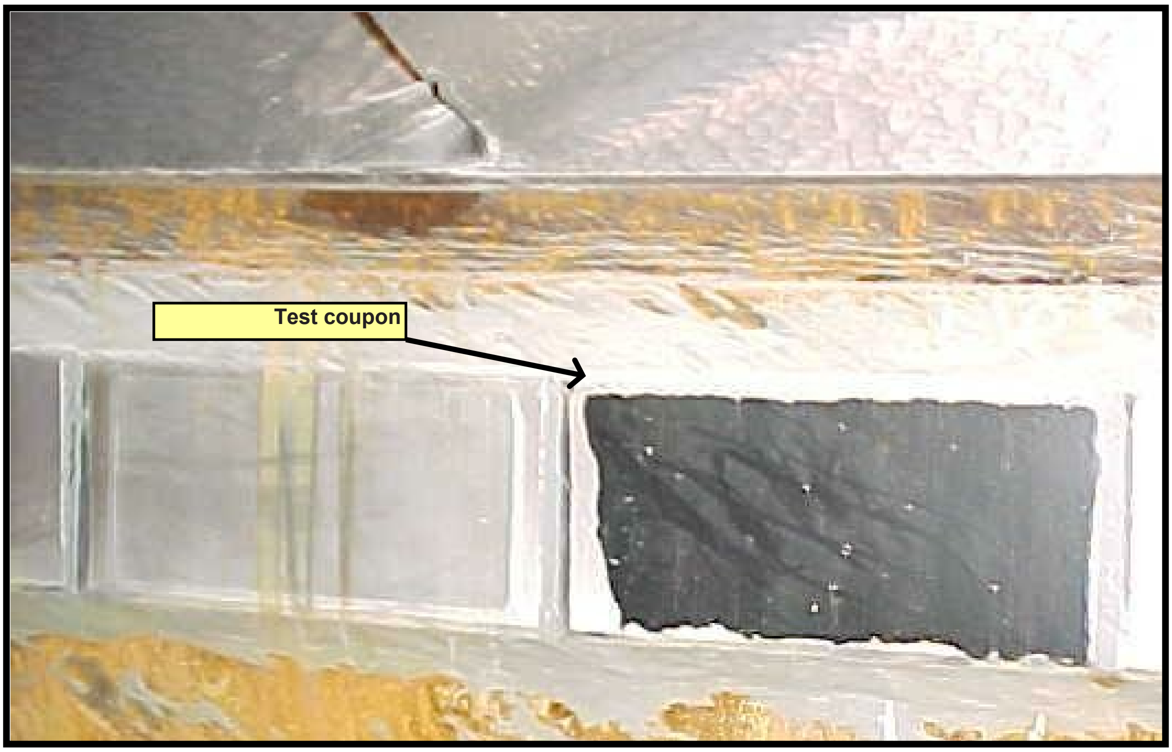


Figure E.3 – Test coupon

The coatings are essentially the same as in test 3. However, in this case there was no stainless steel reference coupon. The results are therefore reported with one of the HVOF thermal spray coatings as a reference instead. See IEC 60609-2 in the Bibliography. Table E.4 shows the results of this test.

Table E.4 – Relative wear resistance in test 4

Material	Deposition method	Brand	Wear resistance index
Polymer coating	Paintbrush	Duratough	0,08
Polymer coating	Paintbrush	CIBA	0,15
Polymer coating	Paintbrush	Belzona	0,18
Polymer coating	Paintbrush	Ceramalloy	0,21
Diamond composite	Settling	Version 6	0,25
Diamond composite	Settling	Version 5	0,40
WCCoCr	HVOF	Version 4	1,00
WCCoCr	HVOF	Version 2	1,44
WCCoCr	HVOF	Version 3	1,50
WCCoCr	HVOF	Version 1	2,12
Chromium carbide	Brazed tape	N/a	2,12
Polymer coating	Spray paint	ErodeTek	6,55

E.6 Test 5

This is a “slurry-pot” test facility for a fast and cost efficient comparison of up to four different coatings (see Figure E.4). The cylindrical specimens are fixed to a shaft, which rotates in a particle-water mixture. The maximum circumferential speed at the outer end of the specimens is 20 m/s and the concentration of the particles is 5 % (50 kg/m^3). The grain size ranged between 0,1 mm to 0,3 mm. Every 24 h (shorter times are also possible), the specimen will be weighed and every 48 h the particle/water mixture has to be exchanged as due to the impingement the particles are getting rounded. Table E.4 shows the results of this test.

