IEC 62364

Edition 2.0 2019-01
REDLINE VERSION

# INTERNATIONAL STANDARD

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## Hydraulic machines – Guidelines for dealing with hydro-abrasive erosion in kaplan, francis, and pelton turbines



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

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International Standard IEC 62364 has been prepared by IEC technical committee 4: Hydraulic turbines.

This second edition cancels and replaces the first edition published in 2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) the formula for TBO in Pelton reference model has been modified;
b) the formula for calculating sampling interval has been modified;
c) the chapter in hydro-abrasive erosion resistant coatings has been substantially modified;
d) the annex with test data for hydro-abrasive erosion resistant materials has been removed;
e) a simplified hydro-abrasive erosion evaluation has been added.

The text of this International Standard is based on the following documents:

| FDIS | Report on voting |
|---|---|
| 4/351/FDIS | 4/366/RVD |

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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# 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.~~

The number of hydro power plants with hydro-abrasive erosion is increasing worldwide.

An overall approach is needed to minimize the impact of this phenomenon. Already at the start of the planning phase an evaluation should be done to quantify the hydro-abrasive erosion and the impact on the operation. For this, the influencing parameters and their impact on the hydro-abrasive erosion have to be known. The necessary information for the evaluation comprises among others the future design, the particle parameters of the water, which will pass the turbine, the reservoir sedimentation and the power plant owner's framework for the future operation like availability or maximum allowable efficiency loss, before an overhaul needs to be done.

Based on this evaluation of the hydro-abrasive erosion, an optimised solution can then be found, by analysing all measures in relation to investments, energy production and maintenance costs as decision parameters. Often a more hydro-abrasive erosion-resistant design, instead of choosing the turbine design with the highest efficiency, will lead to higher revenue. This analysis is best performed by the overall plant designer.

With regards to the machines, owners should find the means to communicate to potential suppliers 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 hydro-abrasive erosion.

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~~ hydro-abrasive erosion service. This has led some owners to write into their specifications, conditions which cannot be met with known methods and materials.

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

## 1 Scope

This document gives guidelines for:

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

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

c) developing guidelines based on "experience data" concerning the relative resistance of materials faced with ~~particle abrasion~~ hydro-abrasive erosion problems;

d) developing guidelines concerning the maintainability of ~~abrasion resistant~~ materials with high resistance to hydro-abrasive erosion and hard ~~facing~~ coatings;

e) developing 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) developing guidelines concerning operation mode of the hydro turbines in water with particle materials to increase the operation life.

It is assumed in this document 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 document to address these issues.

It is assumed in this document that cavitation is not present in the turbine. Cavitation and ~~abrasion may~~ hydro-abrasive erosion can reinforce each other so that the resulting erosion is larger than the sum of cavitation erosion plus ~~abrasion~~ hydro-abrasive erosion. The quantitative relationship of the resulting ~~abrasion~~ hydro-abrasive erosion is not known and it is beyond the scope of this document to assess it, except to ~~recommend~~ suggest 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~~ can impact turbine components and produce damage. This damage ~~may~~ can in turn increase the flow turbulence thereby accelerating wear by both cavitation and ~~abrasion~~ hydro-abrasive erosion. ~~Abrasion~~ Hydro-abrasive erosion resistant coatings can also be damaged locally by impact of large solids. It is beyond the scope of this document to address these issues.

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

## 2 Terms, definitions and symbols

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

NOTE 1 Terms and definitions are also based, where relevant, on IEC TR 61364.

NOTE 2 The International System of Units (S.I.) is adopted throughout this document but other systems are allowed.

| 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<br><br>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<br><br>Note 1 to entry: For full information, see IEC 60193. | $g$ | $m/s^2$ |
| 2.2.3 | turbine head<br>pump head | available head at hydraulic machine terminal<br><br>$H = E/g$ | $H$ | m |
| 2.2.4 | reference diameter | reference diameter of the hydraulic machine<br><br>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<br><br>Note 2 to entry: See IEC 60193 for further information. | $D$ | m |
| 2.2.5 | hub diameter | the diameter of runner hub for Kaplan turbines | $D_h$ | mm |
| 2.2.~~5~~6 | ~~abrasion~~ hydro-abrasive erosion depth | depth of ~~metal layer that has been removed from a component due to particle abrasion~~ material removed (measured perpendicular to the original surface) from a component due to hydro-abrasive erosion | $S$ | mm |
| 2.2.~~6~~7 | characteristic velocity | characteristic velocity defined for each machine component and used to quantify ~~particle abrasion~~ hydro-abrasive erosion damage<br><br>Note 1 to entry: See also 2.2.20 to 2.2.24. | $W$ | m/s |
| 2.2.~~7~~8 | particle concentration | mass concentration of ~~all solid particles per m³ of water solution~~ particles, i.e. the mass of solid particles per volume of water-particle mixture<br><br>Note 1 to entry: In case the particle concentration is expressed in parts per million (ppm) it is recommended to use the mass of particles per ~~mass~~ volume of water, so that 1 000 ppm approximately corresponds to 1 $kg/m^3$. | $C$ | $kg/m^3$ |

| Sub-clause | Term | Definition | Symbol | Unit |
|---|---|---|---|---|
| 2.2.~~8~~9 | particle load | ~~the particle concentration integrated over the time, $T$, that is under consideration~~<br>the integral of the modified particle concentration over time:<br>$$PL=\int_0^T C(t)\times K_{\text{size}}(t)\times K_{\text{shape}}(t)\times K_{\text{hardness}}(t)dt$$<br>$$\left(\approx\sum_{n=1}^{N} C_n\times K_{\text{size},n}\times K_{\text{shape},n}\times K_{\text{hardness},n}\times T_{s,n}\right)$$<br>$C(t)$ = 0 if no water is flowing through the turbine.<br>~~If the unit is at standstill with pressurized spiral case then $C(t)$=0 when calculating $PL$ for runner and labyrinth seals, but $C(t)\neq 0$ when calculating $PL$ for guide vanes and facing plates.~~<br>Note 1 to entry: For Francis turbines $C(t)$ = 0 when calculating $PL$ for runner and labyrinth seals, if the unit is at standstill with pressurized spiral case, but $C(t) \neq 0$ when calculating $PL$ for guide vanes and facing plates. | $PL$ | kg × h/m$^3$ |
| 2.2.~~9~~10 | size factor | factor that characterizes how the ~~abrasion~~ hydro-abrasive erosion relates to the size of the abrasive particles = median particle size $dP_{50}$ in mm | $K_{\text{size}}$ | |
| 2.2.~~10~~11 | shape factor | factor that characterizes how the ~~abrasion~~ hydro-abrasive erosion relates to the shape of the abrasive particles<br>Note 1 to entry: See Annex D. | $K_{\text{shape}}$ | |
| 2.2.~~11~~12 | hardness factor | factor that characterizes how the ~~abrasion~~ hydro-abrasive erosion relates to the hardness of the abrasive particles<br>for 13Cr4Ni stainless steel: $K_{\text{hardness}}$ = fraction of particles harder than Mohs 4,5.<br>for hard coated surfaces: $K_{\text{hardness}}$ = fraction of particles harder than Mohs 7,0. | $K_{\text{hardness}}$ | |
| 2.2.~~12~~13 | material factor | factor that characterizes how the ~~abrasion~~ hydro-abrasive erosion relates to the material properties of the base material | $K_{\text{m}}$ | |
| 2.2.~~13~~14 | flow coefficient | coefficient that characterizes how the ~~abrasion~~ hydro-abrasive erosion relates to the water flow around each component | $K_{\text{f}}$ | $\dfrac{\text{mm}\times \text{s}^{3,4}}{\text{kg}\times \text{h}\times \text{m}^{\alpha}}$ |
| 2.2.~~14~~15 | sampling interval | time interval between two water samples taken to determine the concentration of abrasive particles in the water | $T_{\text{s}}$ | h |
| 2.2.~~15~~16 | yearly particle load | Total load ($PL$) for 1 year of operation, i.e. $PL$ for $T$ = 8 760 h calculated in accordance with 2.2.~~8~~9 | $PL_{\text{year}}$ | kg × h/m$^3$ |
| ~~2.2.16~~ | ~~maximum concentration~~ | ~~the maximum concentration of abrasive particles over a specified time interval~~ | ~~$C_{\text{max}}$~~ | ~~kg/m$^3$~~ |
| 2.2.17 | maximum particle load | maximum value of the integrand in the $PL$ integral during a specified time interval, i.e. the maximum value of the following expression<br>$$PL_{\text{max}}=C(t)\times K_{\text{size}}(t)\times K_{\text{shape}}(t)\times K_{\text{hardness}}(t)$$ | $PL_{\text{max}}$ | kg/m$^3$ |

| Sub-clause | Term | Definition | Symbol | Unit |
|---|---|---|---|---|
| 2.2.~~17~~18 | particle median diameter | 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 | angle between the particle trajectory and the surface of the substrate | | ° |
| 2.2.20 | characteristic velocity in Francis guide vanes<br><br>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<br><br>$W_{\text{gv}} = \dfrac{Q}{a \times Z_0 \times B_0}$ | $W_{\text{gv}}$ | 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~~<br>~~$W_{\text{gv}} = 0{,}5 \times \sqrt{2 \times E}$~~ | ~~$W_{\text{gv}}$~~ | ~~m/s~~ |
| 2.2.~~22~~21 | characteristic velocity in Pelton injector | speed of the water flow at injector location<br><br>$W_{\text{inj}} = \sqrt{2 \times E}$ | $W_{\text{inj}}$ | m/s |
| 2.2.~~23~~22 | characteristic velocity in ~~Kaplan or Francis tubular~~ turbine runner | relative velocity between the water and the runner blade estimated with below formulas at best efficiency point<br><br>$W_{\text{run}} = \sqrt{u_2{}^2 + c_2{}^2}$<br>$u_2 = n \times \pi \times D$<br>$c_2 = \dfrac{Q \times 4}{\pi \times D^2}(Francis)$<br>$c_2 = \dfrac{Q \times 4}{\pi \times (D^2 - D_h{}^2)}(Kaplan)$<br><br>~~Note 1 to entry: In calculation of $c_2$ for Kaplan turbines, the hub diameter has been neglected in the interest of simplicity.~~ | $W_{\text{run}}$ | m/s |
| 2.2.~~24~~23 | characteristic velocity in Pelton runner | ~~speed of the water flow at a Pelton runner~~<br>relative velocity between the water and the runner bucket<br><br>$W_{\text{run}} = 0{,}5 \times \sqrt{2 \times E}$ | $W_{\text{run}}$ | m/s |
| 2.2.~~25~~24 | discharge ~~(volume flow rate)~~ | volume of water per unit time passing through any section in the system | $Q$ | m³/s |
| 2.2.~~26~~25 | guide vane opening | average shortest distance between adjacent guide vanes (at a specified section if necessary)<br><br>Note 1 to entry: For further information, see IEC 60193. | $a$ | m |
| 2.2.~~27~~26 | number of guide vanes | total number of guide vanes in a turbine | $z_0$ | |

| Sub-clause | Term | Definition | Symbol | Unit |
|---|---|---|---|---|
| 2.2.~~28~~27 | distributor height | height of the distributor in a turbine | $B_0$ | m |
| 2.2.~~29~~28 | rotational speed | number of revolutions per unit time | $n$ | 1/s |
| 2.2.~~30~~29 | specific speed | commonly used specific speed ~~to~~ of a hydraulic machine<br>$$n_S = \frac{60 \times n \times \sqrt{P}}{H^{5/4}}$$<br>$P$ and $H$ are taken in the rated operating point and given in kW and m respectively | $n_s$ | rpm |
| 2.2.~~31~~30 | output | output of the turbine in the rated operating point | $P$ | kW |
| 2.2.~~32~~31 | ~~actual abrasion~~ hydro-abrasive erosion depth of target unit | estimated actual depth of metal that will be removed from a component of the target turbine due to particle ~~abrasion~~ hydro-abrasive erosion<br><br>Note 1 to entry: For use with the reference model. | $S_{target~~, actual~~}$ | mm |
| 2.2.~~33~~32 | ~~actual abrasion~~ hydro-abrasive erosion depth of reference unit | ~~the actual~~ hydro-abrasive erosion depth of metal that has been removed from a component of the reference turbine due to ~~particle abrasion~~ hydro-abrasive erosion<br><br>Note 1 to entry: For use with the reference model. | $S_{ref~~, actual~~}$ | mm |
| 2.2.~~34~~33 | number of nozzles | number of nozzles in a Pelton turbine | ~~$z_0$~~ $z_{jet}$ | |
| 2.2.~~35~~34 | bucket width | bucket width in a Pelton runner | $B_2$ | mm |
| 2.2.~~36~~35 | number of buckets | number of buckets in a Pelton runner | $z_2$ | |
| 2.2.~~37~~36 | time between overhaul for target unit | time between overhaul for target unit<br><br>Note 1 to entry: For use with the reference model. | $TBO_{target}$ | h |
| 2.2.~~38~~37 | time between overhaul for reference unit | time between overhaul for reference unit<br><br>Note 1 to entry: For use with the reference model. | $TBO_{ref}$ | h |
| 2.2.~~39~~38 | turbine reference size | reference size for calculation curvature dependent effects of hydro-abrasive erosion<br><br>Note 1 to entry: For Francis turbines, it is the reference diameter, $D$ (see 2.2.4).<br><br>Note 2 to entry: For Pelton turbines it is the inner bucket width, $B_2$.<br><br>Note 3 to entry: For further information in the inner bucket width, $B_2$, see IEC 60609-2. | $RS$ | m |
| 2.2.~~40~~39 | size exponent | exponent that describes the size dependant effects of hydro-abrasive erosion in evaluating $RS$ | $p$ | |
| 2.2.~~41~~40 | exponent | numerical value of 0,4-$p$ that balances units for $K_f$ | $\alpha$ | |

# 3 ~~Abrasion rate~~ Prediction of hydro-abrasive erosion rate

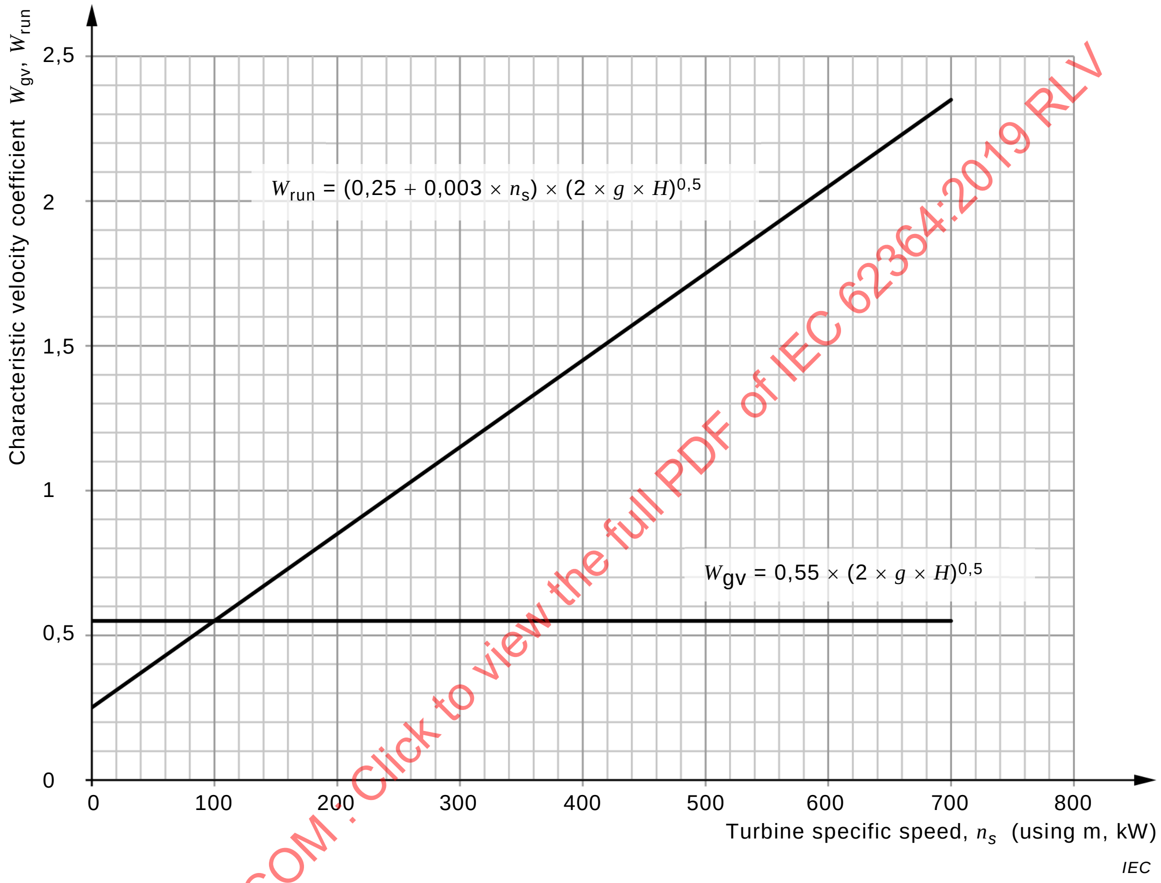
## 3.1 Model for hydro-abrasive erosion depth

The following formula can be used to estimate the hydro-abrasive erosion depth in a Francis turbine:

$$S = W^{3,4} \times PL \times K_m \times K_f / RS^p$$

- The characteristic velocity, $W$, is defined in 2.2.20 to 2.2.23. If detailed data to calculate $W$ is not available it can be estimated based on Figure 1,
- $PL$, $K_m$ and $RS$ are defined in 2.2.9, 2.2.13 and 2.2.38 respectively,
- For uncoated components of Francis turbines $K_f$ and $p$ are taken from Table 1 below.

For additional information of the background for this formula please refer to Annex I. A sample calculation is found in Annex G.






NOTE Values of $n_s$ and $H$ in this figure refer to the rated operating point while the characteristic velocities are given for the points noted in Clause 2.

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

**Table 1 – Values of $K_f$ and $p$ for various components**

| Component | $K_f$ | Exponent $p$ (for $RS$) |
|---|---|---|
| Francis guide vanes | $1,06 \times 10^{-6}$ | 0,25 |
| Francis facing plates | $0,86 \times 10^{-6}$ | 0,25 |
| Francis labyrinth seals | $0,38 \times 10^{-6}$ | 0,75 |
| Francis runner inlet | $0,90 \times 10^{-6}$ | 0,25 |
| Francis runner outlet | $0,54 \times 10^{-6}$ | 0,75 |

### 3.2 Reference model

In the reference model presented in this document 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 hydro-abrasive 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 hydro-abrasive 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~~ hydro-abrasive erosion 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:

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

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

Pelton turbines:

$K_{f,\,ref} / K_{f,\,target}$ =

~~$z_{0,ref} \times n_{ref} \times z_{2,target} / (z_{0,target} \times n_{target} \times z_{2,ref})$~~ $z_{jet,ref} \times z_{2,target} / (z_{jet,target} \times z_{2,ref})$

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

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. A sample calculation is found in Annex H.

### 3.3 Simplified hydro-abrasive erosion evaluation

In addition to the formulas in 3.1 and 3.2 other methods to estimate hydro-abrasive erosion have been proposed, such as in [15] and [22][1]. Each method may have its advantages and disadvantages.

[1] Numbers in square brackets refer to the Bibliography.

As a quick and easy rule of thumb to make a first assessment of the severity at a particular site it is recommended to evaluate the following expression, which is shown graphically in Figure 2.

If $C \times H^{1,5} \leq 150$ then the hydro-abrasive erosion may not be significant.

If $150 < C \times H^{1,5} < 1\,500$ then the hydro-abrasive erosion may be significant.

If $C \times H^{1,5} \geq 1\,500$ then the hydro-abrasive erosion may be severe.

Of course this rule of thumb is approximate, but it may help decide whether further analysis is advisable.

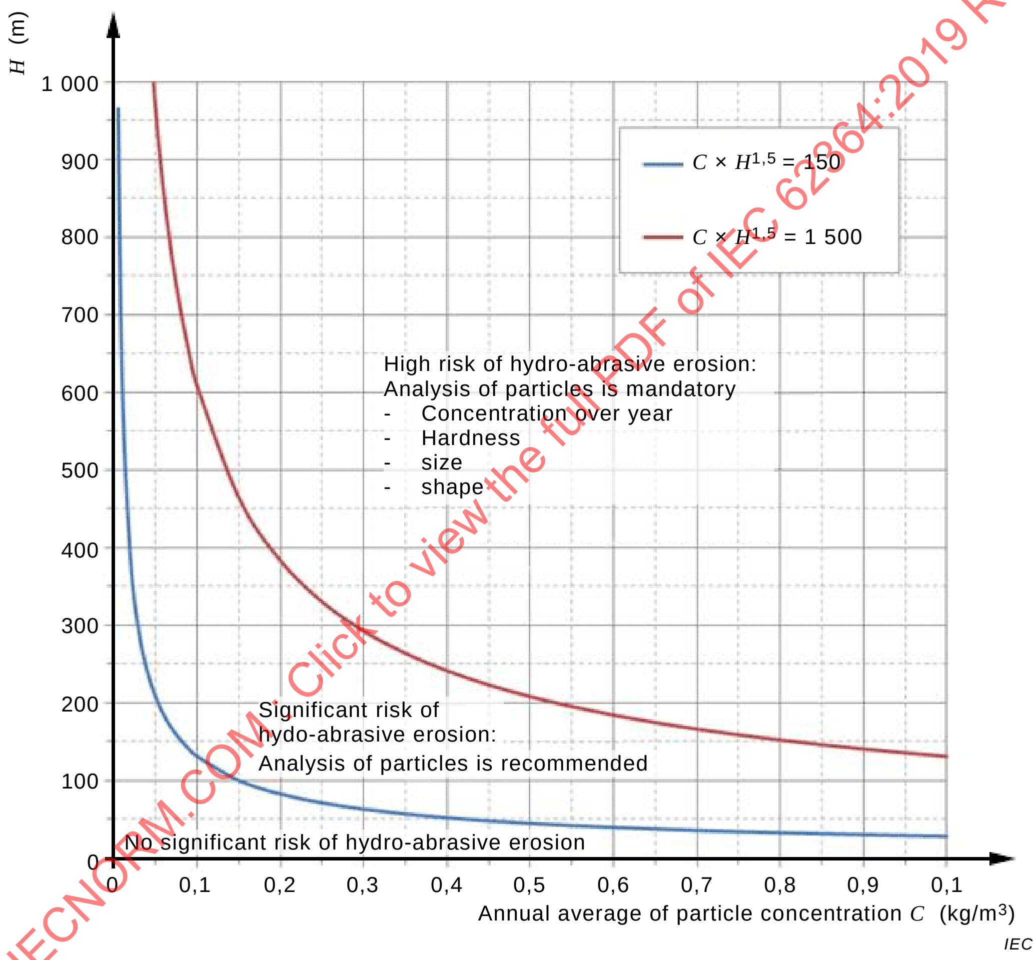





**Figure 2 – Simplified evaluation of risk of hydro-abrasive erosion for first assessment**

# 4 Design

## 4.1 General

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

It should be understood that every ~~hydraulic~~ design of a hydro powerplant is a compromise between several requirements. While it is possible to design a unit to be more resistant against ~~particle abrasion~~ hydro-abrasive erosion 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 Kármán 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 against hydro-abrasive erosion may initially result in increased surface roughness, which may reduce the efficiency. The initially increased surface roughness may be reduced due to the polishing effect of operating with particle laden water. Of course, over time the coated turbine will maintain a higher efficiency compared to the uncoated turbine;
- 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 to reduce the impact of a high particle concentration will increase the total cost of the ~~powerplant~~ power house.

The optimum combination of ~~abrasion resistant~~ design features to reduce the impact of a high particle concentration should be considered and selected for each site based on its specific conditions, taking the economic impact for the lifetime of the powerplant into account.

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.

### 4.2 Selection of ~~abrasion resistant~~ materials with high resistance to hydro-abrasive erosion 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.~~

The selection of materials and possible coatings with high resistance to hydro-abrasive erosion is important. See also Clause 6.

Because corrosion would increase the hydro-abrasive erosion rate, stainless steel is the preferred selection. Weldable stainless steel materials are preferred.

In case coatings resistant to hydro-abrasive erosion are not applied in the beginning, it is recommended to make a hydraulic and mechanical component design where such coatings can easily be applied at a later stage.

Labyrinth seals made of aluminium bronze have in general lower resistance against hydro-abrasive erosion than stainless steel. There are also examples with relative good behaviour of labyrinth seals made of aluminium bronze.

### 4.3 Stainless steel overlays

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

### 4.4 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. Often a very large amount of particles can be removed from the water. The negative side of this is that reservoirs can fill up fast. This will have the result that more and more particles and also larger ones will reach the intake and pass through the turbine. Sedimentation can be reduced by different methods, even if it cannot be completely prevented. Possibilities are extensive flushing and also using a bypass channel/tunnel during the high flood season to divert the highest particle laden water around the reservoir downstream of the hydro power plant. Maintaining the active storage capacity of reservoirs is one possibility of keeping also the turbine operation and the repair costs relatively constant.

If a large reservoir is not available, sand traps (also called desilting basins/ chambers), possibly with preceding gravel traps and other facilities to exclude mainly coarse sediment at intakes may be built. It appears that the minimum particle size that can be removed by desilting chambers is to these structures is in 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 document.

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. At the end of unlined tunnels, rock traps should be provided and deposits should periodically be removed

Due to generally low velocity the water conveyance system itself seldom sees significant abrasion hydro-abrasive erosion damage and normal coating paint on the steel structures of the system is usually enough to protect it.



### 4.5 Valve

#### 4.5.1 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.

If hydro-abrasive erosion is expected, as a general rule all mechanical disturbances in the flow are subject to high hydro-abrasive erosion attack. Therefore the choice between butterfly valve and spherical valve should be discussed by customer and supplier because the sealing disc of a butterfly valve is continuously exposed to the abrasive water flow.

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.

### 4.5.2 Protection (closing) of the gap between housing and trunnion

The area between trunnion and housing is especially susceptible for hydro-abrasive ~~wear~~ erosion. Since the transition of the 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~~ Several design can be proposed, as an example, the transitions can be protected against the direct attack of hydro-abrasive ~~particles~~ erosion by a pre-labyrinth (see Figure 3).

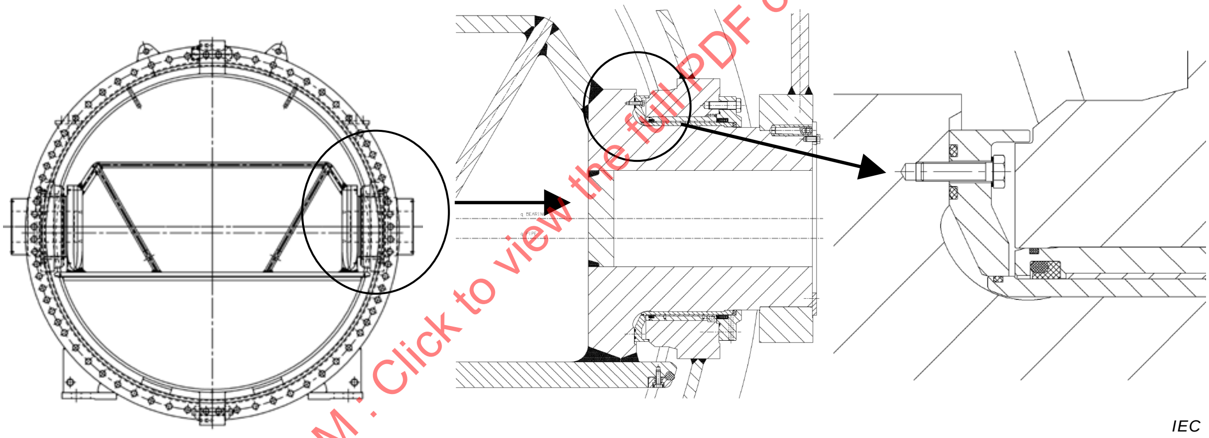



**Figure 3 – Example of protection of transition area**

### 4.5.3 Stops located outside the valve

In hydro-abrasive erosion 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.

### 4.5.4 Proper capacity of inlet valve operator

Normally inlet valves (rotors) will be opened or closed with an approximately balanced pressure (eg. 100:75) that is established by the bypass or the movable sealing rings.

If excessive ~~abrasion~~ hydro-abrasive erosion 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.~~

#### 4.5.5 Increase bypass size to allow higher guide vane leakage

As already mentioned in 4.5.4 above, due to the excessive ~~abrasion~~ hydro-abrasive erosion at the guide vanes the leakage water flow ~~will~~ may 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.

#### 4.5.6 Bypass system design

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

### 4.6 Turbine

#### 4.6.1 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.

#### 4.6.2 Hydraulic design

##### 4.6.2.1 Selection of type of machine

It is advantageous to select a type of machine that has low relative water velocity, that can easily be serviced and that can easily be coated with ~~abrasion~~ hydro-abrasive erosion 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 relative 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 relative velocity. On the other hand, the Kaplan runner has better access for applying ~~abrasion~~ hydro-abrasive erosion 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 relative maximum velocity, which leads to less hydro-abrasive erosion in the Francis turbine. However, the parts in a Pelton turbine that are subject to the relative 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.

##### 4.6.2.2 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~~ hydro-abrasive erosion damage will be in the runner so the specific speed is important. For high head Francis turbines much of the ~~abrasion~~ hydro-abrasive erosion damage will be in the guide vane apparatus, so the specific speed is not so important.

For Pelton turbines, the relative 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~~ hydro-abrasive erosion damage. A lower number of jets ~~will automatically result in a lower specific speed~~ also reduces the time that each bucket is filled with water.

#### 4.6.2.3 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~~ hydro-abrasive erosion.

#### 4.6.2.4 Turbine submergence

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

#### 4.6.2.5 Runner blade overhang

During the refurbishment of a Francis turbine ~~wheel it is sometimes necessary to significantly increase the turbine output~~, the turbine output is sometimes significantly increased. 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 turbulence 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 overhanging blades is to create a lower pressure zone downstream of the runner band seal, thus creating higher seal leakage and more ~~particle abrasion~~ hydro-abrasive erosion at the band seal. These negative effects are always present if a runner is designed with overhang.



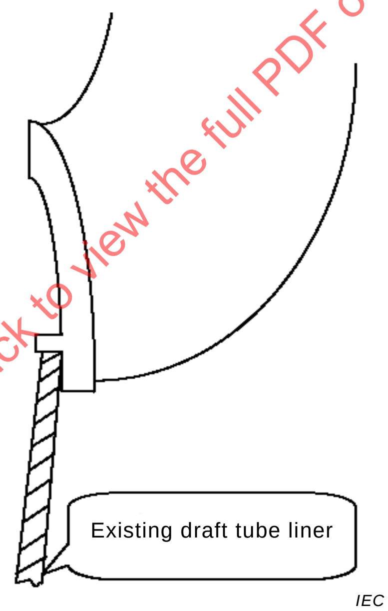



**Figure 4 – Runner blade overhang in refurbishment project**

#### 4.6.2.6 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 Kármán vortices. Also, the risk of ~~"mouse-ear" cavitation (~~ cavitation damage on the runner band, downstream of the blade may increase (see Figure 5). In this context, it can be mentioned that ~~abrasion~~ hydro-abrasive erosion resistant coatings may provide a means to design thin profiles with only a marginal increase in the thickness due to the coating.

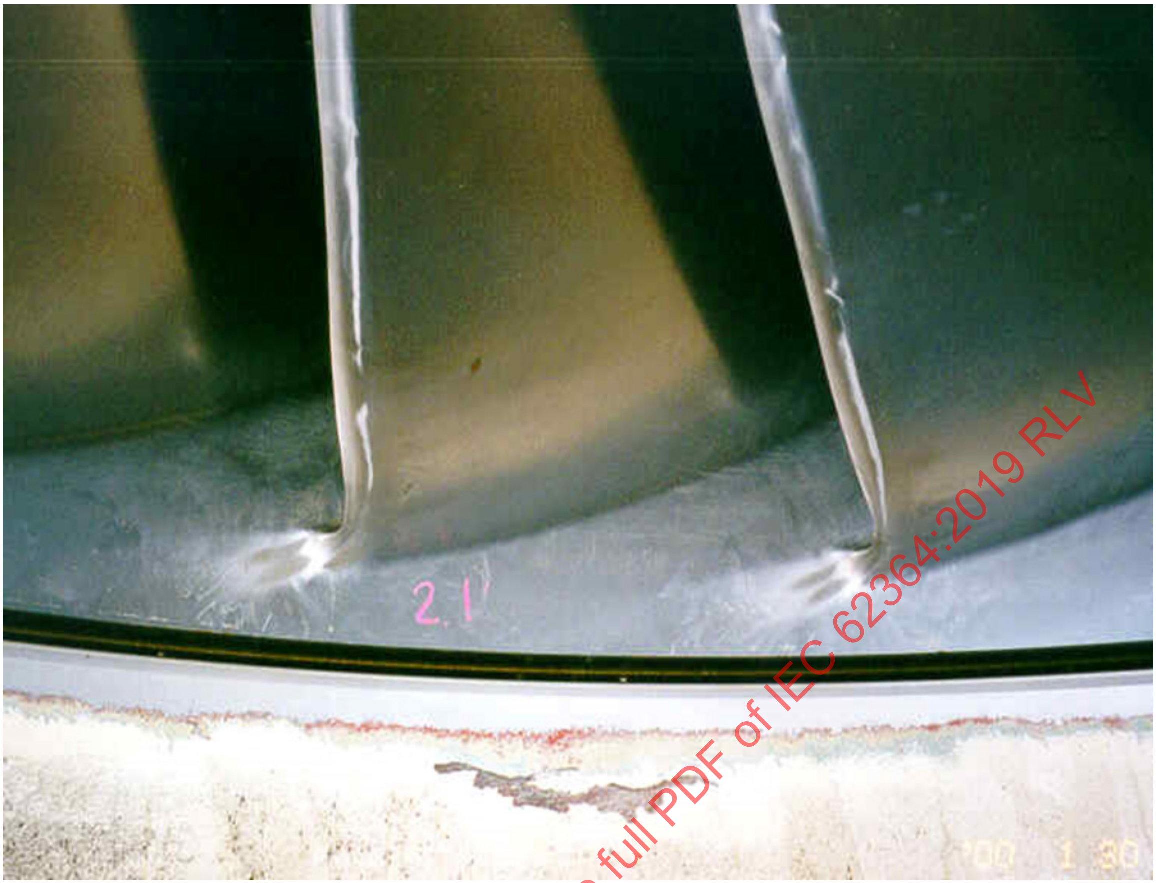


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**Figure 5 – Example of "mouse-ear" cavitation on runner band due to thicker blades**

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.

#### 4.6.2.7 Guide vane overhang

When guide vane overhang exists, the area underneath the guide vane will experience high turbulence and high recirculation and particle abrasion hydro-abrasive erosion 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.

### 4.6.3 Mechanical design

#### 4.6.3.1 General

If abrasion hydro-abrasive erosion 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 hydro-abrasive erosion rate and to allow easy maintenance or replacement of the abraded eroded 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 coating 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 into direct measures to reduce ~~abrasion~~ hydro-abrasive erosion and measures to allow an easy maintenance to dismantle the abraded components.

#### 4.6.3.2 Direct measures to reduce ~~abrasion~~ hydro-abrasive erosion or increase lifetime under abrasive attack

##### 4.6.3.2.1 Guide vane seals

There are three different types of seals: end seals, seals between the inlet and trailing edge of ~~the~~ two neighbouring 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~~ hydro-abrasive erosion of the adjacent components. However, the seals themselves are subject to attack by ~~abrasion~~ hydro-abrasive erosion and the lifetime of these seals may be limited.

The use of guide vane end seals to avoid ~~abrasion~~ hydro-abrasive erosion 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 one example of 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~~ hydro-abrasive erosion rate. The material of the seal rings should be solid ~~wear resistant stainless~~ steel with relatively high resistance to hydro-abrasive erosion or coated stainless steel.



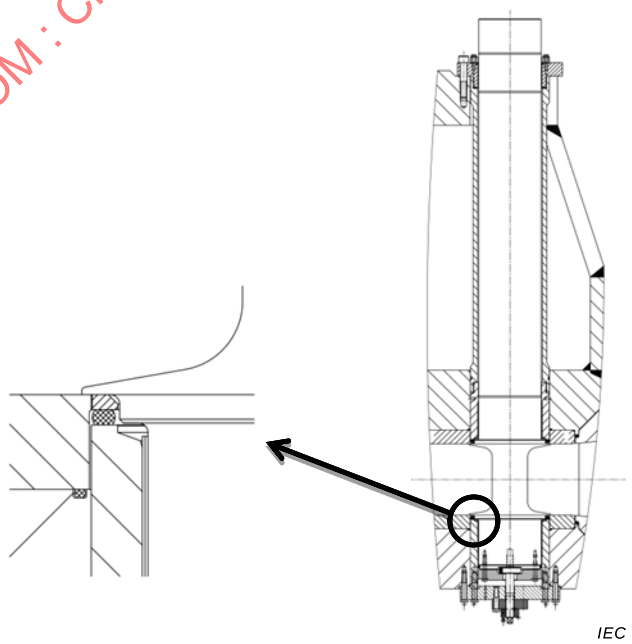



**Figure 6 – ~~Detailed~~ Example of design of guide vane trunnion seals**

All seals should have a stainless steel or a ~~wear~~ hydro-abrasive erosion 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.

#### 4.6.3.2.2 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. This could help to avoid collecting particles in front of the labyrinths.

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 thrust bearing.

#### 4.6.3.2.3 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~~ hydro-abrasive erosion. 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.~~

#### 4.6.3.2.4 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.

#### 4.6.3.2.5 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 hydro-abrasive ~~wear~~ erosion. 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~~ hydro-abrasive erosion is high and if the accessibility allows it, 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.

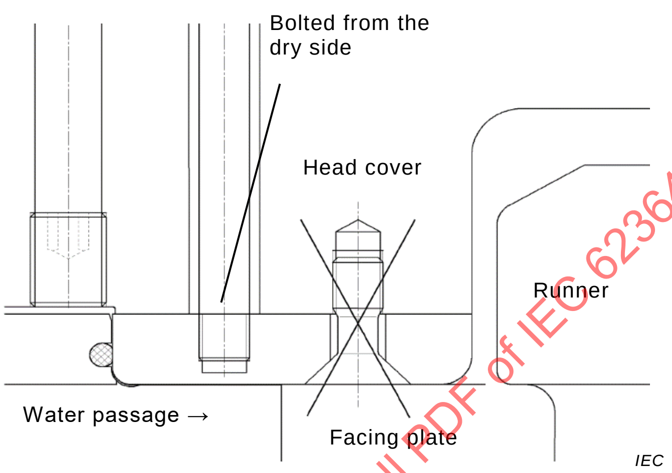



**Figure 7 – Example of fixing of facing plates from the dry side (bolt to the left)**

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 plate 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. If coated facing plates are used the bolting should be from the dry side.

According to the expected ~~wear~~ hydro-abrasive erosion 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.

#### 4.6.3.2.6 Stainless steel overlay in ~~throat rings~~ runner chambers

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

#### 4.6.3.2.7 Stainless steel overlay ~~in areas adjacent to runner band and crown~~ on head cover and bottom ring

Also the water exposed surfaces of the head covers and bottom rings are subject to hydro-abrasive erosion. 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.

