OPTIMIZATION OF HYDRO POWER PLANTS PERFORMANCE IMPORTANCE OF REHABILITATION AND MAINTENANCE IN PARTICULAR FOR THE RUNNER PROFILES

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ABSTRACT

Hydraulic efficiency plays a relevant role on the performance of Hydro Power Plants (HPP) and constitutes one of the main elements for selecting the most appropriated interventions both of ordinary and extraordinary maintenance as well as for the choice of the consequent amount of investment.

Objective of this article is to give an overview on the actual approach to this theme in Italy. The article describes the main methods of intervention for optimizing the HPP performance, such as:

- Partial renewal with complete replacement of obsolete active parts;
- Rehabilitation of deteriorated profiles with different techniques, according to type and cause of deterioration.

At the end of the article are also reported some economic considerations of the authors as well as their conclusions.

1. HYDRAULIC MACHINE PERFORMANCE

On a HPP the main aspect is given by the hydraulic machine performance, seen as an indicator of the conversion of the available hydraulic power (resulting from the multiplication of head and discharge) into mechanical one, successively converted into electric power through the generator.

In fact, the absolute level of the HPP performance is characterized by the losses in the turbine active and passive elements, while the amount of losses is varying with the variation of one or both parameters head and discharge. It can be noticed that these two parameters got less and less steady in the course of the years in consequence of the increase of regulating demand, made necessary by the maximum exploitation of the duration curve.

According to the different combinations of the couple of values head and discharge, available for the same turbine power, there are different and well known arrangements, passing from Pelton turbines for high heads, to Francis turbines for medium heads, till Kaplan turbines in their spiral case or ducted arrangement (bulb), for lowest heads (See Fig.1).

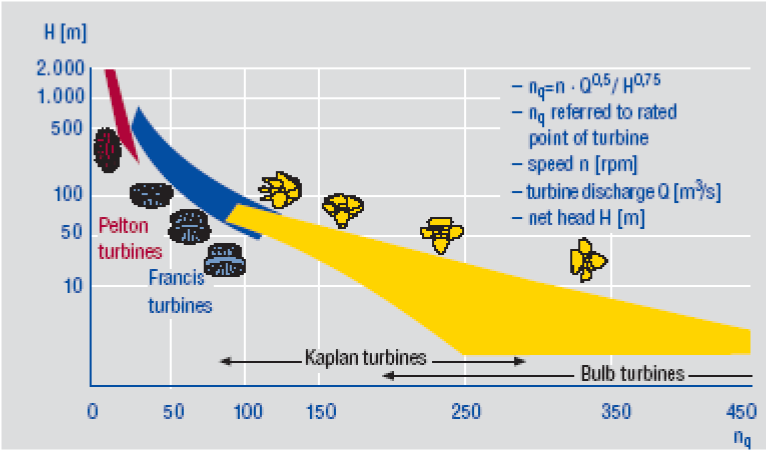

Fig.1 Application range of hydraulic turbines H- nq

On the table of Fig. 2 are reported the utilization limits for the three mentioned types of turbines with an indication of the respective maximum efficiency level up to now measured.

Reaction Rate	Turbine Type	Specific speed n_q	Turbine Power P	Turbine Head H	Turbine Discharge Q	Max. Turbine Efficiency (Function of n_q and power)
Ratio between non converted net head into kinetic energy before the runner and turbine net head	Most frequent type	$n\times\frac{\sqrt{Q}}{H^{0.75}}$	[MW]	[m]	[m^3/s]	Ratio between mechanical power at the coupling and available hydraulic power $\eta=P/(g\times Hn)\times(\rho\times Q)=\eta_h\times\eta_m$
> 0	Pelton	$5 < n_q < 20$	1 ÷ 420	200÷1800	0.15÷50	≤ 92,5 …..
0.25 ÷ 0,70	Francis	$25 < n_q < 100$	1 ÷ 850	20÷600	1÷825	≤ 95,5 ….
< 1	Kaplan	> 80	1 ÷ 160	2÷90	10÷800	≤ 96 ……

Fig.2 Characteristic parameters of non Mini-turbines (P > 1 MW)

In this overview, not only the geometrical form and the dimensions influence the efficiency values, but also the couple of values head and discharge, which define the exact value of the characteristic speed number **nq**, indicating the pertinent influence of each hydraulic turbine component.

As regards steady parts, such as draft tube, the influence on the power transformation is inversely proportional to the head. So the draft tube influence on efficiency rises together with the reaction rate, that is with the characteristic speed number **nq**, as it is shown in the diagram of Fig. 3.

