IGHEM – Kempten 2000

Evaluation of the benefits of turbine refurbishment by means of Index Test Method
Reliability of results and Problems in Applications

Fabio Fausto Muciaccia - Field Tests Engineer
Voith Riva Hydro S.p.A. - Via Fosse Ardeatine 7/9 – Cinisello Balsamo
20144 Milano Italy
Tel. +39-2-4146394
Fax +39-2-425749

Randall B. Walter Senior Mechanical Engineer (case 1)
Chelan County Public Utility District - Wenatchee
Washington U.S.A.
Tel. +39-51-527759
Fax +39-51-6574650

SUMMARY

The Index Test procedure is still widely used to have a comparative estimation of the turbine efficiency especially when it is necessary to check the benefits due to the refurbishment of the unit. Even if new techniques with computerised data acquisition systems are becoming more easy and rapid than they were in the past, Index Testing still remains the most easy way to obtain reliable information of the performances in big low head units and in all those small hydroelectric power plants where a complete efficiency measurement is too expensive.
After a brief description of the different procedures and relevant theories related to the application of this method, some experimental tests are presented. The description of the obtained results is used to report some general evaluations and to focus the attention on some of the most common problems that could arise.

Evaluation of the benefits of turbine refurbishment by means of Index Test Method
Reliability of results and Problems in Applications

Fabio Fausto Muciaccia	Voith Riva Hydro S.p.A. - Milano
Randall B. Walter	Chelan County PUD Whenatchee

1. INTRODUCTION

During efficiency tests at site is generally quite difficult to obtain reliable measurements of the discharge; the Index Test method has the aim to overcome this problem using more simple devices that can only give relative values of discharge using measurement that are related to the flow by mean of proportional laws whose proportionality constants are unknown.
As a consequence, the only relative efficiency values are obtained unless, in some way, the proportionality constant is determined. This result could seem quite minimal but if, for instance, the goal of the test campaign is to analyse costs and benefits of a refurbishment, Index Tests represent the easiest and less expensive way to obtain this target.
As many different measuring techniques can be utilised within the index method, practically there is always the possibility to perform such a kind of test without significant additional costs. This means that in normal cases the cost of an index campaign is one third or less than the cost of an absolute efficiency campaign.
In some cases, nevertheless, absolute values of efficiency could be obtained if there is a possibility of defining the proportionality constants using primary methods or witnessed model test results.

In small hydroelectric plants the total low cost of the plant makes testing activities a non-negligible percentage of the total cost, therefore index test is in fact the preferred technique to verify the performances. In this direction is moving the new specific IEC code

In double regulating units (i.e. Kaplan turbines), Index Tests is also the best way to define the cam correlation between the two independent mechanical devices (blades and gates in Kaplan) to obtain the best efficiency conditions.

Any device able to give a reliable measurement of a quantity whose relationship with flow is theoretically or experimentally known can be used for Index Tests.

The most used Index Test techniques refer to differential pressure measurements (venturi, Winter Kennedy taps etc.), mechanical position of the flow regulating device (needle or gate position), official primary flow measurement device when used outside code requirement. (reduced number of current meters etc).
However, despite the reduced purposes of this test, a deeper investigation on the theory behind each specific application may help in detecting errors that can be deceitful and difficult to identify.

2. DESCRIPTION OF THE METHODS

Theoretical principles

Differential pressure - Winter Kennedy

The Winter Kennedy taps are located in a section of the spiral case. As described in the IEC code. The differential pressure measured between the external (tap 1) and the internal (tap 2) tap2 is supposed to be related to the discharge trough the following relationship.

$$Q = k \cdot \left(2\frac{\Delta p}{\rho} \right)^x$$

Where the value of the exponent ***x*** is theoretically equal to **0.50**. The code itself describes the possibility that the experimental value of the exponent may change from 0.48 to 0.52.
This relation comes from the assumption of validity of the free vortex flow within the spiral case (if the spiral case is so designed), that leads to

$r \cdot V = const. \Rightarrow r_1 V_1 = r_2 V_2$

and from the approximation that the flow is equally distributed through the wicket gate so that the discharge in passing in a section of the spiral case defined by the angle φ respect to the entrance is related to the total discharge by

$$Q_\varphi = Q\frac{\varphi}{2\pi}$$

If the total energy in the section where tap1 and tap 2 are located is constant the Bernoulli law correlates pressures and velocities the analytical conclusion brings to

$$Q = \frac{r_1 \cdot r_2}{\sqrt{r_1^2 - r_2^2}} \frac{2\pi}{\varphi} \left[2\pi \left(R - \sqrt{R^2 - C^2} \right) \right] \cdot \sqrt{2g \cdot \Delta h} \Rightarrow Q = k\sqrt{2\frac{\Delta p}{\rho}}$$

where C is the equivalent radius of the section in which taps are locate and R is the distance from the runner axis to the center of the mentioned section. As already mentioned the theory gives an exponent of 0.50 not strictly verified in real cases.
The mentioned relation also gives the information that the constant ***k*** is dimensionally a surface and in the similitude transposition between model and prototype the constant should vary inversely with the square of the dimensional ratio. This is verified only with fully homologous taps and if the head ratio is not very high.