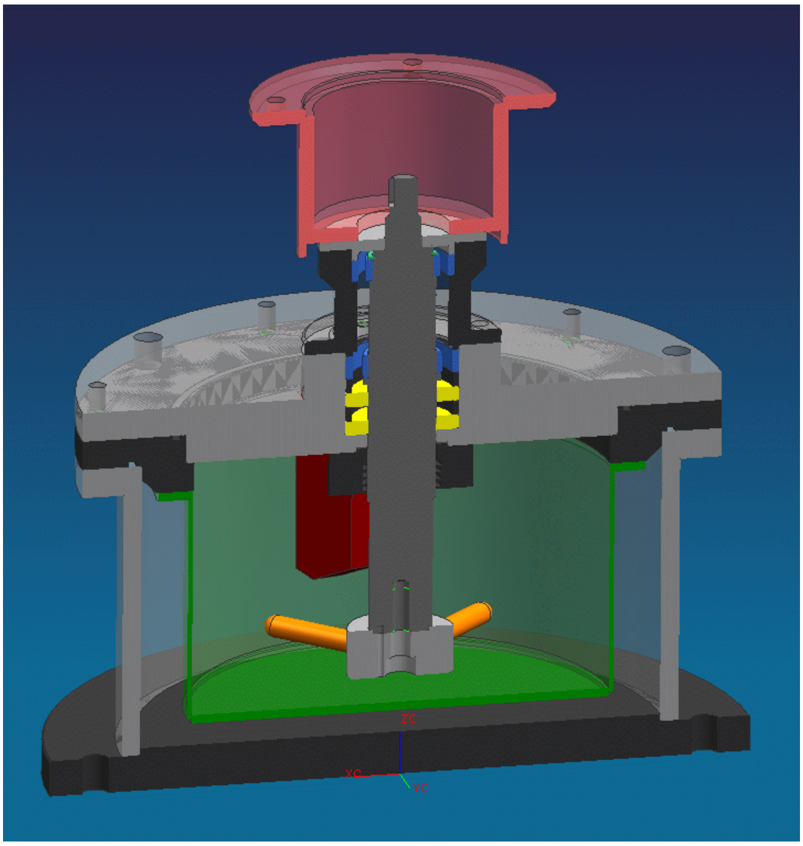


Figure E.4 – Slurry pot test facility

Table E.5 – Results of test

Material	**Wear resistance index**
1.4313	1
EP / PU	1,1
Flame spray	1,4
Stellite 6	5,6
NiCrBSi	8,3
PU 3	14
TC 2	66
Diaturb 532	100
Softurb 80	500

E.7 Test 6

This is a high-velocity test rig (see Figure E.5) able to simulate the flow conditions in a hydraulic machine. Flow velocities up to 45 m/s are possible. The specimens' total mass loss will be determined. Table E.6 shows the results of this test.