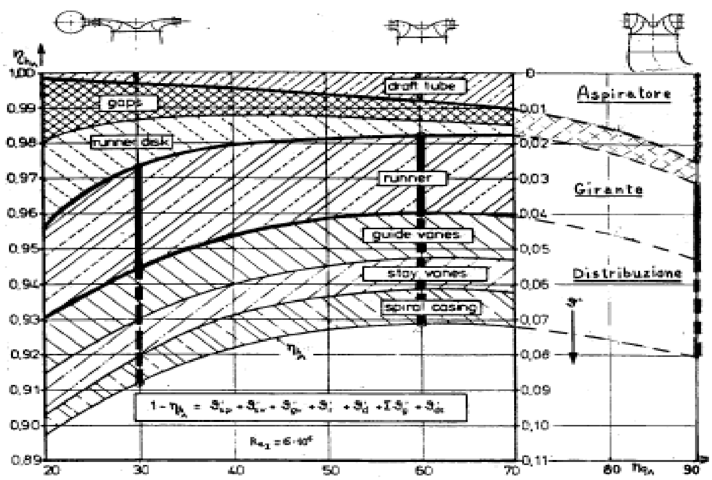

Fig.3 Typical losses distribution as a function of **nq** on Francis model turbine

The historical trend of the reachable performance, available thanks to technological progress, was well represented in the 60s [**1**] and in the following 90s [**2**]. Likewise some of the main causes and effects of performance decay, due to the use in the time, were described by some different authors [**3**].

2. PERFORMANCE IMPROVEMENT AND OPTIMIZATION

Generally speaking, the improvement of hydraulic machinery performance can basically come from two types of intervention:

- Replacement of obsolete stator and/or rotor profiled machinery parts with new ones;
- Repairing both for surface restoration and for improvement of wear resistance, using coating techniques.

It is clear that these interventions are not alternative but complementary, depending on the actual problem:

- Hydraulic design obsolescence and installation possibility, even with a “partial renewal”, of machinery parts (in general active/rotor parts);
- Corrosion, erosion or cavitation of turbine parts submitted to a great wear-out, caused by loaded water or particular operating conditions.

3. POSSIBILITIES GIVEN BY NEW PROFILES “ PARTIAL RENEWAL”

The following examples of performance optimization with partial renewal on the different turbine types give us the level of achievable improvement.

a) Pelton turbine

The partial renewal of 5 horizontal double nozzles Pelton groups, keeping the existing penstock, housing and foundation, made possible a power and efficiency increase (see Fig. 4a&b). Efficiency Test on the Power plant has been made by thermodynamic method foreseen by the IEC code.