Differential pressure - Venturi taps

According to the Bernulli law assuming that the total energy between two sections remains the same, and also the discharge is the same, the increase of the kinetic term corresponds to a decrease of the pressure term so that

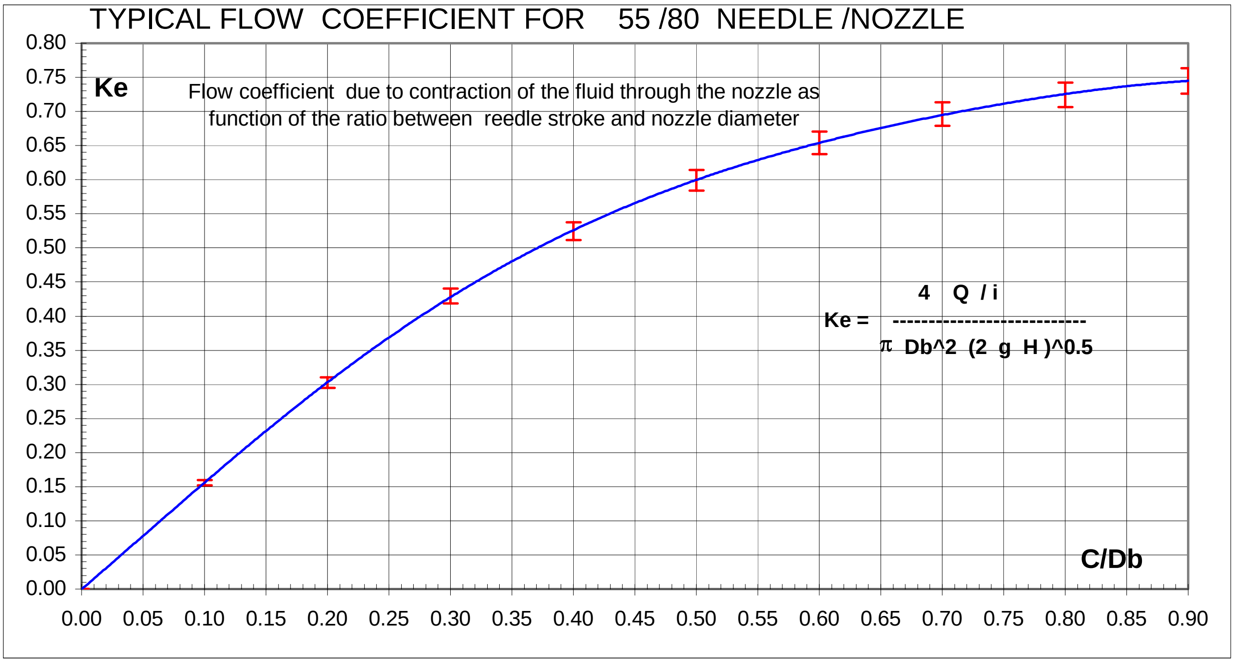
$$\frac{p_1}{\rho_1} + V_1^2 = \frac{p_2}{\rho_2} + V_2^2 \Rightarrow V_1^2 - V_2^2 = \frac{p_2}{\rho_2} - \frac{p_1}{\rho_1} \Rightarrow Q^2 \left(\frac{1}{A_1^2} - \frac{1}{A_2^2} \right) = \frac{p_2}{\rho_2} - \frac{p_1}{\rho_1}$$

The following simplifying hypotheses stay behind these relationships:
1. The effects of the water compressibility and of the penstock elasticity, as well as those of the compressibility and elasticity of the connections to the transducers are negligible.
2. The penstock load losses are almost quadratic with respect to the water velocity.
3. The fluid motion inside the measurement section should be considered as monodimensional (the velocity vectors in one section perpendicular to the penstock axis are

simplified with a direct vector according to the penstock axis and with a modulus equal to the mean velocity)
Differential pressure: Measurement method

From an operational point of view, two measurement sections, connected through manifold to a differential transducer, are prepared.
The differential transducer connecting pipings must be, as short as possible, stiff, and their internal diameter must be of at least 8-mm. Particular care should be put in removing the air present inside the circuit. Some experimental investigations have been performed on the influence of these pipings and on possible alternative installations.
The selection of the transducer is quite important considering the very low differential pressure compared to the average absolute pressure, in these applications the accuracy and the stability of the sensors are predominant respect to frequency response.
Due to these considerations, even small deviations from perpendicular of the orifice axis to the wall or presence of rough surfaces all around the tap may cause relevant deviations in the measured values and may also have different weight at different load conditions.

Stroke measurements
Generally speaking the position of the regulating device is related to the regulated flow through a known relationship. In reaction turbines the pressure field downstream the wicket gate is also due to the presence of the runner. In these cases the relationship between opening and discharge is typical of the total turbine assembly (case, vanes, runner etc.). This means that the mentioned relationship can only be deduced from model tests.
In action turbines a first approximation allows to consider flow independent from the runner and for this reason the nozzle behaviour may be studied separately and its flow coefficient defined both using analytical and experimental approach.



The assumption is that the flow pattern at the injector entrance are fully developed and not distorted: The fluid motion at the entrance should be considered as monodimensional (the

velocity vectors, in any section perpendicular to the injector axis, can be represented by a single vector according to the axis and with a modulus equal to the mean velocity)
The normal industrial needle/nozzle design allows the jet to behave according to Torricelli law $V = \sqrt{2g \cdot h}$
The discharge is then obtained as

$$Q = A_c \cdot \sqrt{2g \cdot h} = k_e \frac{\pi D_b^2}{4} \cdot \sqrt{2g \cdot h}$$

Where $\boldsymbol{A_c}$ is the section of the jet at the exit of the injector. The ratio of this section respect to the total nozzle area (flow coefficient) and is function of the needle stroke and is typical for each combination of needle and nozzle angles.