#### 4.6.3.2.8 Increase of wall thickness

Increasing the wall thickness is one of the methods to increase the time between the overhauls of a component due to ~~abrasion~~ hydro-abrasive erosion. Increasing the thickness of hydraulic components such as runner blades, is discussed in 4.6.2.6.

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 may be reasonable that the total area of the balancing pipes is at least three times the clearance area of worn labyrinth seals. It is, of course, also possible to accomplish the balancing with holes in the runner instead of separate balancing pipes.



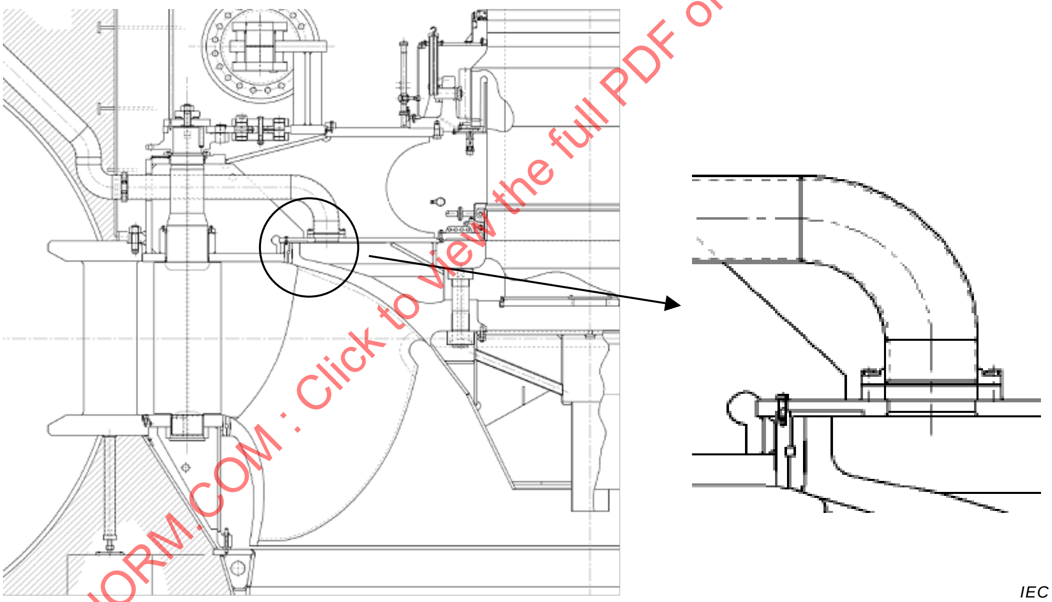



**Figure 8 – Head cover balancing pipes with bends**

#### 4.6.3.2.9 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~~ hydro-abrasive erosion is present, the thrust bearing may be designed to handle additional load so that the unit can be operated with some ~~wear~~ hydro-abrasive erosion of the labyrinth seals.

### 4.6.3.3 Design concepts to allow easy maintenance or replacement

#### 4.6.3.3.1 General

If the components are damaged by ~~abrasion~~ hydro-abrasive erosion 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 take this into account.

#### 4.6.3.3.2 Component removal

The main components which have to be replaced or dismantled for repair in Francis turbines are the runner, the guide vanes, the labyrinth seals 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 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. Especially, if the maintenance management is planning to use two runners (one in operation, one in service) for one unit (one shaft). 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~~ or couplings without necessary mechanical joint machining on site are possible solutions.

#### 4.6.3.3.3 Appropriate design for coating

The resistance of the components against ~~abrasion~~ hydro-abrasive erosion can be considerably improved through appropriate ~~abrasion~~ hydro-abrasive erosion 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~~ Hydro-abrasive erosion 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~~ hydro-abrasive erosion protection, accessibility and economy:

**Francis turbine, pump, pump turbine:**

- Runner
  - labyrinth seals
  - if possible the entire flow ~~tunnel~~ channel. If access for coating is difficult the coated areas may be limited ~~to the runner blade outlet and runner blade inlet~~ to the suction side of runner outlet, the band and runner inlet. Note that the part limiting the Francis runner lifetime is normally the runner blade pressure side
  - 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~~ non-destructive testing is required
- Needle tip
- ~~Nozzle~~ Seat ring
- ~~Nozzle head (beak)~~
- Nozzle housing
- Deflector (if used for long time)

**Kaplan, propeller and bulb turbines:**

- Runner blades
- Runner hub (in extreme cases)
- ~~Runner chamber~~
- Guide vanes (in extreme cases)
- Facing plates (in extreme cases)

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.

#### 4.6.3.3.4 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 of carbon steel can also be considered for economic reasons (with possible increased risk of corrosion~~, abrasion~~ and ~~cavitation~~ adhesion failure).

#### 4.6.3.3.5 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.~~ Hydraulic and mechanical design should consider the limitation for accessibility for thermal spray coating.

~~Step- labyrinths~~ Finger labyrinths have small space between the fingers thus special solutions may be adopted such as concentrically split seals. For ~~straight~~ step labyrinths it ~~is recommended~~ could be an advantage to use a straight gap or to optimize the shape of the step regarding accessibility for thermal spray coating. However, this may influence the sealing performance of the labyrinth. See Figure 9 below.

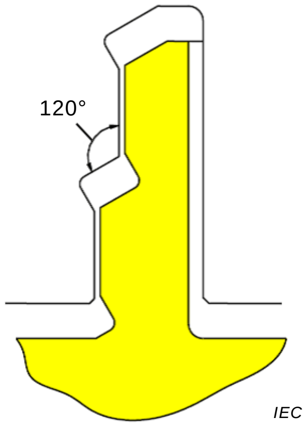



**Figure 9 – Step labyrinth with optimized shape for hardcoating**

## 5 Operation and maintenance

### 5.1 Operation

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

- ~~Shut down the units at higher particle concentration periods.~~ Temporal shut down of the units and closure of the intakes in periods of high concentrations and/or coarse particles. The switch-off concentration is typically above 1 g/l or several 10 g/l. The switch-off concentration results from a site-specific economic optimization, typically based on operation and maintenance records. This may prevent excessive ~~wear~~ hydro-abrasive erosion 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 occur in a short time. 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, through a special system, and open the penstock drainage valve to flush out particles immediately in front of the inlet valve. In this case it is important to analyse the possible consequences on main gates, if any, due to large amount of air into the penstock.
- 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~~ hydro-abrasive erosion resistant coatings. Damage to hydraulic surfaces may increase the turbulence of the flow, which will, in turn, increase the ~~abrasion~~ hydro-abrasive erosion 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~~ hydro-abrasive erosion damage jeopardizes the safety of operation. As the ~~abrasion~~ hydro-abrasive erosion 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 and with the results of the latest and earlier inspections.
- For Pelton turbines the best ratio of produced electricity to hydro-abrasive ~~wear~~ erosion is at full opening of one or more nozzles. Contrary to other turbine types, Pelton turbines allow for reducing the ~~wear~~ hydro-abrasive erosion with reduced load by fully closing individual nozzles, if allowed by the mechanical design of the turbine.

- For Pelton turbines leakage flow through closed nozzles may cause severe locally concentrated hydro-abrasive erosion in seat rings. Closing the upstream spherical valves at standstill avoids this problem. In severe conditions it can be favourable to avoid operation of some nozzles while others are closed (operation restriction at part load)
- For other types of turbines the best ratio of produced electricity to hydro-abrasive ~~wear~~ erosion 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~~ hydro-abrasive erosion for most components and turbine types.
- ~~Close inlet valve at shutdown. With a~~ For Francis turbines 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~~ hydro-abrasive erosion in the guide vane apparatus. By closing the inlet valve this ~~abrasion~~ hydro-abrasive erosion is eliminated. Closing the inlet valve is especially important for high head units.
- Hardcoatings 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 7 regarding cavitation requirements.

### 5.2 Spares and regular inspections

- Keep additional spares in stock for parts subject to ~~abrasion~~ hydro-abrasive erosion. In case of severe ~~abrasion~~ hydro-abrasive erosion a complete set of exchangeable parts (for example guide vanes, facing plates or 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 and to the results of the latest and earlier inspections. Keep adequate records of the amount of ~~abrasion~~ hydro-abrasive erosion 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~~ hydro-abrasive erosion damage. Please see also Annex B.

### 5.3 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 analysed in a laboratory. In addition, several types of ~~equipment~~ instruments for continuous monitoring of the particle concentration ~~in the water~~ have become available, but the accuracy for particle concentration measurements under site conditions is very low. 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~~ concentration in the river and the particle ~~load~~ concentration 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:~~

~~$T_s = 0{,}01 \times PL_{year} / C_{max}$~~

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

- ~~"High particle" period:~~

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

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

  ~~then:~~

  ~~$T_s = 0{,}01 \times 2\ 352 / 26 = 1$ h for "high particle" period~~

- ~~"Low particle" period:~~

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

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

  ~~then:~~

  ~~$T_s = 0{,}01 \times 2\ 352 / 0{,}05 = 470$ 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.~~

Normally a powerplant will have a period(s) with high particle concentration and other period(s) with low particle concentration, see Figure 10. As can be seen the concentration may change in a very short time.

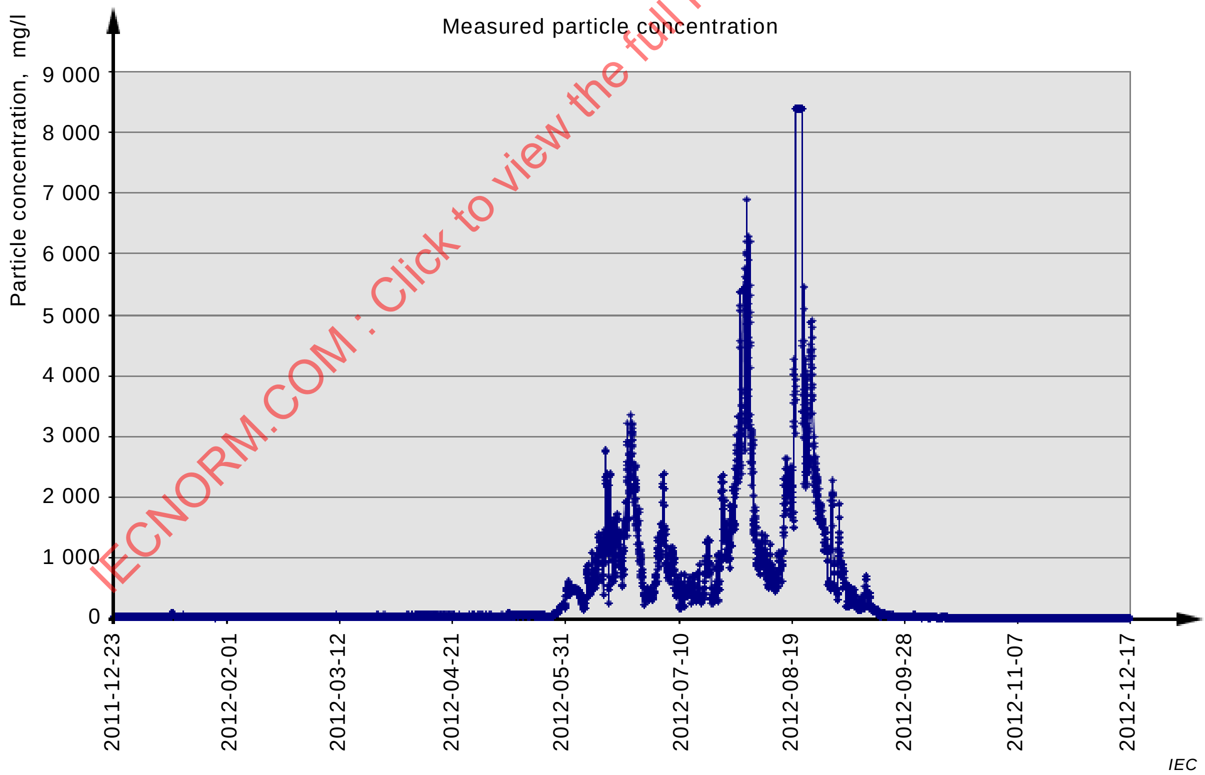



**Figure 10 – Sample plot of particle concentration versus time**

In the low particle concentration period, where there are only small absolute variations in the concentration, the sampling can be done once per day or week.

In the high particle concentration period the sampling has to be done with a frequency between 1 h and 6 h, depending on the concentration difference between consecutive measurements. The final interval should be selected so that at least three measuring points are defining each peak of particle concentration.

If historical data on particle properties is already available a calculation for the sampling interval is given in Annex E. Please see also Annex C for further information.

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;
- discharge (if available);
- 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~~ hydro-abrasive erosion of the labyrinths;
- discharge of the headcover balancing pipes (if applicable). This can give an indication about the wear of the labyrinth seals;
- axial thrust (if applicable or available).

~~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.~~

It should be possible to relate the operating parameters to the records of particle concentration and particle properties. This information can be used to correlate with the observed damages.

Vibration and noise could also be an indication for hydro-abrasive erosion.



# 6 ~~Abrasion resistant materials~~ Materials with high resistance to hydro-abrasive erosion

## 6.1 Guidelines concerning relative ~~abrasion~~ hydro-abrasive erosion resistance of materials including ~~abrasion~~ hydro-abrasive erosion resistant coatings

### 6.1.1 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.

Several comparative tests of materials against hydro-abrasive erosion have been performed. It is however, difficult to compare the results of different tests to each other. The results can therefore be confusing. It was chosen not to report any such tests in this document.

In addition to the wear resistance index against hydro-abrasive erosion several other factors should be considered when selecting an abrasion a hydro-abrasive erosion 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 hydro-abrasive erosion resistance index may have longer lifetime than a very thin layer of a material with a high wear hydro-abrasive erosion resistance index;
- the dimensional tolerance of the coating;
- how easy it is to remove the coating.

### 6.1.2 Discussion and conclusions

Protection of hydro power plant equipment by using abrasion resistant materials or abrasion with high resistance to hydro-abrasive erosion or hydro-abrasive erosion resistant coatings can often increase the lifetime between major overhauls.

At present, the most common abrasion hydro-abrasive erosion resistant coating material in hydraulic machines is thermal sprayed tungsten carbide held in a matrix of cobalt chromium, WC-CoCr. Sometimes also various types of polymer coatings (sometimes referred to as “soft coatings") are used.

The thermal spray coating, often referred to as “hardcoating”, can be applied to most abrasion hydro-abrasive erosion 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 hydro-abrasive erosion resistance, if applied properly. It is worth to note that substantial variations in abrasion hydro-abrasive erosion 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.

Sometimes polymer coatings may also be an option, but only on surfaces not requiring tight tolerances. These coatings, if used, are therefore restricted to water passages in Francis and Kaplan turbines.

Stainless steel facing plates or stainless steel overlay welds can increase the hydro-abrasive erosion resistance compared to carbon steel. It is common to protect, for example, carbon steel head covers and bottom rings with stainless steel at sensitive locations. The hydro-abrasive erosion resistance of stainless steel is far from the level of thermal spray or polymer coating. Abraded stainless steel facing plates are relatively easy and quick to replace. Further improvement in hydro-abrasive erosion 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.



### 6.2 Guidelines concerning maintainability of ~~abrasion~~ hydro-abrasive erosion resistant coating materials

#### 6.2.1 Definition of terms used in this subclause

1) *Overhaul*: Restoration of entire part to the original geometry and quality level including ~~restoration of~~ new protective coating.
2) *Repair*: *Localized* 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.

#### 6.2.2 Time between overhaul for protective coatings

Protective coatings that have been deposited onto part surfaces will also be subject to ~~wear~~ hydro-abrasive erosion but at a considerably lower rate than the underlying steel. After a certain period of operation the coating will be worn ~~out~~ off and the underlying steel will appear. From this moment on, the ~~wear~~ hydro-abrasive erosion 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~~ hydro-abrasive erosion at which the overhaul is necessary is basically the same as for unprotected hydraulic parts and given by the following points:

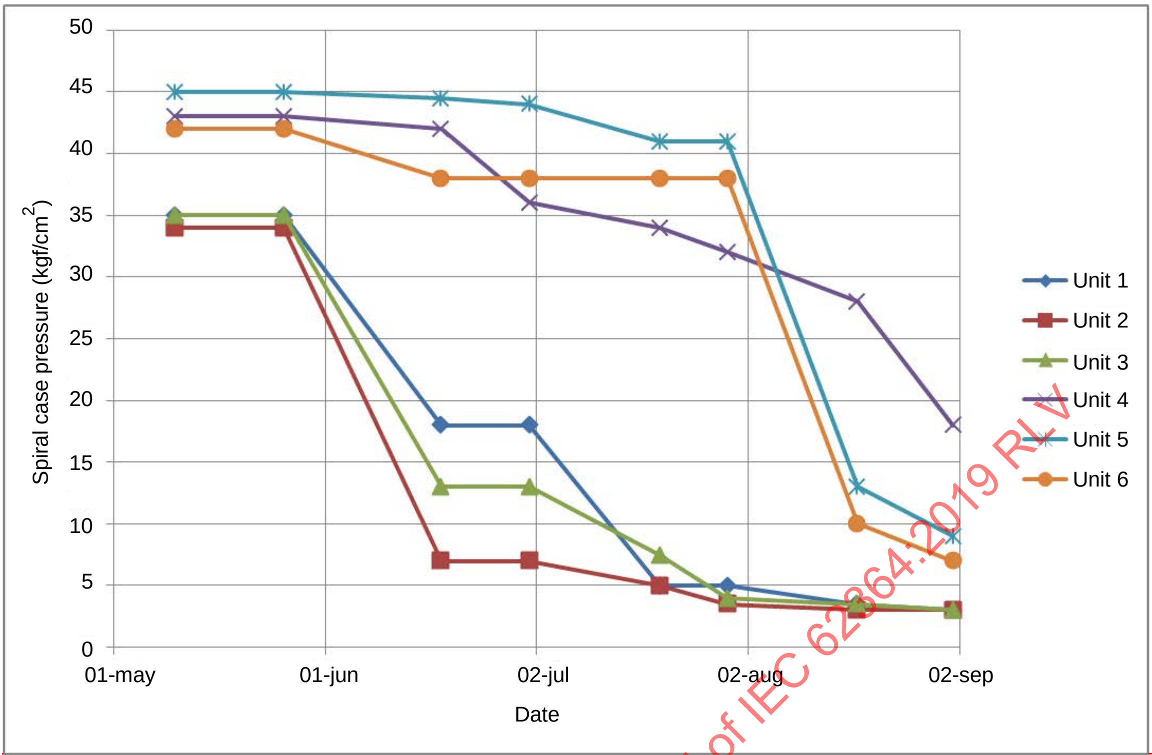
1) As soon as safe operation is no longer possible, the overhaul has to be carried out: for example, when the wall thickness of a part is reduced to a level where mechanical ~~stability~~ integrity of the part can no longer be assured and injury to people or substantial damage to the entire turbine is possible.
2) Provided safety is still ~~intact~~ ensured, 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 a model cited in 3.1 or 3.2 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 previous experience.

- 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~~

### 6.2.3 ~~Maintenance~~ Repair of protective coatings

In order to achieve best quality it is recommended to execute overhauls and repairs in a ~~dedicated~~ specialized workshop 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.~~ In some cases (mainly horizontal Pelton) also an in-situ repair of the coating should be discussed as it might be feasible and could be the best solution. Extreme care should be taken to protect all relevant parts (including generator) from the dust, e.g. by suitable ventilation during the works. Please see also Table 2.

In case of repairs the amount of damage and the necessity of welding and heat treatment plays a significant role in the decision if the repair of the coating can be done on-site. If only grinding without welding or only minor welding repairs are necessary, re-applying the coating may be done on-site with mobile equipment.

On-site reapplication of hard coating may be done for fully coated Francis runners or Pelton runners. For these components the amount of damage is in most cases very small compared to the whole coated area.

**Table 2 – Overview over the feasibility for repair C on site**

| Coating type | Feasibility | Remarks |
|---|---|---|
| Hardcoating | 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 hydro-abrasive erosion 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.

# 7 Guidelines on insertions into specifications

## 7.1 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 hydro-abrasive erosion may mutually reinforce each other as explained in 4.6.2.4. Also some popular abrasion hydro-abrasive erosion 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 hydro-abrasive erosion 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. This can, for example, mean that sigma plant should be higher than sigma incipient and that the plant should be operated accordingly.

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 F. 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 communicate clearly 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 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 hydro-abrasive erosion, in accordance with the guidelines in this document, and estimate the *TBO* required overhaul interval and overhaul scope for safe operation of the unit.

If a hydro-abrasive erosion guarantee is agreed between the owner and the turbine supplier, it should specify the $PL$ that is guaranteed between overhauls, based on some agreed overhaul criteria. Also the recording needed to measure the actual $PL$ and how this data should be communicated between the parties shall be agreed.

## 7.2 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/m³ | Average particle concentration kg/m³ | Particle size, $dP_{50}$ mm | Fraction of hard particles Mohs > 4,5 % | Typical shape of hard particle[b] | Operating net head m | Operating 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. | | | | | | | | | | | | | |
| Typical flood event | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |

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

[b] Refer to Annex D for further details.

## 7.3 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<br>>Mesh 230[a] | Fraction 63 µm to 125 µm<br>Mesh 230 to 120[a] | Fraction 125 µm to 250 µm<br>Mesh 120 to 60[a] | Fraction > 250 µm<br>< Mesh 60[a] | Total |
|---|---|---|---|---|---|
| Jan. – April | | | | | |
| May – Sept. | | | | | |
| Oct. – Dec. | | | | | |
| | | | | | |

[a] Mesh sizes according to ASTM E11 – 15.

NOTE 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~~<br>~~>Mesh 230~~ | ~~Fraction 63 µm to125 µm~~<br>~~Mesh 230 to 120~~ | ~~Fraction 125 µm to 250 µm~~<br>~~Mesh 120 to 60~~ | ~~Fraction > 250 µm~~<br>~~<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 particles had similar shapes as in Figure D.1 b). The results were as shown in Table A.1.

**Table A.1 – Example of documenting sample tests**

| ID | Date, Time | Event | Particle concentration<br>kg/m³ | Particle size, $dP_{50}$<br>mm | Fraction harder than Mohs ~~number~~ hardness > 4,5<br>% |
|---|---|---|---|---|---|
| 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:

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

where

$C_{\text{n}}$ is the particle concentration in kg/m³ for each sample;

$K_{\text{size}}$ 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;

$K_{\text{shape}}$ = 1,5, see Annex D (only the shape of the abrasive particles is relevant);

$K_{\text{hardness}}$ 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**

| $n$ | $C_n$<br>kg/m$^3$ | $K_{size,n}$ | $K_{shape,n}$ | $K_{hardness,n}$ | $T_{s,n}$<br>h | $PL_n$<br>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~~ hydro-abrasive erosion damages

## B.1 Recording ~~abrasion~~ hydro-abrasive erosion damage

The following is a guideline to measure the ~~wear~~ hydro-abrasive erosion of the individual parts of machines.

The goal of this guideline is to get reliable results of the hydro-abrasive 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 and be possible to correlate with the operating parameters:

- 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.~~

It can be noted that declining maximum output may indicate progressing hydro-abrasive erosion damage.

## 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~~ above the centre of the bucket. Sketches of the hydro-abrasive 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~~ hydro-abrasive erosion 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 hydro-abrasive 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 tip and mouth piece without coating

Photos should be taken in closed needle tip position to see any gaps between needle tip 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 should be taken to give an 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 hardcoating

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~~ hydro-abrasive erosion 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.

If the coating on the splitter edge has been completely eroded measurement of the splitter width should also be made.

## B.5 Needle tip, 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~~ possible height of steps as well as ~~eventual~~ possible 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 hydro-abrasive 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;~~

2) the ~~thickness~~ hydro-abrasive erosion depth 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, close-up photos of areas with hydro-abrasive erosion ~~in~~ with 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~~ hydro-abrasive erosion usually occurs and should be given special attention. A mirror could be helpful e.g. at the pressure side of the outlet.

On areas of major hydro-abrasive 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 well as overview and details should be photographed and recorded in sketches.

The gap between the runner and the ~~bottom~~ facing plates 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 with location ~~of the damages~~ and sizes 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 eroded away at the trailing edge: see measurements for Francis without coating.

The gap between the runner and the bottom facing plates 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 be taken.

If reference points still exist the abrasion hydro-abrasive erosion measurements on facing plates (maximum) consist of measuring the biggest gaps between guide vanes and facing plates at minimum 4 vanes.

An additional simple indication of the abrasion hydro-abrasive erosion damage to the guide vane apparatus consists of measuring the spiral case pressure at standstill with closed guide vanes and MIV closed but open main inlet valve bypass valve. This should be measured as often as possible with the exact information indicating the time and parameters when the measurement took place. This may be logged automatically during normal MIV opening together with HWL, TWL, date and time.

An additional indication can also be logged by recording the time it takes for the turbine to stop after a shutdown with the MIV open. The hydro-abrasive erosion in the guide vanes will cause leakage in the guide vanes when they are fully closed. This will cause the unit to use longer time to stop when shutting down.

## 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 hydro-abrasive 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 Stay vanes

Hydro-abrasive erosion is normally not an issue on the stay vanes due to lower velocities. However, failure of stay vanes can have dramatic consequences and stay vanes should also be inspected regularly. No particular inspection records for the stay vanes are included in this clause, but a simple note stating if damage has occurred or not, together with pictures, is recommended.

If hydro-abrasive erosion has occurred the thickness should be measured using templates of the stay vane geometry. If the stay vane thickness is reduced by 20 % or more, the stay vane should be checked by carrying out a stress analysis.

## B.11 Francis labyrinth seals uncoated

It is recommended to carry out measurement of the leakage flow rate from the upper seal (if possible) once a week in the wet season and once a month in the dry season.

## B.12 Kaplan uncoated

The measurement of the hydro-abrasive 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 hydro-abrasive erosion with a sketch showing the location of photos should be supplied in the report. At least all areas with major ~~wear~~ hydro-abrasive erosion have to be photographed.

On areas of major hydro-abrasive erosion damage the depth of hydro-abrasive 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.13 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 with location ~~of the damages~~ and sizes 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~~ completely eroded 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.14 Sample data sheets

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

If possible the records should directly show the abrasion hydro-abrasive erosion 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 hydro-abrasive erosion 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 hydro-abrasive erosion depth and location in the turbine of several individual components should be recorded in such cases. It is normal for the abrasion hydro-abrasive erosion depth to vary significantly between the individual components.

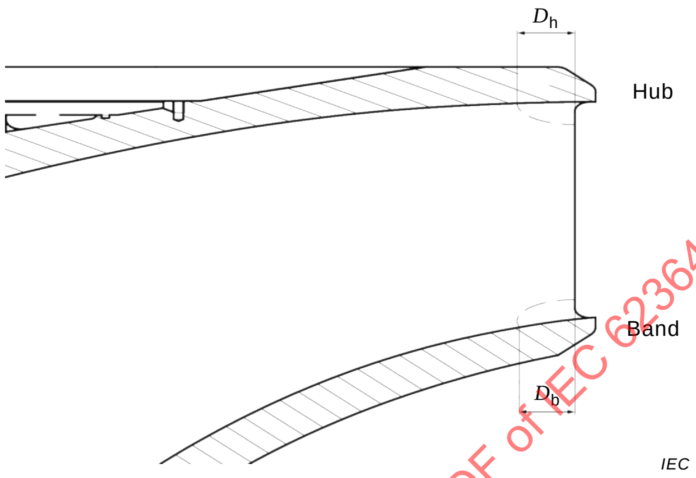
The abrasion hydro-abrasive erosion depth on the same component usually varies with location on the component. It is recommended to record abrasion hydro-abrasive erosion depth in a few typical locations on the component. In each location the maximum abrasion hydro-abrasive erosion depth should be considered.

Enclosed below, are a set of sample data sheets for recording damage in a high head Francis turbine and a Pelton runner, see Tables B.1 to B.11. 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 hydro-abrasive erosion and areas that may affect the safe operation of the unit.

## B.15 Inspection record, runner blade inlet

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

| Plant | Unit Nb | Date | Sign |
|---|---|---|---|
| | | | |

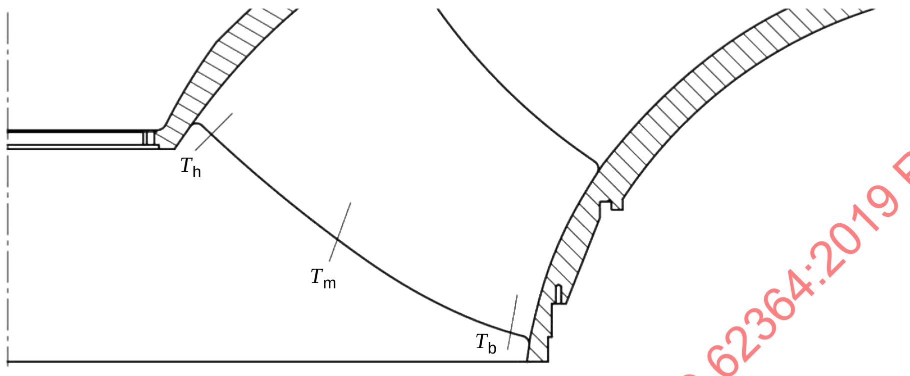



| Blade number | Hub erosion depth, $D_h$ | Band erosion depth, $D_b$ |
|---|---|---|
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | | |
| 7 | | |
| 8 | | |
| 9 | | |
| 10 | | |
| 11 | | |
| 12 | | |
| 13 | | |
| 14 | | |
| 15 | | |
| 16 | | |
| 17 | | |

## B.16 Inspection record, runner blade outlet

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |



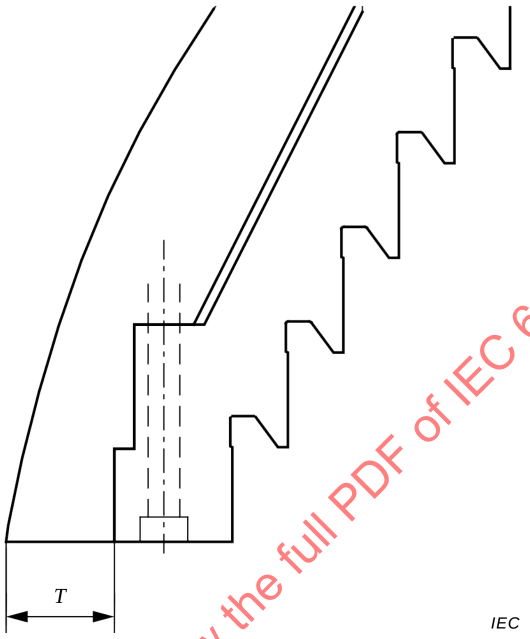



| Blade number | Thickness at hub, $T_h$ | Thickness at middle, $T_m$ | Thickness at band, $T_b$ |
|---|---|---|---|
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |
| 6 | | | |
| 7 | | | |
| 8 | | | |
| 9 | | | |
| 10 | | | |
| 11 | | | |
| 12 | | | |
| 13 | | | |
| 14 | | | |
| 15 | | | |
| 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.17 Inspection record, runner band

**Table B.3 – Inspection record, runner band form**

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |

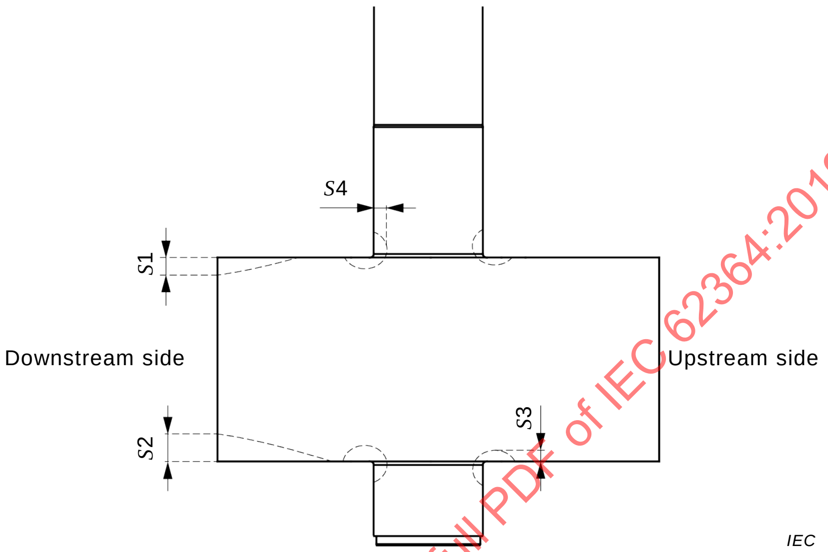



| Measuring point | Thickness, *T* |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| 4 | |
| NOTE Measuring points are 90° apart. | |

## B.18 Inspection record, guide vanes

**Table B.4 – Inspection record, guide vanes form**

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |

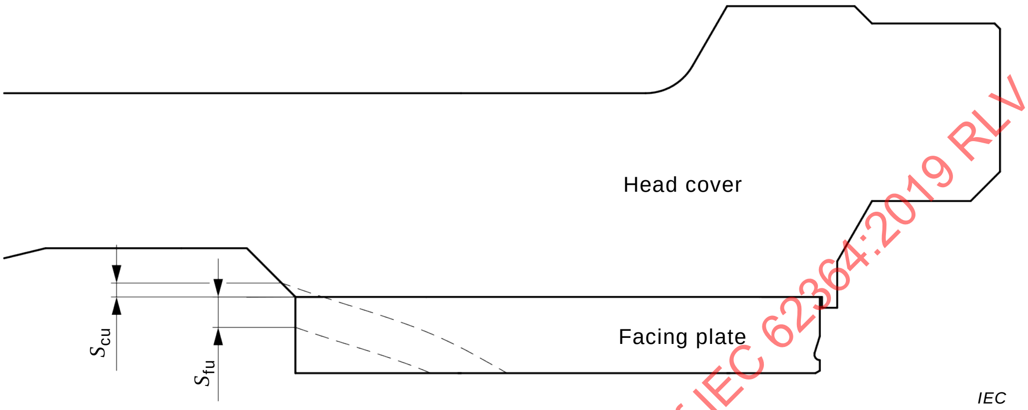



| Guide vane number | Face towards head cover, ~~D1~~ *S*1 | Face towards bottom cover, ~~D2~~ *S*2 | Face around bottom stem, ~~D3~~ *S*3 | Guide vane top stem, ~~D4~~ *S*4 |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |
| 13 | | | | |
| 14 | | | | |
| 15 | | | | |
| 16 | | | | |
| 17 | | | | |
| 18 | | | | |
| 19 | | | | |
| 20 | | | | |

## B.19 Inspection record, facing plates and covers

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |




| Measuring point number | Upper facing plate, ~~$D_{fu}$~~ $S_{fu}$ | Head cover, ~~$D_{cu}$~~ $S_{cu}$ | Lower facing plate, ~~$D_{fl}$~~ $S_{fl}$ | Lower cover, ~~$D_{cl}$~~ $S_{cl}$ |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |

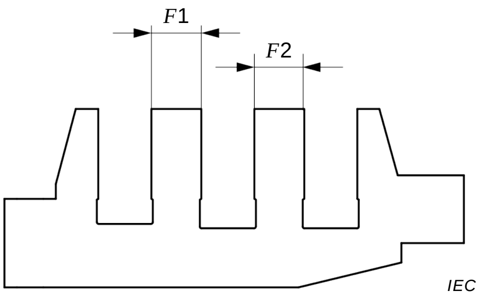
NOTE 1 ~~Dc is~~ $S_{cu}$ and $S_{cl}$ are only measured in case there is no more facing plate material remaining.

NOTE 2 Measuring points are 90° apart.