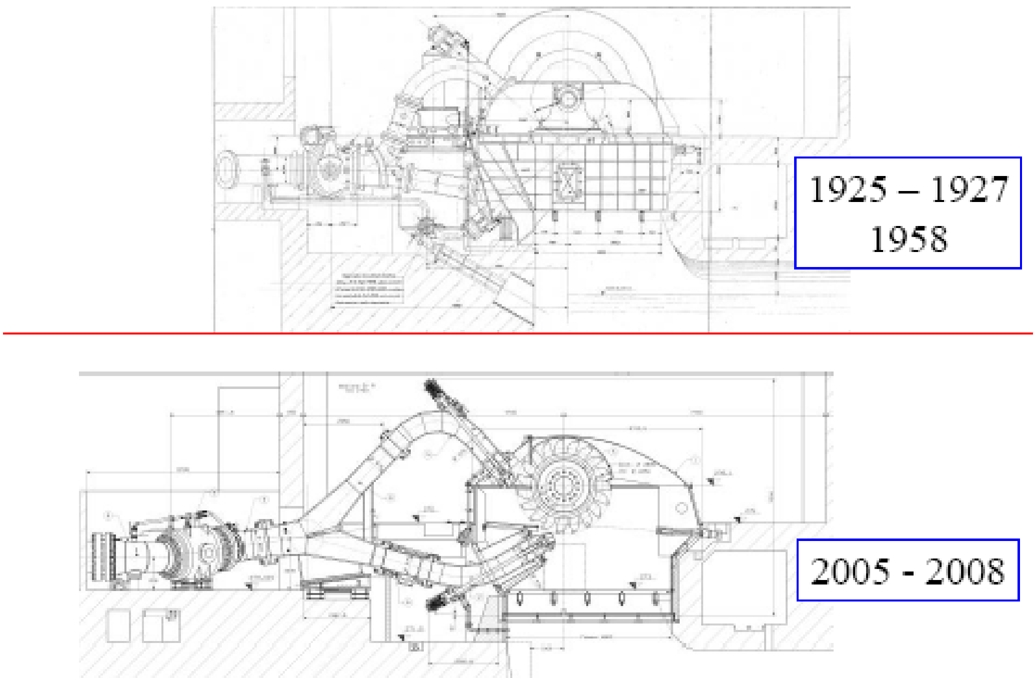

Fig.4a Pelton partial renewal: old and new design

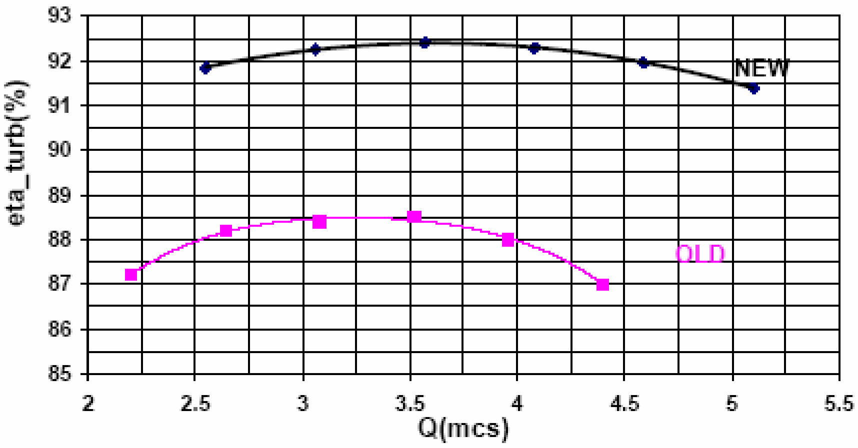

Fig.4b Pelton partial renewal: comparison of guaranteed efficiencies

b) Francis turbine

The following example (see Fig.5) shows the study of partial renewal of a vertical Francis group with replacement of active rotor components, which allow to guarantee a higher level of efficiency and power.