3. MEASURED CASES

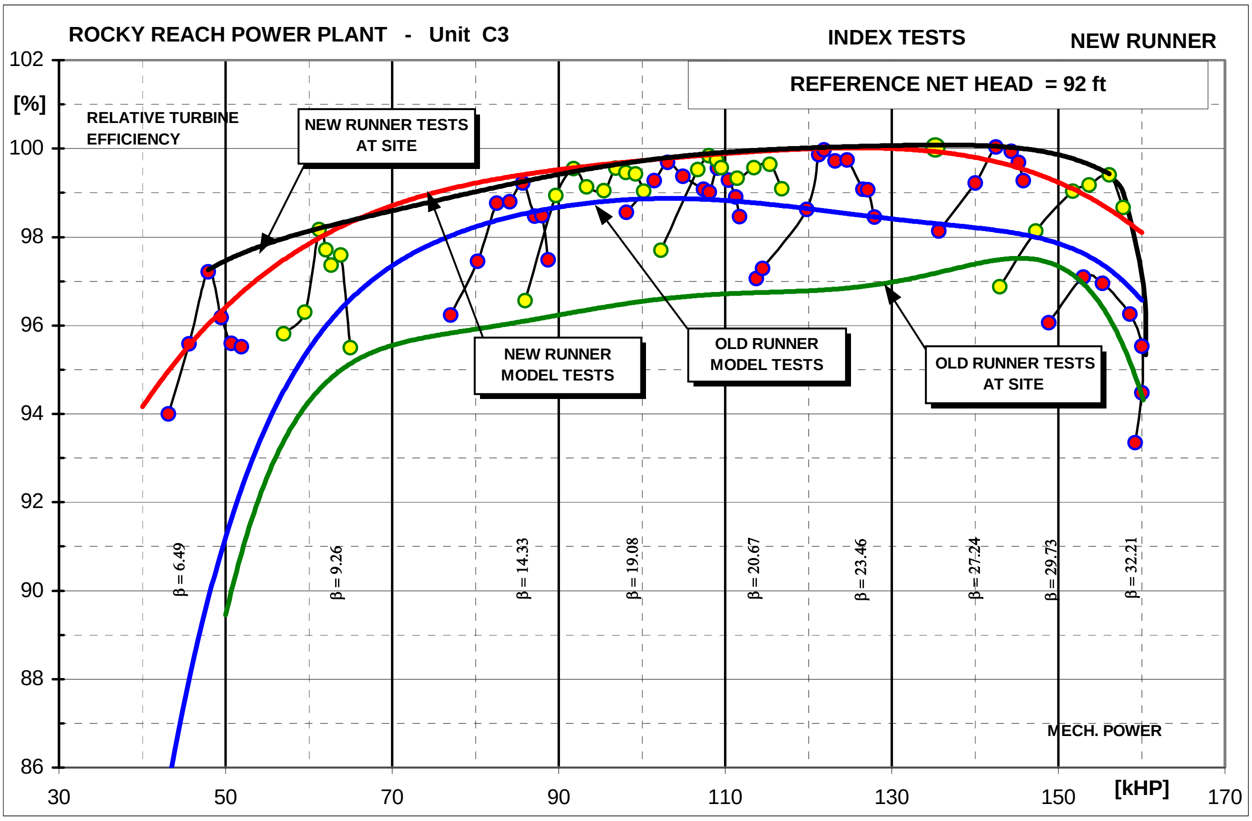
This paper deals with the efficiency measurements performed on few different powerplants where the index tests have been used with different purposes. The results have been analysed (and when possible compared) from the point of view of the reliability of the method in order to define the causes of possible errors.

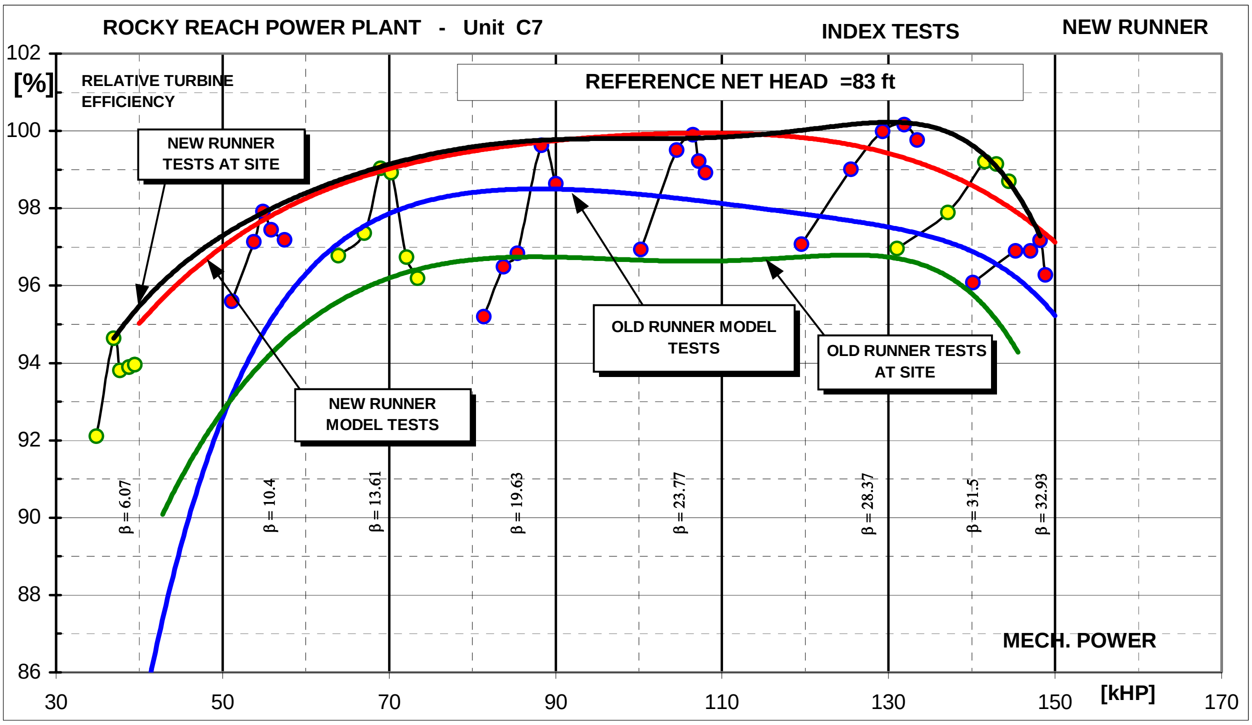
Case 1*:Vertical shaft Kaplan turbine*
Characteristic data:
H = 30 m Q = 460 m^3/s P = 125 MW

Two-index test campaigns were performed before and after a complete refurbishment of the power plant in order to evaluate and quantify the benefits of this activity. Both old and new hydraulic design had been tested in laboratory using two fully homologous hydraulic models but some effect due to the specific dam and powerhouse location was expected.
As far as the powerhouse has quite high head variability, and for technical reason was not possible to perform both old and new runner tests with the same constant head, a specific procedure was adopted to analyse and compare test results.