## B.20 Inspection record, upper stationary seal

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |

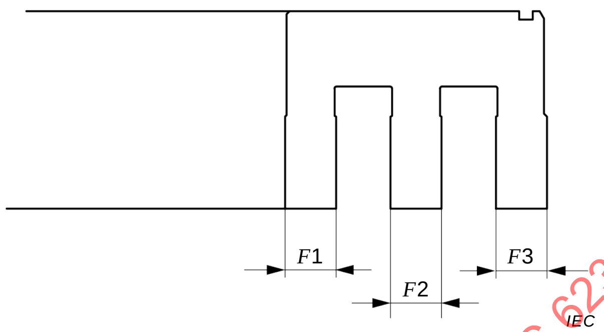



| | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| Finger 1, *F*1 | | | | |
| Finger 2, *F*2 | | | | |
| NOTE Measuring points are 90° apart. | | | | |

## B.21 Inspection record, upper rotating seal

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |

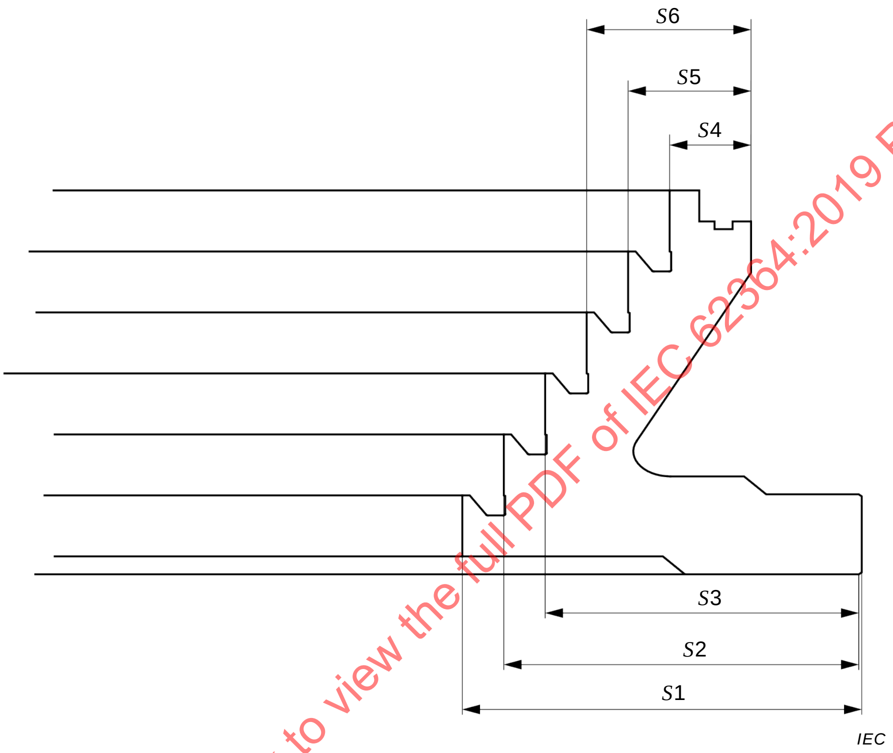



| | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| Finger 1, $F1$ | | | | |
| Finger 2, $F2$ | | | | |
| Finger 3, $F3$ | | | | |
| NOTE Measuring points are 90° apart. | | | | |

## B.22 Inspection record, lower stationary seal

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |



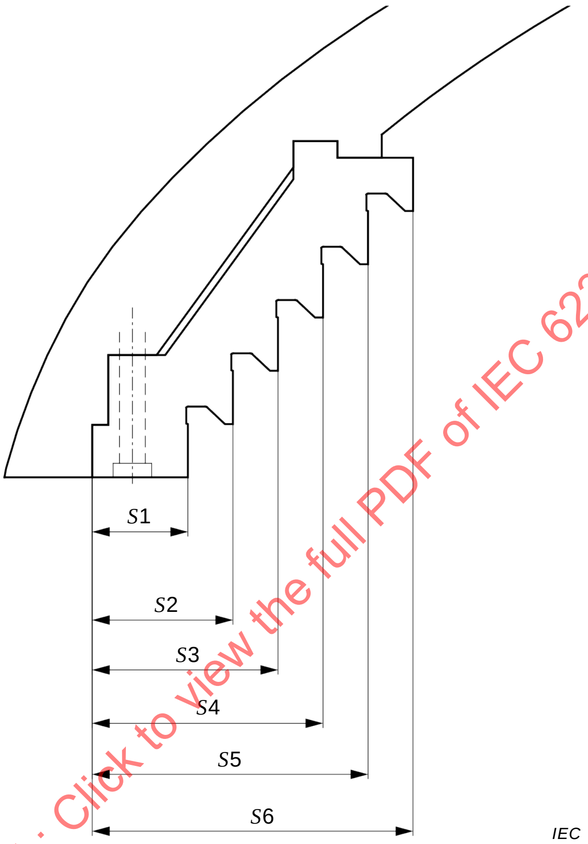



| | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| Surface 1, *S*1 | | | | |
| Surface 2, *S*2 | | | | |
| Surface 3, *S*3 | | | | |
| Surface 4, *S*4 | | | | |
| Surface 5, *S*5 | | | | |
| Surface 6, *S*6 | | | | |
| NOTE Measuring points are 90° apart. | | | | |

## B.23 Inspection record, lower rotating seal

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |



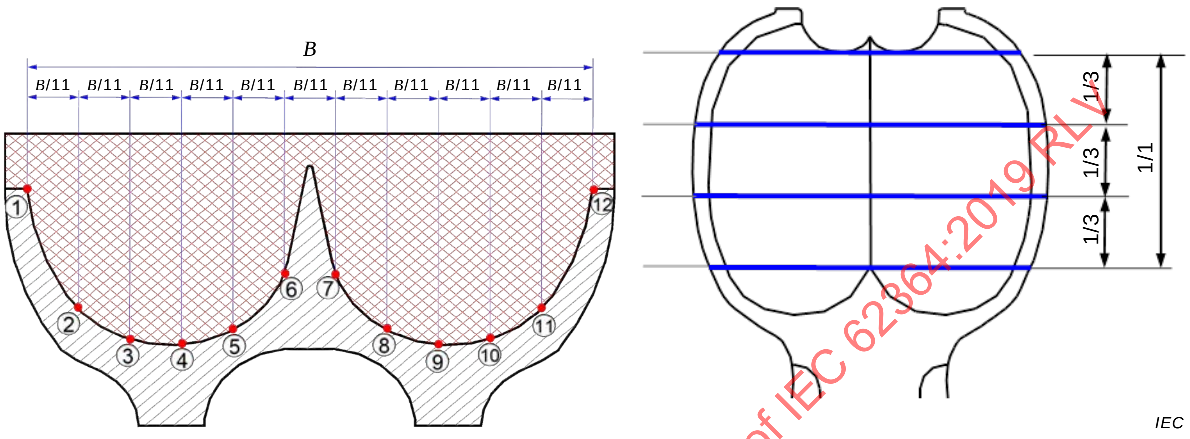



| | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| Surface 1, *S*1 | | | | |
| Surface 2, *S*2 | | | | |
| Surface 3, *S*3 | | | | |
| Surface 4, *S*4 | | | | |
| Surface 5, *S*5 | | | | |
| Surface 6, *S*6 | | | | |
| NOTE Measuring points are 90° apart. | | | | |

## B.24 Inspection record, runner bucket

**Table B.10 – Inspection record, runner bucket**

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |

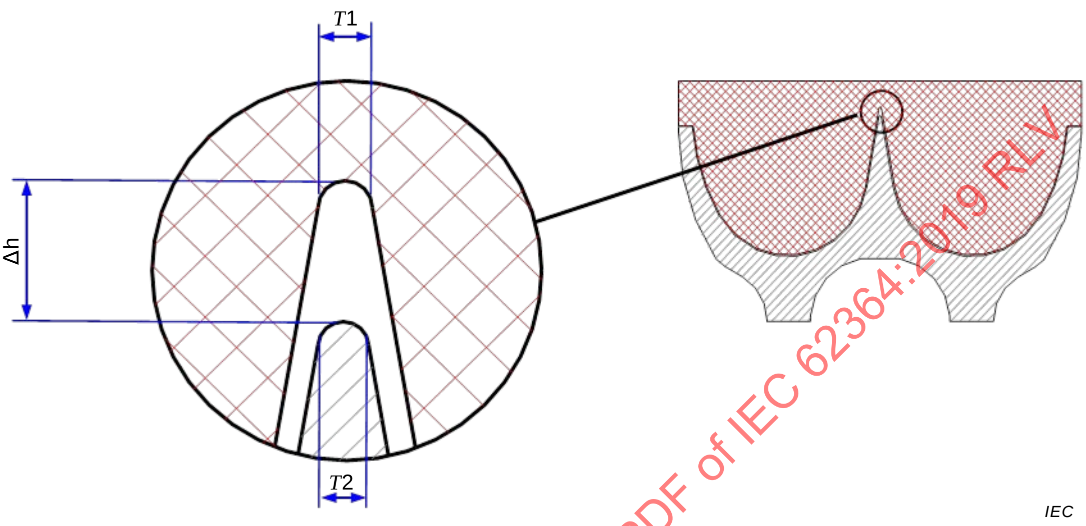



| | Template gap | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bucket number** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| 1 | | | | | | | | | | | |
| 2 | | | | | | | | | | | |
| 3 | | | | | | | | | | | |
| 4 | | | | | | | | | | | |
| 5 | | | | | | | | | | | |
| 6 | | | | | | | | | | | |
| 7 | | | | | | | | | | | |
| 8 | | | | | | | | | | | |
| 9 | | | | | | | | | | | |
| 10 | | | | | | | | | | | |
| 11 | | | | | | | | | | | |
| 12 | | | | | | | | | | | |
| 13 | | | | | | | | | | | |
| 14 | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 16 | | | | | | | | | | | |
| 17 | | | | | | | | | | | |
| 18 | | | | | | | | | | | |
| 19 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 21 | | | | | | | | | | | |
| 22 | | | | | | | | | | | |

## B.25 Inspection record, Pelton runner splitter

**Table B.11 – Inspection record, Pelton runner splitter**

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |




| Bucket number | *T1* | *T2* | Δh |
|---|---|---|---|
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |
| 6 | | | |
| 7 | | | |
| 8 | | | |
| 9 | | | |
| 10 | | | |
| 11 | | | |
| 12 | | | |
| 13 | | | |
| 14 | | | |
| 15 | | | |
| 16 | | | |
| 17 | | | |
| 18 | | | |
| 19 | | | |
| 20 | | | |
| 21 | | | |
| 22 | | | |

# Annex C
(informative)

# Monitoring of particle concentration and properties and water sampling procedure

## C.1 General

~~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.~~

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



Sampling in connection with hydro turbine installations can be divided in two distinct phases with different requirements as follows.

Phase 1. Sampling in natural rivers to estimate the amount and properties of particles passing future installations. The result of this sampling can be used to plan various strategies to minimize abrasion, such as desilting basins, abrasion resistant coatings, turbine selection, maintenance intervals, etc.

Phase 2. Sampling in existing hydro turbine installations to document the amount and properties of particles actually passing the hydro turbine unit. The result of this sampling can be used to evaluate the effectiveness of various strategies to reduce abrasion damage, plan overhaul and maintenance, etc. In particular, concentration measurements can be used for operational decisions, such as temporary turbine shut-offs during floods.

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. Some commercial automatic systems are available, but there is still little field experience with these. Such online measurement systems are strongly recommended to be calibrated before use with the future range of particles (size, shape, concentration, colour, etc.) that will actually pass the measurement system. It is preferred to use actual sediments from the river for this calibration. The measured concentration should be checked at least once per week during high discharge season and once per month during low discharge season. This check should be done against a manual filtration measurement (see Annex D).

If the measurement is not done "continuously", the measurement frequency depends on the change of particle concentration over time as explained in Annex E.

## C.2 Sampling before building a power station

Several publications and manuals describe the procedures. See for example [22].

The sampling should be done at least over 2 years, preferably longer. It is important to measure the particle concentration. Data on the river's sediment load are less meaningful for turbine hydro-abrasive erosion.

When using the sampling results to estimate the amount of particles that will pass a hydro turbine, several additional factors need to be taken into account.

- bedload should not enter the water conveyance system of the hydro turbine;
- if a reservoir is planned, the geometry of the reservoir and the discharge of the river will influence the sedimentation in the reservoir. To estimate particle retention in reservoirs is very complicated and should be performed by specialists;
- desander, if planned, has to be taken into account.

The above points should also be taken into account when measuring upstream of an existing power plant for the purpose of getting an early warning of very high particle concentration.

## C.3 Sampling in existing power stations

Water sampling during this phase is relatively easy, if means for sampling are properly prepared during the construction of the facility. Suitable sampling locations are

- draft tube cone, for example at the inspection man door.

Other possible locations are

- in the water conveyance system downstream of the desander to control the efficiency of the desander;
- in tailrace channel for Pelton turbines.

If the sampling is intermittent and water is not flowing continuously, it is important to let the water run for a suitable time (not less than 2 min) before collecting the sample. This in order to flush away any accumulated sediment in, or in the vicinity of, the sampling system piping.

To avoid misinterpretation, it is advisable not to take any samples unless there is a continuous flow in the water conveyance system. Such samples could be misleading as they would be influenced by the internal particle settling in the water conveyance system.

## C.4 Logging of samples

It is important to document the procedure for taking the samples and include it into the report.

Physical samples should be collected in suitable containers (e.g. bottles) and immediately labelled. A record should be established which clearly identifies the time and location of taking the sample. Sketches and pictures are useful for good understanding of sampling locations.

# 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;
- particle size distribution;
- mineralogical composition of sediment;
- particle geometry;
- fraction of organic matter, if applicable.



## D.2 Particle concentration

Particle concentration is non-dissolved particles in the water. Particle content should be given in kg/m$^3$. For the definition refer to 2.2.8. It may be analysed in accordance with ISO 4365:2005.

## D.3 Particle size distribution

As different particle sizes have 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 with adequate intervals. 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.

The particle size distribution has to be done in two steps. For the large particle fraction (> 0,063 mm) sieving is a good way. The small particle fraction (< 0,05 mm) has to be analysed with laser granulometry.

Sieving is described in ISO 4365:2005.

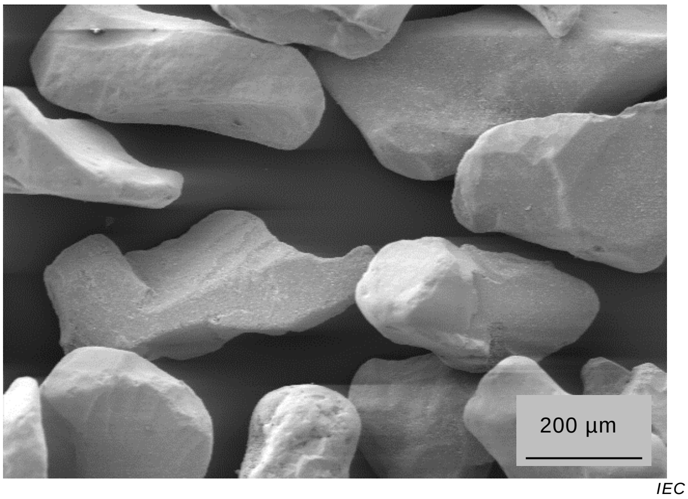
## D.4 Mineralogical composition of the particles

The mineral composition should be done by X-ray diffraction (XRD) of a representative sample of the particles. If the grain size distribution is very wide, Using the different particle size fractions from the particle size distribution should be used for an analysis of each fraction should be made to determine the mineralogical composition, as due to the different hardness of minerals the impact on hydro-abrasive erosion differs considerably. A petrographic analysis is not enough as the inaccuracy may be too high.

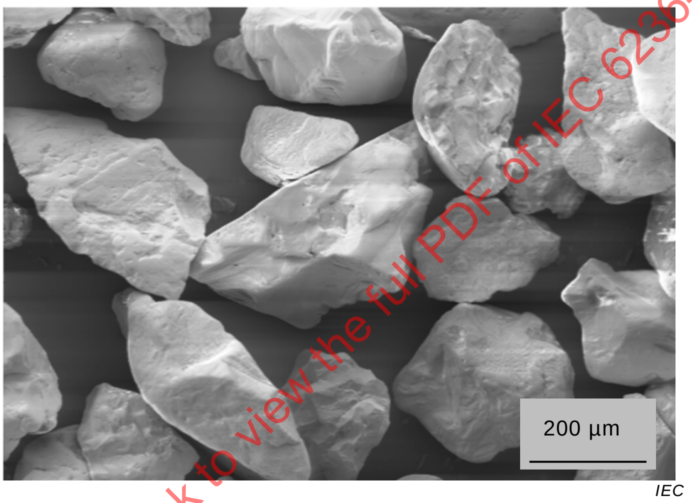
## D.5 Particle geometry

Microscope 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.

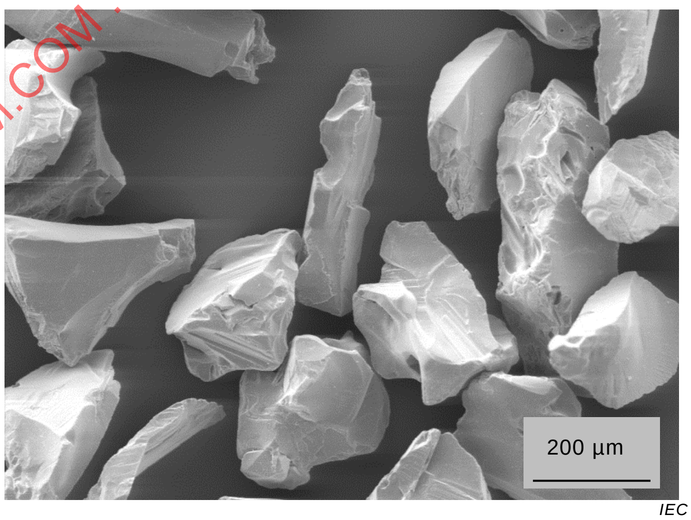
The following Figure D.1 gives three typical examples of such images, designated rounded, sub-angular and angular from top to bottom. ~~Please note that the magnification is not the same in each picture.~~ Pictures should be chosen in such a way that a representative choice of particles can be clearly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




**a) Rounded particle geometry, $K_{shape}$ = 1**




**b) Subangular particle geometry, $K_{shape}$ = 1,5**




**c) Angular particle geometry, $K_{shape}$ = 2**

**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.

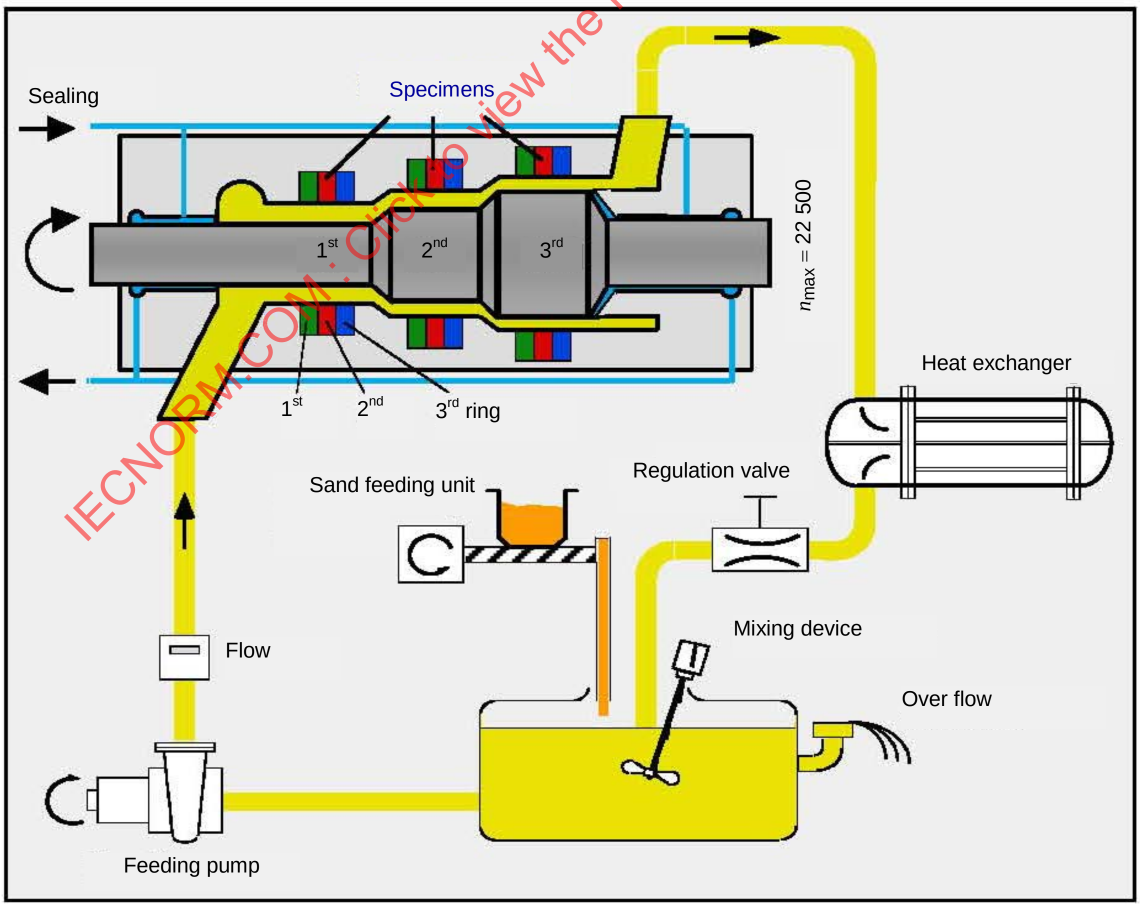



Figure E.1 – Schematic of test rig used for test 1

**~~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 |

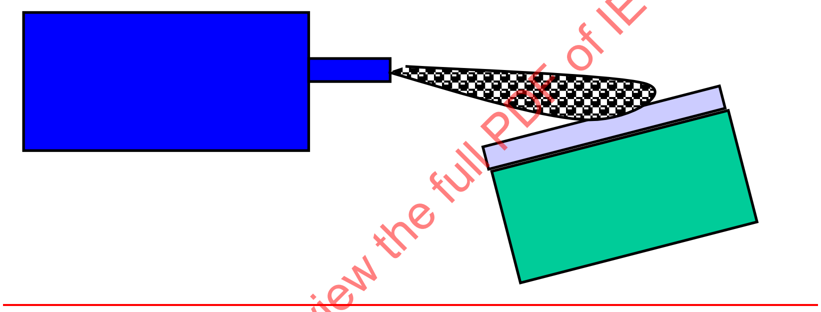


**Figure E.2 – ASTM test apparatus**

## 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.

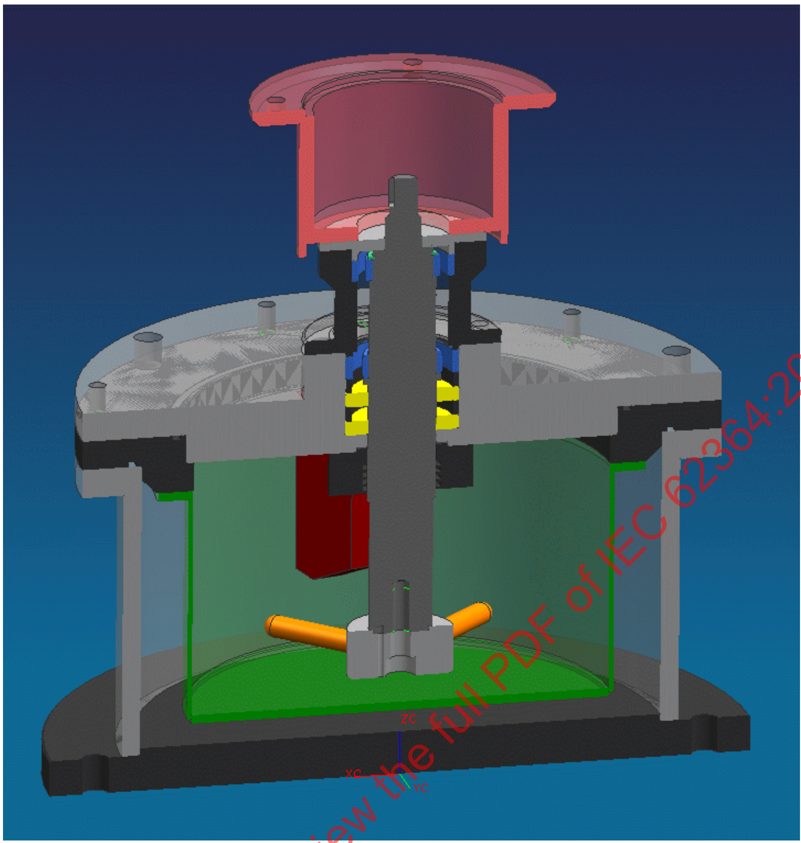
Table E.4 – Relative wear resistance in test 4

| 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/m³). 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.~~

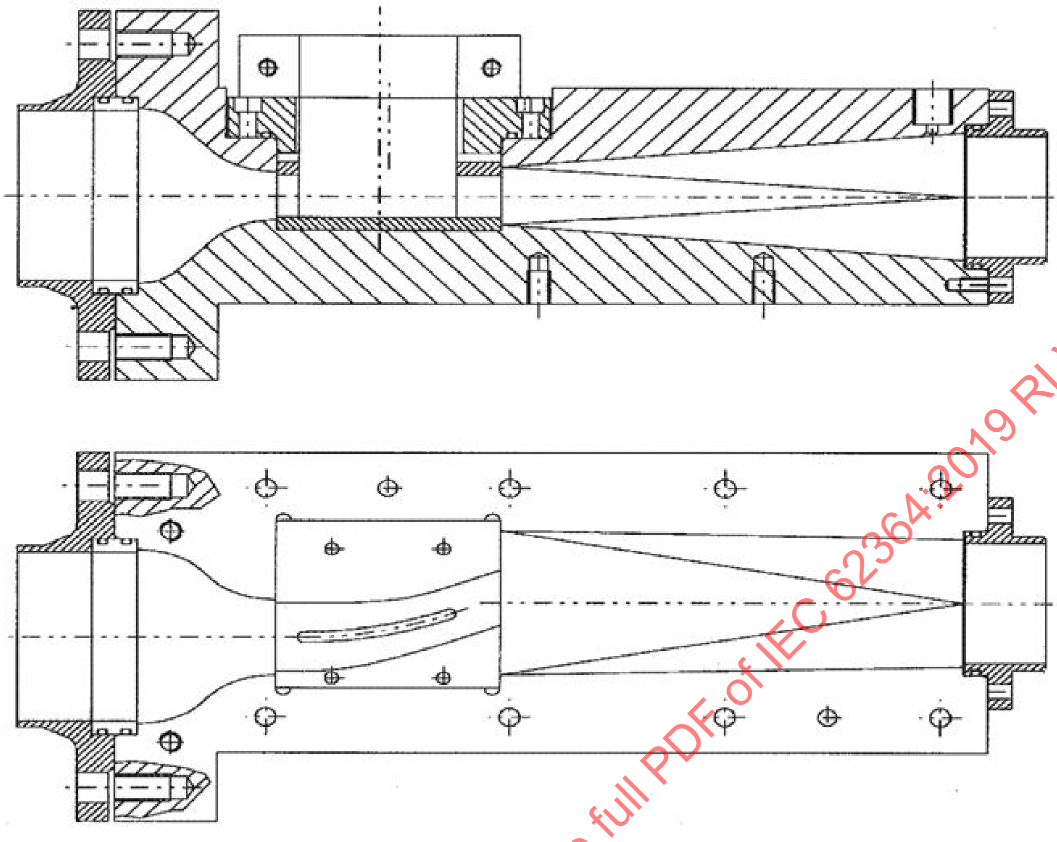


Figure E.5 – High velocity test rig



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.

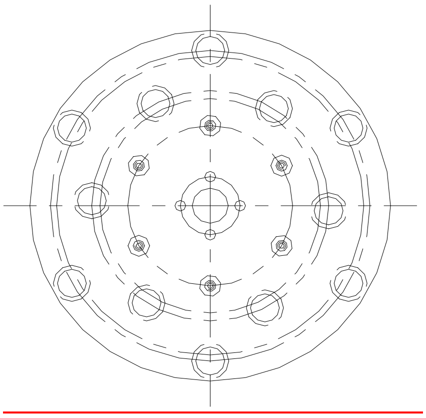
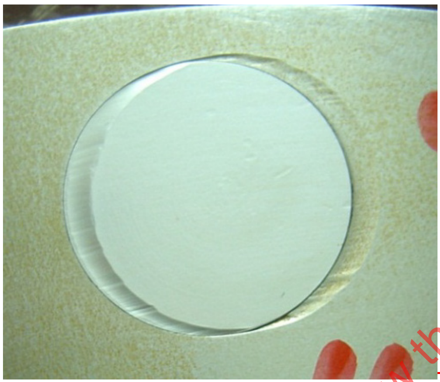


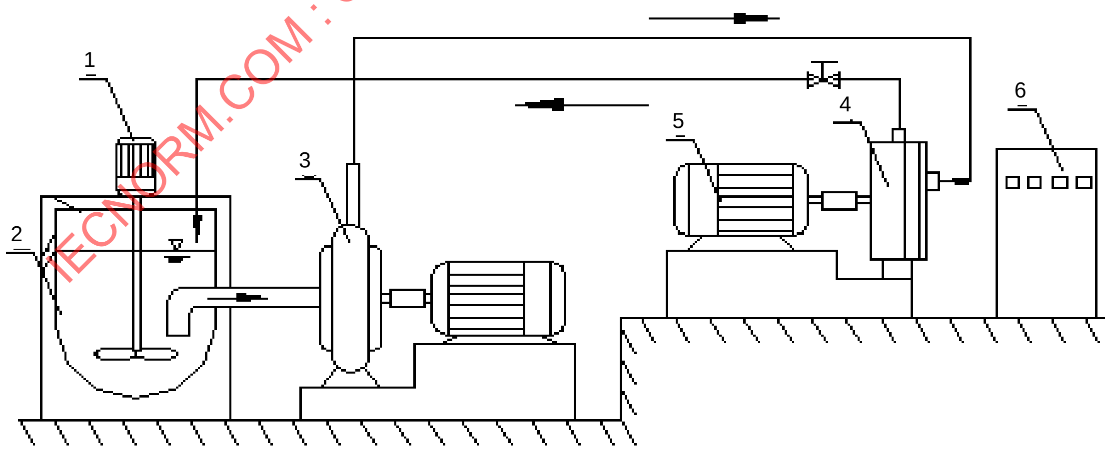
Figure E.6 – Samples are located on the rotating disk



a) Sound material

b) Polymer coating

Figure E.7 – Comparison of two samples after testing




Key

(1) Puddle
(2) Reservoir
(3) Slurry pump
(4) Rotating disk
(5) Motor
(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 |

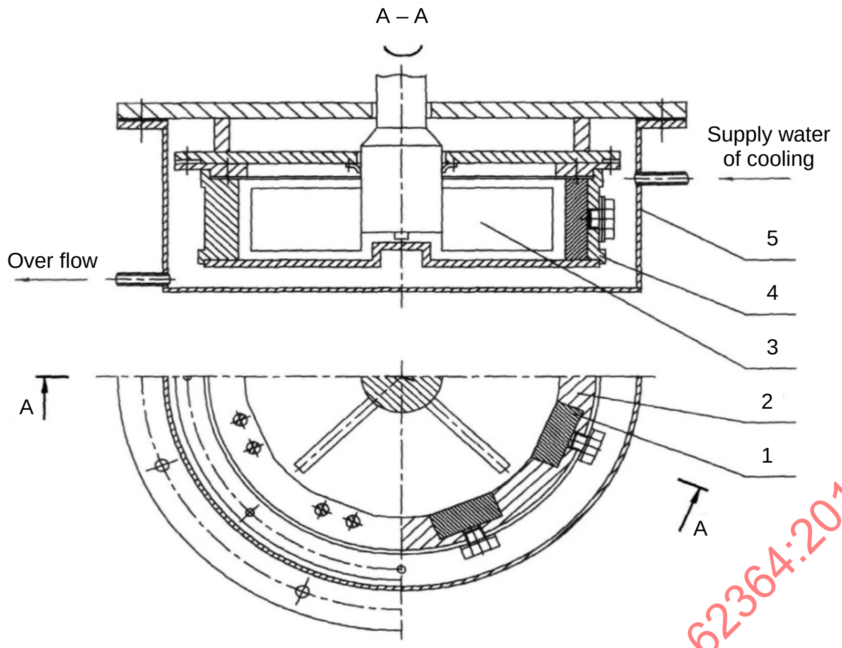
## E.9 Test 8

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.

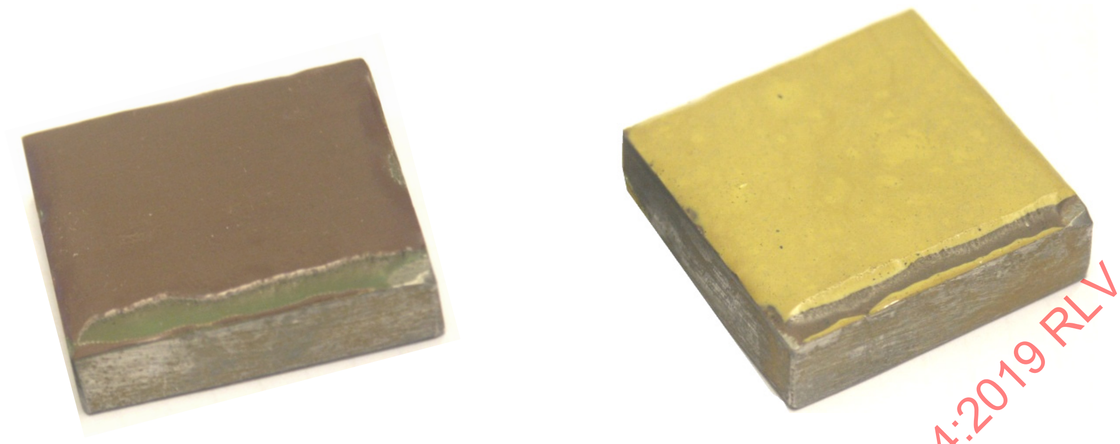
Section A-A refers to a broken line that goes from A to A through the center.

**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 |

1) 2)



**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 ($\varepsilon$) vs. circumferential velocity ($U$), i.e. $h=f_1$ ($U$), or $\varepsilon=f_2$ ($U$). 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).

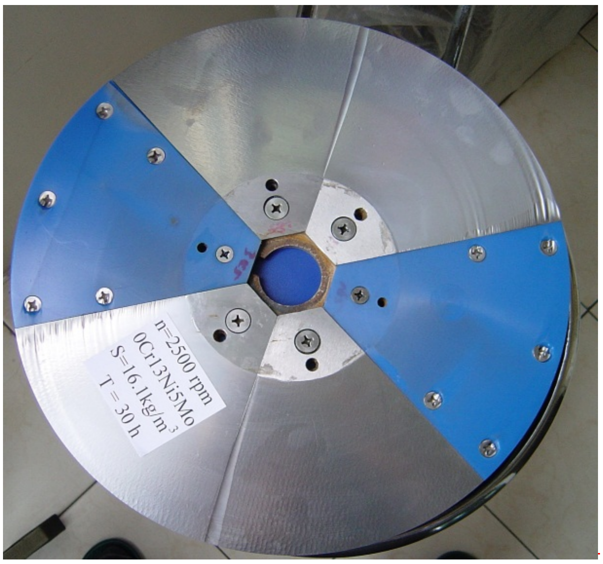


**Figure E.11 – Cover of disc**

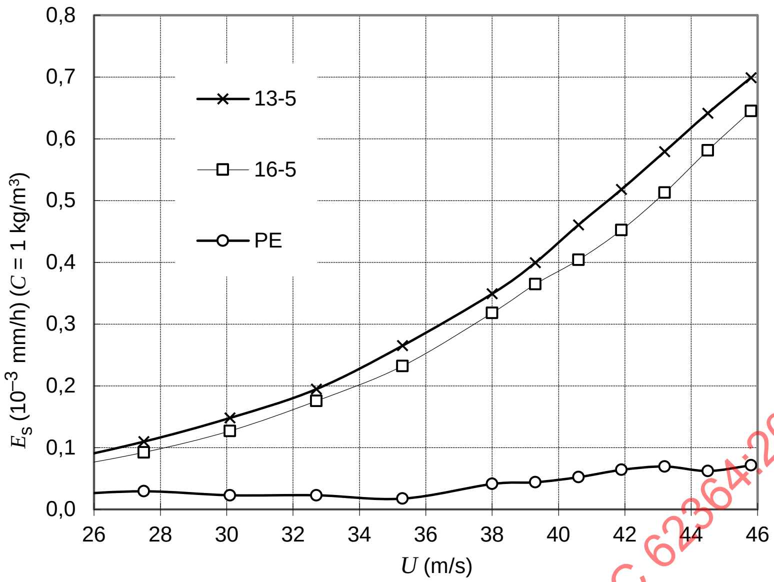



**Figure E.12 – Curve of unit abrasion rate with circumference velocity for 3 kinds of materials**

**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 E
(informative)

## Frequency of sediment sampling

In the case where the *PL* measurement procedure 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 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:

$$T_s = 0{,}01 \times PL_{year} / PL_{max}$$

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

- "High particle" period:

  $PL_{year}$ = 85 kg x h/m$^3$

  $PL_{max}$ = 0,12 kg/m$^3$

  then:

  $T_s$ = 0,01 x 85 / 0,12 h ≈ 8 h for "high particle" period

- "Low particle" period:

  $PL_{year}$ = 85 kg x h/m$^3$

  $PL_{max}$ = 0,002 5 kg/m$^3$

  then:

  $T_s$ = 0,01 × 85 / 0,002 5 = 340 h ≈ 14 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 can be halved as soon as this variation is detected.

# Annex F
(informative)

# Typical criteria to determine overhaul time due to ~~abrasion~~ hydro-abrasive 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.~~

## F.1 General

The optimum time to overhaul a unit is normally determined by economic criteria. It is a combination of many factors specific to each powerplant such as

1) the cost of reduced efficiency,
2) the cost of the overhaul,
3) the increased risk of unavailability,
4) the convenient time of year for overhaul,
5) etc.

As an ultimate technical limit, a situation where it is no longer safe to operate the unit may be considered.

Following are some typical criteria that may be used. It is emphasized that the powerplant operator will gain a lot of experience of how their particular unit functions and what is the optimal overhaul interval in their particular case. The list below only serves as a first outline of possible overhaul criteria.

The criteria have been divided in criteria that can be observed while the unit is in operation and criteria that require internal inspection of the unit.

## F.2 Parameters which are observable while the unit is in operation

1) The efficiency has deteriorated to an extent that it is economically beneficial to restore the unit to its design efficiency. To determine the reduction in efficiency some sort of efficiency test is required. Since only the relative efficiency decrease needs to be measured some simple system based on Winter Kennedy flow measurement or permanently installed ultrasonic flowmeter may be used instead of complete efficiency tests per IEC 60041. Another possibility is continuous efficiency monitoring based on operation data.

2) Reduction of output at some defined opening. Note, however, that the discharge for the same opening may change as a result of hydro-abrasive erosion. This method should therefore be used only after some further experience is gained about the correlation between the measured output and corresponding hydro-abrasive damage.

3) If the turbine design incorporates balancing pipes from the head cover a very good indication of labyrinth seal hydro-abrasive erosion is the water discharge in the balancing pipes. This may then be used as a criterion for overhaul.

4) The axial thrust can also be an indication of labyrinth seal hydro-abrasive erosion, even though it is less accurate than the discharge in the balancing pipes. It should be combined with experience about the correlation between the measured axial thrust and corresponding hydro-abrasive erosion damage before being used as a criterion for overhaul.

5) The time it takes for the unit to stop, or alternatively the steady state speed it reaches, after the guide vanes are closed and the inlet valve kept open. This correlates to the hydro-abrasive erosion of the guide vanes and covers.

6) The spiral case pressure with closed inlet valve and open bypass. This correlates to the hydro-abrasive erosion of the guide vanes and covers.

7) Wear of main shaft seal may bear correlation with the hydro-abrasive erosion of the unit, although this depends on the shaft seal design. This criterion should therefore be used only after some further experience is gained about the correlation between the seal wear and corresponding hydro-abrasive damage.

## F.3 Criteria that require internal inspection of the unit

1) Thickness of runner blade outlet is abraded more than two thirds (for large turbines) or is completely abraded (for small turbines). Note that a reduction of blade thickness will reduce the strength of the blade and that a blade crack would of course override any blade thickness measurement.

2) Facing plates, of head cover and bottom ring completely abraded.

3) Clearance of runner labyrinth seals is more than doubled.

4) For components coated with hydro-abrasive erosion resistant coating, the area of coating removed exceeds 5 % to 10 % of the total coated area.

Items 1) to 3) above refer to Francis turbines, while item 4) refers to all types of turbines.

# Annex G
(informative)

## Example to calculate the amount of erosion in the full model the hydro-abrasive erosion depth

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 hydro-abrasive 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 hydro-abrasive erosion depth is

$$S = W^{3,4} \times PL \times K_m \times K_f / RS^p$$

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

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

According to Figure 1:

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

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

According to 3.1 I.1 $K_m$ for martensitic stainless steel is 1.

According to 3.2 Table 1 $K_f$ and $p$ for the various components are as follows:

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

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

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

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

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

For the guide vanes the total wear hydro-abrasive erosion depth is thus

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

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*<br>mm |
|---|---|---|---|---|---|---|
| Guide vanes | 50,4 | 3,84 | 1 | $1,06 \times 10^{-6}$ | 0,25 | 20 |
| Facing plates | 50,4 | 3,84 | 1 | $0,86 \times 10^{-6}$ | 0,25 | 16 |
| Runner inlet | 50,4 | 3,84 | 1 | $0,90 \times 10^{-6}$ | 0,25 | 17 |
| Runner outlet | 44,3 | 3,84 | 1 | $0,54 \times 10^{-6}$ | 0,75 | 6,5 |
| Labyrinth seals | 44,3 | 3,84 | 1 | $0,38 \times 10^{-6}$ | 0,75 | 4,6 |

The standard deviation for the guide vanes is 42 % according to ~~3.2~~ Table I.1. 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 | ~~$z_0$~~ $z_{jet}$ | | 1 | 6 |
| Number of buckets | $z_2$ | | 21 | 22 |
| Average particle concentration | $C$ | kg/m³ | 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~~ **5 500** |

Calculation of *TBO*

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

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

= 3,59 × 1,19 × 1 × ~~0,210~~ 0,180 × 0,521

= ~~0,454~~ 0,401

with:

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

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

Assumptions:

- constant over the year
- $K_{size,ref} / K_{size,target} = 1$
  (grain size distribution in both cased is assumed to be the same)
- $K_{hardness,ref} / K_{hardness,target} \approx 0,73$
  (as both runners are coated only the fraction of Mohs hardness above 7 is used. Ratio of both fractions is 0,73)

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

$K_{f,ref}$ / $K_{f,target}$ = ~~$[z_{0,ref} \times n_{ref} / z_{2,ref})] / [z_{0,target} \times n_{target} / z_{2,target}]$ = 0,210~~ $[z_{jet,ref} / z_{2,ref}] / [z_{jet,target} / z_{2,target}]$ = 0,180

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

$TBO_{target}$ = ~~0,470 × 13 600 h ~ 6 400 h~~ 0,401 × 13 600 h ~ 5 500 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) | $Wr_{un}$ | m/s | 59,9 | 47,6 |
| Time between overhaul | $TBO$ | h | 22 800 | **5 800** |

Calculation of $TBO$

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

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

= 2,185 × 0,059 × 1 × 1 × 1,97

= 0,254

with:

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

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

= 0,176 × 0,667 × 1 × 0,5

= 0,058 7

Assumptions:

- constant over the year
- $K_{size,ref} / K_{size,target}$ = 1
  (grain size distribution in both cased is assumed to be the same)
- $K_{hardness,ref} / K_{hardness,target}$ ≈ 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 in accordance with 2.2.11)

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

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

$TBO_{target}$ = 0,254 × 22 800 h

= 5 800 h

# Annex I
(informative)

# Background for hydro-abrasive erosion depth model

## I.1 ~~Theoretical model~~ Model background and derivation

Please refer also to [21]. In order to demonstrate how different critical aspects impact the ~~particle abrasion~~ hydro-abrasive erosion 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 document 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, see 2.2.12.
- *f*(flow pattern) = $K_f$ / $RS^p$ ($K_f$ = 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) = $K_{size}$ × $K_{shape}$. Note that in this simplification it is 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,
- $K_{shape}$ = *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~~ angular,
- *f*(turbine material properties) = $K_m$. In this document we consider $K_m$ = 1 for martensitic stainless steel with 13 % Cr and 4 % Ni and $K_m$ = 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:

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

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~~9 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~~9) 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 I.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~~23.