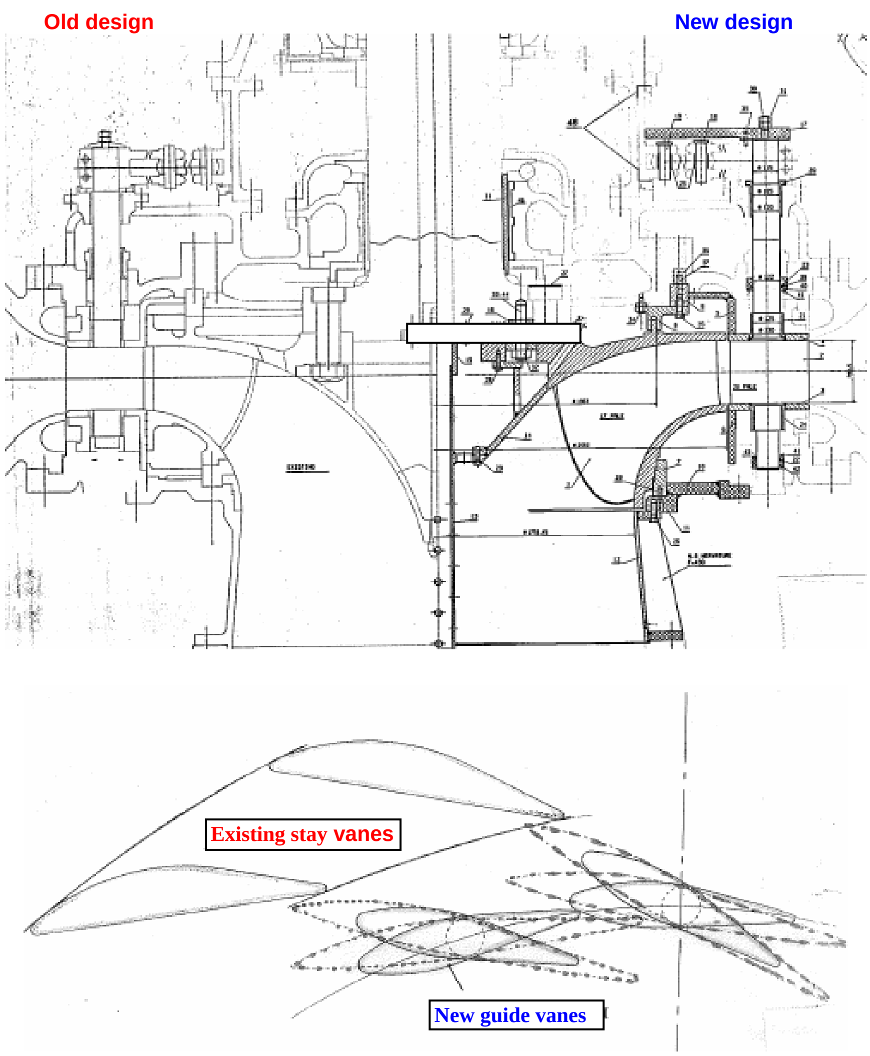

Fig.5a Partial renewal of a vertical Francis group

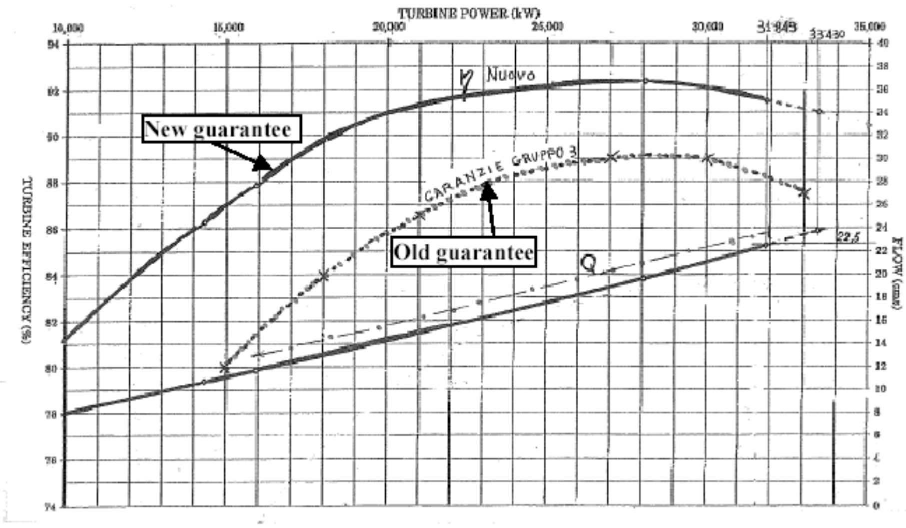

Fig.5b Francis partial renewal: comparison of efficiencies

c) Kaplan turbine

An example of performance improvement thanks to partial renewal of a vertical Kaplan group, with new runner and distributor, while the embedded parts are left unchanged, is reported in Fig .6.

The measured performances, before and after the intervention, are here compared.

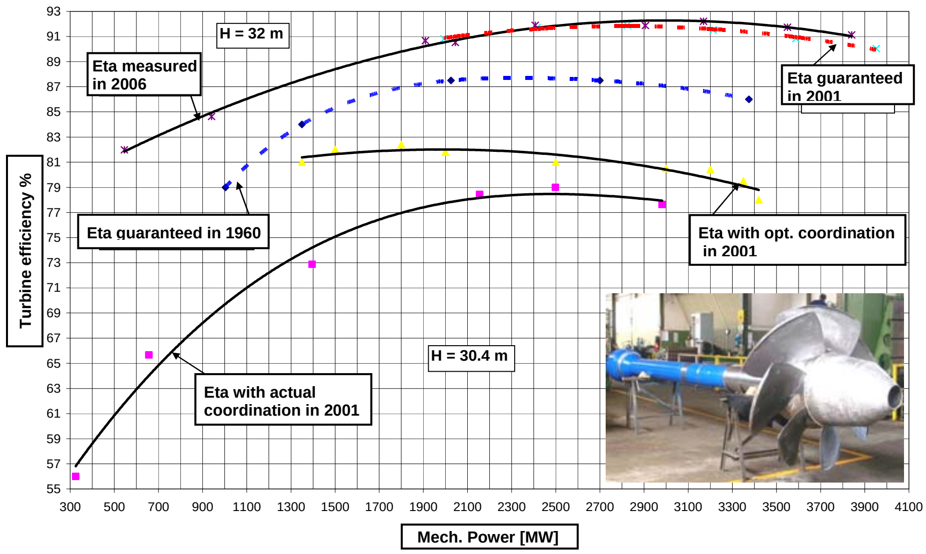

Fig 6 Partial renewal of Kaplan group

As it is shown in the above said examples, the level of performance improvement, that can be reached by a partial renewal, can rise up to 5%, depending on the obsolete machine conditions.
To complete what above described, some concrete aspects coming from the manufacturer experience, are here analyzed:

- Most frequent causes of hydraulic profile deterioration and their consequences on the machinery performance;
- Maintenance and surface protection techniques;

At the end some considerations on the Economic aspect and conclusion from the point of view of the manufacturer, are reported.

4. THE MOST FREQUENT CAUSES OF DETERIORATION FOR HYDRAULIC PROFILES AND THEIR CONSEQUENCES ON THE MACHINERY PERFORMANCE

Impulse (action) turbines

Wear on Pelton turbines damages particularly injectors and runner, with two main types of consequences on their performance:

- *Jet distortion at the runner inlet*

As known, the purpose of needle and nozzle is to concentrate the jet in a cylindrical and uniform shape in order to maximize the energy transformation in the runner. Wear on needle and nozzle causes a jet deformation which results in a decay of efficiency and possibly an appearance of cavitation.

This phenomenon was described and quantified already in 1931 during experiments of VA TECH HYDRO on a prototype in Switzerland: A test nozzle was connected to the manifold of the HPP Handeck in order to measure the jet deformations from different upstream bends, nozzle geometries and obstacles.

Fig. 7 – Eroded needle

In worn nozzles, the boundary layer is thickened and disturbed, due to an increased waviness of the walls in the nozzle pipe and nozzle mouth.

This effect was simulated using a ring fixed inside of the nozzle pipe (see Fig. 8). At the test head of 400m, this obstacle caused a dramatic increase in jet divergence angle as shown in Fig. 9.

It has also been demonstrated by numerical simulations and model tests, that obstacles as torpedo ribs can cause a substantial deformation of the jet surface.