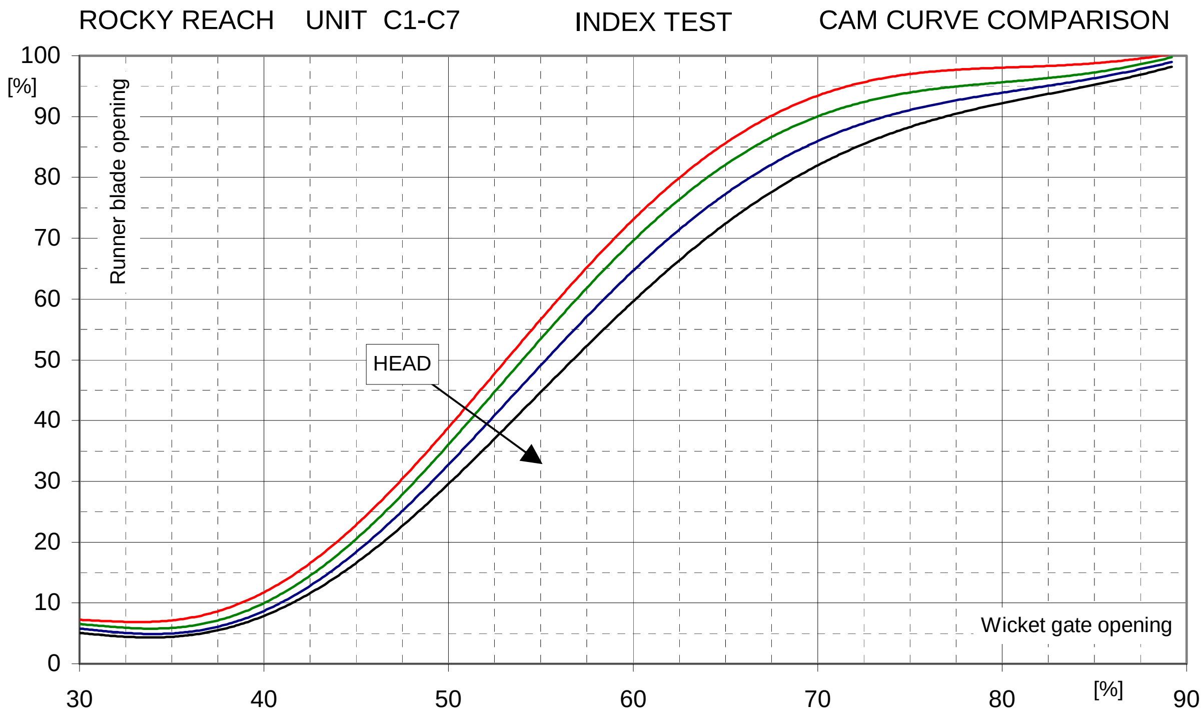
1. The new runner model test results were used to calibrate the Winter Kennedy constant and exponent. The adopted basis was a section deduced from the model digital hill diagram and obtained with the same test conditions of the site tests.
2. The same constant and exponent were used to process old runner index data, and the results were compared with the relevant model digital section. A curve of the difference of index and model efficiency was obtained
3. A digital section of the old model results was calculated with the same test conditions as the new runner index test. To the obtained curve, the curve of the difference obtained at the previous step was added. The result was an estimated old runner index curve with the same test conditions of the index tests performed on the new runner.
4. Finally homogeneous index results were compared

The test performed on six of the seven units show a similar behaviour. The index curves of both new and old runner show a small depression in correspondence of 7/10 power while the efficiency looks higher at full load. This pattern could be either effect of the tap location or a real efficiency shape due to the forebay/power house/afterbay interaction.