~~$W$ 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.~~

So the final, time integrated formula becomes:

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

where

$S$ is the numerical value of the ~~abrasion~~ hydro-abrasive erosion depth in mm.

## I.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.~~

In this document the $PL$ variable is used to quantify the particles that pass the turbine and reflects the relative hydro-abrasive erosion potential in a certain period. In the past a common way to integrate hydro-abrasive erosion over time has been to consider the total weight of particles that pass the turbine. The benefits of the $PL$ variable include:

- The $PL$ variable gives more accurate results considering variations in flow and head. Please see example below for further details,
- The $PL$ will inherently consider variations in all particle properties, not only the particle concentration,
- The $PL$ depends only on the water used and is independent of the turbine size and / or discharge. It can thus be used directly to compare the conditions at different sites and for different configurations.

To illustrate the first point above, consider the following example. A Pelton injector (see Figure I.1) 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 I.1) 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~~ mass 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 I.1) 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~~ mass 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~~ hydro-abrasive erosion with the same particle concentration, the same water velocity and the same amount of time. Therefore, the expected ~~abrasion~~ hydro-abrasive erosion damage is the same. The $PL$ variable also gives the same value in both cases. However, the total ~~weight~~ mass 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~~ hydro-abrasive erosion damage than the total ~~weight~~ mass of particles that has passed the seat ring.

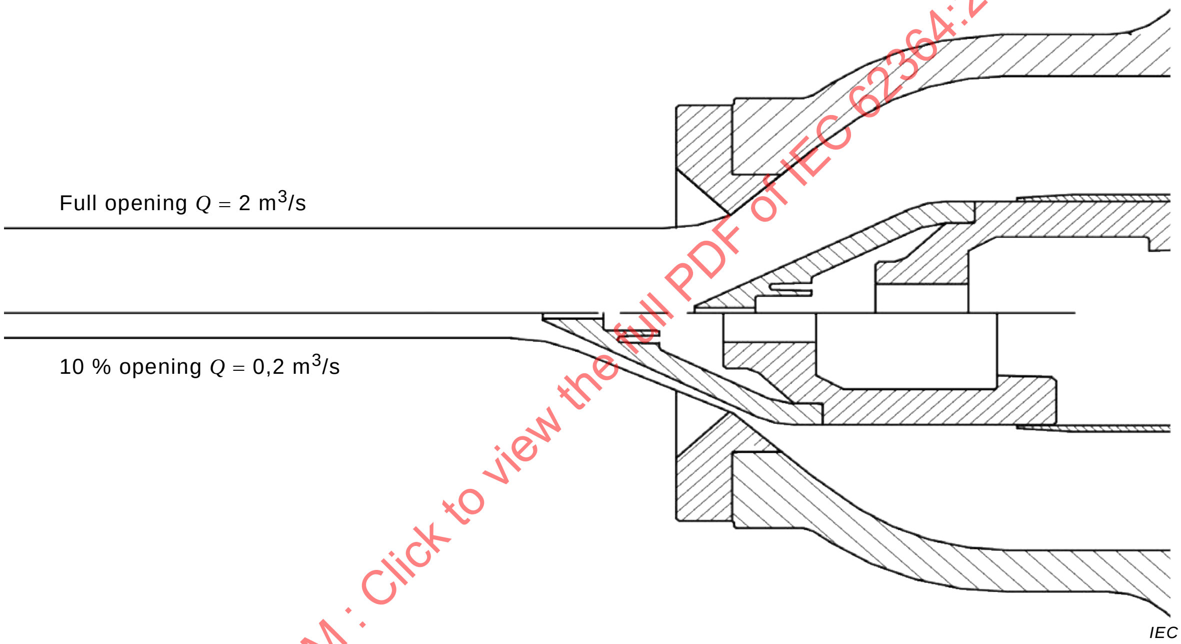



**Figure I.1 – Example of flow pattern in a Pelton injector at different load**

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

- Pelton needle tip

Very good correlation between $PL$ and ~~abrasion~~ hydro-abrasive erosion 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 tip 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~~ hydro-abrasive erosion 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~~ hydro-abrasive erosion 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~~ hydro-abrasive erosion 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~~ hydro-abrasive erosion 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~~ hydro-abrasive erosion damage with minor influence of turbine discharge or head is expected. At part load there are two main phenomena that influence the ~~wear~~ hydro-abrasive erosion. 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~~ hydro-abrasive erosion in opposite ways, but it is expected that the turbulence effect will dominate and thus that the ~~wear~~ hydro-abrasive erosion 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~~ hydro-abrasive erosion 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~~ hydro-abrasive erosion 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.

## I.3 ~~Survey results~~ Calibration of the formula

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

This data was analysed 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 hydro-abrasive erosion. The average $K_f$ and $p$ 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.~~ The results are in Table 1 in the main part of the document.

The ratio between the measured and calculated values of the hydro-abrasive erosion depth was determined and the standard deviation calculated. Table I.1 below shows the standard deviation in this analysis as well as number of observations for each type of component.

**Table I.1 – ~~Data analysis of the supplied questionnaire~~ Analysis of the calibration constant $K_f$ and $p$**

| Component | ~~$K_f$~~ | ~~Exponent $p$ (for $RS$)~~ | Number of observations | Standard deviation<br>% |
|---|---|---|---|---|
| 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 hydro-abrasive erosion model.

# Annex J
(informative)

# Quality control of thermal sprayed WC-CoCr

## J.1 Specification

The quality of this hard coating strongly depends on several influencing factors like the technical specification of the coating process, the preparation of the surface to be coated, the process parameters and the consumables used. Also the qualification of the personnel applying the coating plays an important role.

Hard coatings which are used to protect hydraulic machines from hydro-abrasive erosion should meet certain demands on quality to ensure proper functionality. Some guide line reference values for WC-CoCr (86/10-4) are listed below:

- surface roughness Ra should be < 8µm;
- adhesive bond strength should be > 60 MPa;
- average hardness over ten measurement points of the coating should be > 1 000 $HV_{0,3}$.

## J.2 Quality control

It is recommended to coat test specimens during the coating of the part, applying exactly the same process (e.g. surface preparation, pre-heating, coating etc.) as used on the components to be coated.

Measurements and inspections should be done by trained personnel. Evidence of qualification should be provided. Table J.1 lists some items recommended to be included in an inspection report:

**Table J.1 – Recommended items to include in HVOF inspection**

| Characteristics | Unit | To be measured by | Measured on component | Measured on test specimen |
|---|---|---|---|---|
| Surface roughness | Ra | ISO 4288 or related | X | |
| Coating thickness | µm | ASTM B499 – 09 or ISO 2178 | X | |
| Bond strength | MPa | ASTM C633 – 13 or EN 14916 | | X |
| Vickers hardness | HV 0,3 | ISO 6507-1 | | X |

The coated area should be visually inspected by 100 %. The coated surface, as defined in the drawings, shall not show any defects like cracks, pores or uncoated areas.

If the coating is ground dye penetrant test can also be an indication of cracks in the coating. Note that dye penetrant test is not applicable for non-ground (as sprayed) surfaces.

# Bibliography


[1] IEC 60193:1999, *Hydraulic turbines, storage pumps and pump-turbines – Model acceptance tests*

[2] IEC 60609-2:~~2004~~ 1997, *Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines – Part 2: Evaluation in Pelton turbines*

[3] IEC TR 61364, *Nomenclature for hydroelectric powerplant machinery*

[4] ISO 4365:2005, *Liquid flow in open channels – Sediment in streams and canals – Determination of concentration, particle size distribution and relative density*

[5] ISO 11657:2014, *Hydrometry – Suspended sediment in streams and canals – Determination of concentration by surrogate techniques*

[6] ASTM G76:1995, *Standard test method for conducting erosion tests by solid particle impingement using gas jets*

[7] Gray, Aunemo and Rommetveit:2004, *Recent developments in silt erosion coatings, IAHR 22nd Symposium on Hydraulic Machinery and Systems*

[8] Wedmark:2006, *Recent progress in silt erosion research, Hydro 2006*

[9] Dr. Y. C. Agrawal, Mr. H. Chuck Pottsmith:2005, *Turbine erosion: Lasers warn of abrasive sediments, Hydro 2005 Conference, Villach, Austria*

[10] Mann B.S., Arya V., Dadu V., Manea L:2001, *Hydro Project Equipment: Solutions for Common Challenges, HRW/July 2001*

[11] Mann B.S., Arya V.:2001, *Abrasive and erosive wear characteristics of plasma nitriding and HVOF coatings: their application in hydro turbines, Wear 249 (2001) 354-360*

[12] Mann B.S., Arya V., Maiti A.K., Rao M.U.B., Joshi P.:2006, *Corrosion and erosion performance of HVOF/TiAlN PVD coatings and candidate materials for high pressure gate valve application, Wear 260 (2006) 75-83*

[13] Engelhardt M., Oechsle D.:2003, *Countermeasures to Reduce Hydro Abrasive Wear at Hydro Turbine Parts, Proceedings, Hydro 2003, Vol. I, Croatia*

[14] Gummer J.H.:2009, *Combating Silt Erosion in Hydraulic Turbines HRW / March 2009*

[15] Proceedings of the Oslo Workshop:2003, *Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, Proceedings of the Oslo Workshop, June 2002, IAHS Publ. 283, 2003*

[16] Nozaki T.:1985, *Nuevo Metodo Para La Decision de la Capacidad y dimension del desarendador, considerando el desgaste de la turbina por el material solido flotante* (only available in Spanish)

[17] Bishwakarma M.B:2008, *Research on optimum sediment exclusion,* www.waterpowermagazine.com, *2008*

[18] Duan C.G., Karelin:2002, *Abrasive Erosion & Corrosion of Hydraulic Machinery, Imperial College Press*

[19] *Proceedings of „Silting Problems in Hydropower Projects", 3rd International Conference, 2008, India*

[20] M Meng and Ludema:~~1985~~ 1995, *Wear models and predictive equations: their form and content* 181-183: 443-457*, WEAR* ~~*1985*~~ *1995*

[21] Wedmark, Winkler and Dekumbis:2010, *Finding a way to estimate abrasion amount, Hydro 2010 conference, Lisbon, Portugal*

[22] Norwegian Water Resources and Energy Administration, Hydrology Department:1997, *Manual on Procedures in Operational Hydrology, Volume 5, Sediment Transport in Streams – Sampling, Analysis and Computation, Second edition*

[23] Mei, Zu-Yan:1996, *Protecting hydro turbines in silt-laden rivers, Hydropower & Dams magazine, issue 4, 1996*

[24] IEC 60041, *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*

[25] ISO 4288, *Geometrical Product Specifications (GPS) – Surface texture: Profile method – Rules and procedures for the assessment of surface texture*

[26] ISO 2178, *Non-magnetic coatings on magnetic substrates – Measurement of coating thickness – Magnetic method*

[27] ISO 6507-1, *Metallic materials – Vickers hardness test – Part 1: Test method*

[28] ASTM B499-09, *Standard Test Method for Measurement of Coating Thicknesses by the Magnetic Method: Nonmagnetic Coatings on Magnetic Basis Metals*

[29] ASTM C633-13, *Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings*

[30] ISO 14916:2017, *Thermal spraying – Determination of tensile adhesive strength*

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**Hydraulic machines – Guidelines for dealing with hydro-abrasive erosion in kaplan, francis, and pelton turbines**

**Machines hydrauliques – Lignes directrices relatives au traitement de l'érosion hydro-abrasive des turbines kaplan, francis et pelton**

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# CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

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International Standard IEC 62364 has been prepared by IEC technical committee 4: Hydraulic turbines.

This second edition cancels and replaces the first edition published in 2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) the formula for TBO in Pelton reference model has been modified;
b) the formula for calculating sampling interval has been modified;
c) the chapter in hydro-abrasive erosion resistant coatings has been substantially modified;
d) the annex with test data for hydro-abrasive erosion resistant materials has been removed;
e) a simplified hydro-abrasive erosion evaluation has been added.

The text of this International Standard is based on the following documents:

| FDIS | Report on voting |
|---|---|
| 4/351/FDIS | 4/366/RVD |

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

**IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.**

# INTRODUCTION

The number of hydro power plants with hydro-abrasive erosion is increasing worldwide.

An overall approach is needed to minimize the impact of this phenomenon. Already at the start of the planning phase an evaluation should be done to quantify the hydro-abrasive erosion and the impact on the operation. For this, the influencing parameters and their impact on the hydro-abrasive erosion have to be known. The necessary information for the evaluation comprises among others the future design, the particle parameters of the water, which will pass the turbine, the reservoir sedimentation and the power plant owner's framework for the future operation like availability or maximum allowable efficiency loss, before an overhaul needs to be done.

Based on this evaluation of the hydro-abrasive erosion, an optimised solution can then be found, by analysing all measures in relation to investments, energy production and maintenance costs as decision parameters. Often a more hydro-abrasive erosion-resistant design, instead of choosing the turbine design with the highest efficiency, will lead to higher revenue. This analysis is best performed by the overall plant designer.

With regards to the machines, owners should find the means to communicate to potential suppliers 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 hydro-abrasive erosion.

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 hydro-abrasive erosion service. This has led some owners to write into their specifications, conditions which cannot be met with known methods and materials.

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

## 1 Scope

This document gives guidelines for:

a) presenting data on hydro-abrasive erosion rates on several combinations of water quality, operating conditions, component materials, and component properties collected from a variety of hydro sites;

b) developing guidelines for the methods of minimizing hydro-abrasive erosion by modifications to hydraulic design for clean water. These guidelines do not include details such as hydraulic profile shapes which are determined by the hydraulic design experts for a given site;

c) developing guidelines based on “experience data” concerning the relative resistance of materials faced with hydro-abrasive erosion problems;

d) developing guidelines concerning the maintainability of materials with high resistance to hydro-abrasive erosion and hardcoatings;

e) developing 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) developing guidelines concerning operation mode of the hydro turbines in water with particle materials to increase the operation life.

It is assumed in this document 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 document to address these issues.

It is assumed in this document that cavitation is not present in the turbine. Cavitation and hydro-abrasive erosion can reinforce each other so that the resulting erosion is larger than the sum of cavitation erosion plus hydro-abrasive erosion. The quantitative relationship of the resulting hydro-abrasive erosion is not known and it is beyond the scope of this document to assess it, except to suggest 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 can impact turbine components and produce damage. This damage can in turn increase the flow turbulence thereby accelerating wear by both cavitation and hydro-abrasive erosion. Hydro-abrasive erosion resistant coatings can also be damaged locally by impact of large solids. It is beyond the scope of this document to address these issues.

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

## 2 Terms, definitions and symbols

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

NOTE 1 Terms and definitions are also based, where relevant, on IEC TR 61364.

NOTE 2 The International System of Units (S.I.) is adopted throughout this document but other systems are allowed.

| 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<br><br>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<br><br>Note 1 to entry: For full information, see IEC 60193. | $g$ | m/s² |
| 2.2.3 | turbine head pump head | available head at hydraulic machine terminal<br><br>$H = E/g$ | $H$ | m |
| 2.2.4 | reference diameter | reference diameter of the hydraulic machine<br><br>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<br><br>Note 2 to entry: See IEC 60193 for further information. | $D$ | m |
| 2.2.5 | hub diameter | the diameter of runner hub for Kaplan turbines | $D_h$ | mm |
| 2.2.6 | hydro-abrasive erosion depth | depth of material removed (measured perpendicular to the original surface) from a component due to hydro-abrasive erosion | $S$ | mm |
| 2.2.7 | characteristic velocity | characteristic velocity defined for each machine component and used to quantify hydro-abrasive erosion damage<br><br>Note 1 to entry: See also 2.2.20 to 2.2.24. | $W$ | m/s |
| 2.2.8 | particle concentration | mass concentration of particles, i.e. the mass of solid particles per volume of water-particle mixture<br><br>Note 1 to entry: In case the particle concentration is expressed in parts per million (ppm) it is recommended to use the mass of particles per volume of water, so that 1 000 ppm approximately corresponds to 1 kg/m³. | $C$ | kg/m³ |

| Sub-clause | Term | Definition | Symbol | Unit |
|---|---|---|---|---|
| 2.2.9 | particle load | the integral of the modified particle concentration over time:<br><br>$$PL = \int_0^T C(t) \times K_{\text{size}}(t) \times K_{\text{shape}}(t) \times K_{\text{hardness}}(t)dt$$<br><br>$$\left( \approx \sum_{n=1}^{N} C_n \times K_{\text{size},n} \times K_{\text{shape},n} \times K_{\text{hardness},n} \times T_{s,n} \right)$$<br><br>$C(t)$ = 0 if no water is flowing through the turbine.<br><br>Note 1 to entry: For Francis turbines $C(t)$ = 0 when calculating $PL$ for runner and labyrinth seals, if the unit is at standstill with pressurized spiral case, but $C(t) \neq 0$ when calculating $PL$ for guide vanes and facing plates. | $PL$ | kg × h/m³ |
| 2.2.10 | size factor | factor that characterizes how the hydro-abrasive erosion relates to the size of the abrasive particles = median particle size $dP_{50}$ in mm | $K_{\text{size}}$ | |
| 2.2.11 | shape factor | factor that characterizes how the hydro-abrasive erosion relates to the shape of the abrasive particles<br><br>Note 1 to entry: See Annex D. | $K_{\text{shape}}$ | |
| 2.2.12 | hardness factor | factor that characterizes how the hydro-abrasive erosion relates to the hardness of the abrasive particles<br><br>for 13Cr4Ni stainless steel: $K_{\text{hardness}}$ = fraction of particles harder than Mohs 4,5.<br><br>for hard coated surfaces: $K_{\text{hardness}}$ = fraction of particles harder than Mohs 7,0. | $K_{\text{hardness}}$ | |
| 2.2.13 | material factor | factor that characterizes how the hydro-abrasive erosion relates to the material properties of the base material | $K_{\text{m}}$ | |
| 2.2.14 | flow coefficient | coefficient that characterizes how the hydro-abrasive erosion relates to the water flow around each component | $K_{\text{f}}$ | $\frac{\text{mm} \times \text{s}^{3,4}}{\text{kg} \times \text{h} \times \text{m}^{\alpha}}$ |
| 2.2.15 | sampling interval | time interval between two water samples taken to determine the concentration of abrasive particles in the water | $T_{\text{s}}$ | h |
| 2.2.16 | yearly particle load | Total load ($PL$) for 1 year of operation, i.e. $PL$ for $T$ = 8 760 h calculated in accordance with 2.2.9 | $PL_{\text{year}}$ | kg × h/m³ |
| 2.2.17 | maximum particle load | maximum value of the integrand in the $PL$ integral during a specified time interval, i.e. the maximum value of the following expression<br><br>$$PL_{\text{max}} = C(t) \times K_{\text{size}}(t) \times K_{\text{shape}}(t) \times K_{\text{hardness}}(t)$$ | $PL_{\text{max}}$ | kg/m³ |
| 2.2.18 | particle median diameter | 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 |
| 2.2.19 | impingement angle | angle between the particle trajectory and the surface of the substrate | | ° |

| Sub-clause | Term | Definition | Symbol | Unit |
|---|---|---|---|---|
| 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 at best efficiency point $$W_{gv} = \frac{Q}{a \times Z_0 \times B_0}$$ | $W_{gv}$ | m/s |
| 2.2.21 | characteristic velocity in Pelton injector | speed of the water flow at injector location $$W_{inj} = \sqrt{2 \times E}$$ | $W_{inj}$ | m/s |
| 2.2.22 | characteristic velocity in turbine runner | relative velocity between the water and the runner blade estimated with below formulas at best efficiency point $$W_{run} = \sqrt{{u_2}^2 + {c_2}^2}$$ $$u_2 = n \times \pi \times D$$ $$c_2 = \frac{Q \times 4}{\pi \times D^2} (Francis)$$ $$c_2 = \frac{Q \times 4}{\pi \times (D^2 - {D_h}^2)} (Kaplan)$$ | $W_{run}$ | m/s |
| 2.2.23 | characteristic velocity in Pelton runner | relative velocity between the water and the runner bucket $$W_{run} = 0{,}5 \times \sqrt{2 \times E}$$ | $W_{run}$ | m/s |
| 2.2.24 | discharge | volume of water per unit time passing through any section in the system | $Q$ | m³/s |
| 2.2.25 | guide vane opening | average shortest distance between adjacent guide vanes (at a specified section if necessary)<br><br>Note 1 to entry: For further information, see IEC 60193. | $a$ | m |
| 2.2.26 | number of guide vanes | total number of guide vanes in a turbine | $z_0$ | |
| 2.2.27 | distributor height | height of the distributor in a turbine | $B_0$ | m |
| 2.2.28 | rotational speed | number of revolutions per unit time | $n$ | 1/s |
| 2.2.29 | specific speed | commonly used specific speed of a hydraulic machine $$n_s = \frac{60 \times n \times \sqrt{P}}{H^{5/4}}$$ $P$ and $H$ are taken in the rated operating point and given in kW and m respectively | $n_s$ | rpm |
| 2.2.30 | output | output of the turbine in the rated operating point | $P$ | kW |
| 2.2.31 | hydro-abrasive erosion depth of target unit | estimated actual depth of metal that will be removed from a component of the target turbine due to particle hydro-abrasive erosion<br><br>Note 1 to entry: For use with the reference model. | $S_{target}$ | mm |
| 2.2.32 | hydro-abrasive erosion depth of reference unit | hydro-abrasive erosion depth of metal that has been removed from a component of the reference turbine due to hydro-abrasive erosion<br><br>Note 1 to entry: For use with the reference model. | $S_{ref}$ | mm |

| Sub-clause | Term | Definition | Symbol | Unit |
|---|---|---|---|---|
| 2.2.33 | number of nozzles | number of nozzles in a Pelton turbine | $z_{jet}$ | |
| 2.2.34 | bucket width | bucket width in a Pelton runner | $B_2$ | mm |
| 2.2.35 | number of buckets | number of buckets in a Pelton runner | $z_2$ | |
| 2.2.36 | time between overhaul for target unit | time between overhaul for target unit<br><br>Note 1 to entry: For use with the reference model. | $TBO_{target}$ | h |
| 2.2.37 | time between overhaul for reference unit | time between overhaul for reference unit<br><br>Note 1 to entry: For use with the reference model. | $TBO_{ref}$ | h |
| 2.2.38 | turbine reference size | reference size for calculation curvature dependent effects of hydro-abrasive erosion<br><br>Note 1 to entry: For Francis turbines, it is the reference diameter, $D$ (see 2.2.4).<br><br>Note 2 to entry: For Pelton turbines it is the inner bucket width, $B_2$.<br><br>Note 3 to entry: For further information in the inner bucket width, $B_2$, see IEC 60609-2. | $RS$ | m |
| 2.2.39 | size exponent | exponent that describes the size dependant effects of hydro-abrasive erosion in evaluating $RS$ | $p$ | |
| 2.2.40 | exponent | numerical value of 0,4-$p$ that balances units for $K_f$ | $\alpha$ | |



# 3 Prediction of hydro-abrasive erosion rate

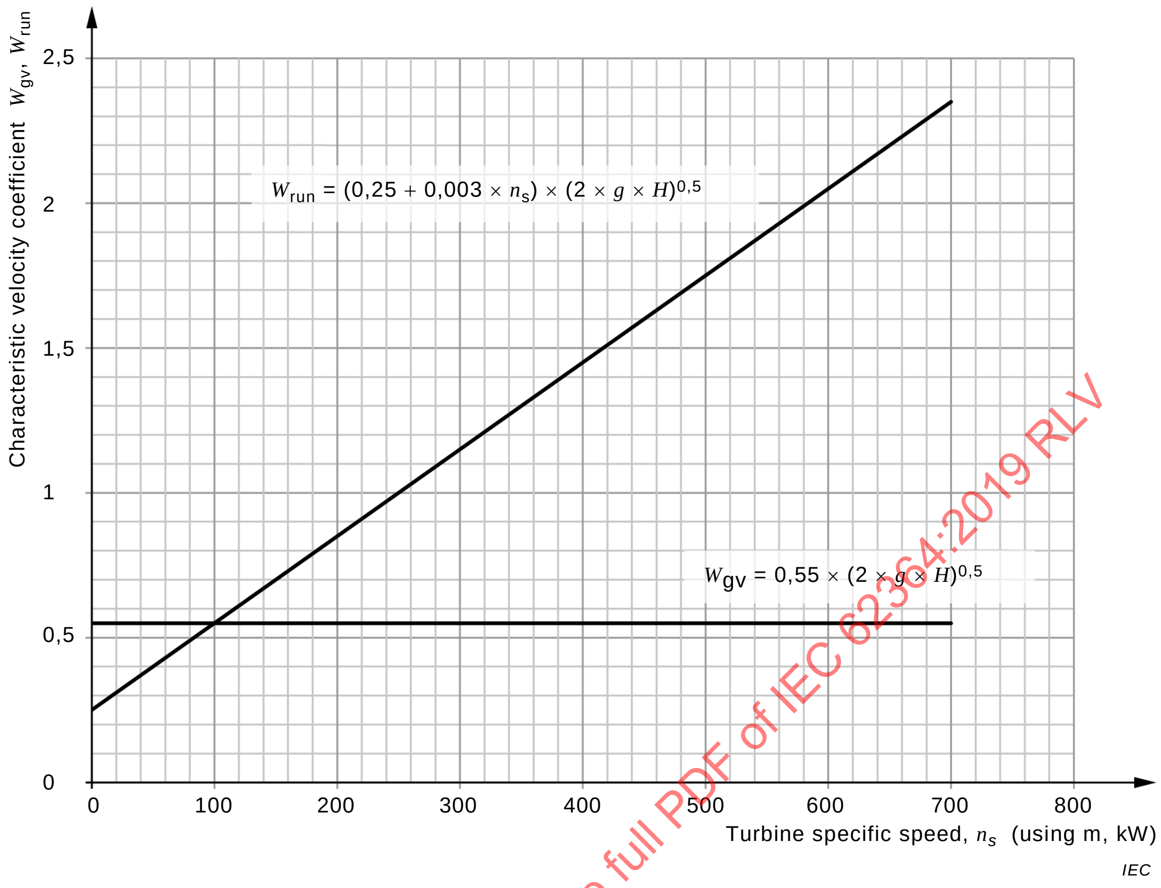
## 3.1 Model for hydro-abrasive erosion depth

The following formula can be used to estimate the hydro-abrasive erosion depth in a Francis turbine:

$$S = W^{3,4} \times PL \times K_m \times K_f / RS^p$$

- The characteristic velocity, $W$, is defined in 2.2.20 to 2.2.23. If detailed data to calculate $W$ is not available it can be estimated based on Figure 1,
- $PL$, $K_m$ and $RS$ are defined in 2.2.9, 2.2.13 and 2.2.38 respectively,
- For uncoated components of Francis turbines $K_f$ and $p$ are taken from Table 1 below.

For additional information of the background for this formula please refer to Annex I. A sample calculation is found in Annex G.






NOTE Values of $n_s$ and $H$ in this figure refer to the rated operating point while the characteristic velocities are given for the points noted in Clause 2.

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

**Table 1 – Values of $K_f$ and $p$ for various components**

| Component | $K_f$ | Exponent $p$ (for $RS$) |
|---|---|---|
| Francis guide vanes | 1,06 × 10$^{-6}$ | 0,25 |
| Francis facing plates | 0,86 × 10$^{-6}$ | 0,25 |
| Francis labyrinth seals | 0,38 × 10$^{-6}$ | 0,75 |
| Francis runner inlet | 0,90 × 10$^{-6}$ | 0,25 |
| Francis runner outlet | 0,54 × 10$^{-6}$ | 0,75 |

### 3.2 Reference model

In the reference model presented in this document 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 hydro-abrasive 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 hydro-abrasive 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 hydro-abrasive erosion 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;

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

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

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

| | |
|---|---|
| Pelton turbines: | $K_{f,\ ref} / K_{f,\ target} = z_{jet,ref} \times z_{2,target} / (z_{jet,target} \times z_{2,ref})$ |
| Francis and Kaplan turbines: | $K_{f,ref} / K_{f,target} = 1$ |
| 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. A sample calculation is found in Annex H.

### 3.3 Simplified hydro-abrasive erosion evaluation

In addition to the formulas in 3.1 and 3.2 other methods to estimate hydro-abrasive erosion have been proposed, such as in [15] and [22][1]. Each method may have its advantages and disadvantages.

As a quick and easy rule of thumb to make a first assessment of the severity at a particular site it is recommended to evaluate the following expression, which is shown graphically in Figure 2.

If $C \times H^{1,5} \leq 150$ then the hydro-abrasive erosion may not be significant.

If $150 < C \times H^{1,5} < 1\,500$ then the hydro-abrasive erosion may be significant.

If $C \times H^{1,5} \geq 1\,500$ then the hydro-abrasive erosion may be severe.

Of course this rule of thumb is approximate, but it may help decide whether further analysis is advisable.



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[1] Numbers in square brackets refer to the Bibliography.

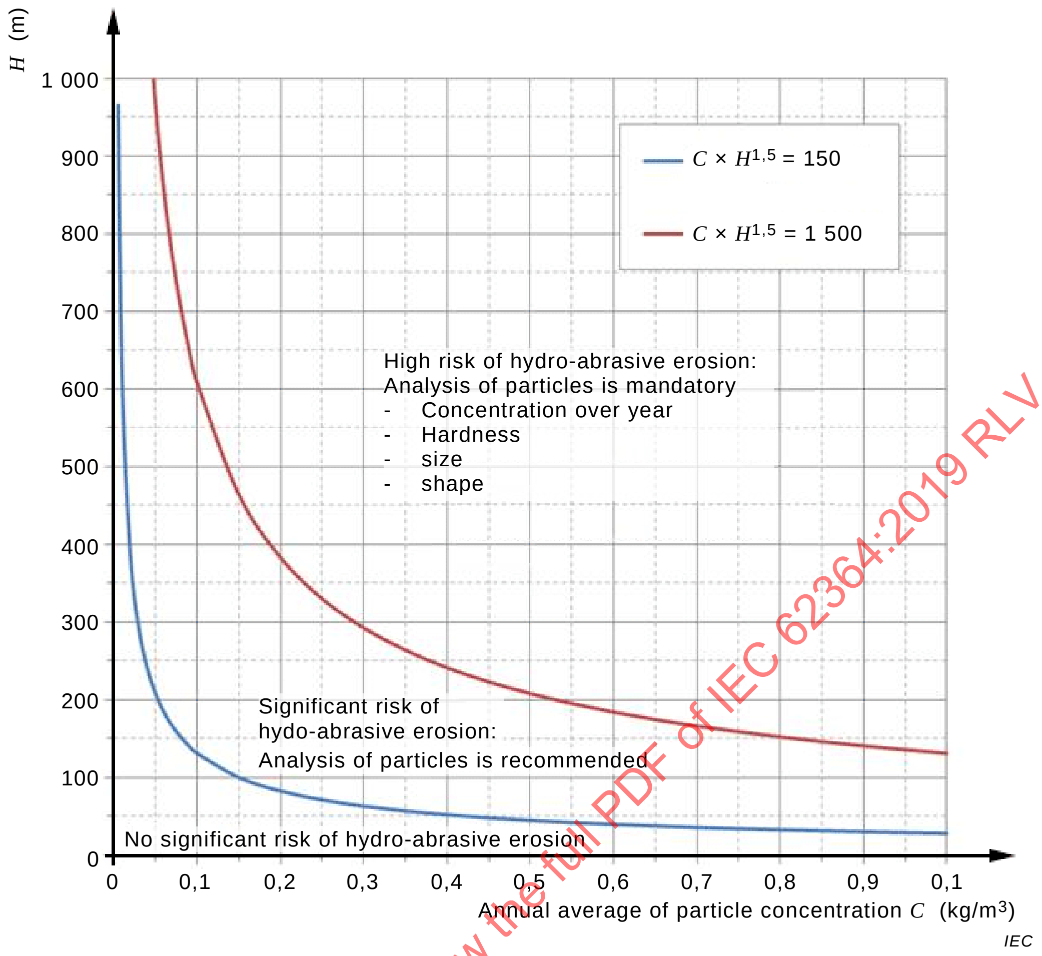



**Figure 2 – Simplified evaluation of risk of hydro-abrasive erosion for first assessment**



# 4 Design

## 4.1 General

The following guidelines explain some recommended methods to minimize hydro-abrasive erosion and the effects thereof, by modifying the design for clean water.

It should be understood that every design of a hydro powerplant is a compromise between several requirements. While it is possible to design a unit to be more resistant against hydro-abrasive erosion 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 Kármán 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;
- coatings against hydro-abrasive erosion may initially result in increased surface roughness, which may reduce the efficiency. The initially increased surface roughness may be reduced due to the polishing effect of operating with particle laden water. Of course, over time the coated turbine will maintain a higher efficiency compared to the uncoated turbine;
- 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 design features to reduce the impact of a high particle concentration will increase the total cost of the power house.

The optimum combination of design features to reduce the impact of a high particle concentration should be considered and selected for each site based on its specific conditions, taking the economic impact for the lifetime of the powerplant into account.

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.

### 4.2 Selection of materials with high resistance to hydro-abrasive erosion and coating

The selection of materials and possible coatings with high resistance to hydro-abrasive erosion is important. See also Clause 6.

Because corrosion would increase the hydro-abrasive erosion rate, stainless steel is the preferred selection. Weldable stainless steel materials are preferred.

In case coatings resistant to hydro-abrasive erosion are not applied in the beginning, it is recommended to make a hydraulic and mechanical component design where such coatings can easily be applied at a later stage.

Labyrinth seals made of aluminium bronze have in general lower resistance against hydro-abrasive erosion than stainless steel. There are also examples with relative good behaviour of labyrinth seals made of aluminium bronze.

### 4.3 Stainless steel overlays

Stainless steel welded overlays with sufficient thickness may be used instead of solid stainless steel components, if the cost of the overlay welding is lower than the cost of solid stainless steel components.

### 4.4 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. Often a very large amount of particles can be removed from the water. The negative side of this is that reservoirs can fill up fast. This will have the result that more and more particles and also larger ones will reach the intake and pass through the turbine. Sedimentation can be reduced by different methods, even if it cannot be completely prevented. Possibilities are extensive flushing and also using a bypass channel/tunnel during the high flood season to divert the highest particle laden water around the reservoir downstream of the hydro power plant. Maintaining the active storage capacity of reservoirs is one possibility of keeping also the turbine operation and the repair costs relatively constant.

If a large reservoir is not available, sand traps (also called desilting basins/ chambers), possibly with preceding gravel traps and other facilities to exclude mainly coarse sediment at intakes may be built. It appears that the minimum particle size that can be removed by these structures is in 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 document.

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. At the end of unlined tunnels, rock traps should be provided and deposits should periodically be removed

Due to generally low velocity the water conveyance system itself seldom sees significant hydro-abrasive erosion damage and normal coating paint on the steel structures of the system is usually enough to protect it.

## 4.5 Valve

### 4.5.1 General

If hydro-abrasive erosion is expected, as a general rule all mechanical disturbances in the flow are subject to high hydro-abrasive erosion attack. Therefore the choice between butterfly valve and spherical valve should be discussed by customer and supplier because the sealing disc of a butterfly valve is continuously exposed to the abrasive water flow.

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 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.

### 4.5.2 Protection (closing) of the gap between housing and trunnion

The area between trunnion and housing is especially susceptible for hydro-abrasive erosion. Since the transition of the 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. Several design can be proposed, as an example, the transitions can be protected against the direct attack of hydro-abrasive erosion by a pre-labyrinth (see Figure 3).

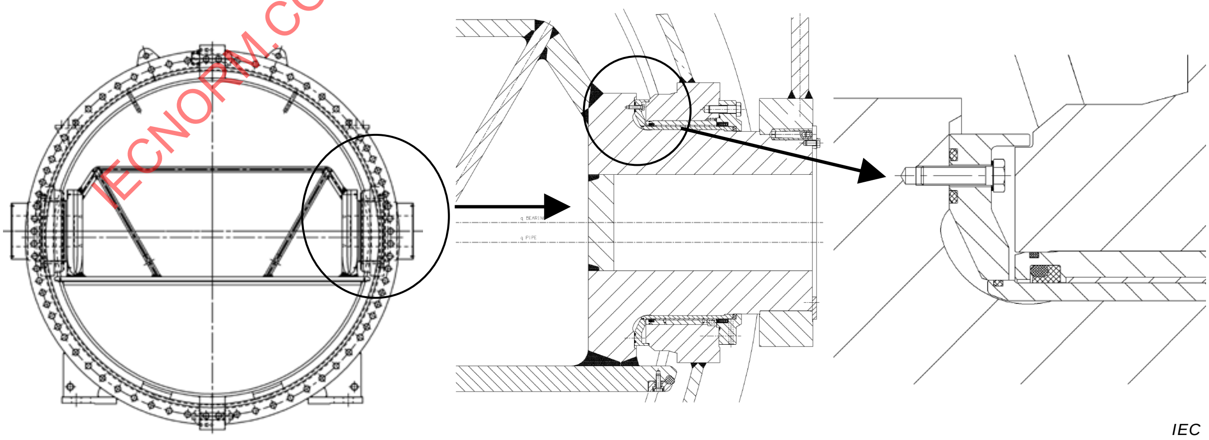



**Figure 3 – Example of protection of transition area**

### 4.5.3 Stops located outside the valve

In hydro-abrasive erosion 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.

#### 4.5.4 Proper capacity of inlet valve operator

Normally inlet valves (rotors) will be opened or closed with an approximately balanced pressure (eg. 100:75) that is established by the bypass or the movable sealing rings.

If excessive hydro-abrasive erosion 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.

#### 4.5.5 Increase bypass size to allow higher guide vane leakage

As already mentioned in 4.5.4 above, due to the excessive hydro-abrasive erosion at the guide vanes the leakage water flow may 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.