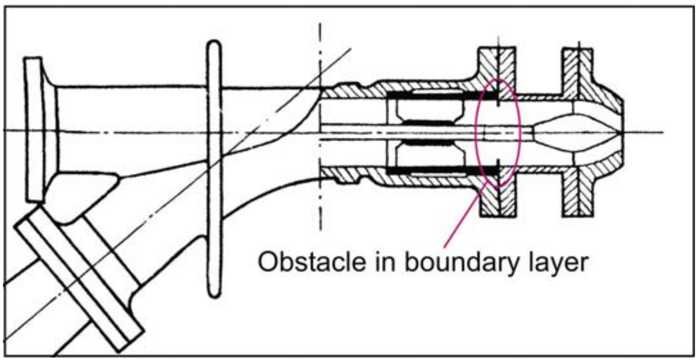

Fig. 8 – *Design of a prototype test nozzle with obstacle in the boundary layer of the nozzle pipe.*

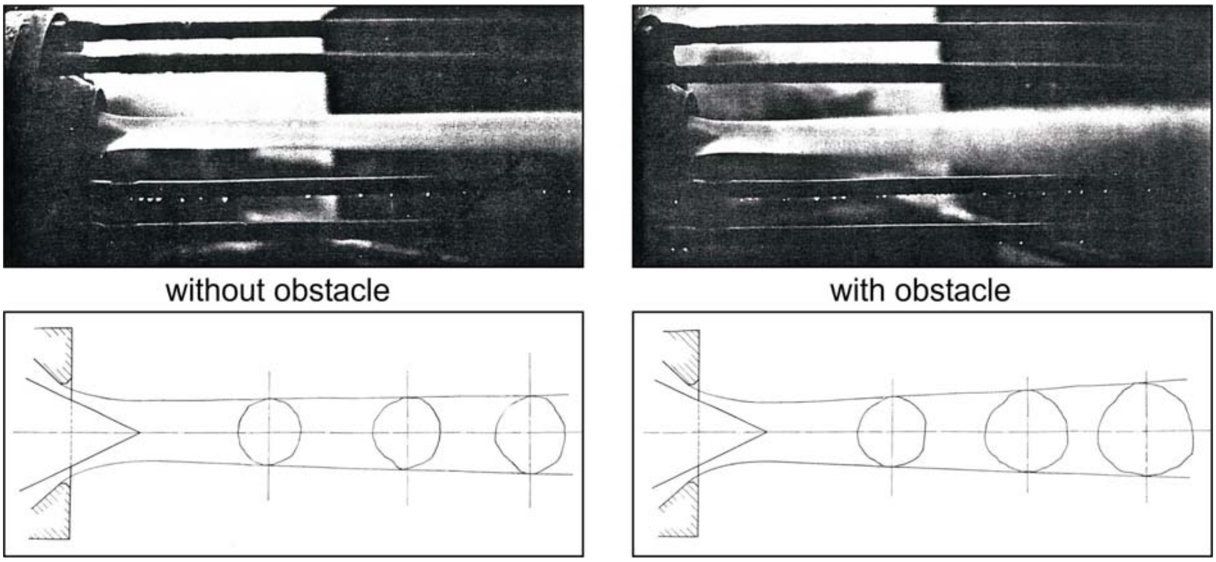

Fig. 9 - Photos and sketches of the resulting jet without and with obstacle.

- *Active surface deformation*

The losses due to increased roughness of active bucket surfaces are higher and therefore worsening energy transformation.

They are increased due to…

  - increased friction losses from waviness of the worn surface and
  - an offset from the optimum hydraulic profile.

Fig. 10 – Eroded buckets

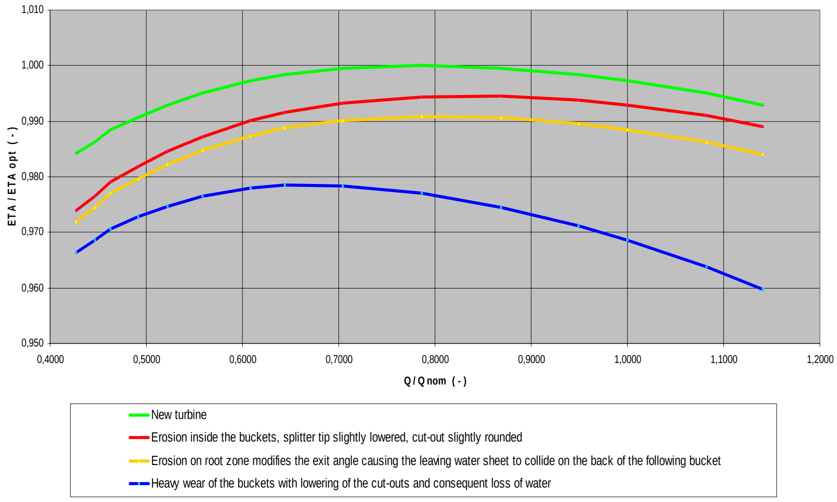

Fig. 11 - Influence of buckets erosion on efficiency of a Pelton turbine

Reaction Turbines

Also in absence of peculiar wear phenomena, the performance of a turbine is destined to degrade as years go by.
At side is reported an example of performance decay , measured on horizontal 13 MW Francis turbine after 20 years of operation.
In presence of particular wear conditions, for instance sediments transported by the water, mainly three phenomena appear:

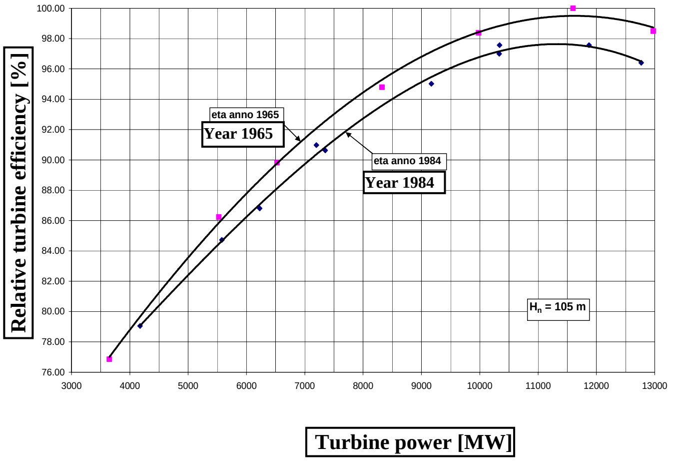

Fig.12 – Decay of efficiency produced by wear

- *Wear of wicket gate components with increase of clearance between wicket gate and wearing plates.*

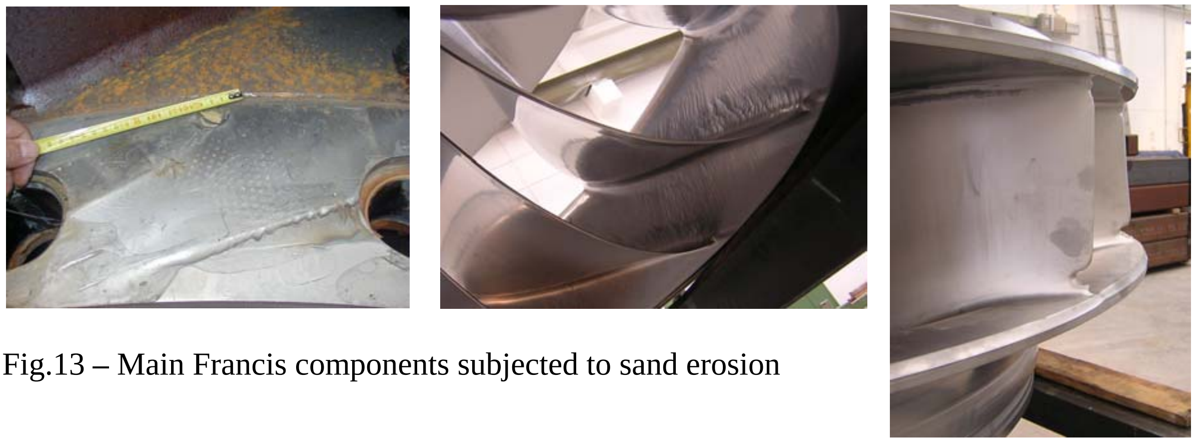

Fig.13 – Main Francis components subjected to sand erosion

The gap increase between wicket gate and wearing plates produces an increase of volumetric losses and vortices, thus disturbing the flow at the outlet of the distributor and therefore causing decay of the energy transformation in the runner and efficiency loss.

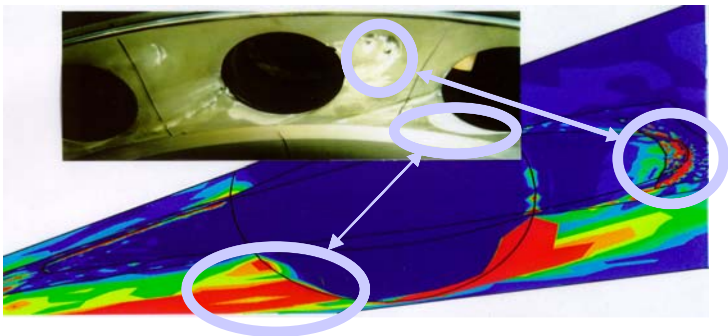

Fig.14 - Numerical simulation of the flow distortion caused by the increase of clearance between wicket gates and wearing plates and effects of concentrated erosion on the runner (dx).