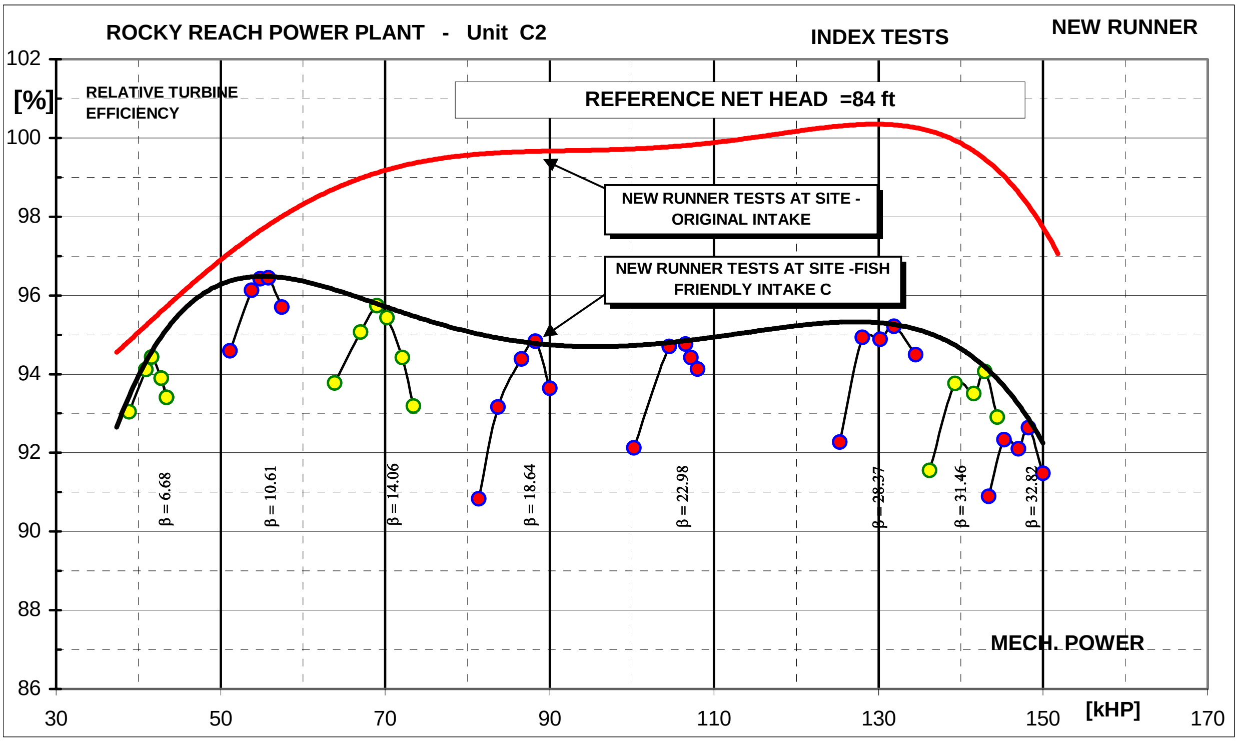


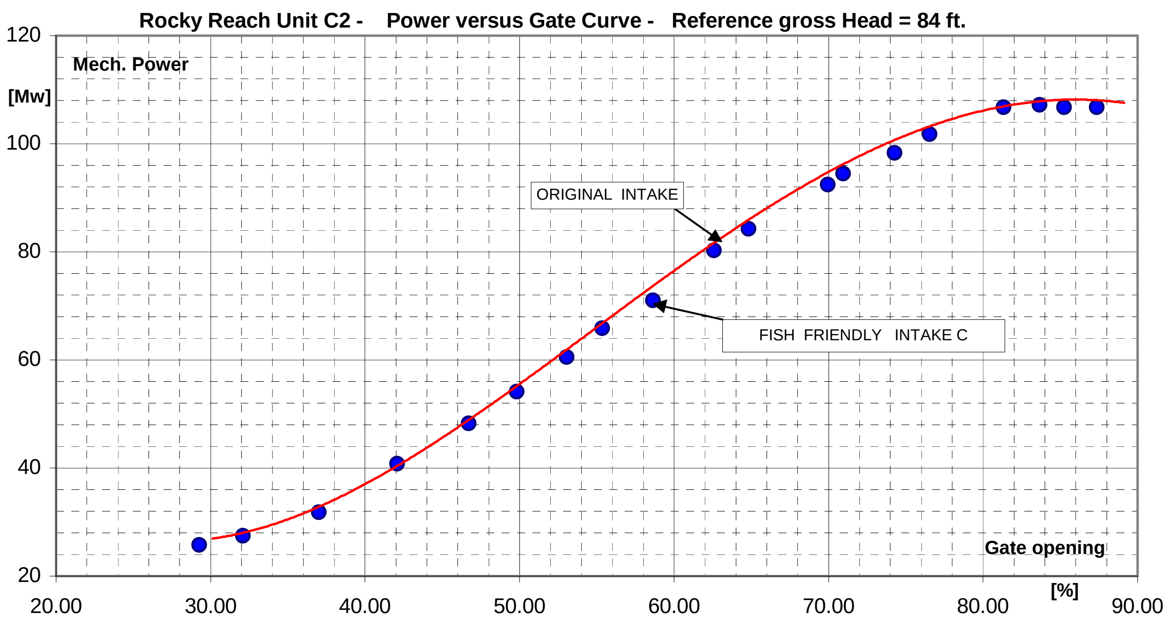
In any case the benefit of the refurbishment campaign looks more consistent than expected from model tests, in fact old runner model tests refer to the original hydraulic design while the actual turbine conditions were somehow deteriorated from the original.



The tests also allowed defining the best cam correlation between runner and wicket gate. After the completion of six over the seven units the index test campaign gave a full 3D matrix able to optimise efficiency, dynamic behaviour and noise at each operating head.