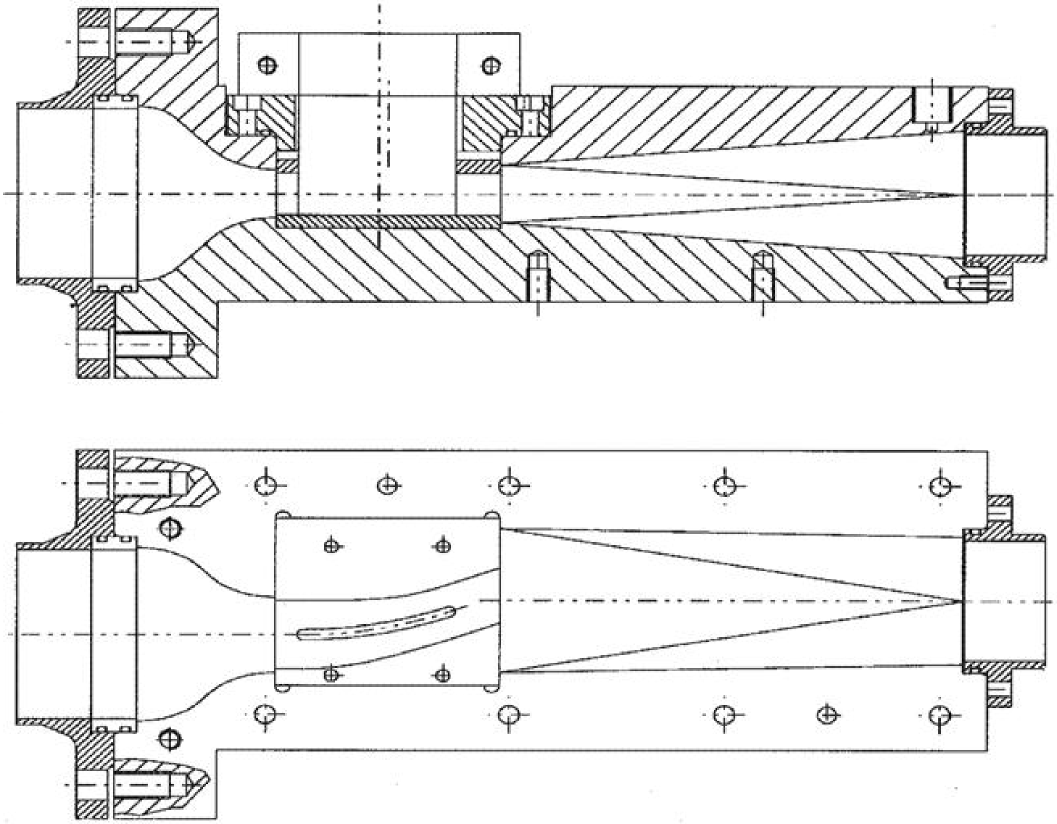


Figure E.5 – High velocity test rig

Table E.6 – Results of test

Material	Wear resistance index
1,431 3	1
TC / metal matrix (Nb 1)	1,2
NiCrBSi	1,5
TC / alloy matrix	1,9
Mix Carbide / metal matrix	11
CrC / metal matrix	14
Diaturb 532	20
PU 2	133
Softurb 80	200

E.8 Test 7

This is a rotating disc test rig as shown in Figures E.6, E.7 and E.8.

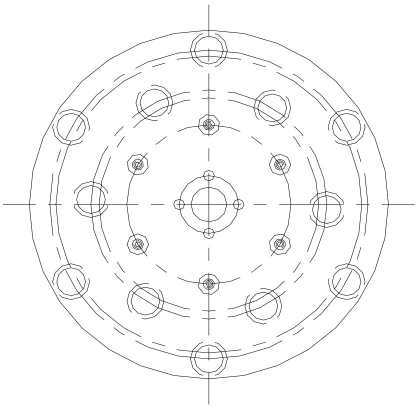
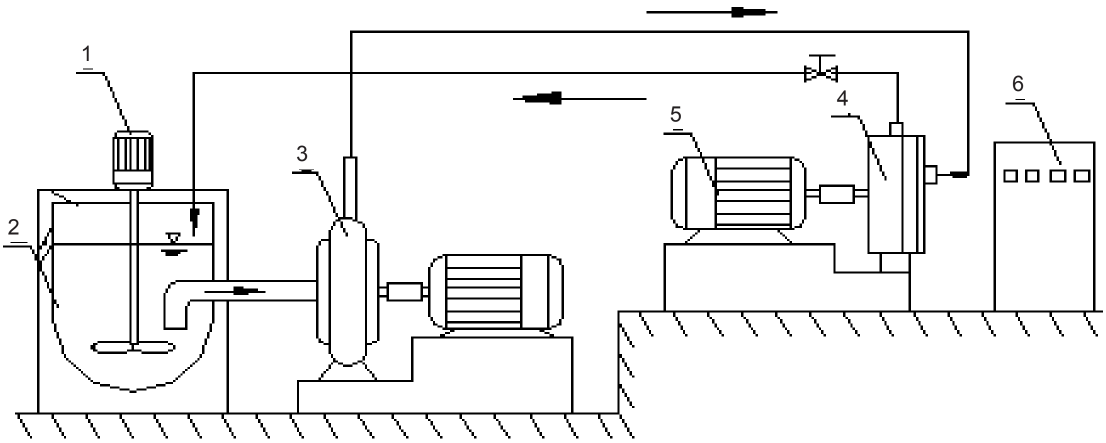


Figure E.6 – Samples are located on the rotating disk

a) Sound material

b）Polymer coating

Figure E.7 – Comparison of two samples after testing



Key

(1) Puddle	(4) Rotating disk
(2) Reservoir	(5) Motor
(3) Slurry pump	(6) Control panel

Figure E.8 – Whole test system of rotating disk

Some test results from this test rig are summarized in Table E.7.