#### 4.5.6 Bypass system design

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

### 4.6 Turbine

#### 4.6.1 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.

#### 4.6.2 Hydraulic design

##### 4.6.2.1 Selection of type of machine

It is advantageous to select a type of machine that has low relative water velocity, that can easily be serviced and that can easily be coated with hydro-abrasive erosion 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 relative 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 relative velocity. On the other hand, the Kaplan runner has better access for applying hydro-abrasive erosion 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 relative maximum velocity, which leads to less hydro-abrasive erosion in the Francis turbine. However, the parts in a Pelton turbine that are subject to the relative maximum velocity (i.e. the needle tips and seat rings) are small and have better access for applying coatings. The Pelton turbine is also easier to service.

##### 4.6.2.2 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 hydro-abrasive erosion damage will be in the runner so the specific speed is important. For high head Francis turbines much of the hydro-abrasive erosion damage will be in the guide vane apparatus, so the specific speed is not so important.

For Pelton turbines, the relative 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 hydro-abrasive erosion damage. A lower number of jets also reduces the time that each bucket is filled with water.

#### 4.6.2.3 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 hydro-abrasive erosion.

#### 4.6.2.4 Turbine submergence

Cavitation and hydro-abrasive erosion may mutually reinforce each other. For this reason it is recommended that the turbine submergence is higher for plants where hydro-abrasive erosion is expected.

#### 4.6.2.5 Runner blade overhang

During the refurbishment of a Francis turbine, the turbine output is sometimes significantly increased. 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 turbulence 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 overhanging blades is to create a lower pressure zone downstream of the runner band seal, thus creating higher seal leakage and more hydro-abrasive erosion at the band seal. These negative effects are always present if a runner is designed with overhang.

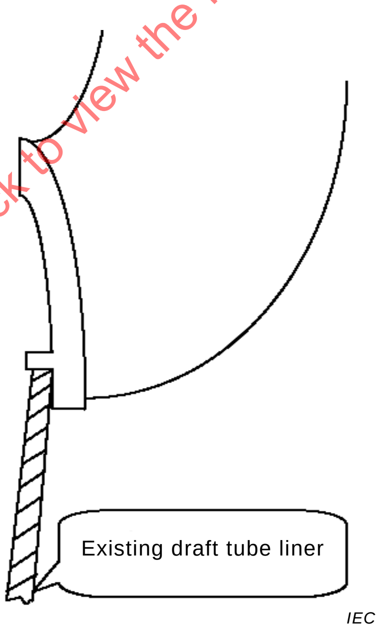



**Figure 4 – Runner blade overhang in refurbishment project**

#### 4.6.2.6 Thicker runner blades

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 Kármán vortices. Also, the risk of cavitation damage on the runner band, downstream of the blade may increase (see Figure 5). In this context, it can be mentioned that hydro-abrasive erosion resistant coatings may provide a means to design thin profiles with only a marginal increase in the thickness due to the coating.

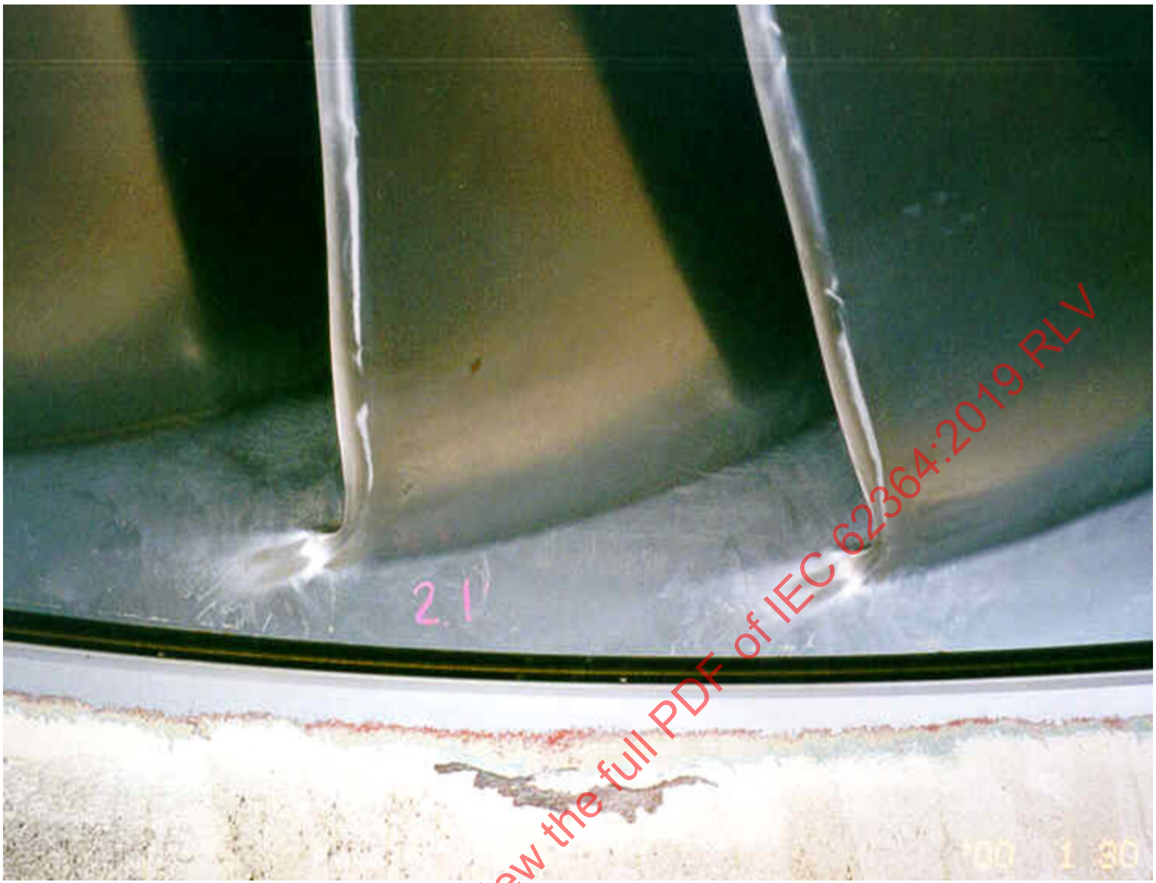



**Figure 5 – Example of cavitation on runner band due to thicker blades**



#### 4.6.2.7 Guide vane overhang

When guide vane overhang exists, the area underneath the guide vane will experience high turbulence and high recirculation and hydro-abrasive erosion 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.

### 4.6.3 Mechanical design

#### 4.6.3.1 General

If hydro-abrasive erosion 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 hydro-abrasive erosion rate and to allow easy maintenance or replacement of the eroded parts. In this subclause some features are mentioned.

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

The following subclauses are divided into direct measures to reduce hydro-abrasive erosion and measures to allow an easy maintenance to dismantle the abraded components.

#### 4.6.3.2 Direct measures to reduce hydro-abrasive erosion or increase lifetime under abrasive attack

##### 4.6.3.2.1 Guide vane seals

There are three different types of seals: end seals, seals between the inlet and trailing edge of two neighbouring 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 hydro-abrasive erosion of the adjacent components. However, the seals themselves are subject to attack by hydro-abrasive erosion and the lifetime of these seals may be limited.

The use of guide vane end seals to avoid hydro-abrasive erosion 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 one example of 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 hydro-abrasive erosion rate. The material of the seal rings should be solid steel with relatively high resistance to hydro-abrasive erosion or coated stainless steel.



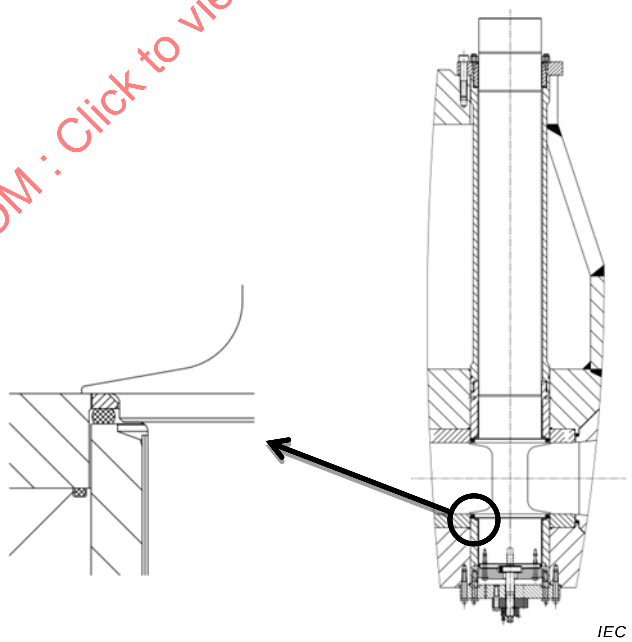



**Figure 6 – Example of design of guide vane trunnion seals**

All seals should have a stainless steel or a hydro-abrasive erosion 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 with the headwater pressure acting on the closed guide vanes.

#### 4.6.3.2.2 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. This could help to avoid collecting particles in front of the labyrinths.

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 thrust bearing.

#### 4.6.3.2.3 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 hydro-abrasive erosion. In this case, the limit of the flow velocity is recommended to be 4 m/s to 5 m/s.

#### 4.6.3.2.4 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.

#### 4.6.3.2.5 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 hydro-abrasive erosion. They are fixed on the head cover and bottom ring and are removable.

If the expected hydro-abrasive erosion is high and if the accessibility allows it, 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.

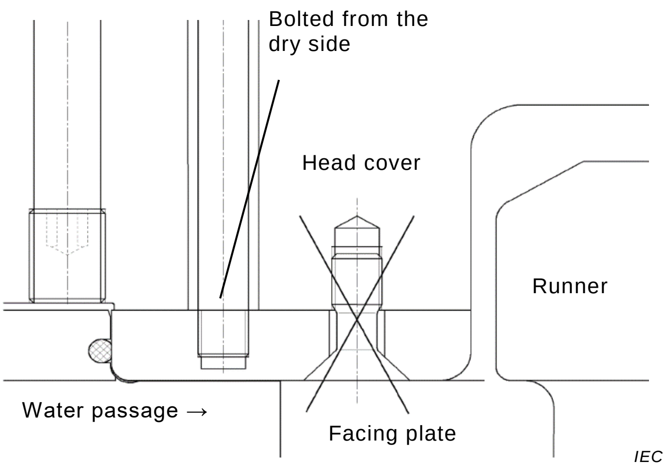



**Figure 7 – Example of fixing of facing plates from the dry side (bolt to the left)**



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 plate 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. If coated facing plates are used the bolting should be from the dry side.

According to the expected hydro-abrasive erosion 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.

#### 4.6.3.2.6 Stainless steel overlay in runner chambers

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

#### 4.6.3.2.7 Stainless steel overlay on head cover and bottom ring

Also the water exposed surfaces of the head covers and bottom rings are subject to hydro-abrasive erosion. Applying a stainless steel overlay or stainless steel protection plates is recommended, especially in areas of discontinuities or flow changes. Repair of stainless steel overlay can be done by new welded stainless steel overlay, welding on stainless steel tiles or a thermal spray coating.

#### 4.6.3.2.8 Increase of wall thickness

Increasing the wall thickness is one of the methods to increase the time between the overhauls of a component due to hydro-abrasive erosion. Increasing the thickness of hydraulic components such as runner blades, is discussed in 4.6.2.6.

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 may be reasonable that the total area of the balancing pipes is at least three times the clearance area of worn labyrinth seals. It is, of course, also possible to accomplish the balancing with holes in the runner instead of separate balancing pipes.

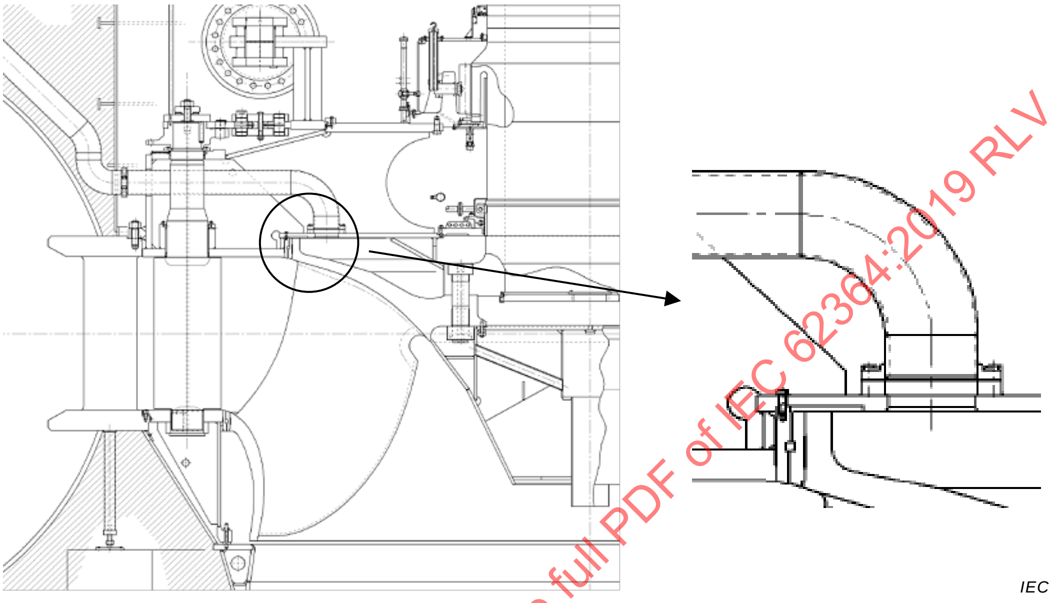



**Figure 8 – Head cover balancing pipes with bends**



#### 4.6.3.2.9 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 hydro-abrasive erosion is present, the thrust bearing may be designed to handle additional load so that the unit can be operated with some hydro-abrasive erosion of the labyrinth seals.

### 4.6.3.3 Design concepts to allow easy maintenance or replacement

#### 4.6.3.3.1 General

If the components are damaged by hydro-abrasive erosion 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 take this into account.

#### 4.6.3.3.2 Component removal

The main components which have to be replaced or dismantled for repair in Francis turbines are the runner, the guide vanes, the labyrinth seals 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 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. Especially, if the maintenance management is planning to use two runners (one in operation, one in service) for one unit (one shaft). Friction type couplings or couplings without necessary mechanical joint machining on site are possible solutions.

#### 4.6.3.3.3 Appropriate design for coating

The resistance of the components against hydro-abrasive erosion can be considerably improved through appropriate hydro-abrasive erosion 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.

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

The following main components, classified according to the type of turbine, can 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 hydro-abrasive erosion protection, accessibility and economy:

**Francis turbine, pump, pump turbine:**

- Runner
  - labyrinth seals
  - if possible the entire flow channel. If access for coating is difficult the coated areas may be limited to the suction side of runner outlet, the band and runner inlet. Note that the part limiting the Francis runner lifetime is normally the runner blade pressure side
  - 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 non-destructive testing is required
- Needle tip
- Seat ring
- Nozzle housing
- Deflector (if used for long time)

**Kaplan, propeller and bulb turbines:**

- Runner blades
- Runner hub (in extreme cases)
- Guide vanes (in extreme cases)
- Facing plates (in extreme cases)

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 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.

#### 4.6.3.3.4 Exceptional use of carbon steel as base material

In general, stainless steel is recommended. However, the use of carbon steel can also be considered for economic reasons (with possible increased risk of corrosion and adhesion failure).

#### 4.6.3.3.5 Accessibility for thermal spray coating

A minimum space is required for the application of a thermal spray coating. Hydraulic and mechanical design should consider the limitation for accessibility for thermal spray coating.

Finger labyrinths have small space between the fingers thus special solutions may be adopted such as concentrically split seals. For step labyrinths it could be an advantage to use a straight gap or to optimize the shape of the step regarding accessibility for thermal spray coating. However, this may influence the sealing performance of the labyrinth. See Figure 9 below.



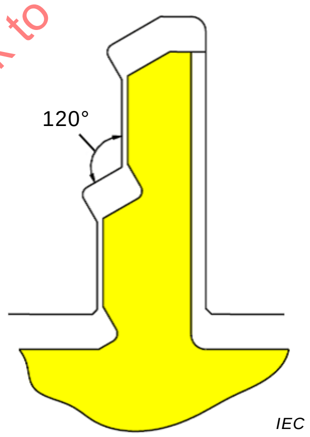



**Figure 9 – Step labyrinth with optimized shape for hardcoating**

## 5 Operation and maintenance

### 5.1 Operation

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

- Temporal shut down of the units and closure of the intakes in periods of high concentrations and/or coarse particles. The switch-off concentration is typically above 1 g/l or several 10 g/l. The switch-off concentration results from a site-specific economic optimization, typically based on operation and maintenance records. This may prevent excessive hydro-abrasive erosion 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 occur in a short time. 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, through a special system, and open the penstock drainage valve to flush out particles immediately in front of the inlet valve. In this case it is important to analyse the possible consequences on main gates, if any, due to large amount of air into the penstock.
- 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 hydro-abrasive erosion resistant coatings. Damage to hydraulic surfaces may increase the turbulence of the flow, which will, in turn, increase the hydro-abrasive erosion 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 hydro-abrasive erosion damage jeopardizes the safety of operation. As the hydro-abrasive erosion 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 and with the results of the latest and earlier inspections.
- For Pelton turbines the best ratio of produced electricity to hydro-abrasive erosion is at full opening of one or more nozzles. Contrary to other turbine types, Pelton turbines allow for reducing the hydro-abrasive erosion with reduced load by fully closing individual nozzles, if allowed by the mechanical design of the turbine.
- For Pelton turbines leakage flow through closed nozzles may cause severe locally concentrated hydro-abrasive erosion in seat rings. Closing the upstream spherical valves at standstill avoids this problem. In severe conditions it can be favourable to avoid operation of some nozzles while others are closed (operation restriction at part load)
- For other types of turbines the best ratio of produced electricity to hydro-abrasive erosion 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 hydro-abrasive erosion for most components and turbine types.
- For Francis turbines 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 hydro-abrasive erosion in the guide vane apparatus. By closing the inlet valve this hydro-abrasive erosion is eliminated. Closing the inlet valve is especially important for high head units.
- Hardcoatings 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 7 regarding cavitation requirements.

## 5.2 Spares and regular inspections

- Keep additional spares in stock for parts subject to hydro-abrasive erosion. In case of severe hydro-abrasive erosion a complete set of exchangeable parts (for example guide vanes, facing plates or 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 and to the results of the latest and earlier inspections. Keep adequate records of the amount of hydro-abrasive erosion 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 hydro-abrasive erosion damage. Please see also Annex B.

## 5.3 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 analysed in a laboratory. In addition, several types of instruments for continuous monitoring of the particle concentration have become available, but the accuracy for particle concentration measurements under site conditions is very low. 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 concentration in the river and the particle concentration 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.

Normally a powerplant will have a period(s) with high particle concentration and other period(s) with low particle concentration, see Figure 10. As can be seen the concentration may change in a very short time.



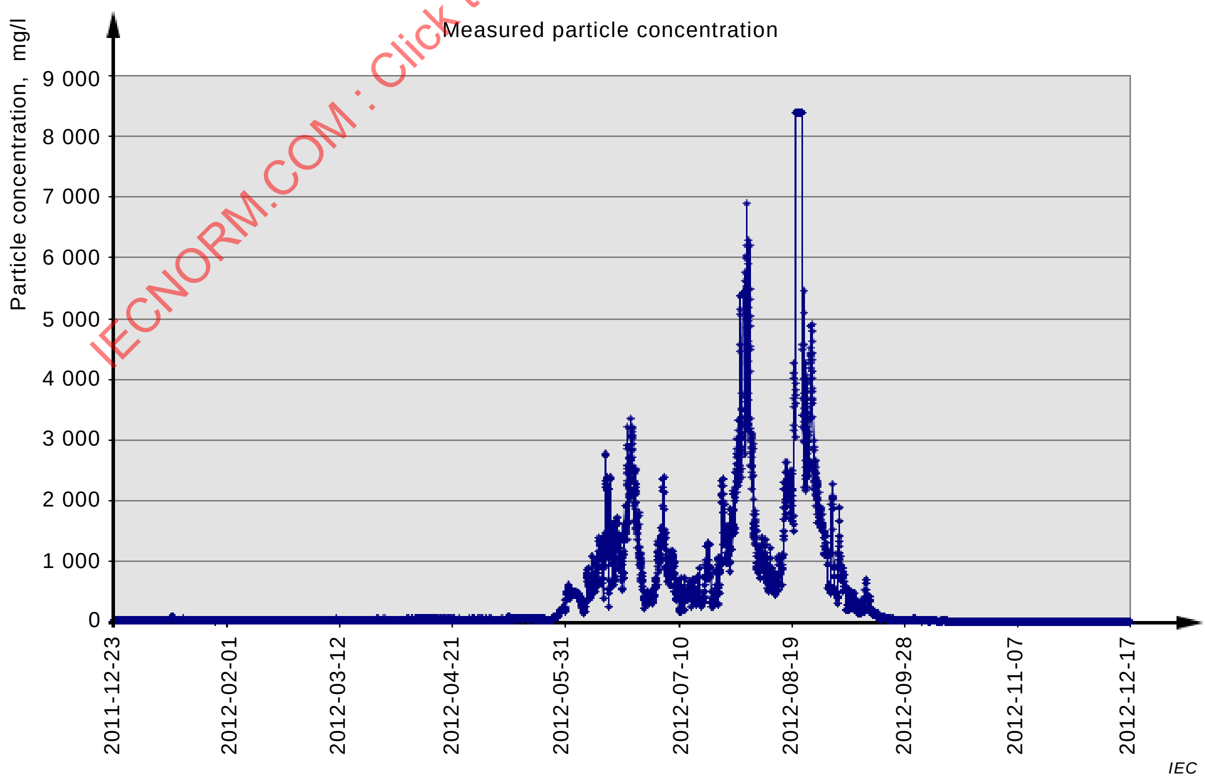



**Figure 10 – Sample plot of particle concentration versus time**

In the low particle concentration period, where there are only small absolute variations in the concentration, the sampling can be done once per day or week.

In the high particle concentration period the sampling has to be done with a frequency between 1 h and 6 h, depending on the concentration difference between consecutive measurements. The final interval should be selected so that at least three measuring points are defining each peak of particle concentration.

If historical data on particle properties is already available a calculation for the sampling interval is given in Annex E. Please see also Annex C for further information.

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;
- discharge (if available);
- 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 hydro-abrasive erosion of the labyrinths;
- discharge of the headcover balancing pipes (if applicable). This can give an indication about the wear of the labyrinth seals;
- axial thrust (if applicable or available).

It should be possible to relate the operating parameters to the records of particle concentration and particle properties. This information can be used to correlate with the observed damages.

Vibration and noise could also be an indication for hydro-abrasive erosion.



# 6 Materials with high resistance to hydro-abrasive erosion

## 6.1 Guidelines concerning relative hydro-abrasive erosion resistance of materials including hydro-abrasive erosion resistant coatings

### 6.1.1 General

Several comparative tests of materials against hydro-abrasive erosion have been performed. It is however, difficult to compare the results of different tests to each other. The results can therefore be confusing. It was chosen not to report any such tests in this document.

In addition to the resistance against hydro-abrasive erosion several other factors should be considered when selecting a hydro-abrasive erosion resistant coating, such as:

- how easy it is to apply the coating;

- how easy it is to repair the coating;
- how thick is the coating layer. A thick layer of a material with a lower hydro-abrasive erosion resistance index may have longer lifetime than a very thin layer of a material with a high hydro-abrasive erosion resistance index;
- the dimensional tolerance of the coating;
- how easy it is to remove the coating.

#### 6.1.2 Discussion and conclusions

Protection of hydro power plant equipment by using materials with high resistance to hydro-abrasive erosion or hydro-abrasive erosion resistant coatings can often increase the lifetime between major overhauls.

At present, the most common hydro-abrasive erosion resistant coating material in hydraulic machines is thermal sprayed tungsten carbide cobalt chromium, WC-CoCr. Sometimes also various types of polymer coatings (sometimes referred to as “soft coatings") are used.

The thermal spray coating, often referred to as “hardcoating”, can be applied to most hydro-abrasive erosion 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 hydro-abrasive erosion resistance, if applied properly. It is worth to note that substantial variations in hydro-abrasive erosion resistance are present between different thermal spray versions. This is due to variations in powder composition, environmental conditions during application and spray parameters.

Sometimes polymer coatings may also be an option, but only on surfaces not requiring tight tolerances. These coatings, if used, are therefore restricted to water passages in Francis and Kaplan turbines.

Stainless steel facing plates or stainless steel overlay welds can increase the hydro-abrasive erosion resistance compared to carbon steel. It is common to protect, for example, carbon steel head covers and bottom rings with stainless steel at sensitive locations. The hydro-abrasive erosion resistance of stainless steel is far from the level of thermal spray or polymer coating. Abraded stainless steel facing plates are relatively easy and quick to replace. Further improvement in hydro-abrasive erosion 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.



### 6.2 Guidelines concerning maintainability of hydro-abrasive erosion resistant coating materials

#### 6.2.1 Definition of terms used in this subclause

1) *Overhaul*: Restoration of entire part to the original geometry and quality level including new protective coating.
2) *Repair*: *Localized* 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 A or B.

#### 6.2.2 Time between overhaul for protective coatings

Protective coatings that have been deposited onto part surfaces will also be subject to hydro-abrasive erosion but at a considerably lower rate than the underlying steel. After a certain period of operation the coating will be worn off and the underlying steel will appear. From this moment on, the hydro-abrasive erosion progresses at a higher rate on such stripped areas, leading to a modification of the geometry of the hydraulic profile. 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 hydro-abrasive erosion 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 integrity 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 ensured, 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 a model cited in 3.1 or 3.2.

Once the plant has been operated for some time a more refined estimate can be made considering previous experience.

### 6.2.3 Repair of protective coatings

In order to achieve best quality it is recommended to execute overhauls and repairs in a specialized workshop 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. In some cases (mainly horizontal Pelton) also an in-situ repair of the coating should be discussed as it might be feasible and could be the best solution. Extreme care should be taken to protect all relevant parts (including generator) from the dust, e.g. by suitable ventilation during the works. Please see also Table 2.

In case of repairs the amount of damage and the necessity of welding and heat treatment plays a significant role in the decision if the repair of the coating can be done on-site. If only grinding without welding or only minor welding repairs are necessary, re-applying the coating may be done on-site with mobile equipment.

On-site reapplication of hard coating may be done for fully coated Francis runners or Pelton runners. For these components the amount of damage is in most cases very small compared to the whole coated area.

**Table 2 – Overview over the feasibility for repair C on site**

| Coating type | Feasibility | Remarks |
|---|---|---|
| Hardcoating | 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 hydro-abrasive erosion induced shape changes of the cutting edge and the inlet edges.

# 7 Guidelines on insertions into specifications

## 7.1 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 hydro-abrasive erosion may mutually reinforce each other as explained in 4.6.2.4. Also some popular hydro-abrasive erosion 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 hydro-abrasive erosion is expected. This can, for example, mean that sigma plant should be higher than sigma incipient and that the plant should be operated accordingly.

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 F. 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 communicate clearly 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 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 hydro-abrasive erosion, in accordance with the guidelines in this document, and estimate the required overhaul interval and overhaul scope for safe operation of the unit.

If a hydro-abrasive erosion guarantee is agreed between the owner and the turbine supplier, it should specify the $PL$ that is guaranteed between overhauls, based on some agreed overhaul criteria. Also the recording needed to measure the actual $PL$ and how this data should be communicated between the parties shall be agreed.

## 7.2 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/m³ | **Average particle concentration** kg/m³ | **Particle size, $dP_{50}$** mm | **Fraction of hard particles** Mohs > 4,5 % | **Typical shape of hard particle**[b] | **Operating net head** m | **Operating 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. | | | | | | | | | | | | | |
| Typical flood event | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |

[a] In column “Period” select the appropriate interval.

[b] Refer to Annex D for further details.

### 7.3 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**<br>>Mesh 230[a] | **Fraction 63 µm to 125 µm**<br>Mesh 230 to 120[a] | **Fraction 125 µm to 250 µm**<br>Mesh 120 to 60[a] | **Fraction > 250 µm**<br>< Mesh 60[a] | **Total** |
|---|---|---|---|---|---|
| Jan. – April | | | | | |
| May – Sept. | | | | | |
| Oct. – Dec. | | | | | |
| | | | | | |

[a] Mesh sizes according to ASTM E11 – 15.

NOTE 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.

# 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 particles had similar shapes as in Figure D.1 b). The results were as shown in Table A.1.

**Table A.1 – Example of documenting sample tests**

| ID | Date, Time | Event | Particle concentration<br>kg/m$^3$ | Particle size, $dP_{50}$<br>mm | Fraction harder than Mohs hardness > 4,5<br>% |
|---|---|---|---|---|---|
| 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

$C_{\mathrm{n}}$ is the particle concentration in kg/m$^3$ for each sample;

$K_{\mathrm{size}}$ 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;

$K_{\mathrm{shape}}$ = 1,5, see Annex D (only the shape of the abrasive particles is relevant);

$K_{\mathrm{hardness}}$ 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/m³ | $K_{size,n}$ | $K_{shape,n}$ | $K_{hardness,n}$ | $T_{s,n}$ h | $PL_n$ kg × h/m³ |
|---|---|---|---|---|---|---|
| 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/m³.

# Annex B
(informative)

# Measuring and recording hydro-abrasive erosion damages

## B.1 Recording hydro-abrasive erosion damage

The following is a guideline to measure the hydro-abrasive erosion of the individual parts of machines.

The goal of this guideline is to get reliable results of the hydro-abrasive 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 and be possible to correlate with the operating parameters:

- 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 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.

It can be noted that declining maximum output may indicate progressing hydro-abrasive erosion damage.

## 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 above the centre of the bucket. Sketches of the hydro-abrasive 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 hydro-abrasive erosion 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 hydro-abrasive 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 tip and mouth piece without coating

Photos should be taken in closed needle tip position to see any gaps between needle tip 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.

Photos should be taken to give an overview of parts (if taken apart) and in closed position to see gaps between the parts.

## B.4 Pelton runner with hardcoating

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 hydro-abrasive erosion 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.

If the coating on the splitter edge has been completely eroded measurement of the splitter width should also be made.

## B.5 Needle tip, 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 possible height of steps as well as possible width of gaps between the seat ring and nozzle housing should be recorded.

## B.6 Francis runner and stationary labyrinth without coating

The measurement of the hydro-abrasive 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 hydro-abrasive erosion depth 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, close-up photos of areas with hydro-abrasive erosion with 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 hydro-abrasive erosion usually occurs and should be given special attention. A mirror could be helpful e.g. at the pressure side of the outlet.

On areas of major hydro-abrasive erosion damage the depth 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, the complete outside of the runner and the rotary and stationary labyrinth, as well as overview and details should be photographed and recorded in sketches.

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

## B.7 Francis runner with coating and stationary labyrinth

For all blades a sketch should be made of the areas with damaged coating with location and sizes of the areas.

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 eroded away at the trailing edge: see measurements for Francis without coating.

The gap between the runner and the facing plates 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 be taken.

If reference points still exist the hydro-abrasive erosion measurements on facing plates consist of measuring the biggest gaps between guide vanes and facing plates at minimum 4 vanes.

A simple indication of the hydro-abrasive erosion damage to the guide vane apparatus consists of measuring the spiral case pressure at standstill with closed guide vanes and MIV closed but open main inlet valve bypass. This may be logged automatically during normal MIV opening together with HWL, TWL, date and time.

An additional indication can also be logged by recording the time it takes for the turbine to stop after a shutdown with the MIV open. The hydro-abrasive erosion in the guide vanes will cause leakage in the guide vanes when they are fully closed. This will cause the unit to use longer time to stop when shutting down.

## 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 hydro-abrasive 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).

## B.10 Stay vanes

Hydro-abrasive erosion is normally not an issue on the stay vanes due to lower velocities. However, failure of stay vanes can have dramatic consequences and stay vanes should also be inspected regularly. No particular inspection records for the stay vanes are included in this clause, but a simple note stating if damage has occurred or not, together with pictures, is recommended.

If hydro-abrasive erosion has occurred the thickness should be measured using templates of the stay vane geometry. If the stay vane thickness is reduced by 20 % or more, the stay vane should be checked by carrying out a stress analysis.

## B.11 Francis labyrinth seals uncoated

It is recommended to carry out measurement of the leakage flow rate from the upper seal (if possible) once a week in the wet season and once a month in the dry season.

## B.12 Kaplan uncoated

The measurement of the hydro-abrasive 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 hydro-abrasive erosion with a sketch showing the location of photos should be supplied in the report. At least all areas with major hydro-abrasive erosion have to be photographed.

On areas of major hydro-abrasive erosion damage the depth of hydro-abrasive 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.13 Kaplan coated

For all blades a sketch should be made of the areas with damaged coating with location and sizes of the areas.

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 completely eroded 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.14 Sample data sheets

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

If possible the records should directly show the hydro-abrasive erosion 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 hydro-abrasive erosion 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 hydro-abrasive erosion depth and location in the turbine of several individual components should be recorded in such cases. It is normal for the hydro-abrasive erosion depth to vary significantly between the individual components.

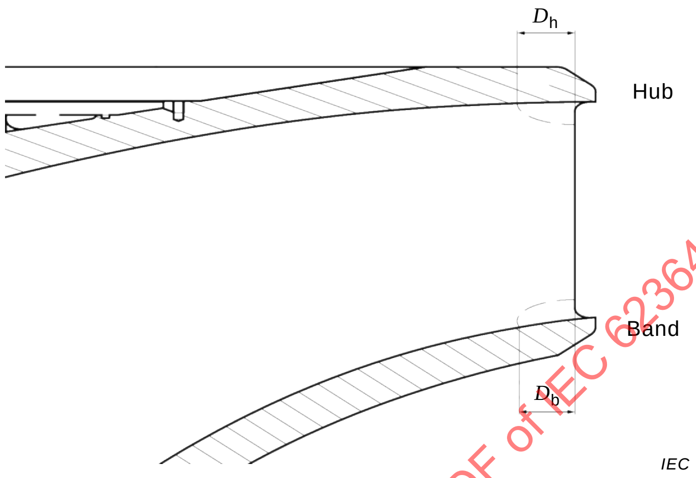
The hydro-abrasive erosion depth on the same component usually varies with location on the component. It is recommended to record hydro-abrasive erosion depth in a few typical locations on the component. In each location the maximum hydro-abrasive erosion depth should be considered.

Enclosed below, are a set of sample data sheets for recording damage in a high head Francis turbine and a Pelton runner, see Tables B.1 to B.11. 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 hydro-abrasive erosion and areas that may affect the safe operation of the unit.

## B.15 Inspection record, runner blade inlet

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

| Plant | Unit Nb | Date | Sign |
|---|---|---|---|
| | | | |

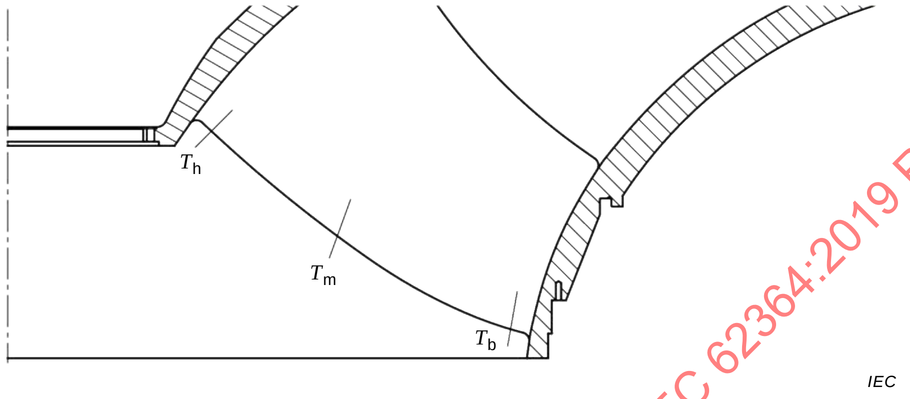



| Blade number | Hub erosion depth, $D_h$ | Band erosion depth, $D_b$ |
|---|---|---|
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | | |
| 7 | | |
| 8 | | |
| 9 | | |
| 10 | | |
| 11 | | |
| 12 | | |
| 13 | | |
| 14 | | |
| 15 | | |
| 16 | | |
| 17 | | |

## B.16 Inspection record, runner blade outlet

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |

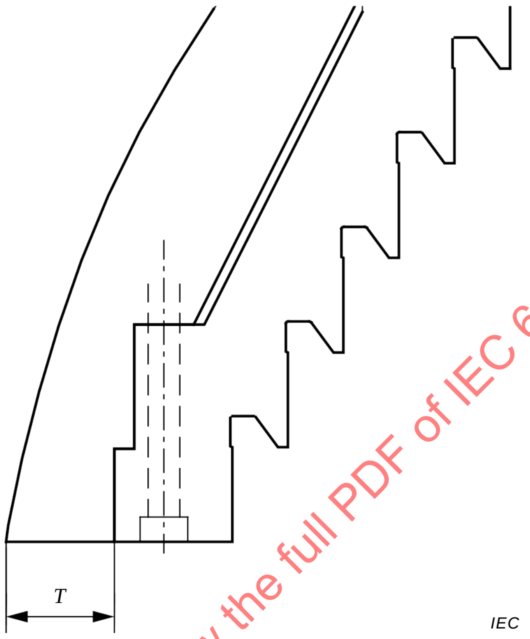



| Blade number | Thickness at hub, $T_h$ | Thickness at middle, $T_m$ | Thickness at band, $T_b$ |
|---|---|---|---|
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |
| 6 | | | |
| 7 | | | |
| 8 | | | |
| 9 | | | |
| 10 | | | |
| 11 | | | |
| 12 | | | |
| 13 | | | |
| 14 | | | |
| 15 | | | |
| 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.17 Inspection record, runner band

**Table B.3 – Inspection record, runner band form**

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |



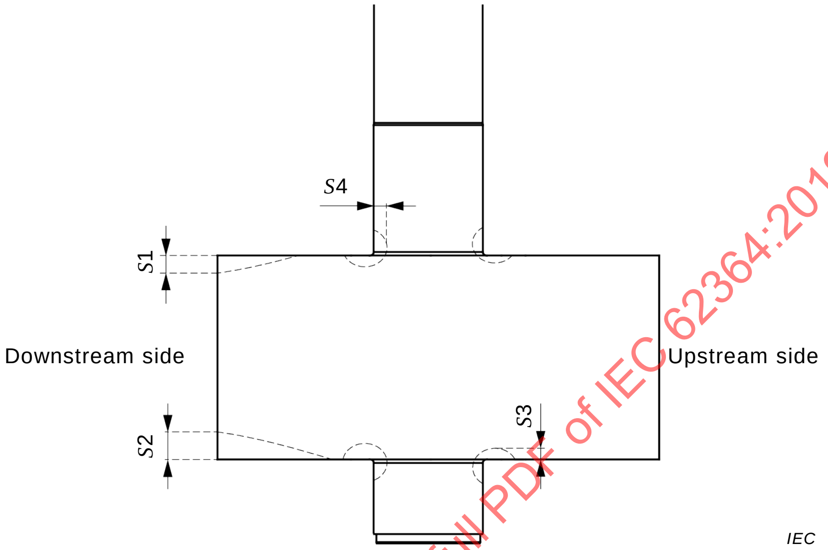

| Measuring point | Thickness, $T$ |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| 4 | |

NOTE Measuring points are 90° apart.