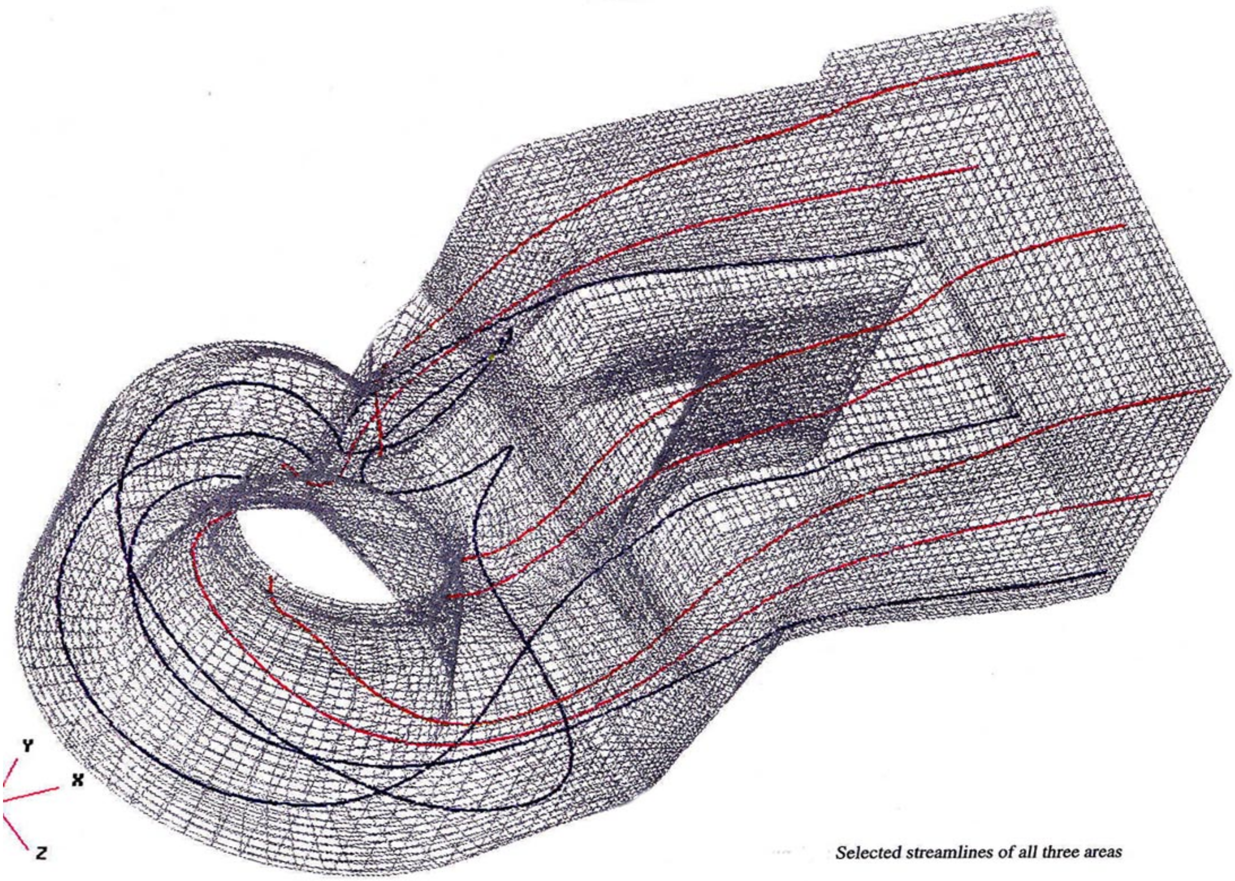
Due to the importance of wildlife protection in NW U.S.A. and to the economical interest towards salmon hatcheries a wide campaign to develop a fish safe power plant was conducted. This also caused some consistent changes in the hydraulic profiles of the runners. An important part of the study was finalised to develop a new turbine intake that could prevent juvenile salmons to fall into the turbines during their migration to the sea.
The intake could have had a relevant impact on the turbine efficiency and a wide index test campaign was scheduled to define this aspect. Another aim of the campaign was to determine if the different intake could require a different runner vs. wicket gate cam correlation.
Three different intake configurations were tested; Index test showed dramatic impact on the efficiency. The measured efficiency drop with the complete intake was in the order of ≈5% while the pressure loss due to the obstruction was less than 1%.
Even if new probes and taps were installed the Index Method was found not adequate to analyse this kind of change. A more deep evaluation of the results, even with the uncertainty due to a continuos head change, shows that the maximum power had a reduction that confirms the numbers derived from the friction losses.
As seem unbelievable that obstructions may cause an increase of flow the only answer is that the new intake caused a completely different flow distribution within the spiral case that do not allow to compare the results.
On the other end the cam correlation obtained during the tests with modified intake may be reliable, as the flow patterns may not sensibly vary during tests performed at constant blade angle. In any case the weight of these results were not considered enough to modify the cam derived from several test campaigns.





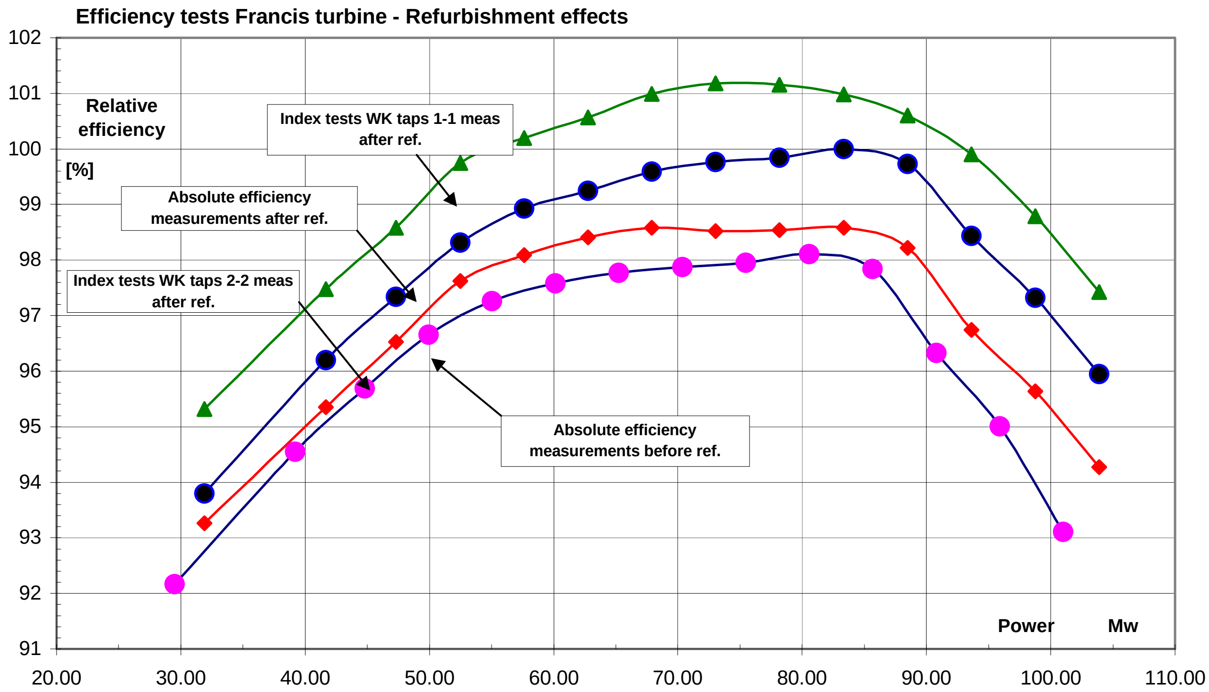
In the spiral case inside a Kaplan turbine the flow patterns are deeply influenced by the intake. In fact water may move following very odd ways, quite different in different load and head conditions. A numeric study of a specific spiral case made by the Stuttgart University gives an impressing picture of this behaviour.