Table E.7 – Results from test

Name of materials	Deposition method	Brand	Wear resistance index
ZG06Cr13Ni4Mo/ A743 CA-6NM	Found stainless steel		1
Stainless steel	Foundry	28	1
Polyurethane	Overlay	PU26	1,17
ZG28Mn	Heat treatment		1,22
Crude rubber			2,36
Polyurethane	Overlay	PUS2	3,34
Polyurethane modified Epoxy resin corundum	Overlay	EP-PU/CSi	3,4
Epoxy resin corundum	Overlay	EP/CSi	4
Dual phase cast	Heat treatment	NI	8,89
Super high polyethylene			9
Dual phase cast	Heat treatment	NIW	13,38

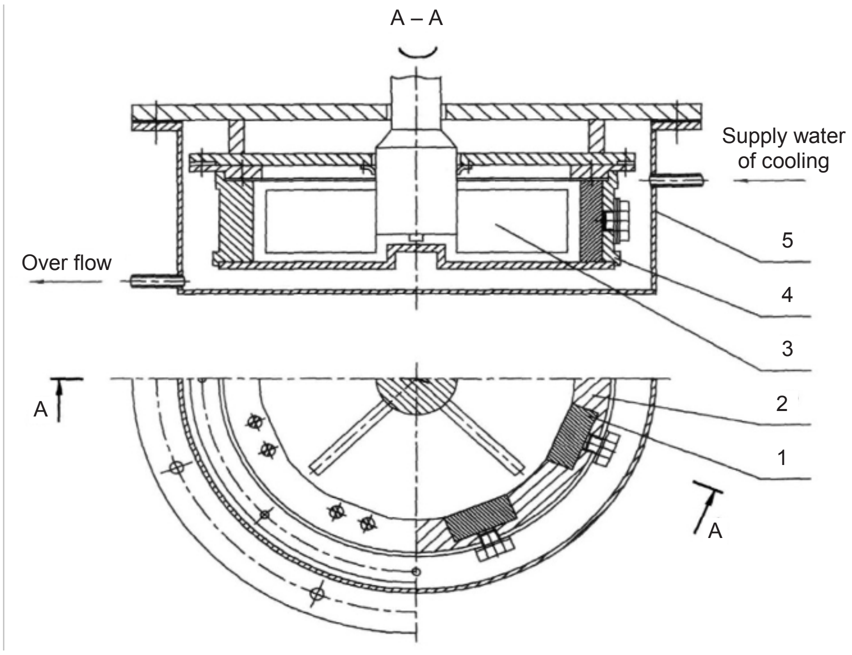
E.9 Test 8

Hydroabrasive stand material wear process is reproduced by a hydroabrasive blend rotation past test model. The test stand diagram is given in Figure E.9. The main part of the stand is a holder (2); samples (1) are placed in the seats of the holder. The holder is filled with hydroabrasive blend of specified concentration (200 g of river sand with the size of particles equal to 0,5 mm to 0,25 mm per 1 liter of water). Samples are subjected to attrition with rotating hydroabrasive mass.

Mass rotation is realized by impeller (3) that is secured on the vertical shaft by means of sleeve coupled with engine shaft. When stand is in use, the holder that is a component part of bath (4) undergo the quenching with flowing water entering into the casing (5) from service water piping.

Test length totals 4 h. After every test samples are weighed on analytical balance and hydroabrasive blend is changed for the next test.

Figure E.10 shows test samples after testing on the rig. The rotational speed of abrasive mass is 16 m/s. Note the wear on leading edge.