## B.18 Inspection record, guide vanes

**Table B.4 – Inspection record, guide vanes form**

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |



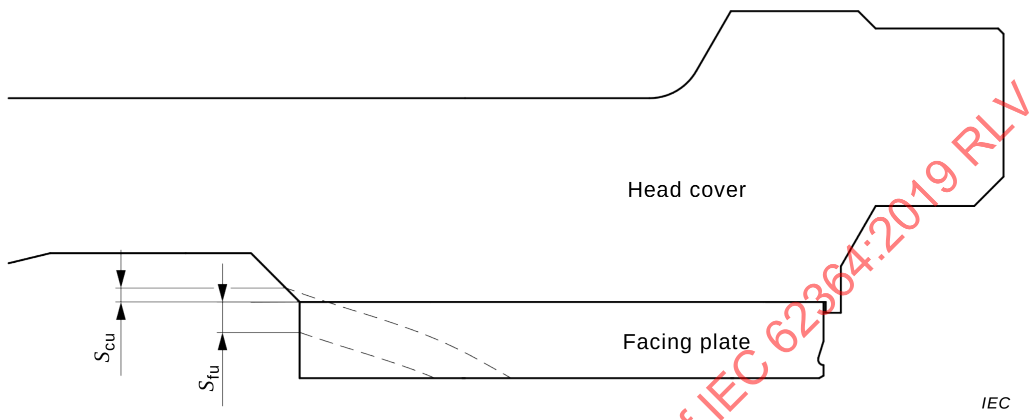



| Guide vane number | Face towards head cover, *S*1 | Face towards bottom cover, *S*2 | Face around bottom stem, *S*3 | Guide vane top stem, *S*4 |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10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

## B.19 Inspection record, facing plates and covers

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |




| Measuring point number | Upper facing plate, $S_{fu}$ | Head cover, $S_{cu}$ | Lower facing plate, $S_{fl}$ | Lower cover, $S_{cl}$ |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |

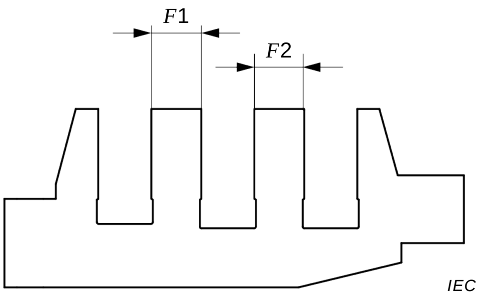
NOTE 1 $S_{cu}$ and $S_{cl}$ are only measured in case there is no more facing plate material remaining.

NOTE 2 Measuring points are 90° apart.

## B.20 Inspection record, upper stationary seal

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |

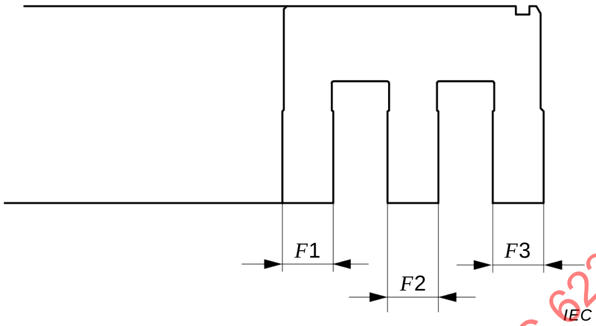



| | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| Finger 1, $F1$ | | | | |
| Finger 2, $F2$ | | | | |
| NOTE Measuring points are 90° apart. | | | | |

## B.21 Inspection record, upper rotating seal

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |

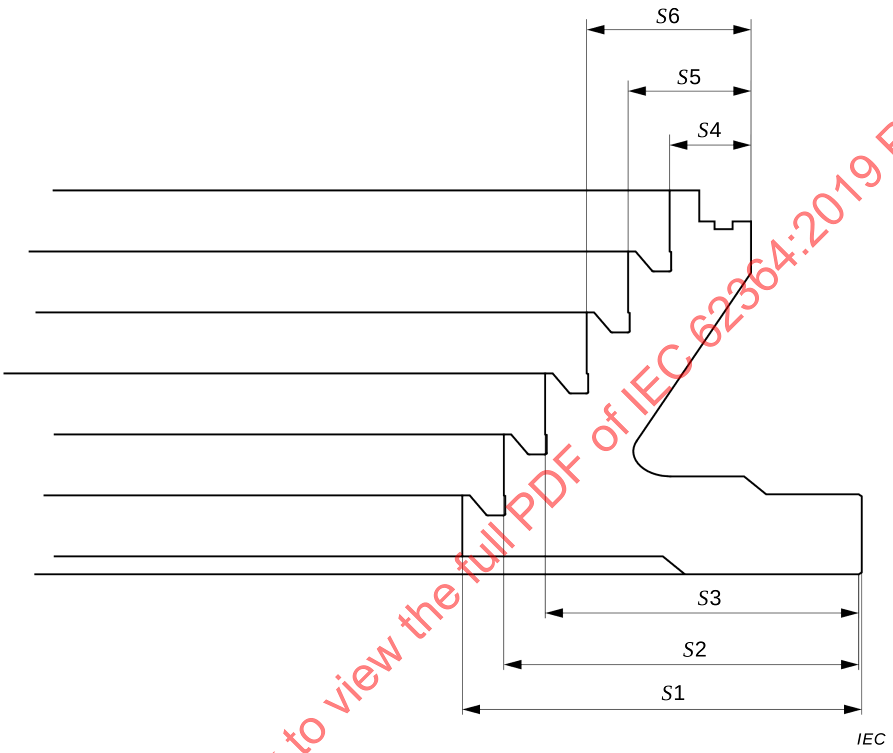



| | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| Finger 1, *F*1 | | | | |
| Finger 2, *F*2 | | | | |
| Finger 3, *F*3 | | | | |
| NOTE Measuring points are 90° apart. | | | | |

## B.22 Inspection record, lower stationary seal

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |



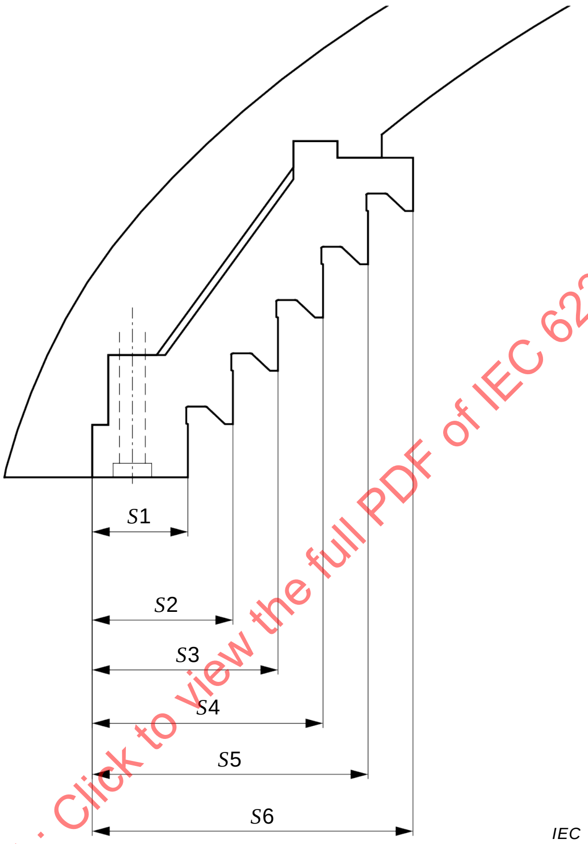



| | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| Surface 1, *S*1 | | | | |
| Surface 2, *S*2 | | | | |
| Surface 3, *S*3 | | | | |
| Surface 4, *S*4 | | | | |
| Surface 5, *S*5 | | | | |
| Surface 6, *S*6 | | | | |
| NOTE Measuring points are 90° apart. | | | | |

## B.23 Inspection record, lower rotating seal

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

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |



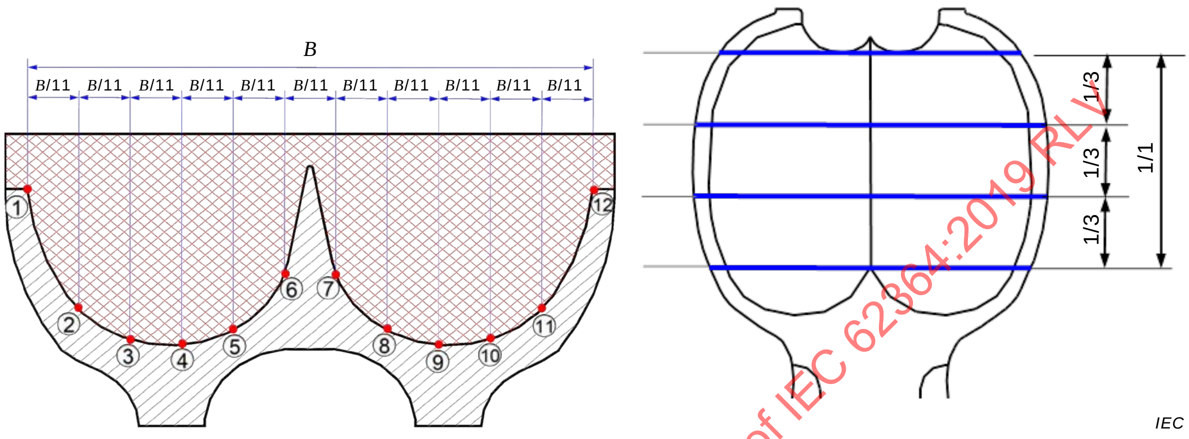



| | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| Surface 1, *S*1 | | | | |
| Surface 2, *S*2 | | | | |
| Surface 3, *S*3 | | | | |
| Surface 4, *S*4 | | | | |
| Surface 5, *S*5 | | | | |
| Surface 6, *S*6 | | | | |
| NOTE Measuring points are 90° apart. | | | | |

## B.24 Inspection record, runner bucket

**Table B.10 – Inspection record, runner bucket**

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |

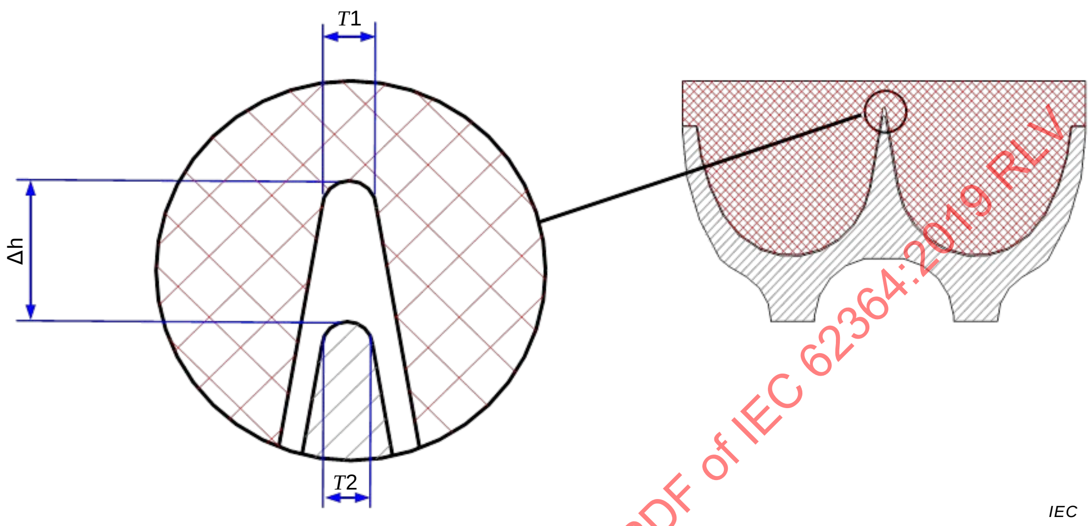



| | Template gap | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bucket number** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| 1 | | | | | | | | | | | |
| 2 | | | | | | | | | | | |
| 3 | | | | | | | | | | | |
| 4 | | | | | | | | | | | |
| 5 | | | | | | | | | | | |
| 6 | | | | | | | | | | | |
| 7 | | | | | | | | | | | |
| 8 | | | | | | | | | | | |
| 9 | | | | | | | | | | | |
| 10 | | | | | | | | | | | |
| 11 | | | | | | | | | | | |
| 12 | | | | | | | | | | | |
| 13 | | | | | | | | | | | |
| 14 | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 16 | | | | | | | | | | | |
| 17 | | | | | | | | | | | |
| 18 | | | | | | | | | | | |
| 19 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 21 | | | | | | | | | | | |
| 22 | | | | | | | | | | | |

## B.25 Inspection record, Pelton runner splitter

**Table B.11 – Inspection record, Pelton runner splitter**

| Plant | Unit number | Date | Sign |
|---|---|---|---|
| | | | |






| Bucket number | *T1* | *T2* | Δh |
|---|---|---|---|
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |
| 6 | | | |
| 7 | | | |
| 8 | | | |
| 9 | | | |
| 10 | | | |
| 11 | | | |
| 12 | | | |
| 13 | | | |
| 14 | | | |
| 15 | | | |
| 16 | | | |
| 17 | | | |
| 18 | | | |
| 19 | | | |
| 20 | | | |
| 21 | | | |
| 22 | | | |

# Annex C
(informative)

# Monitoring of particle concentration and properties and water sampling procedure

## C.1 General

Sampling in connection with hydro turbine installations can be divided in two distinct phases with different requirements as follows.

Phase 1. Sampling in natural rivers to estimate the amount and properties of particles passing future installations. The result of this sampling can be used to plan various strategies to minimize abrasion, such as desilting basins, abrasion resistant coatings, turbine selection, maintenance intervals, etc.

Phase 2. Sampling in existing hydro turbine installations to document the amount and properties of particles actually passing the hydro turbine unit. The result of this sampling can be used to evaluate the effectiveness of various strategies to reduce abrasion damage, plan overhaul and maintenance, etc. In particular, concentration measurements can be used for operational decisions, such as temporary turbine shut-offs during floods.

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. Some commercial automatic systems are available, but there is still little field experience with these. Such online measurement systems are strongly recommended to be calibrated before use with the future range of particles (size, shape, concentration, colour, etc.) that will actually pass the measurement system. It is preferred to use actual sediments from the river for this calibration. The measured concentration should be checked at least once per week during high discharge season and once per month during low discharge season. This check should be done against a manual filtration measurement (see Annex D).

If the measurement is not done "continuously", the measurement frequency depends on the change of particle concentration over time as explained in Annex E.

## C.2 Sampling before building a power station

Several publications and manuals describe the procedures. See for example [22].

The sampling should be done at least over 2 years, preferably longer. It is important to measure the particle concentration. Data on the river's sediment load are less meaningful for turbine hydro-abrasive erosion.

When using the sampling results to estimate the amount of particles that will pass a hydro turbine, several additional factors need to be taken into account.

- bedload should not enter the water conveyance system of the hydro turbine;
- if a reservoir is planned, the geometry of the reservoir and the discharge of the river will influence the sedimentation in the reservoir. To estimate particle retention in reservoirs is very complicated and should be performed by specialists;
- desander, if planned, has to be taken into account.

The above points should also be taken into account when measuring upstream of an existing power plant for the purpose of getting an early warning of very high particle concentration.

## C.3 Sampling in existing power stations

Water sampling during this phase is relatively easy, if means for sampling are properly prepared during the construction of the facility. Suitable sampling locations are

- draft tube cone, for example at the inspection man door.

Other possible locations are

- in the water conveyance system downstream of the desander to control the efficiency of the desander;
- in tailrace channel for Pelton turbines.

If the sampling is intermittent and water is not flowing continuously, it is important to let the water run for a suitable time (not less than 2 min) before collecting the sample. This in order to flush away any accumulated sediment in, or in the vicinity of, the sampling system piping.

To avoid misinterpretation, it is advisable not to take any samples unless there is a continuous flow in the water conveyance system. Such samples could be misleading as they would be influenced by the internal particle settling in the water conveyance system.

## C.4 Logging of samples

It is important to document the procedure for taking the samples and include it into the report.

Physical samples should be collected in suitable containers (e.g. bottles) and immediately labelled. A record should be established which clearly identifies the time and location of taking the sample. Sketches and pictures are useful for good understanding of sampling locations.

# Annex D
(informative)

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

## D.1 General

The analysis of the 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;
- particle size distribution;
- mineralogical composition;
- particle geometry;
- fraction of organic matter, if applicable.

## D.2 Particle concentration

Particle concentration is non-dissolved particles in the water. For the definition refer to 2.2.8. It may be analysed in accordance with ISO 4365:2005.

## D.3 Particle size distribution

As different particle sizes have 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 with adequate intervals. Also here the method of measurement should be given with the data.

The particle size distribution has to be done in two steps. For the large particle fraction (> 0,063 mm) sieving is a good way. The small particle fraction (< 0,05 mm) has to be analysed with laser granulometry.

Sieving is described in ISO 4365:2005.

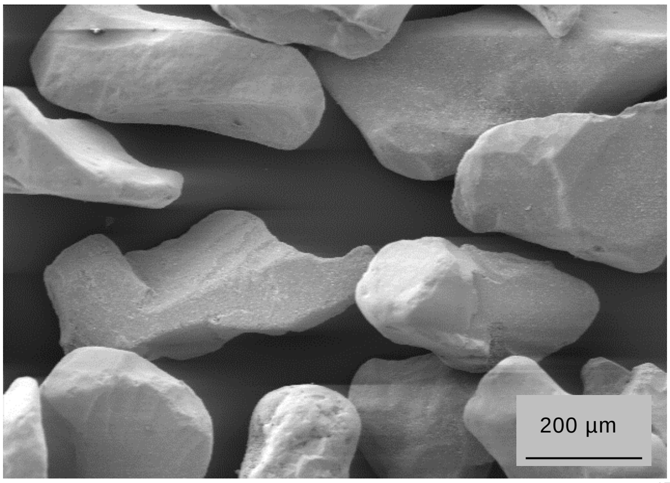
## D.4 Mineralogical composition

The mineral composition should be done by X-ray diffraction (XRD) of a representative sample of the particles. If the grain size distribution is very wide, the different particle size fractions from the particle size distribution should be used for an analysis of each fraction to determine the mineralogical composition, as due to the different hardness of minerals the impact on hydro-abrasive erosion differs considerably. A petrographic analysis is not enough as the inaccuracy may be too high.

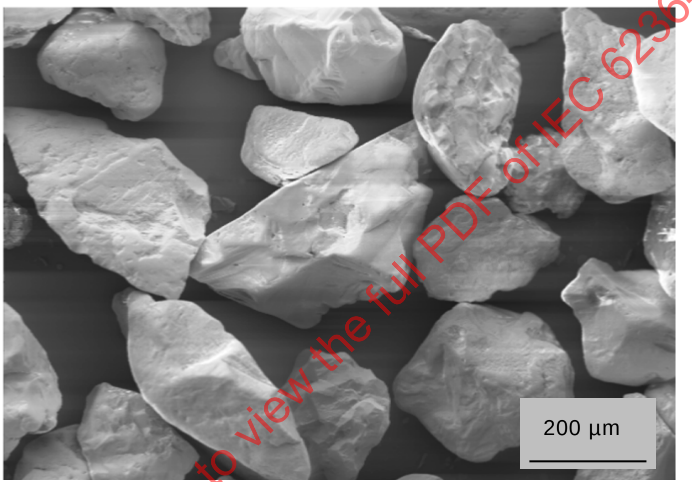
## D.5 Particle geometry

Microscope 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.

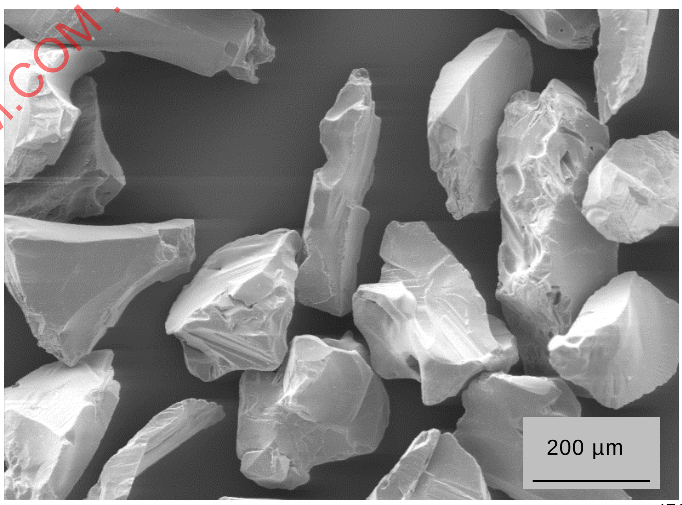
The following Figure D.1 gives three typical examples of such images, designated rounded, sub-angular and angular from top to bottom. Pictures should be chosen in such a way that a representative choice of particles can be clearly seen.




a) Rounded particle geometry, $K_{shape}$ = 1




b) Subangular particle geometry, $K_{shape}$ = 1,5




c) Angular particle geometry, $K_{shape}$ = 2

**Figure D.1 – Typical examples of particle geometry**

# Annex E
(informative)

## Frequency of sediment sampling

In the case where the $PL$ measurement procedure 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 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:

$$T_s = 0{,}01 \times PL_{year} / PL_{max}$$

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

- "High particle" period:

  $PL_{year}$ = 85 kg x h/m$^3$

  $PL_{max}$ = 0,12 kg/m$^3$

  then:

  $T_s$ = 0,01 x 85 / 0,12 h ≈ 8 h for "high particle" period
- "Low particle" period:

  $PL_{year}$ = 85 kg x h/m$^3$

  $PL_{max}$ = 0,002 5 kg/m$^3$

  then:

  $T_s$ = 0,01 × 85 / 0,002 5 = 340 h ≈ 14 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 can be halved as soon as this variation is detected.

# Annex F
(informative)

# Typical criteria to determine overhaul time due to hydro-abrasive erosion

## F.1 General

The optimum time to overhaul a unit is normally determined by economic criteria. It is a combination of many factors specific to each powerplant such as

1) the cost of reduced efficiency,
2) the cost of the overhaul,
3) the increased risk of unavailability,
4) the convenient time of year for overhaul,
5) etc.

As an ultimate technical limit, a situation where it is no longer safe to operate the unit may be considered.

Following are some typical criteria that may be used. It is emphasized that the powerplant operator will gain a lot of experience of how their particular unit functions and what is the optimal overhaul interval in their particular case. The list below only serves as a first outline of possible overhaul criteria.

The criteria have been divided in criteria that can be observed while the unit is in operation and criteria that require internal inspection of the unit.



## F.2 Parameters which are observable while the unit is in operation

1) The efficiency has deteriorated to an extent that it is economically beneficial to restore the unit to its design efficiency. To determine the reduction in efficiency some sort of efficiency test is required. Since only the relative efficiency decrease needs to be measured some simple system based on Winter Kennedy flow measurement or permanently installed ultrasonic flowmeter may be used instead of complete efficiency tests per IEC 60041. Another possibility is continuous efficiency monitoring based on operation data.
2) Reduction of output at some defined opening. Note, however, that the discharge for the same opening may change as a result of hydro-abrasive erosion. This method should therefore be used only after some further experience is gained about the correlation between the measured output and corresponding hydro-abrasive damage.
3) If the turbine design incorporates balancing pipes from the head cover a very good indication of labyrinth seal hydro-abrasive erosion is the water discharge in the balancing pipes. This may then be used as a criterion for overhaul.
4) The axial thrust can also be an indication of labyrinth seal hydro-abrasive erosion, even though it is less accurate than the discharge in the balancing pipes. It should be combined with experience about the correlation between the measured axial thrust and corresponding hydro-abrasive erosion damage before being used as a criterion for overhaul.
5) The time it takes for the unit to stop, or alternatively the steady state speed it reaches, after the guide vanes are closed and the inlet valve kept open. This correlates to the hydro-abrasive erosion of the guide vanes and covers.
6) The spiral case pressure with closed inlet valve and open bypass. This correlates to the hydro-abrasive erosion of the guide vanes and covers.

7) Wear of main shaft seal may bear correlation with the hydro-abrasive erosion of the unit, although this depends on the shaft seal design. This criterion should therefore be used only after some further experience is gained about the correlation between the seal wear and corresponding hydro-abrasive damage.

## F.3 Criteria that require internal inspection of the unit

1) Thickness of runner blade outlet is abraded more than two thirds (for large turbines) or is completely abraded (for small turbines). Note that a reduction of blade thickness will reduce the strength of the blade and that a blade crack would of course override any blade thickness measurement.
2) Facing plates, of head cover and bottom ring completely abraded.
3) Clearance of runner labyrinth seals is more than doubled.
4) For components coated with hydro-abrasive erosion resistant coating, the area of coating removed exceeds 5 % to 10 % of the total coated area.

Items 1) to 3) above refer to Francis turbines, while item 4) refers to all types of turbines.

# Annex G
(informative)

## Example to calculate the hydro-abrasive erosion depth

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 hydro-abrasive 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 hydro-abrasive erosion depth is

$$S = W^{3,4} \text{ x } PL \text{ x } K_m \text{ x } K_f / RS^p$$

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

$$n_s = n \text{ x } P^{0,5} / H^{1,25} = 300 \text{ x } 255\,000^{0,5} / 428^{1,25} = 77,8$$

According to Figure 1:

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

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

According to I.1 $K_m$ for martensitic stainless steel is 1.

According to Table 1 $K_f$ and $p$ for the various components are as follows:

Guide vanes: $K_f$ = 1,06 × 10$^{-6}$, $p$ = 0,25

Facing plates: $K_f$ = 0,86 × 10$^{-6}$, $p$ = 0,25

Runner inlet: $K_f$ = 0,90 × 10$^{-6}$, $p$ = 0,25

Runner outlet: $K_f$ = 0,54 × 10$^{-6}$, $p$ = 0,75

Labyrinth seals: $K_f$ = 0,38 × 10$^{-6}$, $p$ = 0,75

For the guide vanes the hydro-abrasive erosion depth is thus

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

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

**Table G.1 – Calculations**

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

The standard deviation for the guide vanes is 42 % according to Table I.1. 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 |
| Bucket width | $B_2$ | mm | 700 | 365 |
| Number of nozzles | $z_{jet}$ | | 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 | **5 500** |

Calculation of *TBO*

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

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

$= 3,59 \times 1,19 \times 1 \times 0,180 \times 0,521$

$= 0,401$

with:

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

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

Assumptions:

- constant over the year
- $K_{size,ref} / K_{size,target} = 1$
  (grain size distribution in both cased is assumed to be the same)
- $K_{hardness,ref} / K_{hardness,target} \approx 0,73$
  (as both runners are coated only the fraction of Mohs hardness above 7 is used. Ratio of both fractions is 0,73)

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

$K_{f,ref} / K_{f,target} = [z_{jet,ref} / z_{2,ref}] / [z_{jet,target} / z_{2,target}] = 0,180$

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

$TBO_{target}$ = 0,401 × 13 600 h ~ 5 500 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) | $Wr_{un}$ | m/s | 59,9 | 47,6 |
| Time between overhaul | $TBO$ | h | 22 800 | **5 800** |



Calculation of $TBO$

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

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

= 2,185 × 0,059 × 1 × 1 × 1,97

= 0,254

with:

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

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

= 0,176 × 0,667 × 1 × 0,5

= 0,058 7

Assumptions:

- constant over the year
- $K_{size,ref} / K_{size,target} = 1$
  (grain size distribution in both cased is assumed to be the same)
- $K_{hardness,ref} / K_{hardness,target} \approx 0,5$
  (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 in accordance with 2.2.11)

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

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

$TBO_{target}$ = 0,254 × 22 800 h

= 5 800 h

# Annex I
(informative)

# Background for hydro-abrasive erosion depth model

## I.1 Model background and derivation

Please refer also to [21]. In order to demonstrate how different critical aspects impact the hydro-abrasive erosion 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 document 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, see 2.2.12.
- *f*(flow pattern) = $K_f / RS^p$ ($K_f$ = 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) = $K_{size} \times K_{shape}$. Note that in this simplification it is 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,
- $K_{shape}$ = *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 angular,
- *f*(turbine material properties) = $K_m$. In this document we consider $K_m$ = 1 for martensitic stainless steel with 13 % Cr and 4 % Ni and $K_m$ = 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:

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

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) $C$, $K_{\text{hardness}}$, $K_{\text{size}}$ and $K_{\text{shape}}$: these variables vary with the particle properties. Integrated over time these variables become particle load, $PL$ (see 2.2.9 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 2.2.9) is introduced. $PL$ integrates $C$, $K_{\text{hardness}}$, $K_{\text{size}}$ and $K_{\text{shape}}$ 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 I.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 2.2.23.



So the final, time integrated formula becomes:

$$S = W^{3,4} \times PL \times K_m \times K_f / RS^p$$

where

$S$ is the numerical value of the hydro-abrasive erosion depth in mm.

## I.2 Introduction to the *PL* variable

In this document the $PL$ variable is used to quantify the particles that pass the turbine and reflects the relative hydro-abrasive erosion potential in a certain period. In the past a common way to integrate hydro-abrasive erosion over time has been to consider the total weight of particles that pass the turbine. The benefits of the $PL$ variable include:

- The $PL$ variable gives more accurate results considering variations in flow and head. Please see example below for further details,
- The $PL$ will inherently consider variations in all particle properties, not only the particle concentration,
- The $PL$ depends only on the water used and is independent of the turbine size and / or discharge. It can thus be used directly to compare the conditions at different sites and for different configurations.

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

<u>Case 1:</u> At full opening (top half of Figure I.1) 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 mass 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.

<u>Case 2:</u> At 10 % opening (bottom half of Figure I.1) the water with particles flows over the seat ring with the same velocity as in case 1 (125 m/s). In one day the mass 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 hydro-abrasive erosion with the same particle concentration, the same water velocity and the same amount of time. Therefore, the expected hydro-abrasive erosion damage is the same. The $PL$ variable also gives the same value in both cases. However, the total mass 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 hydro-abrasive erosion damage than the total mass of particles that has passed the seat ring.

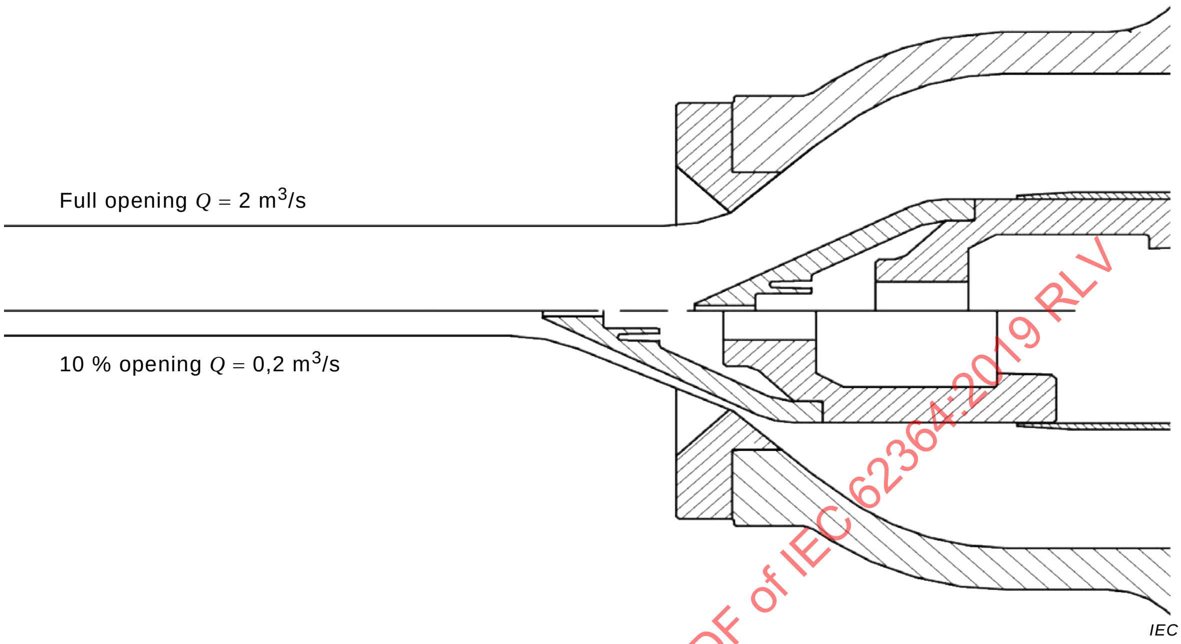



**Figure I.1 – Example of flow pattern in a Pelton injector at different load**

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

- Pelton needle tip

Very good correlation between *PL* and hydro-abrasive erosion 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 tip 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 hydro-abrasive erosion 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 hydro-abrasive erosion 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 hydro-abrasive erosion 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 hydro-abrasive erosion 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 hydro-abrasive erosion damage with minor influence of turbine discharge or head is expected. At part load there are two main phenomena that influence the hydro-abrasive erosion. 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 hydro-abrasive erosion in opposite ways, but it is expected that the turbulence effect will dominate and thus that the hydro-abrasive erosion 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 hydro-abrasive erosion 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 hydro-abrasive erosion 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.

## I.3 Calibration of the formula

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

This data was analysed 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 hydro-abrasive erosion. The average $K_f$ and $p$ was then determined for all observations with components of the same type. The results are in Table 1 in the main part of the document.

The ratio between the measured and calculated values of the hydro-abrasive erosion depth was determined and the standard deviation calculated. Table I.1 below shows the standard deviation in this analysis as well as number of observations for each type of component.

**Table I.1 – Analysis of the calibration constant $K_f$ and $p$**

| Component | Number of observations | Standard deviation<br>% |
|---|---|---|
| Francis guide vanes | 7 | 42 |
| Francis facing plates | 7 | 38 |
| Francis labyrinth seals | 7 | 30 |
| Francis runner inlet | 6 | 26 |
| Francis runner outlet | 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 hydro-abrasive erosion model.

# Annex J
(informative)

# Quality control of thermal sprayed WC-CoCr

## J.1 Specification

The quality of this hard coating strongly depends on several influencing factors like the technical specification of the coating process, the preparation of the surface to be coated, the process parameters and the consumables used. Also the qualification of the personnel applying the coating plays an important role.

Hard coatings which are used to protect hydraulic machines from hydro-abrasive erosion should meet certain demands on quality to ensure proper functionality. Some guide line reference values for WC-CoCr (86/10-4) are listed below:

- surface roughness Ra should be < 8µm;
- adhesive bond strength should be > 60 MPa;
- average hardness over ten measurement points of the coating should be > 1 000 $HV_{0,3}$.

## J.2 Quality control

It is recommended to coat test specimens during the coating of the part, applying exactly the same process (e.g. surface preparation, pre-heating, coating etc.) as used on the components to be coated.

Measurements and inspections should be done by trained personnel. Evidence of qualification should be provided. Table J.1 lists some items recommended to be included in an inspection report:

**Table J.1 – Recommended items to include in HVOF inspection**

| Characteristics | Unit | To be measured by | Measured on component | Measured on test specimen |
|---|---|---|---|---|
| Surface roughness | Ra | ISO 4288 or related | X | |
| Coating thickness | µm | ASTM B499 – 09 or ISO 2178 | X | |
| Bond strength | MPa | ASTM C633 – 13 or EN 14916 | | X |
| Vickers hardness | HV 0,3 | ISO 6507-1 | | X |

The coated area should be visually inspected by 100 %. The coated surface, as defined in the drawings, shall not show any defects like cracks, pores or uncoated areas.

If the coating is ground dye penetrant test can also be an indication of cracks in the coating. Note that dye penetrant test is not applicable for non-ground (as sprayed) surfaces.

# Bibliography


[1] IEC 60193:1999, *Hydraulic turbines, storage pumps and pump-turbines – Model acceptance tests*

[2] IEC 60609-2:1997, *Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines – Part 2: Evaluation in Pelton turbines*

[3] IEC TR 61364, *Nomenclature for hydroelectric powerplant machinery*

[4] ISO 4365:2005, *Liquid flow in open channels – Sediment in streams and canals – Determination of concentration, particle size distribution and relative density*

[5] ISO 11657:2014, *Hydrometry – Suspended sediment in streams and canals – Determination of concentration by surrogate techniques*

[6] ASTM G76:1995, *Standard test method for conducting erosion tests by solid particle impingement using gas jets*

[7] Gray, Aunemo and Rommetveit:2004, *Recent developments in silt erosion coatings, IAHR 22nd Symposium on Hydraulic Machinery and Systems*

[8] Wedmark:2006, *Recent progress in silt erosion research, Hydro 2006*

[9] Dr. Y. C. Agrawal, Mr. H. Chuck Pottsmith:2005, *Turbine erosion: Lasers warn of abrasive sediments, Hydro 2005 Conference, Villach, Austria*

[10] Mann B.S., Arya V., Dadu V., Manea L:2001, *Hydro Project Equipment: Solutions for Common Challenges, HRW/July 2001*

[11] Mann B.S., Arya V.:2001, *Abrasive and erosive wear characteristics of plasma nitriding and HVOF coatings: their application in hydro turbines, Wear 249 (2001) 354-360*

[12] Mann B.S., Arya V., Maiti A.K., Rao M.U.B., Joshi P.:2006, *Corrosion and erosion performance of HVOF/TiAlN PVD coatings and candidate materials for high pressure gate valve application, Wear 260 (2006) 75-83*

[13] Engelhardt M., Oechsle D.:2003, *Countermeasures to Reduce Hydro Abrasive Wear at Hydro Turbine Parts, Proceedings, Hydro 2003, Vol. I, Croatia*

[14] Gummer J.H.:2009, *Combating Silt Erosion in Hydraulic Turbines HRW / March 2009*

[15] Proceedings of the Oslo Workshop:2003, *Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, Proceedings of the Oslo Workshop, June 2002, IAHS Publ. 283, 2003*

[16] Nozaki T.:1985, *Nuevo Metodo Para La Decision de la Capacidad y dimension del desarendador, considerando el desgaste de la turbina por el material solido flotante* (only available in Spanish)

[17] Bishwakarma M.B:2008, *Research on optimum sediment exclusion*, www.waterpowermagazine.com, *2008*

[18] Duan C.G., Karelin:2002, *Abrasive Erosion & Corrosion of Hydraulic Machinery, Imperial College Press*

[19] *Proceedings of „Silting Problems in Hydropower Projects", 3rd International Conference, 2008, India*

[20] M Meng and Ludema: 1995 *Wear models and predictive equations: their form and content* 181-183: 443-457, *WEAR 1995*

[21] Wedmark, Winkler and Dekumbis:2010, *Finding a way to estimate abrasion amount, Hydro 2010 conference, Lisbon, Portugal*

[22] Norwegian Water Resources and Energy Administration, Hydrology Department:1997, *Manual on Procedures in Operational Hydrology, Volume 5, Sediment Transport in Streams – Sampling, Analysis and Computation, Second edition*

[23] Mei, Zu-Yan:1996, *Protecting hydro turbines in silt-laden rivers, Hydropower & Dams magazine, issue 4, 1996*

[24] IEC 60041, *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*

[25] ISO 4288, *Geometrical Product Specifications (GPS) – Surface texture: Profile method – Rules and procedures for the assessment of surface texture*

[26] ISO 2178, *Non-magnetic coatings on magnetic substrates – Measurement of coating thickness – Magnetic method*

[27] ISO 6507-1, *Metallic materials – Vickers hardness test – Part 1: Test method*

[28] ASTM B499-09, *Standard Test Method for Measurement of Coating Thicknesses by the Magnetic Method: Nonmagnetic Coatings on Magnetic Basis Metals*

[29] ASTM C633-13, *Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings*

[30] ISO 14916:2017, *Thermal spraying – Determination of tensile adhesive strength*

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SOMMAIRE

COMMISSION ELECTROTECHNIQUE INTERNATIONALE

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# MACHINES HYDRAULIQUES – LIGNES DIRECTRICES RELATIVES AU TRAITEMENT DE L'EROSION HYDRO-ABRASIVE DES TURBINES KAPLAN, FRANCIS ET PELTON

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La Norme internationale IEC 62364 a été établie par le comité d'études 4 de l'IEC: Turbines hydrauliques.