Nevertheless the Index tests performed at site in parallel with different techniques were very reliable at least under the aspect of the cam correlation.



***Case 2**: Vertical shaft Francis turbine*
Characteristic data:
H = 68 m Q = 160 m^3/s P = 100 MW

Two different sets of Winter Kennedy taps have been installed and the results compared with simultaneous measurements using the Pressure Time method.
Two different test campaigns were performed, before and after the refurbishment of the units. The pressure time gave the result of an increase of the top efficiency of the unit of approximately 2% (no changes to the basic runner design were applied) while the two Winter Kennedy taps gave contradicting results: the higher differential taps were showing 4% increase in efficiency while according with the lower differential taps the benefit was only 1%.
The calibration of the Winter Kennedy coefficient using the discharge obtained from the Pressure Time measurement was in agreement with model tests results during the second test campaign while remarkable differences appeared in the results obtained during the first campaign.
The difference was due to important phenomena of corrosion in the spiral case that led to the decision of sanding and painting the wet passages. The action caused influences on the differential pressure even if the taps had a Φ40mm stainless steel area.



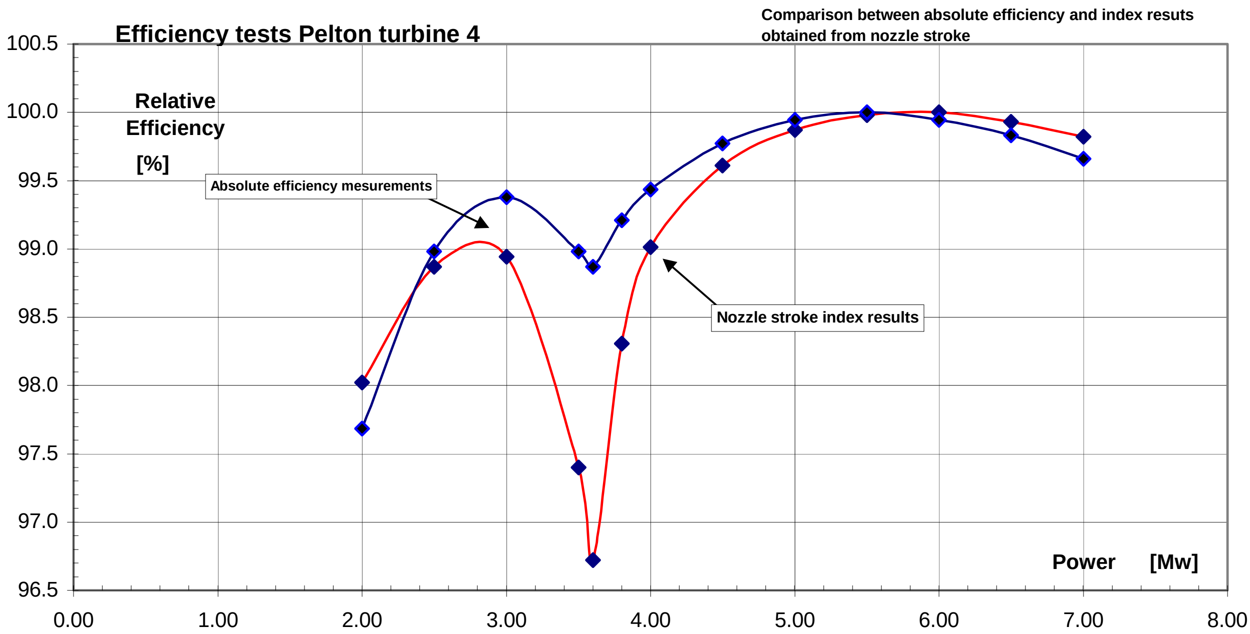
***Case 3:** Vertical shaft Pelton turbine*

Characteristic data:

H = 220 m Q = 3.60 m^3/s P = 7.0 MW

Two different campaigns of tests were performed on a four jet Pelton turbine where a new runner with high performance profile was utilised. Index tests were performed both with old and new runners while with new runners also current meter tests have been used.