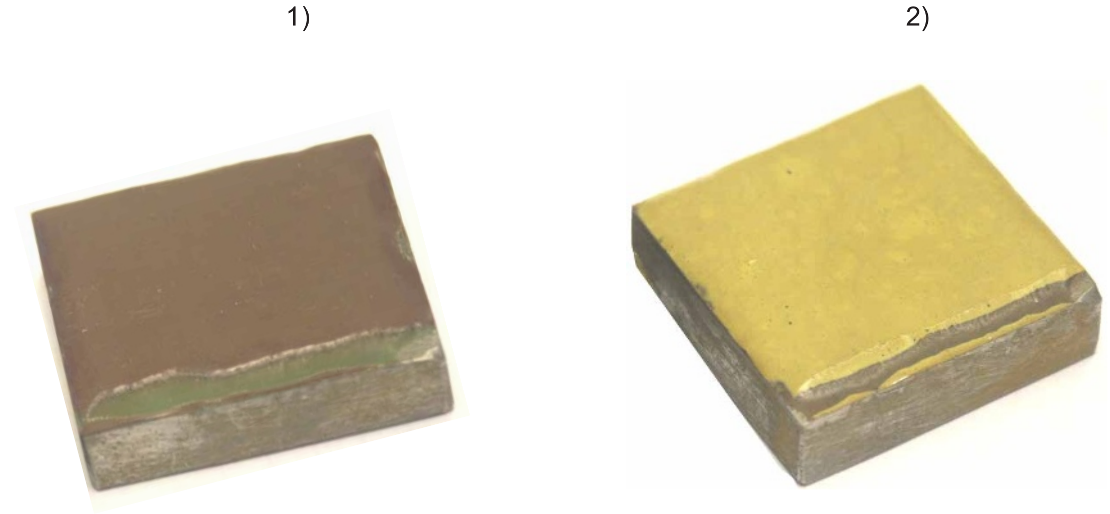
NOTE Items 1 to 5 are defined in E.9.

Section A-A refers to a broken line that goes from A to A through the center.

Figure E.9 – Schematic of test rig used for test 8

Table E.8 – Relative wear resistance in laboratory test 8

Material	Deposition method	Brand	Wear resistance index
Austenite steel		18/10	1,0
Polymer coating	Paintbrush	Agro	1,15
Polymer coating	Paintbrush	Belzona (elastomer)	2,3
Polymer coating	Paintbrush	Metalyne 580	2,1
Polymer coating	Paintbrush	Taff-shtaff	3,2
Polymer coating	Paintbrush	Liturene – 260	5,4
Hard surface	Filling	Belzona (super metal)	0,45
Hard surface	Filling	Belzona (ceramic carbide)	0,8
Cr(17 %)+Mg	Welding rod surfacing		3,2
	Welding rod surfacing	Hydroloy 914	1,3
	Welding rod surfacing	SK Cavidur	1,4
Mo+Ni	Arc spraying metallization		1,8
Mo+Ni+Cr	Arc spraying metallization		1,9
Al_2O_3+TiO_2	Detonation coating		1,6
Ni+Co+Cu+WC	Detonation coating		1,8
Ni+ Cr+B+Si	Plasma spraying		1,7
	Plasma spraying	Metcoloy 2	3,4
Ni+W+Co	Plasma spraying		4,2
Cr+Ni+C+Si+B	Plasma spraing (termal fusing)		4,5



Key

1) Wear of reinforces epoxy coating (brown colour) with sub layer (green colour)

2) Wear of epoxy coating (yellow colour) with embedded nanotubes

Figure E.10 – Testing of samples on hydro abrasive stand

E.10 Test 9

This is a rotating disc type test facility. The disc rotates inside a cylinder filled with silt-laden water and with a flow dampening grid. It gives a parallel flow over the face of the surface (i.e. over the materials tested). The test disc is comprises 6 to 8 pieces of pie-shaped samples (corresponding to 3 to 4 kinds of materials, 2 pieces of sample for each material is shown) as shown in Figure E.11. The amount of abrasion is measured on several points on different radii. Since the circumferential velocities of the different measuring points are not same, the amounts of abrasion for different velocities are found. This gives a relationship curve of abrasion depth (h) or unit abrasion rate (ε) vs. circumferential velocity (U), i.e. h=f_1 (U), or ε=f_2 (U). These results, corrected by experience, can be applied for the estimation of abrasion. If we test 3 kinds of materials, we get 3 curves, as shown in Figure E.12. From this figure we can directly compare the abrasive resistance of various materials. The wear resistance index can also be calculated. Table E.9 shows a relative wear resistance index for some materials in test 9 (circumferential velocity is 40 m/s).