- *Increase of efficiency losses as a consequence of surface roughness increase in the runner channels.*

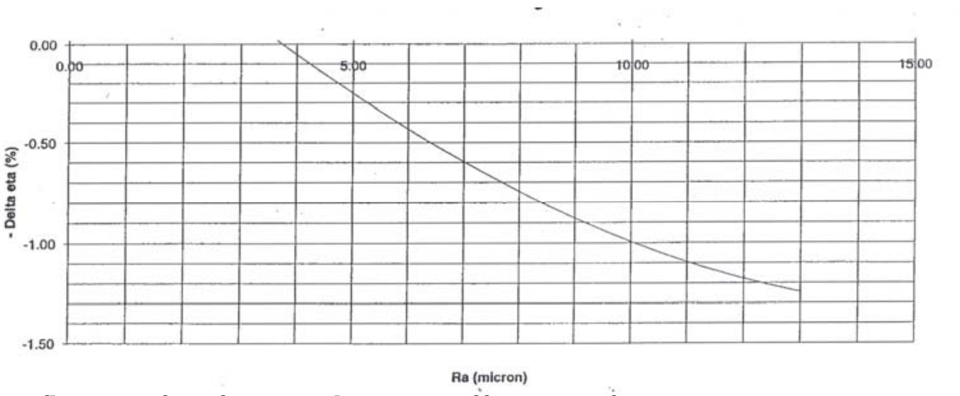

Fig.15 – Influence of surface roughness on efficiency of a Francis runner

- *Increase of volumetric losses through the seal rings, whose amount can be deduced through specific calculation programs in function of seal gaps and surface conditions.*

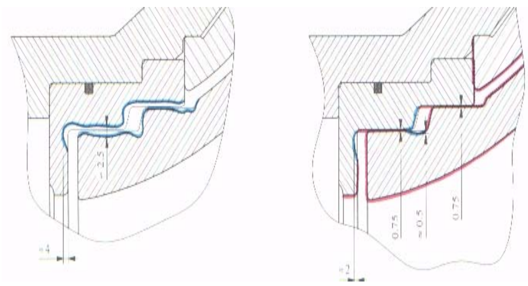

Fig 16 Typical sand erosion on the Francis seal rings

5. *IMPORTANCE OF SERVICE AND SURFACE PROTECTION TECHNOLOGIES*

In presence of abrasion it is of primary importance a timely maintenance for avoiding the progressive advancing of wear or the accumulation of phenomena such as abrasion and cavitation.

Actually, it has been experienced that, with increasing of the surface roughness, the wear phenomenon tends to accelerate, due to increase of flow turbulence in the boundary layers in contact with the wet surface (see diagram Fig 17).

It was also observed that consistent abrasion phenomena tend to couple to cavitation, due to modification of the hydraulic profile; it can also happen that the cavitation becomes not evident at a visual inspection because constantly "ground" away from abrasion.

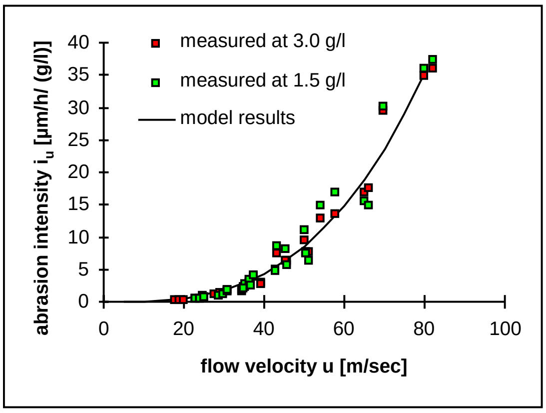

Fig 17 Abrasion rate versus flow velocity

Concerning this, it was formed in 2005 a working group in IEC circles, who is preparing a guide for the problem of erosion due to suspended solid particles in order to distinguish its effect from that of cavitation, supplementing in this way the document IEC 60609-1 . [**5**]

For the above explanation, we advise, whatsoever is possible, to intervene for restoring the smoothness of the wet surface by simple polishing, before being excessively altered by the wear process.

The resulting advantages are the following:

- Maintenance intervention more simple and less expensive, in which the respect of the original hydraulic profile results relatively easy.
- The performance of the machinery will be easily recovered.
- The risk of incipient cavitation will be avoided.

Naturally, after repeated polishing interventions, the restoring of the thicknesses by means of appropriate welding procedures will become a necessity.

With regard to the surface protection technologies, several options are now available on the market, each one of them suitable for different wear situations:

- Utilisation of particularly tenacious materials, as stellite, for the integral construction of components or as a coating (stellitization) for larger dimensions. Stellite is suitable for the fabrication of simple geometry components, indicated in presence of solids transported by the water. Typical case the construction of needles and nozzles for Pelton turbines.
- Surface coatings with wear resistant materials [**6**], such as ceramic compounds and tungsten carbides. At present the market offers quite a lot of these products and different application technologies. The application of these technologies is limited by the accessibility for the application and by the presence of solids transported by the water.

In the following table a comparison of the abrasion resistance for some commercial materials is reported.