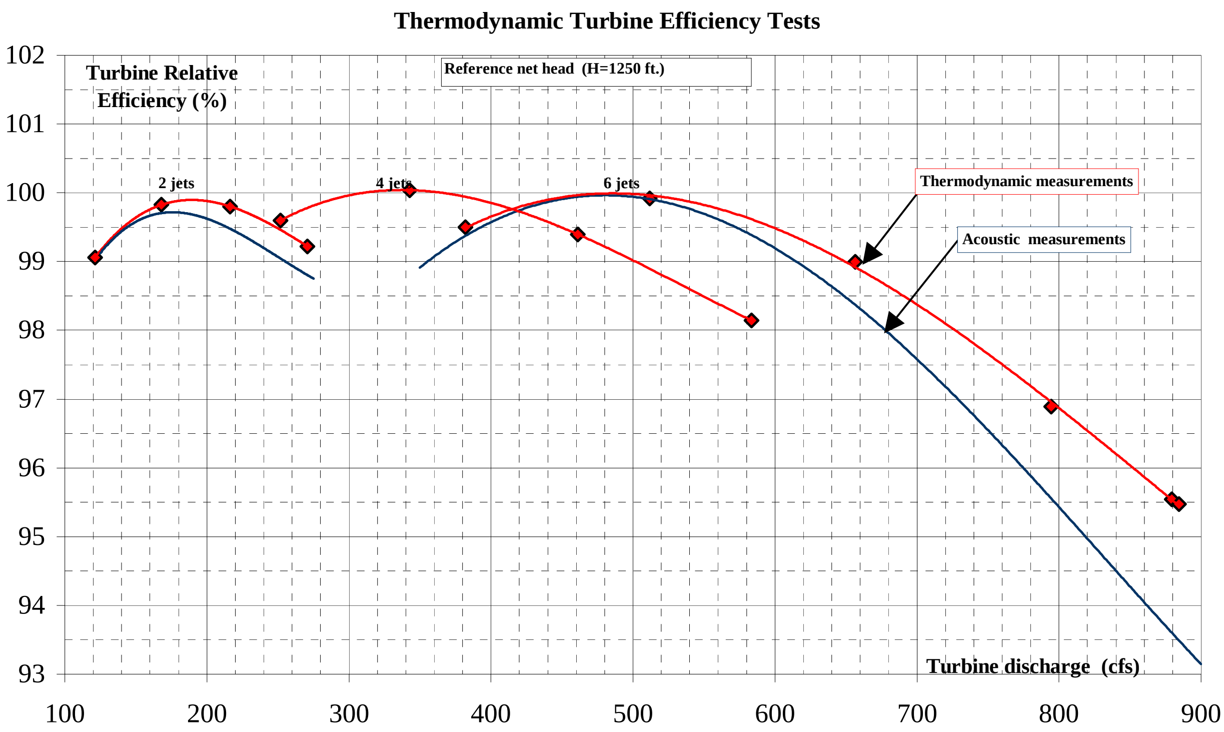
The used index procedure is the evaluation of discharge by means of nozzle stroke and model derived flow coefficient.



Both old and new runners show a quite anomalous efficiency curve with a deep drop of the relative efficiency at approximately 7/10 of the rated discharge. The power curve versus opening also presented a flexes but less important in amplitude. The comparison between index measurements and current meter also show a deviation of the discharge versus opening that means a discrepancy of the flow coefficient respect to model and theoretical expectations.
The result is that the actual efficiency drop at partial load is not as big as it was supposed from index tests. It is necessary to point out that in this case the same error was present both in new and old runner tests and the evaluation of the benefits of the runner replacement was reliable

Case 4: *Vertical shaft Pelton turbine*
Characteristic data:
H = 695 m Q = 11.50 m³/s P = 72 MW D = 1.880 m.

Three different test campaigns have been performed on the mentioned six-jet unit using parallel acoustic and thermodynamic measurements. The acoustic method, according to the International Code IEC 60041, is still an index procedure. In any case only four paths on a single plane were used. So even taking into consideration the activity of IEC WG 25 the obtained efficiency should be considered as Index as the measurement do not fulfil all required technical prescriptions.
The thermodynamic measurements were performed using two probes at the turbine inlet and 6 measuring points at the outlet and did not show any specific problem. It can be considered a primary method.
All three-test campaign made by different terms with different equipment show a remarkable difference between thermodynamic and acoustic methods especially at full load.



The actual top efficiency was almost identical both thermodynamic and acoustic show a consistent efficiency drop at full load. The acoustic method had an efficiency approx. 1.5% lower than the thermodynamic at the maximum nozzle opening.
In this specific case the acoustic results were not so excellent even if used only as index. The shape of the curve has been deeply changed. The causes of the problems of this application consisted in the too wide angle between sensors plane and penstock axis and presence of a disturbing bifurcation approx. 10 diameters upstream the measuring section.

CONCLUSIONS

The experimental data have highlighted from one side the flexibility of the Index Test method in terms of quickness of execution, easiness of installation and possibility of use.
When fully homolologous model tests are available this method can provide reliable values of absolute efficiency too. The main goal of index tests remains in any case to obtain reliable relative efficiency curves and to optimise blade and gate cam curve. This goal has a remarkable importance in those plants were the benefits of refurbishment must be verified. and the overall investment must be economically justified.
On the other side, the good results come out from a deep analysis, as detailed as possible, of all problems related to the method and to obtain this result is very important to focus what are the theoretical assumptions of each specific technique and verify if there is a possibility that the base hypothesis are not fully verified in the real case. .
Anyway, it is necessary to point out that even a careful and precise application of procedures and precautions provided by the current international codes is not enough to prevent said errors from occurring.
The index method, as well as all other methods aiming at determining the efficiency of the hydraulic machines, can supply extremely positive results only if the analysis is carried out in the light of experience and critical sense.

BIBLIOGRAPHY

[1] Codes I.E.C. 41. "Field tests to determine the hydraulic performances of hydro turbines, storage pumps and pump turbines"
Geneve - Nov. 1991.
[2] C Drioli "Esperienze su…controllo di portata in impianti idroelettrici a bassa caduta" Energia Elettrica 1980.
[3] Stuttgart University "Numerical calculation of flow patterns at the intake of Kaplan turbines"1994.
[4] F. Muciaccia - G. Rossi - V. Zanetti "Study of the dynamic behaviour of hydraulic machines" A.I.R.H. Symposium Stirling 1984.