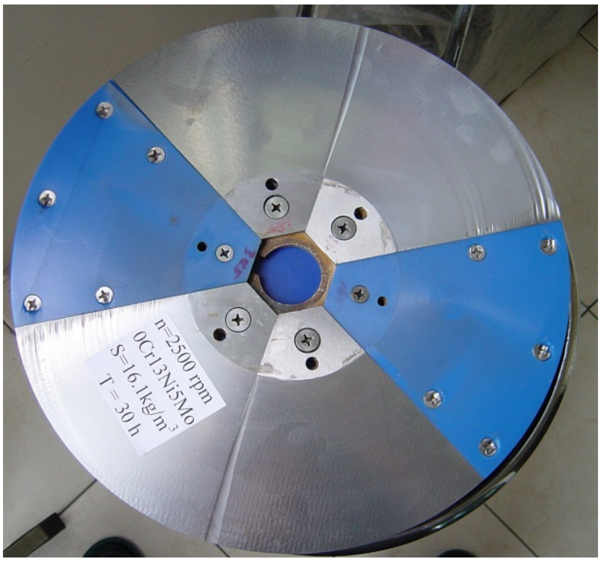


Figure E.11 – Cover of disc

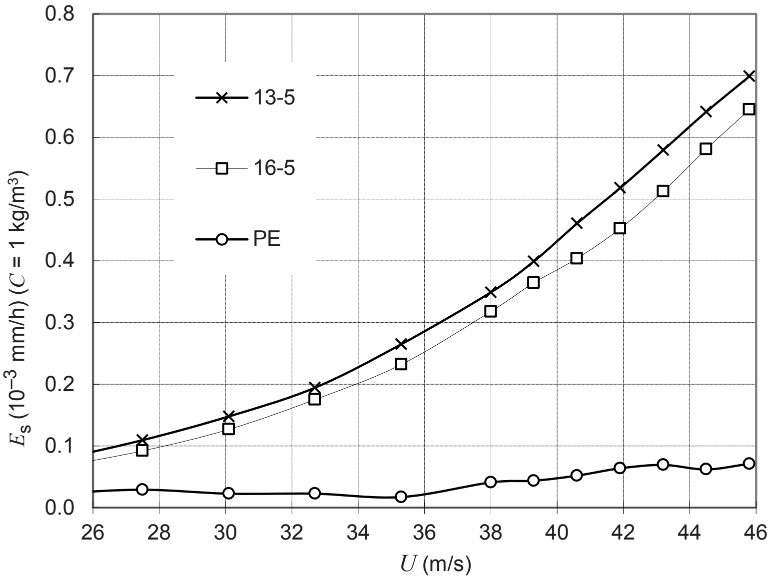


Figure E.12 – Curve of unit abrasion rate with circumference velocity for 3 kinds of materials

Table E.9 – Results of relative wear resistance for some materials (U = 40m/s)

Nb.	Materials	Chemical composition	Wear resistance index
1	0Cr13Ni5Mo		1,0
2	0Cr16Ni5Mo		1,1
3	13Cr4NiMo		1,0
4	HVOF coating	WC-CoCr	4,2
5	Spray fusing	WC-modify alloy	2,9
6	Polyurethane polymer		8,0
7	Super high polyethylene (PE)		8,5

Annex F
(informative)

Typical criteria to determine overhaul time due to abrasion erosion

A unit may be overhauled when the following conditions, caused by particle abrasion, occur:

1) the guide vanes are so worn out that it is difficult for the inlet valve to open normally, or that the unit takes too long to stop when shutting down or does not stop at all;
2) the thickness of the runner blade outlet for large-scale hydro turbines is abraded more than two-thirds, and for smaller turbines it is completely worn away;
3) the facing plates, of head cover and bottom ring are completely worn away;
4) the depth of the overall abrasion for the runner blade is more than 2 mm to 4 mm; depth of the local abrasion for the runner blade is more than 4 mm to 10 mm;
5) the clearance of the runner seals is doubled;
6) the efficiency of the turbine is reduced 1 % to 2 %; output is reduced 2 % to 4 %;
7) for surface coated machines, the worn out area of coating exceeds 5 % of the total coated area;
8) the main shaft seal is so worn out that it cannot run safely, unless the seal can be replaced without disassembling the unit.

Annex G
(informative)

Example to calculate the amount of erosion in the full model

Assuming a Francis unit with the following main data:

n = 300 rpm

P = 255 MW

H = 428 m

$D = RS$ = 2,507 m

The aim is to calculate the expected erosion depth for the guide vanes, facing plates, runner inlet, runner outlet and labyrinth seals that is caused by the PL as calculated in Annex A, i.e. PL = 38,28. The parts are all manufactured from martensitic stainless steel.