Cette deuxième édition annule et remplace la première édition publiée en 2013. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) la formule pour le TBO du modèle de référence des turbines Pelton a été modifiée;
b) la formule pour le calcul de l'intervalle d'échantillonnage a été modifiée;
c) le chapitre sur les revêtements résistant à l'érosion hydro-abrasive a été substantiellement modifié;

d) l'annexe sur les données test pour les matériaux résistant à l'érosion hydro-abrasive a été supprimée;

e) une évaluation simplifiée de l'érosion hydro-abrasive a été ajoutée.

Le texte de cette Norme Internationale est issu des documents suivants:

| FDIS | Rapport de vote |
|---|---|
| 4/351/FDIS | 4/366/RVD |

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette norme.

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# INTRODUCTION

Le nombre de centrales hydroélectriques concernées par l'érosion hydro-abrasive est en augmentation dans le monde entier.

Une approche globale est nécessaire afin de minimiser l'impact lié à ce phénomène. Dès la phase d'avant-projet, il convient qu'une évaluation soit menée afin de quantifier l'érosion hydro-abrasive et son impact sur l'exploitation de la centrale. Pour ceci, les paramètres influents et leurs impacts sur l'érosion hydro-abrasive doivent être connus. Les informations nécessaires pour l'évaluation comprennent entre autres la conception future, les paramètres liés aux particules présentes dans l'eau et qui passeront dans la turbine, la sédimentation du réservoir et le cadre d'application du propriétaire de la centrale concernant l'exploitation future comme la disponibilité ou la perte de rendement maximale admissible avant la réalisation d'une révision.

Basée sur cette évaluation de l'érosion hydro-abrasive, une solution optimisée peut être trouvée, en considérant toutes les mesures liées à l'investissement, à la production d'énergie et aux coûts de maintenance comme paramètres de décision. Bien souvent, une conception adaptée pour résister à l'érosion hydro-abrasive sera plus rentable qu'une conception visant à atteindre un rendement maximal de la turbine. Cette analyse est plus efficace lorsqu'elle est réalisée par le concepteur de la centrale.

Il revient aux propriétaires de machines de communiquer auprès des fournisseurs potentiels des machines destinées à leurs sites, sur le fait que les concepteurs doivent porter une attention toute particulière, lors de la phase de conception de la turbine, à la minimisation de la gravité et des effets de l'érosion hydro-abrasive.

Les étapes que le concepteur pourrait suivre, et dont il convient qu'il les suive effectivement, de manière à prolonger la durée de vie utile avant toute révision importante des composantes d'une turbine fonctionnant dans des conditions sévères d'érosion hydro-abrasive, font l'objet d'un consensus restreint et très peu de données quantitatives existent. Cette situation a conduit certains propriétaires à intégrer dans leurs spécifications des conditions qui ne peuvent être satisfaites en s'appuyant sur des méthodes et des matériaux connus.

# MACHINES HYDRAULIQUES – LIGNES DIRECTRICES RELATIVES AU TRAITEMENT DE L'EROSION HYDRO-ABRASIVE DES TURBINES KAPLAN, FRANCIS ET PELTON

## 1 Domaine d'application

Ce document donne des lignes directrices pour:

a) présenter les données disponibles concernant les taux d'érosion hydro-abrasive avec diverses combinaisons de qualité de l'eau, conditions d'exploitation, matériaux et propriétés des composants; ces données ayant été obtenues sur différents sites hydroélectriques;

b) développer des lignes directrices permettant de réduire au minimum l'érosion hydro-abrasive en apportant des modifications à la conception hydraulique normalement utilisée en l'absence de particules. Ces lignes directrices n'abordent pas les détails tels que les profils hydrauliques que les spécialistes en conception hydraulique déterminent pour un site donné;

c) développer des lignes directrices établies sur le «retour d'expérience» concernant la résistance relative de matériaux confrontés aux problèmes d'érosion hydro-abrasive;

d) développer des lignes directrices concernant la maintenabilité des matériaux résistant à l'érosion hydro-abrasive et des revêtements de surface durs;

e) développer des lignes directrices relatives à la recommandation d'une méthode, que les propriétaires pourraient appliquer, et dont il convient qu'ils l'appliquent effectivement, afin de s'assurer que les spécifications montrent la nécessité d'accorder une attention toute particulière à la conception des formes hydrauliques propres à leur site sans imposer des critères qui ne peuvent être satisfaits dans la mesure où les moyens à mettre en œuvre ne sont pas maitrisables par les constructeurs;

f) développer des lignes directrices concernant le mode de fonctionnement des turbines hydroélectriques en présence de particules afin d'accroître la durée de vie.

Ce document fait l'hypothèse d'une eau chimiquement non agressive; étant donné que cette agressivité dépend des diverses compositions chimiques possibles, ainsi que des matériaux constitutifs de la machine, le domaine d'application de ce document ne traite pas de cette question.

Ce document fait également l'hypothèse de l'absence de cavitation au niveau de la turbine. En effet la cavitation et l'érosion hydro-abrasive peuvent se renforcer mutuellement de sorte que l'érosion résultante est plus importante que la somme des deux. Comme aucune formulation quantitative de cette érosion résultante n'est connue, ce document n'a pas pour objet de l'évaluer, sauf pour suggérer, lors de la phase de conception de la turbine, des efforts particuliers visant à minimiser la cavitation.

Des objets solides de grandes dimensions (comme des pierres, du bois, de la glace, des objets métalliques, etc.) véhiculés par l'eau peuvent percuter les composants de la turbine et les endommager. Ces dommages peuvent pour leur part accroître la turbulence de l'écoulement et accélérer l'usure par cavitation et par érosion hydro-abrasive. Les revêtements durs résistant à l'érosion hydro-abrasive peuvent également être endommagés localement suite à l'impact de ces particules de grandes dimensions. Ce document ne traite pas de ces questions.

Ce document se concentre principalement sur les équipements des centrales hydroélectriques. Certaines parties de ce document peuvent également s'appliquer à d'autres machines hydrauliques.

## 2 Termes, définitions et symboles

Pour les besoins du présent document, les termes et définitions suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

NOTE 1 Ces termes, définitions et symboles s'appuient également, le cas échéant, sur l'IEC TR 61364.

NOTE2 The système international d'unité (S.I.) est utilisé dans ce document mais d'autres systèmes sont autorisés.



| Para-graphe | Terme | Définition | Symbole | Unité |
|---|---|---|---|---|
| 2.2.1 | énergie hydraulique massique d'une machine | énergie massique de l'eau existante entre les sections de référence haute et basse pressions 1 et 2 de la machine<br><br>Note 1 à l'article: Pour plus d'informations, voir l'IEC 60193. | $E$ | J/kg |
| 2.2.2 | accélération due à la pesanteur | valeur locale de l'accélération de la pesanteur sur le site d'essai<br><br>Note 1 à l'article: Pour plus d'informations, voir l'IEC 60193. | $g$ | m/s$^2$ |
| 2.2.3 | hauteur de chute nette d'une turbine ou hauteur nette de refoulement d'une pompe | hauteur de chute disponible aux bornes de la machine hydraulique<br><br>$H = E/g$ | $H$ | m |
| 2.2.4 | diamètre de référence | diamètre de référence de la machine hydraulique<br><br>Note 1 à l'article: Pour les turbines Pelton, il s'agit du diamètre tangent, pour les turbines Kaplan, il s'agit du diamètre du manteau de roue et pour les turbines Francis et les turbines pompes, il s'agit du diamètre de section basse pression des aubes de roue au niveau de la ceinture.<br><br>Note 2 à l'article: Pour plus d'informations, voir l'IEC 60193. | $D$ | m |
| 2.2.5 | diamètre du moyeu | diamètre du moyeu de roue pour les turbines Kaplan | $D_h$ | mm |
| 2.2.6 | profondeur d'érosion hydro-abrasive | profondeur de métal érodé (mesurée perpendiculairement à la surface d'origine) d'un composant du fait de l'érosion hydro-abrasive | $S$ | mm |
| 2.2.7 | vitesse caractéristique | vitesse caractéristique définie pour chaque composant d'une machine et utilisée pour quantifier le dommage dû à l'érosion hydro-abrasive.<br><br>Note 1 à l'article: Voir également 2.2.20 à 2.2.24 | $W$ | m/s |
| 2.2.8 | concentration en particules | masse totale des particules solides par m$^3$ d'eau, c'est-à-dire masse des particules solides par volume de mélange eau-particules<br><br>Note 1 à l'article: Si la concentration en particules est exprimée en parties par million (ppm), il est recommandé d'utiliser la masse des particules par volume d'eau, de sorte que 1 000 | $C$ | kg/m$^3$ |

| Para-graphe | Terme | Définition | Symbole | Unité |
|---|---|---|---|---|
| | | ppm correspondent environ à 1 kg/m$^3$. | | |
| 2.2.9 | charge en particules | concentration en particules intégrée sur la durée $T$ considérée.<br>$$PL = \int_0^T C(t) \times K_{\text{taille}}(t) \times K_{\text{forme}}(t) \times K_{\text{dureté}}(t) \times dt$$<br>$$\left( \approx \sum_{n=1}^{N} C_n \times K_{\text{taille},n} \times K_{\text{forme},n} \times K_{\text{dureté},n} \times T_{s,n} \right)$$<br>$C(t)$ = 0 en l'absence d'écoulement d'eau dans la turbine.<br><br>Note 1 à l'article: Pour les turbines Francis, $C(t)$=0 pour le calcul de $PL$ pour la roue et les labyrinthes, si le groupe est à l'arrêt avec la bâche spirale sous pression, mais $C(t)$≠0 pour le calcul de $PL$ pour les directrices et les plaques d'usure. | $PL$ | Kg × h/m$^3$ |
| 2.2.10 | facteur de taille | facteur qui caractérise le mode d'association de l'érosion hydro-abrasive et de la taille des particules abrasives = diamètre médian des particules $dP_{50}$ en mm | $K_{\text{taille}}$ | |
| 2.2.11 | facteur de forme | facteur qui caractérise le mode d'association de l'érosion hydro-abrasive et de la forme des particules abrasives<br><br>Note 1 à l'article: Voir Annexe D. | $K_{\text{forme}}$ | |
| 2.2.12 | facteur de dureté | facteur qui caractérise le mode d'association de l'érosion hydro-abrasive et de la dureté des particules abrasives<br><br>Pour l'acier inoxydable 13Cr4Ni: $K_{\text{dureté}}$ = fraction des particules ayant une dureté Mohs supérieure à 4,5<br><br>Pour les surfaces ayant un revêtement dur: $K_{\text{dureté}}$ = fraction des particules ayant une dureté Mohs supérieure à 7 | $K_{\text{dureté}}$ | |
| 2.2.13 | facteur de résistance du matériau | facteur qui caractérise le mode d'association de l'abrasion et des propriétés matérielles du matériau de base | $K_{\text{m}}$ | |
| 2.2.14 | coefficient d'écoulement | coefficient qui caractérise le mode d'association de l'érosion hydro-abrasive et de l'écoulement autour de chaque composant | $K_{\text{f}}$ | $\frac{\text{mm x s}^{3,4}}{\text{kg x h x m}^{\alpha}}$ |
| 2.2.15 | intervalle d'échantillonnage | intervalle de temps entre deux échantillons d'eau prélevés pour déterminer la concentration en particules abrasives dans l'eau | $T_{\text{s}}$ | h |
| 2.2.16 | charge annuelle en particules | charge totale ($PL$) pour 1 année d'exploitation, c'est-à-dire $PL$ pour $T$ = 8 760 h calculée conformément au 2.2.9 | $PL_{\text{annuel}}$ | kg × h/m$^3$ |
| 2.2.17 | concentration maximale | la valeur maximale de l'intégrande dans l'intégrale de $PL$ sur un intervalle de temps spécifié, c'est-à-dire la valeur maximale donnée par l'expression suivante:<br>$$PL_{\max} = C(t) \times K_{\text{taille}}(t) \times K_{\text{forme}}(t) \times K_{\text{dureté}}(t)$$ | $PL_{\max}$ | kg/m$^3$ |
| 2.2.18 | diamètre médian des particules | diamètre médian des particules abrasives dans un échantillon, c'est-à-dire que les particules d'un diamètre inférieur à la valeur considérée | $dP_{50}$ | mm |

| Para-graphe | Terme | Définition | Symbole | Unité |
|---|---|---|---|---|
| | | représentent 50 % de la masse totale des particules présentes dans l'échantillon | | |
| 2.2.19 | angle d'impact | angle entre la trajectoire des particules et la surface du substrat | | ° |
| 2.2.20 | vitesse caractéristique au niveau des directrices de turbines Francis ou Kaplan | débit divisé par la section minimale d'écoulement au niveau des directrices pour le point de meilleur rendement<br>$$W_{gv} = \frac{Q}{a \times Z_0 \times B_0}$$ | $W_{gv}$ | m/s |
| 2.2.21 | vitesse caractéristique au niveau des injecteurs Pelton | vitesse de l'eau au niveau des injecteurs<br>$$W_{inj} = \sqrt{2 \times E}$$ | $W_{inj}$ | m/s |
| 2.2.22 | vitesse caractéristique au niveau de la roue de turbine | vitesse relative entre l'eau et les pales/aubes de la roue estimée à l'aide des formules ci-dessous au meilleur point de rendement<br>$$W_{run} = \sqrt{{u_2}^2 + {c_2}^2}$$ $$u_2 = n \times \pi \times D$$ $$c_2 = \frac{Q \times 4}{\pi \times D^2} (Francis)$$ $$c_2 = \frac{Q \times 4}{\pi \times (D^2 - {D_h}^2)} (Kaplan)$$ | $W_{run}$ | m/s |
| 2.2.23 | vitesse caractéristique dans la roue Pelton | vitesse relative entre l'eau et les augets<br>$$W_{run} = 0{,}5 \times \sqrt{2 \times E}$$ | $W_{run}$ | m/s |
| 2.2.24 | débit | volume d'eau s'écoulant par unité de temps dans toute section du circuit | $Q$ | $m^3/s$ |
| 2.2.25 | ouverture du distributeur | plus courte distance moyenne entre deux directrices contiguës (à une section spécifiée si nécessaire)<br><br>Note 1 à l'article: Pour plus d'informations, voir l'IEC 60193. | $a$ | m |
| 2.2.26 | nombre de directrices | nombre total de directrices dans une turbine | $z_0$ | |
| 2.2.27 | hauteur du distributeur | hauteur du distributeur au niveau des aubes directrices dans une turbine | $B_0$ | m |
| 2.2.28 | vitesse de rotation | nombre de rotations de la machine par unité de temps | $n$ | 1/s |
| 2.2.29 | vitesse spécifique | vitesse spécifique communément utilisée pour les machines hydrauliques<br>$$n_s = \frac{60 \times n \times \sqrt{P}}{H^{5/4}}$$<br>$P$ et $H$ correspondent au point de fonctionnement nominal et sont exprimés en kW et m respectivement | $n_s$ | rpm |
| 2.2.30 | puissance | puissance de la turbine au point de fonctionnement nominal | $P$ | kW |

| Para-graphe | Terme | Définition | Symbole | Unité |
|---|---|---|---|---|
| 2.2.31 | profondeur d'érosion hydro-abrasive évaluée pour la turbine cible | profondeur estimée de métal érodé au niveau d'un composant de la turbine cible du fait de l'érosion hydro-abrasive<br><br>Note 1 à l'article: A utiliser pour la modélisation par analogie. | $S_{target}$ | mm |
| 2.2.32 | profondeur d'érosion hydro-abrasive observée sur la turbine de référence | profondeur de métal érodé au niveau d'un composant de la turbine de référence du fait d'érosion hydro-abrasive<br><br>Note 1 à l'article: A utiliser pour la modélisation par analogie. | $S_{ref}$ | mm |
| 2.2.33 | nombre d'injecteurs | nombre d'injecteurs d'une turbine Pelton | $z_{jet}$ | |
| 2.2.34 | largeur d'auget | largeur d'auget d'une roue de turbine Pelton | $B_2$ | mm |
| 2.2.35 | nombre d'augets | nombre d'augets d'une roue de turbine Pelton | $z_2$ | |
| 2.2.36 | temps entre chaque révision de la turbine cible | temps entre chaque révision de la turbine cible.<br><br>Note 1 à l'article: A utiliser pour la modélisation par analogie | $TBO_{cible}$ | h |
| 2.2.37 | temps entre chaque révision de la turbine de référence | temps entre chaque révision de la turbine de référence.<br><br>Note 1 à l'article: A utiliser pour la modélisation par analogie | $TBO_{ref}$ | h |
| 2.2.38 | dimension de référence de la turbine | dimension de référence pour le calcul des effets de l'érosion hydro-abrasive dépendant de la courbure<br><br>Note 1 à l'article: Il s'agit du diamètre de référence *D* pour les turbines Francis (voir 2.2.4)<br><br>Note 2 à l'article: Il s'agit de la largeur d'auget interne $B_2$ pour les turbines Pelton.<br><br>Note 3 à l'article: Pour plus d'informations concernant la largeur d'auget $B_2$, voir l'IEC 60609-2. | $RS$ | m |
| 2.2.39 | exposant de taille | exposant du terme $RS$ décrivant les effets de l'érosion hydro-abrasive liés à la taille de la machine | $p$ | |
| 2.2.40 | exposant | exposant égal à 0,4-$p$ et permettant de compenser le coefficient $K_f$ au niveau des unités | $\alpha$ | |



# 3 Prédiction du taux d'érosion hydro-abrasive

## 3.1 Modélisation de la profondeur d'érosion hydro-abrasive

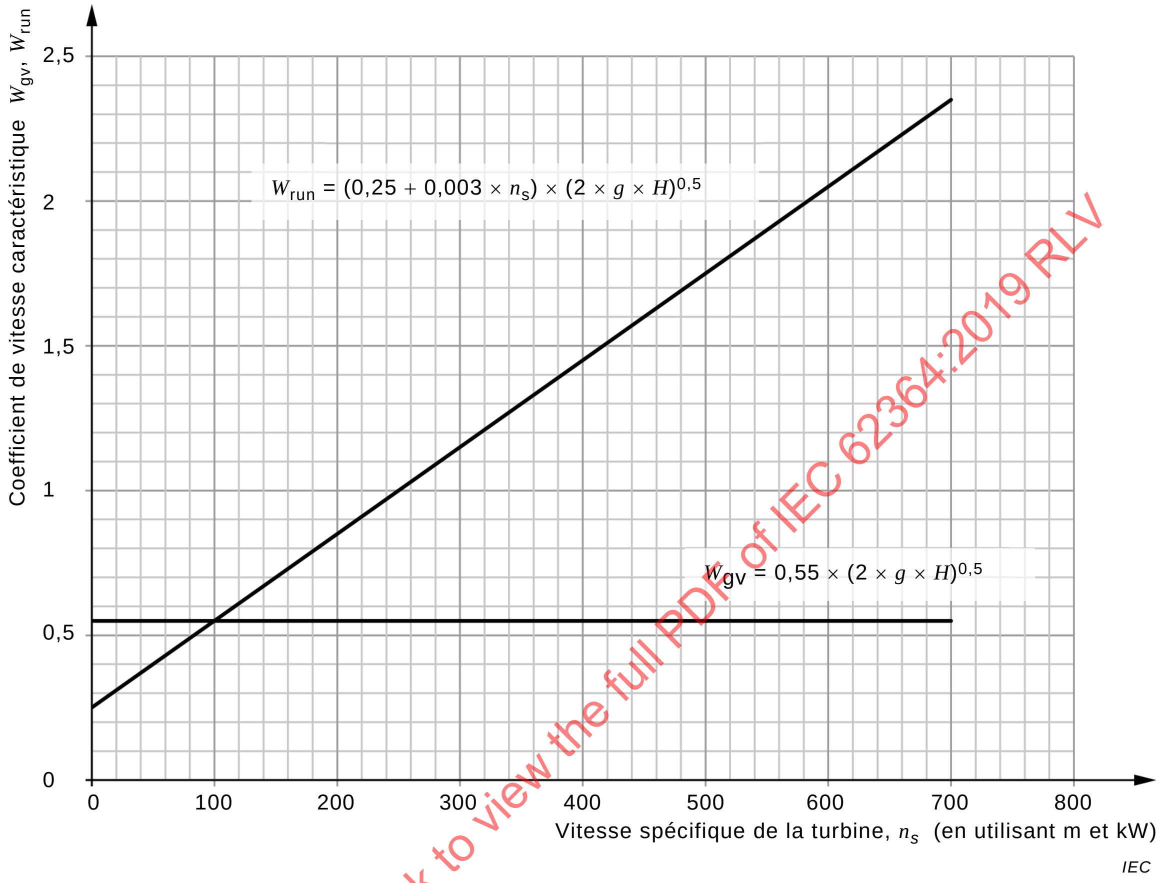
La formule suivante peut être utilisée pour estimer la profondeur d'érosion hydro-abrasive pour une turbine Francis:

$$S = W^{3,4} \times PL \times K_m \times K_f \;/\; RS^p$$

- la vitesse caractéristique, $W$, est définie de 2.2.20 à 2.2.22. Si les données nécessaires au calcul du $W$ ne sont pas disponibles, il est possible d'estimer $W$ avec la Figure 1,
- $PL$, $K_m$ et $RS$ sont respectivement définis en 2.2.9, 2.2.13 and 2.2.38,

- pour les composantes de turbine Francis sans revêtements, $K_f$ and $p$ sont extraits du Tableau 1 ci-dessous.

Pour plus d'informations concernant cette formule, se référer à l'Annexe I. Un calcul d'échantillon est disponible à l'Annexe G.






NOTE Les valeurs de $n_s$ et de $H$ données sur cette figure se réfèrent au point de fonctionnement nominal alors que les vitesses caractéristiques sont celles décrites à l'Article 2.

**Figure 1 – Estimation des vitesses caractéristiques dans les directrices, $W_{gv}$, et dans la roue, $W_{run}$, en fonction de la vitesse spécifique de la turbine**

**Tableau 1 – Valeurs de $K_f$ et $p$ pour différents composantes**

| Composante | $K_f$ | Exposant $p$ (pour $RS$) |
|---|---|---|
| Directrices des Francis | $1,06 \times 10^{-6}$ | 0,25 |
| Plaques d'usure des Francis | $0,86 \times 10^{-6}$ | 0,25 |
| Labyrinthes des Francis | $0,38 \times 10^{-6}$ | 0,75 |
| Entrée de roue des Francis | $0,90 \times 10^{-6}$ | 0,25 |
| Sortie de roue des Francis | $0,54 \times 10^{-6}$ | 0,75 |

## 3.2 Modèle par analogie

Dans le modèle par analogie présenté dans ce document, les *TBO* de deux turbines sont comparés. Pour ce faire le *TBO* d'une turbine (appelée par la suite turbine de référence) ainsi que les différences des paramètres ayant une influence sur l'érosion hydro-abrasive par rapport à une autre turbine (appelée par la suite la turbine cible) doivent être connus pour permettre de calculer le *TBO* de la turbine cible. On doit noter que les mêmes critères de révision doivent être considérés pour ces deux turbines.

Le but du modèle par analogie n'est pas de calculer la profondeur d'érosion hydro-abrasive ($S$). Ce faisant, un modèle étalonné d'évaluation de la profondeur n'est pas nécessaire. Les critères relatifs au *TBO* peuvent être le degré d'endommagement, la perte de rendement ou autres, mais doivent être identiques pour les deux turbines.

Quelques différences concernant la méthode d'élaboration de la formule existent entre le modèle par analogie et le modèle absolu:

- dans la mesure où le modèle par analogie ne calcule pas la profondeur d'érosion hydro-abrasive des composants individuels, des constantes valables pour la turbine dans son ensemble sont utilisées en lieu et place de différentes constantes propres à chacune des composantes;
- une turbine de plus grandes dimensions peut, a priori, tolérer une profondeur d'érosion hydro-abrasive plus importante qu'une turbine de petites dimensions, avant de nécessiter une révision. De ce fait, l'exposant relatif à la taille de référence de la turbine, $p$, est pris égal à 1 pour le modèle par analogie;
- pour les turbines Pelton, on considère que la roue est le composant critique pour la maintenance. Outre les facteurs décrits dans le modèle absolu, le terme $K_{\text{f}}$ pour les roues de turbine Pelton est supposé proportionnel au nombre d'injecteurs, à la vitesse, et inversement proportionnel au nombre d'augets;

Le *TBO* pour la turbine cible est alors évalué comme suit:

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

Les rapports utilisés dans l'équation ci-dessus sont évalués de la manière suivante:

Turbines Pelton: $K_{\text{f, ref}} / K_{\text{f,cible}} = z_{jet,\text{ref}} \times z_{2,\text{cible}} / (z_{jet,\text{cible}} \times z_{2,\text{ref}})$

Turbines Francis et Kaplan: $K_{\text{f,ref}} / K_{\text{f,cible}} = 1$

Exposant de taille: $p = 1$

La précision du modèle par analogie est susceptible de se réduire si les différences entre les turbines de référence et cible deviennent importantes.

La sensibilité de la valeur *TBO* calculée aux variations des données d'entrée peut également être étudiée à l'aide de cette même formule. Un calcul d'échantillon est disponible à l'Annexe H.

### 3.3 Evaluation simplifiée de l'érosion hydro-abrasive

En plus des formules décrites en 3.1 et 3.2, d'autres méthodes pour estimer l'érosion hydro-abrasive ont été proposées en [15] et [22][1]. Chaque méthode peut avoir ses avantages et ses inconvénients.

Comme règle rapide et efficace et dans le but de réaliser une première évaluation de la sévérité sur un site donné, il est recommandé d'évaluer l'expression suivante, comme décrit à la Figure 2.

Si $C \times H^{1,5} \leq 150$ alors l'érosion hydro-abrasive n'est probablement pas significative.

1 Les chiffres entre crochets se réfèrent à la Bibliographie.

Si 150 < $C \times H^{1,5}$ < 1 500 alors l'érosion hydro-abrasive peut être significative.

Si $C \times H^{1,5} \geq$ 1 500 alors l'érosion hydro-abrasive peut être sévère.

Cette règle est évidemment approximative mais elle peut être utile pour décider si une analyse plus approfondie est à envisager.

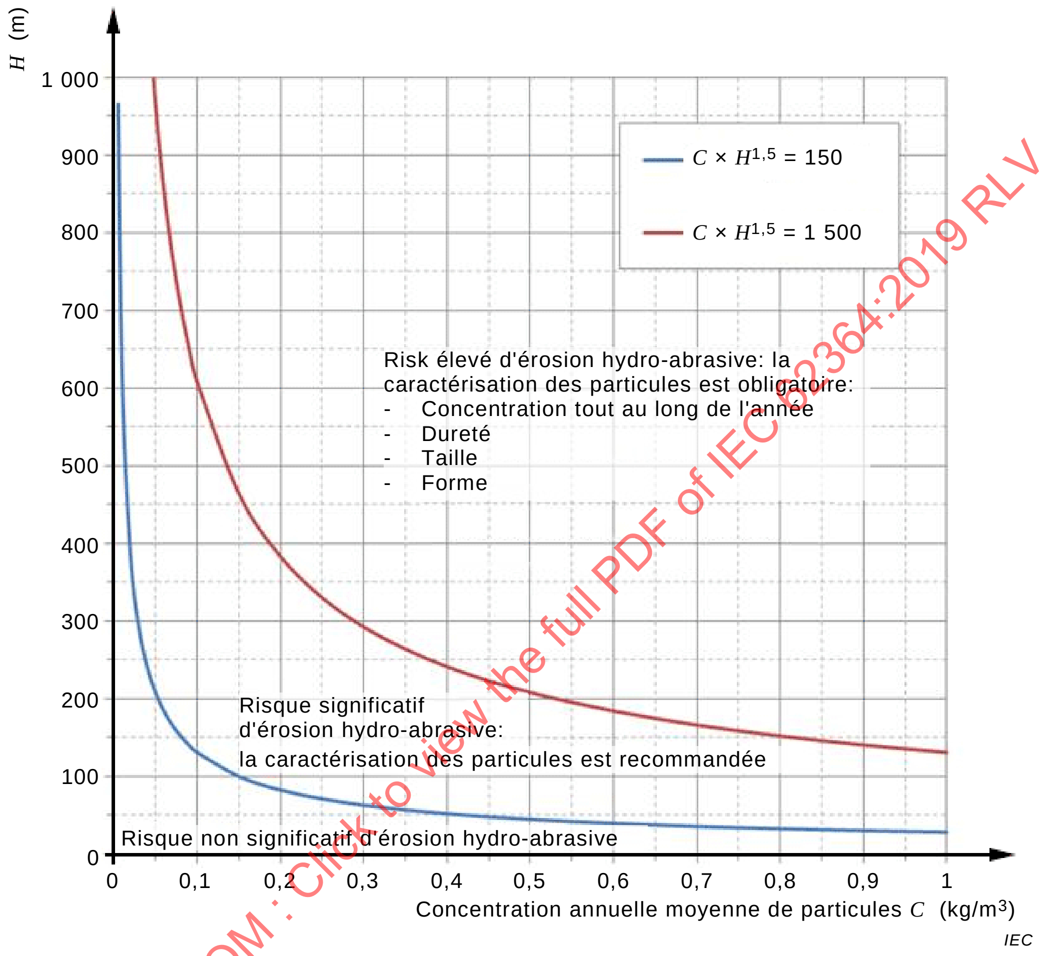



**Figure 2 – Evaluation simplifiée de l'érosion hydro-abrasive pour une première évaluation**



# 4 Conception

## 4.1 Généralités

Les lignes directrices ci-dessous expliquent certaines méthodes recommandées pour réduire au minimum l'érosion hydro-abrasive et ses conséquences, et ce, en apportant des modifications à la conception initialement utilisée lorsque l'eau n'est pas chargée en particules.

Il convient de comprendre que chaque centrale hydraulique est le résultat d'un compromis entre diverses exigences. Même si la conception d'une turbine destinée à résister davantage à l'érosion hydro-abrasive est possible, une telle conception est susceptible d'altérer d'autres caractéristiques de cette dernière. Citons quelques exemples:

- une épaisseur plus importante des pales/aubes peut entraîner une diminution du rendement et un risque accru de vibrations par les tourbillons de von Karman;

- un nombre de pales/aubes réduit (afin d'améliorer l'accès aux surfaces des pales/aubes en vue d'un traitement de surface par projection thermique) peut dégrader le comportement en cavitation;
- les revêtements de surface résistant à l'érosion hydro-abrasive peuvent engendrer une rugosité de surface plus importante susceptible d'altérer le rendement. Cette augmentation initiale de la rugosité peut être réduite par effet de polissage par les particules présentes dans l'eau pendant la phase d'opération. Evidemment, dans le temps, une turbine ayant un revêtement maintiendra un niveau de rendement supérieur comparé à une turbine non revêtue;
- un recouvrement réduit au niveau des aubes/pales peut pénaliser les performances en cavitation ce qui, en conséquence, peut réduire la puissance envisageable dans le cas d'une réhabilitation de turbine;
- les caractéristiques de conception en vue d'améliorer la résistance à l'érosion hydro-abrasive conduisent souvent à augmenter le coût total de la centrale.

Il convient de considérer et de choisir la combinaison optimale des caractéristiques de conception portant sur la résistance à l'érosion hydro-abrasive en tenant compte des conditions spécifiques à chaque site, de l'impact économique lié à la durée de vie de la centrale.

Comme règle générale pour la conception, il convient que la surface exposée à l'eau abrasive soit la plus petite que possible. Il convient également d'éviter les discontinuités, les transitions vives ou les changements brutaux de direction de l'écoulement.



## 4.2 Sélection des matériaux et revêtements présentant une forte résistance à l'érosion hydro-abrasive

La sélection des matériaux et des revêtements possibles qui présentent une forte résistance à l'érosion hydro-abrasive est importante. Voir aussi l'Article 6.

Du fait que la corrosion fait augmenter le taux d'érosion hydro-abrasive, les aciers inoxydables sont recommandés. Des aciers inoxydables soudables sont à privilégier.

Dans le cas où le revêtement résistant à l'érosion hydro-abrasive n'est pas appliqué lors de la fabrication initiale, il est recommandé d'adopter une conception hydraulique et mécanique permettant d'appliquer facilement le revêtement lors d'une phase ultérieure.

Les labyrinthes de roue réalisés en bronze aluminium ont en général une moins bonne tenue à l'érosion hydro-abrasive que les aciers inoxydables. Il existe cependant des exemples montrant un comportement relativement bon de labyrinthes en bronze d'aluminium.

## 4.3 Revêtements en acier inoxydable

Les rechargements par soudage en acier inoxydable présentant une épaisseur suffisante peuvent être utilisés à la place de composants en acier inoxydable massif, si le coût du rechargement par soudage est plus faible que le coût du composant en acier inoxydable.

## 4.4 Système d'adduction hydraulique

Un point important à prendre en compte pour le système d'adduction hydraulique consiste à éliminer le plus grand nombre de particules possible avant que celles-ci ne pénètrent dans les zones à grande vitesse des machines.

Des réservoirs de grande taille peuvent être très utiles à cet effet. Souvent une très grande quantité de particules peut être éliminée de l'eau. L'aspect négatif de cette solution est que les réservoirs peuvent se remplir rapidement. Ceci aura comme conséquence que de plus en plus de particules et aussi de taille plus importante atteindront la prise d'eau et passeront à travers la turbine. La sédimentation peut être réduite de plusieurs manières, même s'il n'est pas possible de la prévenir complètement. Les possibilités sont une chasse d'eau complète et aussi l'utilisation d'un canal/tunnel servant de by-pass pendant la saison des crues afin de dérouter l'eau la plus chargée en particules autour du réservoir aval de la centrale hydroélectrique. Le maintien de la capacité de stockage active des réservoirs est une possibilité afin de maintenir également le fonctionnement de la turbine et des coûts de réparation relativement constants.

En l'absence de tels réservoirs, il est possible d'installer des chambres appelées chambres de dessablage (ou dessableurs) ainsi qu'en amont des pièges à gravier ou autres dispositifs permettant d'exclure les particules les plus grossières de la prise d'eau. Il apparaît que la taille minimale des particules que ces dessableurs peuvent éliminer, se situe entre 0,1 mm et 0,3 mm, avant que le coût et la dimension des structures ne deviennent trop importants. La conception détaillée de ces dessableurs ne relève pas du domaine d'application de ce document.

Il est également important que les conditions transitoires auxquelles la centrale peut être confrontée ne perturbent pas les zones où le sable a pu sédimenter (naturellement ou dans les pièges du dessableur), afin d'éviter que ce dernier ne soit entraîné dans la turbine. Il convient donc que la conception des pièges à sable du dessableur prenne également en considération les conditions transitoires potentielles.

Des quantités même peu importantes de grosses particules, telles que des pierres, peuvent provoquer des dommages importants; ces particules peuvent être bloquées et ne pas être en mesure de traverser la turbine avant d'être réduites en particules plus petites. Ce phénomène est provoqué par la force centrifuge affectant les particules, force qui est induite par l'écoulement de l'eau entre la roue et le distributeur. Il est par conséquent important que les tunnels et conduites forcées soient propres et en bon état lors de la mise en service de la turbine et après tout entretien. Il convient que des pièges à cailloux soient installés en extrémité des conduites d'amenée non blindées et que les gravats soient enlevés périodiquement.

Le système d'adduction proprement dit ne fait généralement pas l'objet de dommage important par érosion hydro-abrasive car la vitesse de l'eau y est généralement faible. Une peinture de revêtement normale est habituellement suffisante pour protéger ce système.

## 4.5 Vannes

### 4.5.1 Généralités

Lorsque l'on anticipe une érosion hydro-abrasive, toutes les perturbations à caractère mécanique de l'écoulement induisent en général une érosion-hydro abrasive importante. Il convient que le choix entre une vanne papillon ou une vanne sphérique soit discuté entre le client et le fournisseur parce que dans le cas d'une vanne papillon, la lentille d'étanchéité est exposée de manière continue à l'écoulement abrasif.

L'état du logement autour du joint de la lentille ou du disque doit être lisse, sans arêtes vives et ne pas induire de changements importants dans la direction de l'écoulement.

Dans le cas où plusieurs turbines sont alimentées par une seule conduite forcée et où une vanne sphérique ou une vanne papillon est utilisée comme vanne de garde, il est préférable d'installer un joint de maintenance en plus du joint de service. Ce dispositif permet de procéder à l'entretien du joint du côté basse pression en gardant les autres turbines en fonctionnement.

La vanne fourreau est un type de vanne particulier, des considérations similaires à celles présentées ci-dessus s'appliquent également à ces dernières.

### 4.5.2 Protection (par obstruction) de l'espace entre le tourillon et son logement

La surface entre le tourillon et son logement est particulièrement sensible à l'érosion hydro-abrasive. La transition tourillon-obturateur constituant une des zones soumises aux contraintes les plus élevées des vannes de garde, cette zone doit faire l'objet d'une protection toute particulière. Des tourillons massifs ou protégés par un rechargement par soudage en acier inoxydable sont recommandés. Plusieurs conceptions peuvent être proposées, à titre d'exemple, la zone de transition peut être protégée contre l'attaque directe de l'érosion hydro-abrasive par un pré-labyrinthe (voir Figure 3).

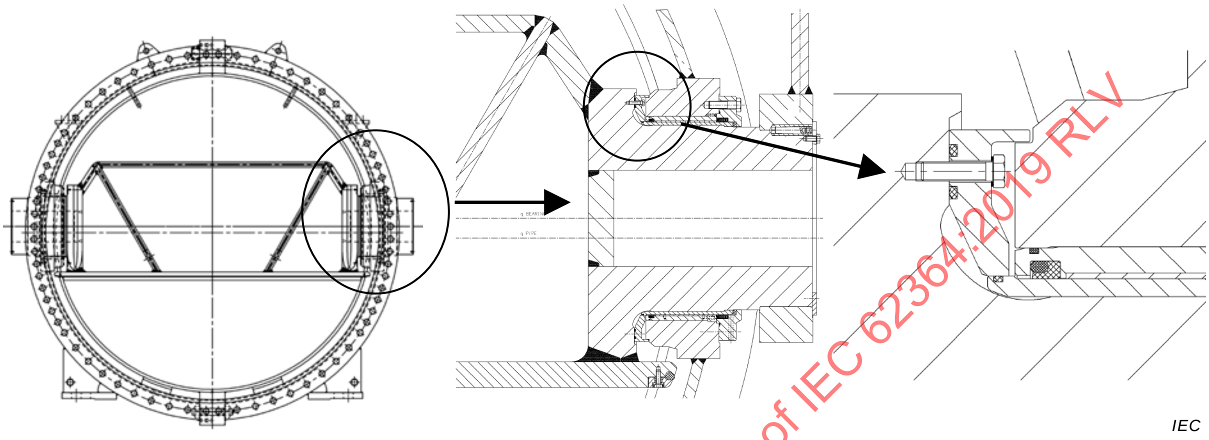



**Figure 3 – Exemple de protection de la zone de transition**

### 4.5.3 Butées extérieures à la vanne

Dans des conditions d'érosion hydro-abrasive, il est recommandé que les butées, qui limitent l'angle de rotation de l'obturateur soient placées à l'extérieur au niveau du servomoteur ou de façon contiguë au levier.