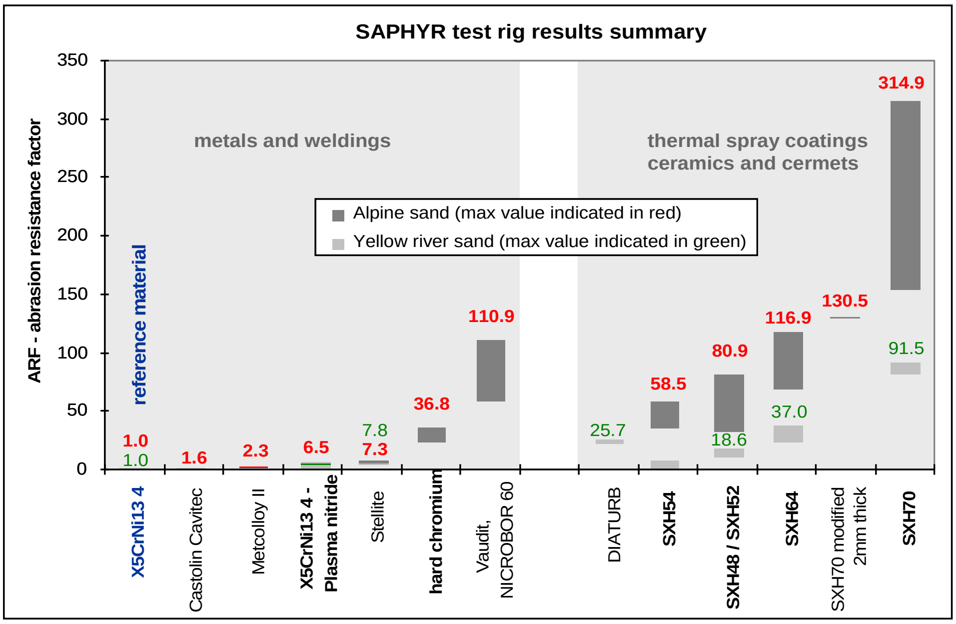

Fig 18 Comparative abrasion resistance for some commercial materials

For the surface coatings with wear resistant materials the following indications can be given:

For **Pelton** turbines, in presence of minor wear phenomena, it results sufficient the coating of needles and nozzles, which is relatively inexpensive and helpful for preserving the quality and the compactness of the jet, essential in order to keep the performance. Coatings on the active surface of the buckets are economically indicated only in presence of more consistent wear phenomena.

For **Francis** turbines the situation is more various, considering the greater complexity of the affected components. The following indications can anyway be given in growing order of economical impact and therefore suggested for more and more important wear phenomena:

- Coating of stationary and rotating seal rings
- Coating of wicket gate wearing plates
- Coating of wicket gates
- Coating of inlet and outlet edges of the runner, which are normally the zones more affected by erosion wear.

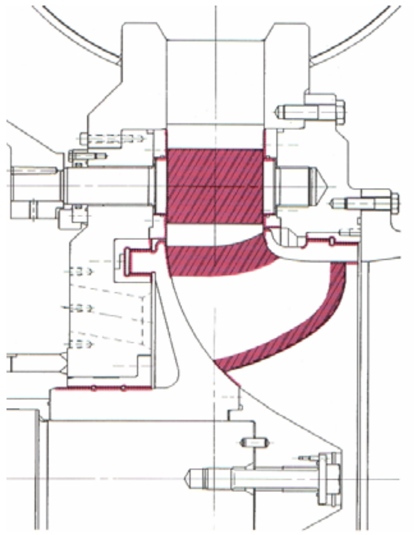

Fig 19 Francis components affected by sand erosion

We draw the attention to the fact that, for the quality of the coating and therefore for its efficacy and time duration, it is very important to respect the constant parameters of application, e.g. thickness, angle and velocity of application.

Fig 20 Coating on Francis components

For components in which the water velocity is lower (spiral case, stay ring and drat tube), are successfully used special paintings particularly "gummy", to be applied with high thicknesses.

6. ECONOMIC CONSIDERATIONS AND CONCLUSIONS

We recognise that, the more or less extended refurbishment of the plants depends, besides from the ageing conditions of the machinery, also, and in a decisive manner, from the related legislation, which can impose repowering for the extension of licences or allow attractive incentives to the production by means of Green Certificates.

We want here to point out as in the maintenance strategy of hydraulic machinery it should be taken into account a "TOTAL COST of MAINTENANCE" which is the sum of:

- Real maintenance cost
- Outage cost during maintenance
- Cost of performance decay

The variety of problems connected with machinery types, water characteristics , kind of operations, has been highlighted as well as the possible solutions suggested by the maintenance and rehabilitation techniques at present available.

We add that it can be helpful the monitoring of parameters affecting the operation quality, both for safety (vibrations) and for performances [**7**] and [**8**].The modern automation systems allow the monitoring of a series of operating parameters such as: head, discharge and power, from which it becomes easy to calculate in real time the turbine and unit efficiency without excessive cost increase.

This opportunity should not only serve for optimization of the maintenance intervals, but also in order to minimize the performance losses between two subsequent maintenance programs.

From the above derives that the economic evaluations should be carefully studied for each plant in order to optimize the kind and consistency of intervention to be chosen and the result to be reached.

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