The basic formula for calculating abrasion depth is

$$S = W^{3,4} \times PL \times K_{\mathrm{m}} \times K_{\mathrm{f}} / RS^{\mathrm{p}}$$

The first step is to calculate the characteristic velocities. The specific speed for this unit is

$$n_{\mathrm{s}} = n \times P^{0,5} / H^{1,25} = 300 \times 255\ 000^{0,5} / 428^{1,25} = 77,8$$

According to Figure 1:

$$W_{\mathrm{run}}=(0,25+0,003 \times n_{\mathrm{s}}) \times (2 \times g \times H)^{0,5} = (0,25+0,003 \times 77,8) \times (2 \times 9,81 \times 428)^{0,5} = 44,3 \text{ m/s}$$

$$W_{\mathrm{gv}} = 0,55 \times (2 \times g \times H)^{0,5} = 0,55 \times (2 \times 9,81 \times 428)^{0,5} = 50,4 \text{ m/s}$$

According to 3.1 K_{m} for martensitic stainless steel is 1.

According to 3.2 K_{f} and p for the various components are as follows:

Guide vanes: $K_{\mathrm{f}} = 1,06 \times 10^{-6}$, $p = 0,25$

Facing plates: $K_{\mathrm{f}} = 0,86 \times 10^{-6}$, $p = 0,25$

Runner inlet: $K_{\mathrm{f}} = 0,90 \times 10^{-6}$, $p = 0,25$

Runner outlet: $K_{\mathrm{f}} = 0,54 \times 10^{-6}$, $p = 0,75$

Labyrinth seals: $K_{\mathrm{f}} = 0,38 \times 10^{-6}$, $p = 0,75$

For the guide vanes the total wear is thus

$$S = W^{3,4} \times PL \times K_{\mathrm{m}} \times K_{\mathrm{f}} / RS^{\mathrm{p}} = 50,4^{3,4} \times 38,28 \times 1 \times 1,06 \times 10^{-6} / 2,507^{0,25} = 20 \text{ mm}$$

For the other components, calculations are shown in Table G.1 below.

Table G.1 – Calculations

Component	W	PL	K_m	K_f	p	S
Guide vanes	50,4	3,84	1	$1{,}06 \times 10^{-6}$	0,25	20 mm
Facing plates	50,4	3,84	1	$0{,}86 \times 10^{-6}$	0,25	16 mm
Runner inlet	50,4	3,84	1	$0{,}90 \times 10^{-6}$	0,25	17 mm
Runner outlet	44,3	3,84	1	$0{,}54 \times 10^{-6}$	0,75	6,5 mm
Labyrinth seals	44,3	3,84	1	$0{,}38 \times 10^{-6}$	0,75	4,6 mm

The standard deviation for the guide vanes is 42 % according to 3.2. This means that with a probability of 67 % the actual value of S for the guide vanes will be between 11 mm and 28 mm. This may not seem very accurate, but it is the best estimate that can be supported by the data received at this time. It is hoped that in the future more data can be gathered in a suitable format so that the formula can be revised in order to make more accurate estimates.

Annex H
(informative)

Examples to calculate the TBO in the reference model

Table H.1 below shows how the calculation should be done for a Pelton turbine.

Table H.1 – Pelton turbine calculation example

			Reference turbine	**Planned turbine**
Type			Pelton	Pelton
Coated / uncoated			Coated	Coated
Rot. speed		rpm	720	600
Bucket width	B_2	mm	700	365
Number of nozzles	z_0		1	6
Number of buckets	z_2		21	22
Average particle concentration	C	kg/m^3	0,220	0,090
Fraction of particles with Mohs hardness 5 to 5,4		%	0	0
Fraction of particles with Mohs hardness 5,5 to 5,9		%	22	25
Fraction of particles with Mohs hardness 6 to 6,9		%	0	0
Fraction of particles with Mohs hardness 7 to 7,9		%	40	55
Fraction of particles with Mohs hardness >8		%	0	0
Shape factor (1=round, 1,5=sub-angular, 2=angular)	K_{shape}	-	1	1,5
Characteristic velocity (runner)	W_{run}	m/s	67	46
Time between overhaul TBO		h	13 600	**6 400**

Calculation of TBO

$TBO_{\text{target}} = S_{\text{ref, calc}}/S_{\text{target, calc}} \times TBO_{\text{ref}}$

$S_{\text{ref, calc}}/S_{\text{target, calc}} = W_{\text{ref}}^{3,4}/W_{\text{target}}^{3,4} \times PL_{\text{ref}}/PL_{\text{target}} \times K_{\text{m,ref}}/K_{\text{m,target}} \times K_{\text{f,ref}}/K_{\text{f,target}} \times B_{\text{2,target}}/B_{\text{2,ref}}$

$= 3.59 \times 1{,}19 \times 1 \times 0{,}210 \times 0{,}521$

$= 0{,}454$

with:

$W_{\text{ref}}^{3,4}/W_{\text{target}}^{3,4} = 3{,}59$

$PL_{\text{ref}}/PL_{\text{target}} = C_{\text{ref}}/C_{\text{target}} \times K_{\text{shape,ref}}/K_{\text{shape,target}} \times K_{\text{size,ref}}/K_{\text{size,target}} \times K_{\text{hardness,ref}}/K_{\text{hardness,target}} = 1{,}19$

Assumptions:

- constant over the year
- $K_{\text{size,ref}}/K_{\text{size,target}} = 1$
  (grain size distribution in both cased is assumed to be the same)

- $K_{\text{hardness,ref}} / K_{\text{hardness,target}}$ ≈ 0,73
  (as both runners are coated only the fraction of Mohs hardness above 7 is used. Ratio of both fractions is 0,73)

$K_{\text{m,ref}}/K_{\text{m,target}}$ = 1 (both coated)

$K_{\text{f,ref}} / K_{\text{f,target}} = [z_{0,\text{ref}} \times n_{\text{ref}} / z_{2,\text{ref}}] / [z_{0,\text{target}} \times n_{\text{target}} / z_{2,\text{target}}]$ = 0,210

$B_{2,\text{target}} / B_{2,\text{ref}}$ = 365 / 700 = 0,521

TBO_{target} = 0,470 × 13 600 h ~ 6 400 h

Table H.2 below shows how the calculation should be done for a Francis turbine.

Table H.2 – Francis turbine calculation example

			Reference turbine	**Unknown turbine**
Type			Francis	Francis
Coated / uncoated			Coated	Coated
Reference diameter	D	M	1.279	2,523
Average particle concentration	C	kg/m^3	0,126	0,716
Fraction of particles with Mohs hardness 5 to 5.4		%	0	0
Fraction of particles with Mohs hardness 5,5 to 5,9		%	2	2
Fraction of particles with Mohs hardness 6 to 6,9		%	16	3,3
Fraction of particles with Mohs hardness 7 to 7,9		%	38	75
Fraction of particles with Mohs hardness >8		%	0	0
Shape factor (1=round, 1,5=sub-angular, 2=angular)	K_{shape}	-	1	1,5
Characteristic velocity (runner)	W_{run}	m/s	59,9	47,6
Time between overhaul	TBO	h	22 800	**5 800**

Calculation of *TBO*

$TBO_{\text{target}} = S_{\text{ref, calc}}/S_{\text{target, calc}} * TBO_{\text{ref}}$

$S_{\text{ref, calc}}/S_{\text{target, calc}} = W_{\text{ref}}^{3,4} / W_{\text{target}}^{3,4} \times PL_{\text{ref}}/PL_{\text{target}} \times K_{\text{m,ref}}/K_{\text{m,target}} \times K_{\text{f,ref}}/K_{\text{f,target}} \times D_{\text{target}} / D_{\text{ref}}$

= 2,185 × 0,059 × 1 × 1 × 1,97

= 0,254

with:

$W_{\text{ref}}^{3,4} / W_{\text{target}}^{3,4}$ = 2,185

$PL_{\text{ref}} / PL_{\text{target}} = C_{\text{ref}} / C_{\text{target}} \times K_{\text{shape,ref}} / K_{\text{shape,target}} \times K_{\text{size,ref}} / K_{\text{size,target}} \times K_{\text{hardness,ref}} / K_{\text{hardness,target}}$

$= 0{,}176 \times 0{,}667 \times 1 \times 0{,}5$

$= 0{,}058\ 7$

Assumptions:

- constant over the year

- $K_{\mathrm{size,ref}} / K_{\mathrm{size,target}} = 1$
  (grain size distribution in both cased is assumed to be the same)
- $K_{\mathrm{hardness,ref}} / K_{\mathrm{hardness,target}} \approx 0{,}5$
  (based that the fraction of hard particles with Mohs hardness of 7 and higher is double in the target turbine, as the runner is coated only the fraction of Mohs hardness above 7 is used)

$K_{\mathrm{m,ref}}/K_{\mathrm{m,target}} = 1$ (both coated)

$K_{\mathrm{f,ref}} / K_{\mathrm{f,target}} = 1$ (for Francis)

$$\boldsymbol{TBO}_{\mathrm{target}} = 0{,}254 \times 22\ 800\ \mathrm{h}$$
$$= 5\ 800\ \mathrm{h}$$

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