### 4.5.4 Capacité appropriée de l'organe de manœuvre des vannes de garde

L'ouverture ou la fermeture des vannes de garde s'effectue habituellement avec une pression quasi équilibrée (exemple 100:75), pression établie à l'aide d'une dérivation ou d'anneaux d'étanchéité mobiles.

En cas d'érosion hydro-abrasive excessive des directrices, la différence de pression pour la fermeture ou l'ouverture de la vanne de garde peut-être plus importante que celle admise ou fixée dans les plans. Il est par conséquent recommandé que la conception prenne en considération une différence de pression pour la fermeture ou l'ouverture plus élevée. Si la vanne de garde a été conçue comme une vanne d'arrêt d'urgence, elle peut être déjà en mesure de s'ouvrir sous une différence de pression supérieure.

### 4.5.5 Augmentation de la taille du circuit de dérivation pour prendre en compte un débit de fuite plus élevé au niveau des directrices

Comme déjà mentionné en 4.5.4 ci-dessus, une érosion hydro-abrasive excessive au niveau des directrices contribue à une augmentation du débit de fuite à un niveau tel que le débit d'eau d'équilibrage qui passe dans le circuit de dérivation de la vanne de garde ne permette pas d'équilibrer la pression entre la conduite forcée et la bâche spirale.

Il est par conséquent recommandé d'augmenter la taille du système de dérivation.

### 4.5.6 Conception du système de dérivation

Il est recommandé d'utiliser un système de dérivation externe et non interne.

## 4.6 Turbine

### 4.6.1 Généralités

Ces recommandations ne comportent pas de détails concernant les profils hydrauliques. Il convient que les spécialistes en conception hydraulique les déterminent pour chaque site.

### 4.6.2 Conception hydraulique

#### 4.6.2.1 Choix du type de machine

Il est avantageux de choisir un type de machine présentant une vitesse d'écoulement peu élevée, dont l'entretien peut être effectué facilement et pour lequel il est facile d'appliquer des revêtements résistants à l'érosion hydro-abrasive. Exemples de recommandations générales:

- Le choix entre une turbine Kaplan à axe vertical et une turbine bulbe doit tenir compte du fait que la turbine Kaplan fonctionne normalement à des vitesses inférieures (voir Figure 1). Les possibilités d'entretien et la facilité d'appliquer un revêtement sont sensiblement équivalentes pour ces deux types de turbines.
- Le choix entre une turbine Kaplan et une turbine Francis doit prendre en compte le fait que la turbine Francis fonctionne normalement avec une vitesse d'écoulement inférieure. Mais par ailleurs, il est plus facile d'accéder à la roue d'une turbine Kaplan afin d'y appliquer des revêtements résistants à l'érosion hydro-abrasive. Les possibilités d'entretien sont sensiblement équivalentes pour ces deux types de turbines.
- Le choix entre une turbine Francis et une turbine Pelton doit prendre en compte le fait que la turbine Francis fonctionne normalement avec une vitesse maximale d'écoulement inférieure, ce qui réduit l'érosion hydro-abrasive pour les turbines Francis. Toutefois, les pièces d'une turbine Pelton soumises à la vitesse d'écoulement maximale (c'est-à-dire les pointeaux et les sièges) sont de petites dimensions et leur accès est plus aisé pour y appliquer des revêtements résistant à l'érosion hydro-abrasive. La maintenance de la turbine Pelton est également plus facile.

#### 4.6.2.2 Vitesse spécifique

Pour une même installation, les machines de plus faible vitesse spécifique sont normalement de plus grandes dimensions, les vitesses d'écoulement étant inférieures au niveau de la sortie roue. Cependant, les vitesses d'écoulement ne sont pas inférieures dans les directrices et au niveau de l'entrée de la roue. Le dommage par érosion hydro-abrasive des turbines Kaplan, bulbes et Francis sous des chutes nettes peu élevées se rencontre principalement au niveau de la roue, d'où l'importance de la vitesse spécifique. Le dommage par érosion hydro-abrasive pour les turbines Francis de haute chute se rencontre principalement au niveau des directrices, d'où une importance moindre de la vitesse spécifique.

Dans le cas des turbines Pelton, la vitesse d'écoulement ne dépend pas de la vitesse spécifique. Toutefois, un nombre réduit de jets constitue un avantage pour une turbine Pelton dans la mesure où les augets étant de plus grande dimension, l'accélération de l'eau y est réduite, ce qui provoque un dommage par érosion hydro-abrasive moindre. Un nombre de jets réduit entraîne automatiquement une vitesse spécifique également réduite.

#### 4.6.2.3 Vitesse variable

Les machines à vitesse variable, bien que peu courantes, sont moins sujettes à la cavitation, y compris si la gamme de chutes nettes est importante. En raison de cette caractéristique, la machine à vitesse variable est probablement plus résistante à l'érosion hydro-abrasive.

#### 4.6.2.4 Enfoncement de la turbine

La cavitation et l'érosion hydro-abrasive se renforcent mutuellement. Il est donc recommandé que l'enfoncement de la turbine soit plus important pour les installations susceptibles d'être soumises à de l'érosion hydro-abrasive.

#### 4.6.2.5 Aubes en porte à faux

Lors de la réhabilitation d'une roue de turbine Francis, la puissance de la turbine de manière est parfois augmentée de manière significative. Une méthode permettant d'y parvenir consiste à étendre la ceinture de roue à l'intérieur du cône d'aspirateur, de manière à augmenter la surface des aubes pour améliorer le comportement en cavitation, voir Figure 4. Ceci génère toutefois des turbulences supplémentaires à l'entrée du cône d'aspirateur, turbulences qui augmenteront la quantité de métal érodé en présence de particules dans l'eau. Une autre conséquence des aubes en porte à faux est la création d'une zone de plus basse pression à l'aval du labyrinthe inférieur, ce qui engendre un débit de fuite plus important et donc une érosion hydro-abrasive plus importante au niveau de ce labyrinthe.

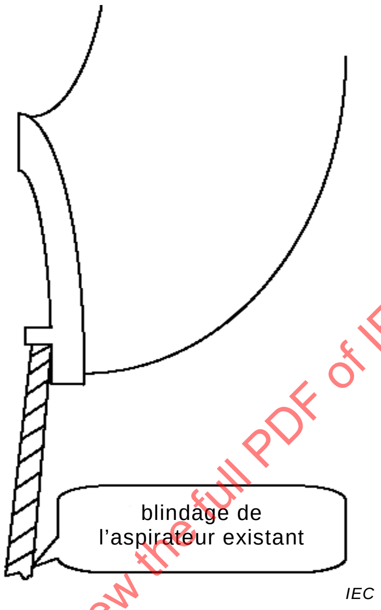



**Figure 4 – Aubes en porte à faux pour un projet de réhabilitation**

#### 4.6.2.6 Pales/aubes plus épaisses

Une plus grande épaisseur des pales/aubes, notamment au niveau de l'arête de sortie, donne une marge de sécurité supplémentaire avant que la perte de matière au niveau des pales/aubes ne devienne critique pour l'intégrité de structure de la roue. Il convient d'accorder le plus grand soin à la conception des aubes/pales plus épaisses. En effet une aube épaisse peut réduire le rendement de la turbine et accroître le risque d'éventuels problèmes liés aux tourbillons de von Karman. Le risque de cavitation au niveau de la ceinture de roue, en aval de l'aube peut également être plus important (voir Figure 5). Dans ce contexte, on peut mentionner que l'utilisation de revêtements résistants à l'érosion hydro-abrasive peut être un moyen pour concevoir des profils de moindre épaisseur, avec une augmentation marginale de l'épaisseur due au revêtement.

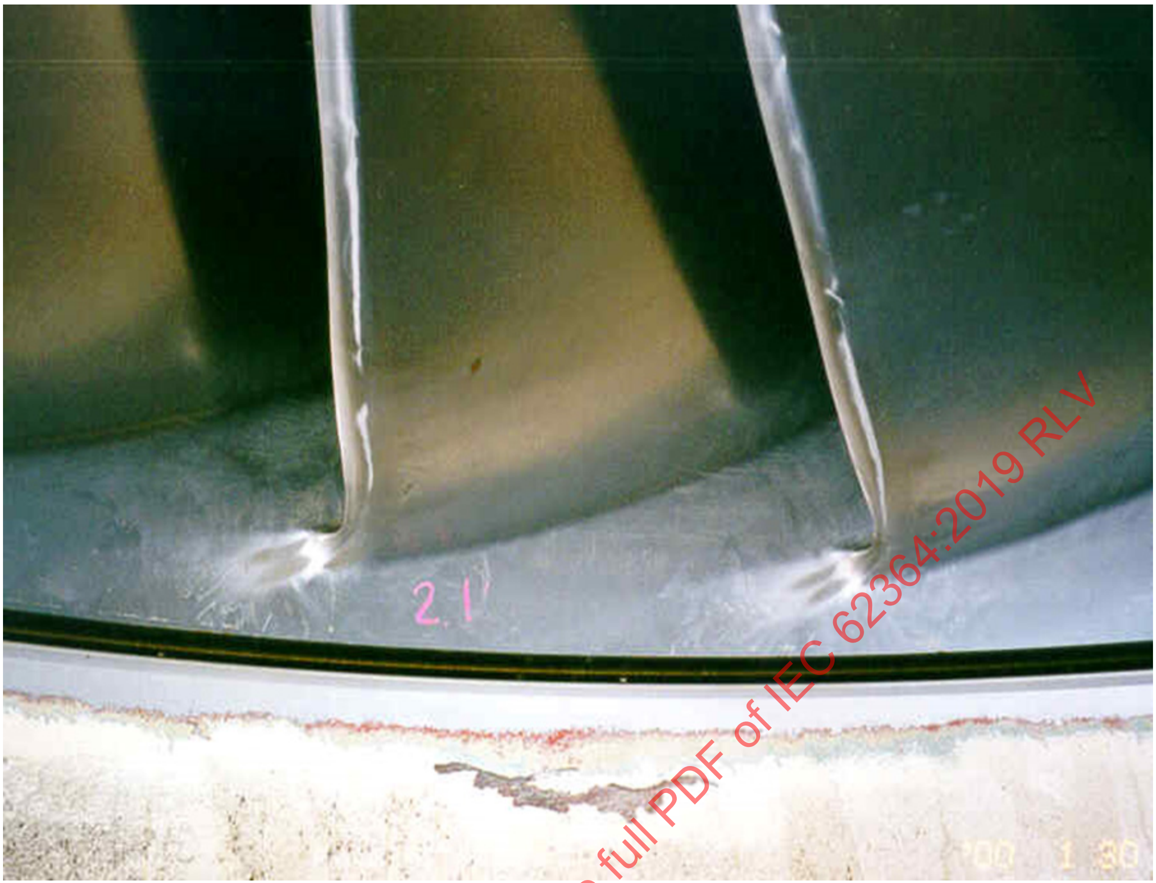



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**Figure 5 – Exemple de cavitation sur la ceinture de roue due à des aubes trop épaisses**



#### 4.6.2.7 Directrices en porte à faux

En cas de directrices en porte à faux, la face inférieure des directrices est soumise à une forte turbulence et à une forte recirculation. L'érosion hydro-abrasive peut donc être importante dans ces zones. La forte turbulence peut également avoir une influence sur l'entrée de la roue au niveau de la ceinture. Il est recommandé de limiter le porte-à-faux au minimum.

### 4.6.3 Conception mécanique

#### 4.6.3.1 Généralités

Lorsqu'un phénomène d'érosion hydro-abrasive est attendu et que le type de turbine est défini, on peut adapter, non seulement la conception hydraulique, mais aussi la conception mécanique, en adoptant certaines mesures de prévention; mesures qui peuvent réduire le taux d'érosion hydro-abrasive et permettre un entretien ou un remplacement aisé des pièces érodées. Ce paragraphe introduit certaines possibilités.

Lorsqu'il est prévu d'appliquer un revêtement spécial, la conception des pièces à revêtir doit permettre l'application du revêtement.

Les paragraphes suivants distinguent des mesures directes permettant de réduire l'érosion hydro-abrasive et des mesures autorisant une maintenance et un démontage aisés des composantes érodées.

#### 4.6.3.2 Mesures directes permettant, en présence d'érosion hydro-abrasive, de réduire l'usure ou de prolonger la durée de vie

##### 4.6.3.2.1 Joints d'étanchéité des directrices

On distingue trois types différents de dispositifs d'étanchéité: les joints d'extrémité, les surfaces de contact entre le bord d'attaque et le bord de fuite des directrices, et les joints entre le tourillon de la directrice et les deux flasques.

Les faces des directrices peuvent comporter des joints d'extrémité. Ce type de dispositif est efficace dans tous les cas de fonctionnement. Un autre type de joint d'extrémité est fixe, il se situe sur les flasques. Ce dispositif n'est efficace que si les directrices sont fermées. Ces deux types de joint réduisent le débit de fuite qui s'écoule dans ces jeux de faible dimension, et réduisent donc l'érosion hydro-abrasive des composantes adjacentes. Cependant, les joints eux-mêmes sont également soumis à érosion hydro-abrasive, et, ce faisant, leur durée de vie peut être limitée.

L'utilisation de ces joints d'extrémité pour éviter l'érosion hydro-abrasive n'est raisonnable que si leur durée de vie est supérieure au temps entre chaque révision ou si leur remplacement est facile. Le remplacement est plus facile lorsque les joints sont situés dans les flasques, et non aux extrémités des directrices.

Des joints d'étanchéité situés entre le bord d'attaque et le bord de fuite des directrices permettent de réduire le débit de fuite lorsque le distributeur est fermé. Généralement, le principe qui s'applique aux joints d'extrémité est également valable dans le cas présent. Ce type de joint est efficace lorsque la turbine est à l'arrêt sans que la vanne de garde soit fermée.

La Figure 6 montre un exemple de joints entre le tourillon des directrices d'une part et les flasques d'autre part. Ces joints réduisent les fuites, que les directrices soient en position ouverte ou fermée. Ils ont par ailleurs un effet positif sur le taux d'érosion hydro-abrasive. Il convient d'utiliser des bagues d'étanchéité en acier inoxydable massif résistant à l'érosion hydro-abrasive ou en acier inoxydable revêtu.



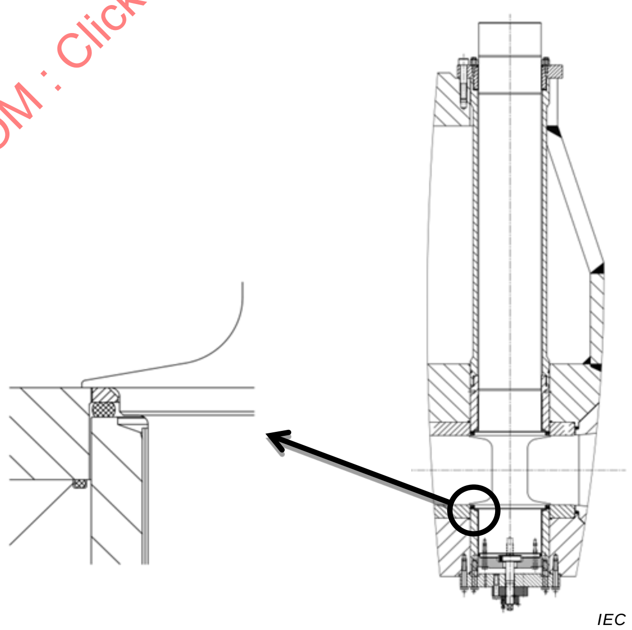


**Figure 6 – Exemple de conception de joints au niveau des tourillons des directrices**

Il convient d'utiliser, pour les pièces placées en vis-à-vis de tous les joints, de l'acier inoxydable ou un revêtement résistant à l'érosion hydro-abrasive.

Une méthode plus efficace pour réduire le débit de fuite, machine à l'arrêt, consiste à soumettre les directrices à une précontrainte en position fermée. De plus, le bord de fuite des directrices peut être fabriqué avec une certaine cambrure pour compenser la déformation sous l'action de la pression de l'eau et permettre ainsi de ne pas avoir de jeux lorsque les directrices sont en position fermée et soumise à la pression exercée par la chute.

#### 4.6.3.2.2 Emplacement des labyrinthes de roue

Une position appropriée des labyrinthes dans les turbines Francis peut également réduire l'érosion hydro-abrasive des labyrinthes. Il convient d'éviter tout captage des particules abrasives à l'amont des labyrinthes, de même que toute augmentation de la concentration.

Dans le cas des turbines de vitesse spécifique moyenne à élevée, les labyrinthes seront de préférence situés directement au niveau de la transition entre les flasques et le plafond ou la ceinture de roue. Cela permettrait d'éviter une accumulation de particules en amont des labyrinthes.

Lorsque cette position des labyrinthes déséquilibre la poussée axiale, le phénomène doit être compensé lors de la conception des tuyaux d'équilibrage ou du pivot.

#### 4.6.3.2.3 Protection du béton par un blindage acier de plus grande dimension

Dans des conditions normales d'utilisation, en l'absence de particules abrasives, il convient de prévoir un blindage acier ou autre protection supplémentaire du béton lorsque la vitesse de l'écoulement dépasse 6 m/s à 7 m/s. Si l'eau contient des particules abrasives, il convient d'étendre cette protection afin de préserver le béton contre l'érosion hydro-abrasive. Dans ce cas, la limite de vitesse recommandée est comprise entre 4 m/s et 5 m/s.

#### 4.6.3.2.4 Arrosage du joint d'arbre avec de l'eau «propre»

Dans le cas de turbines opérant avec de l'eau chargée en particules, les joints d'arbres doivent être alimentés avec de l'eau propre. Il convient d'éviter que la face de contact ou la face d'appui entre en contact avec les particules abrasives.

Des filtres ou hydro-cyclones appropriés doivent permettre d'épurer l'eau, cette épuration peut parfois se révéler difficile.

Un joint d'arrêt est recommandé pour protéger le joint d'arbre contre la pénétration d'eau contenant des particules abrasives. En l'absence de ce joint d'arrêt et lorsque la pression aval s'exerce au niveau du joint d'arbre, il convient d'alimenter ce dernier avec de l'eau propre, même lors de l'arrêt de la turbine.

Il convient également de pouvoir facilement remplacer le joint d'arbre sans avoir à démonter d'autres pièces.

#### 4.6.3.2.5 Plaques d'usure au niveau des flasques

Des plaques d'usure disposées sur les flasques en regard des directrices permettent de réduire l'érosion hydro-abrasive de manière efficace. Ces plaques sont fixées sur les flasques et sont démontables.

Lorsque l'usure par érosion hydro-abrasive prévue est élevée et que les plaques d'usure doivent être souvent remplacées, il est recommandé de fixer les plaques d'usure au moyen de boulons implantés côté «sec» des flasques. Ces boulons doivent être étanchéifiés en conséquence.

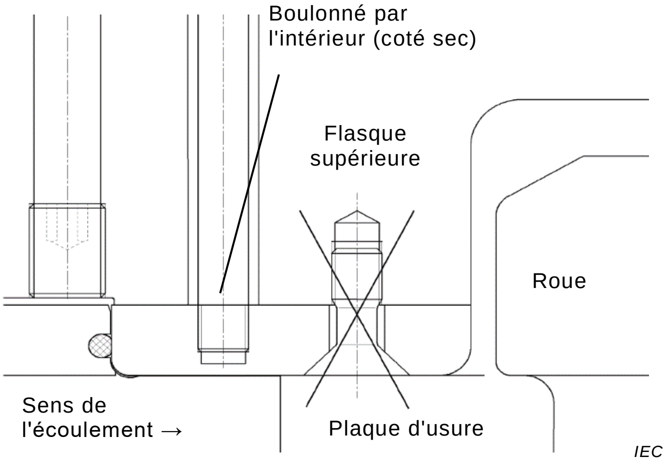


**Figure 7 – Exemple de fixation de plaques d'usure côté sec (élément de fixation à gauche)**

Classiquement, les plaques d'usure sont fixées aux flasques à l'aide de boulons en acier inoxydable implantés côté eau. Les têtes de boulons doivent être arasées au niveau de la surface des plaques d'usure, il convient en outre d'éviter toute discontinuité de surface. Le remplacement de plaques d'usure avec fixation côté eau est plus long que si cette fixation est faite côté sec, de plus ce montage rend plus compliqué la mise en œuvre d'un revêtement. Se référer à la Figure 7. Si des plaques d'usures revêtues sont utilisées, il convient que la fixation soit réalisée côté sec.

Une solution alternative est possible selon le taux d'érosion hydro-abrasive prévu. Un revêtement en acier inoxydable peut également être utilisé en lieu et place de plaques d'usure amovibles. Si la hauteur des directrices est suffisamment importante pour permettre l'accès à ce revêtement en acier inoxydable, il peut également être réparé sur site.

#### 4.6.3.2.6 Revêtement intérieur en acier inoxydable des manteaux de roue

Il est recommandé que le manteau de roue des turbines Kaplan et bulbes soit en acier inoxydable massif ou protégé, côté eau, par un revêtement épais en acier inoxydable. Ceci permet de prolonger la durée de vie du manteau de roue. La réparation de toute surface usée peut s'effectuer par un nouveau rechargement par soudage intérieur en acier inoxydable, par soudage de dalles en acier inoxydable ou par l'application d'un revêtement par projection thermique.

#### 4.6.3.2.7 Revêtement intérieur en acier inoxydable sur les flasques suférieur et inférieur

Toutes les surfaces exposées à l'eau des flasques supérieur et inférieur sont soumises à l'érosion hydro-abrasive. L'application d'un revêtement en acier inoxydable ou de plaques de protection en acier inoxydable, notamment dans les zones présentant des discontinuités ou des variations de direction de l'écoulement, est recommandée. La réparation du revêtement en acier inoxydable usé peut s'effectuer par un nouveau rechargement par soudage en acier inoxydable, par soudage de dalles en acier inoxydable ou par l'application d'un revêtement par projection thermique.

#### 4.6.3.2.8 Épaississement des parois

L'augmentation d'épaisseur de parois d'une composante est une des méthodes permettant d'augmenter le temps entre deux révisions suite à un phénomène d'érosion hydro-abrasive. L'augmentation de l'épaisseur de parois des composantes hydrauliques telles que les pales/aubes, fait l'objet du 4.6.2.6.

En ce qui concerne les composantes strictement liées à la tenue mécanique, et qui n'ont pas d'influence sur le rendement de la turbine, l'épaisseur de paroi peut être augmenté dans les zones critiques pour éviter toute défaillance précoce sous l'action de plus fortes contraintes. Les composantes typiquement concernées sont les tourillons des directrices ainsi qu'une augmentation de l'épaisseur de paroi au niveau des raccordements des flasques supérieur et inférieur, des directrices et des avant-directrices.

Un point important consiste à ce que l'épaisseur de la paroi des tuyaux en acier noyés dans le béton soit suffisante – notamment les tuyaux d'équilibrage (ou de décharge plafond) au niveau du flasque supérieur, si ce type de tuyau est utilisé. Les coudes de ces tuyaux sont plus particulièrement soumis à une érosion hydro-abrasive sévère en raison de changements brusques de direction de l'écoulement. Par conséquent, il convient que l'épaisseur de paroi de ces tuyaux soit renforcée, tout comme il convient d'utiliser des coudes avec un plus grand rayon de courbure. La Figure 8 représente des tuyaux d'équilibrage classiques.

Lorsque de tels tuyaux d'équilibrage sont utilisés, il convient également de les concevoir pour une vitesse d'écoulement faible, prenant en compte toute augmentation de fuites au niveau des labyrinthes. Il peut être raisonnable de considérer que la surface d'ouverture des tuyaux d'équilibrage soit au moins trois fois celle de la surface au niveau des jeux entre les labyrinthes. L'équilibrage est bien entendu également possible en pratique à l'aide de trous dans le plafond de la roue en lieu et place de tuyaux d'équilibrage externes.

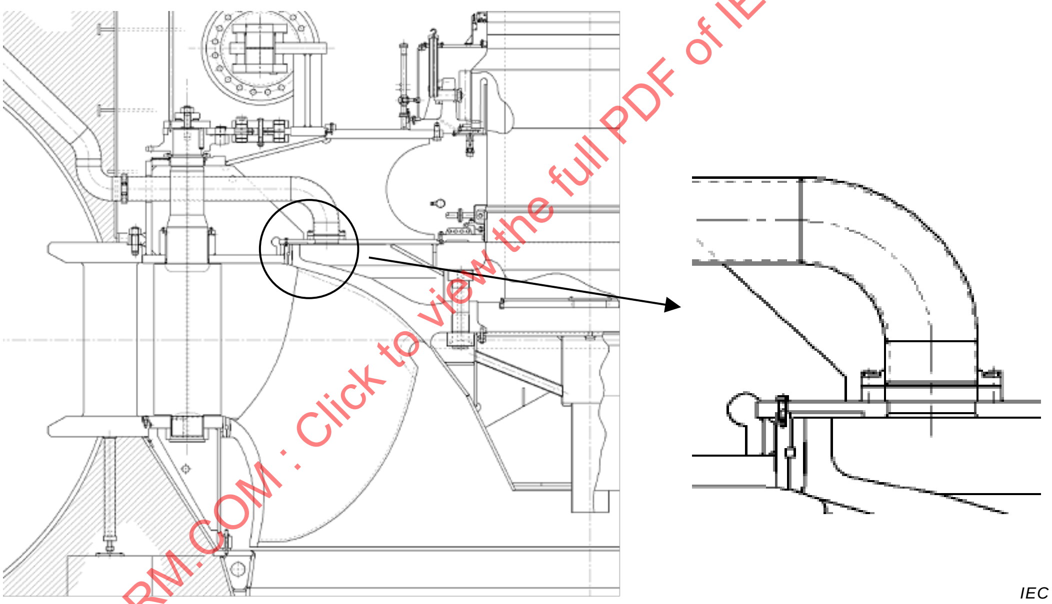


**Figure 8 – Tuyaux d'équilibrage avec coudes au niveau du flasque supérieur**



#### 4.6.3.2.9 Pivot

Dans les turbines Francis, la poussée axiale peut dépendre du niveau de débit de fuite aux labyrinthes et par conséquent du jeu de ces derniers. En cas d'érosion hydro-abrasive, le pivot doit être conçu de manière à supporter toute charge additionnelle, de sorte que la turbine puisse fonctionner avec des labyrinthes présentant un certain degré d'usure.

### 4.6.3.3 Etudes conceptuelles pour faciliter la maintenance ou le remplacement

#### 4.6.3.3.1 Généralités

Lorsque les composantes sont endommagées par érosion hydro-abrasive et doivent être remplacées, il est très important que ces remplacements ou réparations puissent être effectués rapidement et facilement afin de réduire le temps d'arrêt et l'interruption de l'exploitation. Il convient que ceci soit pris en considération dès la phase d'avant-projet de la centrale, et la conception doit le prendre en compte.

#### 4.6.3.3.2 Démontage des composantes

Les principales composantes des turbines Francis qui doivent être remplacées ou démontées pour réparation sont la roue, les directrices et les plaques d'usure. Un démontage par-dessous de la roue et du flasque inférieur permet un démontage rapide sans démontage du générateur, du cercle de vannage, du distributeur et du flasque supérieur.

Si, pour des raisons spécifiques, le démontage depuis la partie inférieure de la turbine n'est pas possible, un "démontage intermédiaire" au niveau du plancher turbine facilite le retrait de la roue sans démonter le générateur. Toutefois le flasque supérieur et le mécanisme de manœuvre du distributeur doivent être démontés.

Afin de faciliter le démontage de la roue, il convient que le montage et le démontage du plateau d'accouplement roue – arbre de la turbine puissent être effectués facilement. Notamment si le programme de maintenance prévoit l'utilisation de deux roues (une en opération, une en attente) pour un groupe (une ligne d'arbre). Les accouplements par friction ou les accouplements ne nécessitant pas d'ajustage mécanique conjoint sur site sont des solutions possibles.

#### 4.6.3.3.3 Conception appropriée pour l'application de revêtements

La résistance à l'érosion hydro-abrasive des composantes peut être améliorée de manière significative par l'application d'un revêtement résistant approprié. La possibilité de prolonger la durée de vie d'une composante revêtue dépend de plusieurs facteurs, par exemple:

- de la composante et du type de turbine;
- de la chute nette et du débit;
- de la concentration et de la composition des particules;
- des conditions d'écoulement autour de la composante.

Les revêtements résistant à l'érosion hydro-abrasive ne sont habituellement pas efficaces contre la cavitation. Le revêtement peut être détruit localement et rapidement suivant l'intensité de la cavitation.

Les principales composantes suivantes, classées selon le type de turbine, peuvent actuellement être envisagées avec revêtement, soit intégralement, soit partiellement, selon l'état actuel de la technique. Il convient que les solutions spécifiques de revêtements soient déterminées au vu de la nécessité d'une protection contre l'érosion hydro-abrasive, de l'accessibilité au niveau des composantes et des impératifs économiques.

**Turbine Francis, pompe, pompe-turbine:**

- Roue
  - labyrinthes
  - si possible, l'ensemble du canal hydraulique. En cas d'accès difficile pour l'application du revêtement, les surfaces revêtues peuvent être restreintes au côté aspiration de la sortie de roue, à la ceinture et à l'entrée des aubes. Il est à noter que la partie limitante d'une durée de vie de roue Francis est normalement la face côté pression des aubes de roue
  - plafond et ceinture de roue
- Directrices – profil dans son ensemble, bagues d'étanchéité au niveau du tourillon
- Flasque supérieur – labyrinthes fixes, plaques d'usure
- Flasque inférieur – labyrinthes fixes, plaques d'usure

**Turbine Pelton:**

- Roue – surface interne de l'auget, à l'exception de la zone d'attache lorsqu'un contrôle non destructif est nécessaire
- Tête de pointeau
- Bec de buse d'injecteur
- Buse d'injecteur
- Déflecteur (si d'utilisation fréquente)

**Turbines Kaplan, hélice et bulbe:**

- Pales de roue
- Moyeu de roue (pour les cas extrêmes)
- Directrices (pour les cas extrêmes)
- Plaques d'usures (pour les cas extrêmes)

Il convient d'accorder une attention toute particulière à la projection thermique pour les composantes soumises à des dilatations importantes de par leur fonction. Dans le cas d'une bague de siège d'injecteur, pour une chute nette supérieure à 1 000 m, la dilatation de la bague de siège peut provoquer des fissures dans le revêtement et donc la défaillance de la composante.

Il convient que l'épaisseur de la couche de revêtement et la tolérance sur cette épaisseur soient prises en considération pour toutes les composantes dont la fonction implique des exigences sévères de tolérances dimensionnelles. Tel est par exemple le cas des labyrinthes, ainsi que de la distance entre plaques d'usure et directrices.

Les contraintes résiduelles présentes dans les couches projetées thermiquement peuvent conduire à un écaillage et à des fissures au niveau des arêtes vives ou des angles vifs. A titre d'exemple, et dans l'état actuel de la technique, pour les revêtements par projection thermique, il est recommandé que le rayon des arêtes soit au minimum de 0,5 mm, et pour les angles vifs de 1 mm.



#### 4.6.3.3.4 Utilisation exceptionnelle d'acier au carbone comme matériau de base

En général, on recommande l'utilisation d'acier inoxydable. Toutefois, l'utilisation d'acier au carbone peut également être envisagée pour des raisons économiques (mais avec possiblement un risque possible accru de corrosion et de défaut d'adhérence).

#### 4.6.3.3.5 Accessibilité pour l'application d'un revêtement par projection thermique

Un espace minimum est requis pour l'application d'un revêtement par projection thermique. Il convient que la conception hydraulique et mécanique prenne en compte les limites d'accessibilité pour l'application d'un revêtement par projection thermique.

Les labyrinthes à doigts présentent un espace réduit entre les doigts, des solutions spéciales peuvent ainsi être adoptées telles que des labyrinthes en plusieurs parties concentriques. Pour les labyrinthes à étages, il peut être avantageux d'utiliser un jeu ou d'optimiser la forme de l'étage du point de vue accessibilité pour la projection thermique. Cependant ceci peut influencer la performance des labyrinthes du point de vue étanchéité. Voir Figure 9 ci-dessous.

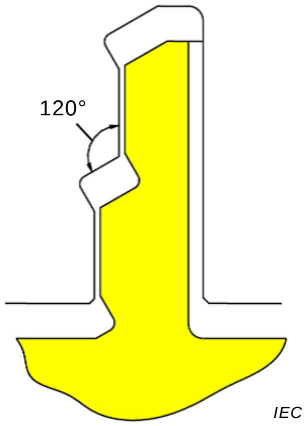


**Figure 9 – Labyrinthe à étages de forme optimisée pour application d'un revêtement dur**



# 5 Exploitation et maintenance

## 5.1 Exploitation

Il est recommandé de prendre en compte les actions suivantes lors de l'exploitation des turbines.

- Arrêter temporairement les turbines et fermer les vannes de garde pendant des périodes de concentration élevée en particules et/ou de présence importante en grosses particules. La concentration déclenchant l'arrêt est généralement comprise entre une et plusieurs dizaines de g/l. La valeur de cette concentration de mise à l'arrêt résulte d'une optimisation économique spécifique à chaque site, généralement basée sur des enregistrements d'exploitation et de maintenance. Cette opération peut éviter une érosion hydro-abrasive excessive de la turbine avec une perte de production réduite. Cette stratégie peut se révéler utile notamment pour des installations au fil de l'eau où une variation importante de la concentration en particules peut se produire très rapidement. Il est recommandé d'installer un système de pré-alerte amont pour mesurer la concentration en particules manuellement ou automatiquement, et arrêter la turbine avant que l'eau fortement concentrée en particules n'atteigne la prise d'eau.
- Lorsque de l'eau fortement concentrée en particules est restée stagnante dans la conduite forcée pendant une longue période, les particules peuvent se déposer dans le bas de cette dernière. L'ouverture de la vanne de garde peut alors se révéler difficile. Dans ce cas, il peut être possible d'injecter de l'air comprimé, par l'intermédiaire d'un système spécial, et d'ouvrir la vanne de vidange de la conduite forcée afin d'éliminer les particules se trouvant juste devant la vanne de garde. Dans ce cas, il est important d'analyser les conséquences possibles sur la vanne de tête, si elle existe, que peut engendrer une grande quantité d'air dans la conduite.
- Réduire au minimum la quantité de débris traversant la turbine. Des corps solides encombrants, par exemple, de gros morceaux de bois, du gravier (d'une dimension supérieure à 2 mm), etc., peuvent endommager les surfaces hydrauliques et les éventuels revêtements résistants à l'érosion hydro-abrasive. Un endommagement des surfaces hydrauliques peut augmenter les turbulences, ce qui, à son tour, renforce les dommages par érosion hydro-abrasive. Ceci est particulièrement important pour les turbines Francis et Pelton de haute chute, étant donné que les vitesses d'écoulement y sont très élevées et que ces turbines présentent des surfaces hydrauliques lisses afin de maintenir les turbulences à un niveau réduit.
- Ne pas faire fonctionner la turbine lorsque le dommage par érosion hydro-abrasive menace la sécurité de fonctionnement. La progression du dommage par érosion hydro-abrasive aboutit au fait que la turbine peut éventuellement devenir peu sûre à exploiter. Cette situation peut arriver, par exemple, lorsque, suite à une augmentation importante du débit d'équilibrage, la poussée axiale dépasse les limites admissibles ou que l'épaisseur résiduelle de matériau de certaines composantes se retrouve en dessous de l'épaisseur

minimum acceptable. Il convient d'inspecter les composantes critiques de façon régulière, à savoir au moins une fois par an, et de comparer les résultats obtenus aux critères d'acceptabilité prédéfinis et aux résultats de la dernière inspection et des inspections précédentes.

- Pour les turbines Pelton, le meilleur rapport «électricité produite / usure par érosion hydro-abrasive» est obtenu à ouverture maximale d'un ou de plusieurs injecteurs. Contrairement aux autres types de turbine, ces turbines, si leur conception mécanique le permet, permettent de réduire l'érosion hydro-abrasive en fonctionnant à charge partielle, en fermant complètement certains injecteurs.
- Pour les turbines Pelton, les débits de fuite au travers des injecteurs en position fermée peuvent causer une érosion hydro-abrasive locale sévère des becs de buse. La fermeture de la vanne sphérique amont lors des périodes d'arrêt évite ce problème. Dans des conditions sévères, il peut être favorable d'éviter de fonctionner avec un nombre réduit d'injecteurs alors que les autres sont fermés (restriction de fonctionnement à charge partielle).
- Pour les autres types de turbine, le meilleur rapport «électricité produite / usure par érosion hydro-abrasive» est obtenu à l'ouverture maximale. Eviter dans la mesure du possible un fonctionnement en marche à vide ou à faible charge. Le fonctionnement en marche à vide et le fonctionnement à faible charge sont les conditions de fonctionnement les plus défavorables du point de vue de l'érosion hydro-abrasive pour la plupart des composantes et des types de turbine.
- Pour les turbines Francis, lors des phases d'arrêt et lorsque le débit d'eau est coupé uniquement par les directrices, les fuites d'eau au niveau des jeux de directrices se produisent à une vitesse très élevée, proche de la vitesse d'un jet libre. Ceci génère une érosion hydro-abrasive des directrices. La fermeture de la vanne de garde permet d'éliminer cette érosion hydro-abrasive. Cette fermeture de la vanne de garde est particulièrement importante dans le cas des turbines de haute chute.
- Les revêtements durs sont très sensibles à la cavitation. Ainsi, dans le cas des machines comportant ce type de revêtement, il convient que toutes les conditions d'exploitation qui génèrent de la cavitation soient évitées:
  – respecter strictement la plage de fonctionnement recommandée pour la turbine;
  – turbines Pelton: Vérifier le bon état de la surface intérieure de l'injecteur, y compris celui de l'aiguille et du siège, et s'assurer de leur alignement correct.

Se reporter également au commentaire de l'Article 7 pour ce qui concerne les exigences relatives à la cavitation.



## 5.2 Pièces de rechange et inspections périodiques

- Disposer de pièces de rechange supplémentaires en stock pour les composantes soumis à l'érosion hydro-abrasive. En cas de forte érosion hydro-abrasive, un jeu complet de pièces de rechange (par exemple directrices, plaques d'usure, flasques supérieur et inférieur et roue) peut être stocké et remplacé à intervalles réguliers. Les pièces démontées peuvent ensuite être réparées sans influer sur l'indisponibilité machine.
- Inspecter les composantes critiques au moins une fois par an et comparer les résultats d'inspection aux critères d'acceptabilité prédéfinis et aux résultats de la dernière inspection et des inspections précédentes. Tenir des enregistrements appropriés du niveau de dommage par érosion hydro-abrasive pour chaque composante. Il est recommandé de mesurer et d'enregistrer la profondeur de perte de métal maximale, ainsi que de prendre des photographies de chaque composante soumise à un dommage par érosion hydro-abrasive. Voir également l'Annexe B.

## 5.3 Echantillonnage et contrôle en continu des particules

Il est important de conserver des enregistrements permanents de la concentration et des propriétés des particules abrasives présentes dans l'eau. Des échantillons d'eau peuvent être prélevés à des intervalles prédéterminés et analysés en laboratoire. De plus, il existe aujourd'hui plusieurs types d'appareils permettant de contrôler la concentration des particules