PERFORMANCE MEASUREMENTS ON REFURBISHED TURBINES OF 770,000 kW AT GURI HYDROELECTRIC COMPLEX

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ABSTRACT

Performance measurements using pressure-time method have been carried out in the refurbished turbines of Guri, powerhouse 2 in order to verify guarantees established in technical specifications, manufacturer bid documents and model testing. A comprehensive discussion regard to the results obtained by means of two software utilized to calculate the discharge, both using the same logged data is presented, in order to demonstrate that increasing the integrating time limits is possible to get a enhanced feasibility of good results. Additionally, a brief comparison between model, prototype and original turbine efficiencies is presented in order to assess the reached benefits.

INTRODUCTION

A large rehabilitation project is being carried out in GURI hydroelectric complex, in Venezuela. As for others refurbishment projects, the main scopes are increase the efficiency and output improving the turbine hydrodynamic performance. The powerhouse nº2 has ten AC generators coupled to Francis turbines of vertical axis of 610 MW (original rated output) was put in service in the early eightieth. Afterwards, during maintenance shut-down was constantly advised that runners of these turbines have had significant damages due to cavitation pitting and erosion on the low-pressure side of blades close to the band, which impacted the reliability and others maintenance indicators. Also these continuous reparations produced important deformations and changes in profiles of the blades and of course fomented a drastic drop of the turbine efficiency. After that, CVG EDELCA decided refurbishes all of ten turbines in the PH2. GE Hydro (under the name of NORCAN Norwegian – Canadian Consortium) was selected to refurbish first five turbines.

In the period March – September 2003, the acceptance tests and performance measurements using pressure-time method in accordance with IEC-41 rev. 1991 of two refurbished turbines were carried out. Contractor has the responsibility to measure the turbine efficiency and deliver it to CVG EDELCA, however Hydro-Québec participated as witness and advisor and therefore, every one of each test run must be checked by Hydro-Québec and CVG EDELCA's engineers. At this time, these two prototypes are already put in service with 5600 and 3400 hours of operation respectively showing to be pretty smooth and stable everywhere in the continuous operating range.

Two different heads have been evaluated, one of this closer of rated net head of 134 m. The turbine efficiency has been increased close to 6 % at the best operating point and the measured weighted efficiency is 0,54 % higher than the guaranteed one. In fact, at the end of rehabilitation of all 10 units in PH2, it will be possible to add at least 1,400 GW-h/year to the firm energy generation of CVG EDELCA.

1. CHARACTERISTICS OF REFURBISHED TURBINES

On based of a complete CFD analysis, maintenance historical database, cost-benefits considerations, technical specifications and model testing results was considered to carry out an upgrading of the main hydraulic passageways in order to improve the performance and hydraulic behavior. GE Hydro proposal was selected to refurbish five turbines, this proposal include a new runner with negative rake angle blades (as described in [Ref. 1]), new guide vanes, modified stay vanes and inlet stay ring, and remove of draft tube fins. In addition, a new air admission system has been installed permitting that airflow reaches the draft tube passing through the shaft and the cone, in order to control airflow, a valves setup was installed at the top of generator shaft [Ref. 2].

Table 1: Characteristics of refurbished turbines

Runner Manufacturer:	GE Hydro (Norway) AS
Type:	Francis
Rated Net Head:	134,0 m
Rated Speed:	112,5 rpm
Rated Output:	715 MW
Maximum Output:	770 MW
Runner Blades:	15
Guide and stay vanes:	20

2. PROTOTYPE PERFORMANCE MEASUREMENTS

These tests were achieved just after commissioning tests, in which was the responsibility of GE Hydro to carry out this test permitting a complete participation of CVG EDELCA and its consultants. Statkraft Gröner AS was engaged by GE Hydro to measure the efficiency of refurbished turbines. Additionally, these tests were also followed and witnessed by technical specialists from Hydro Québec, which was engaged by CVG EDELCA like special advisor. The generator efficiency measurement, which was the responsibility of CVG EDELCA, was achieved at the same time. The turbine efficiency was measured at night and the generator efficiency was measured in daytime through calorimetric method according IEC 34-2 and IEEE 115-1995 rev. 2002. Total uncertainty for generator efficiency measurements was determined in ±0,45 %.

To build the efficiency curve, more than 45 measured points were used. In order to check the repeatability of the measurements, at the start of each measuring session a selected operation point close to best efficiency point was used, this test-run was measured 7 times for units 19 and 13, finding that the measured efficiencies were repeated within of 0,35 % and 0,9 % for units 19 and 13 respectively. Herein is opportune to mention that during the unit 13 measurements, upstream level variations were larger than during unit 19 due to rainy season.

Figures 1-a) and 1-b) shown an assessment between guarantees (model efficiencies with IEC step-up, IMHEF), measured prototype efficiencies (pressure-time method) and original turbines efficiencies. At rated net head, the measured weighted efficiency is 95,79 % close to 0,54 % higher than the guaranteed weighted efficiency. According to most recent correction of the efficiency measurement report, the highest efficiency is 96,42 % for turbine flow of 487,4 m^3/s at rated net head. The uncertainty analysis concluded that the total uncertainty over the turbine efficiency measurements was less than ±1,1 %.

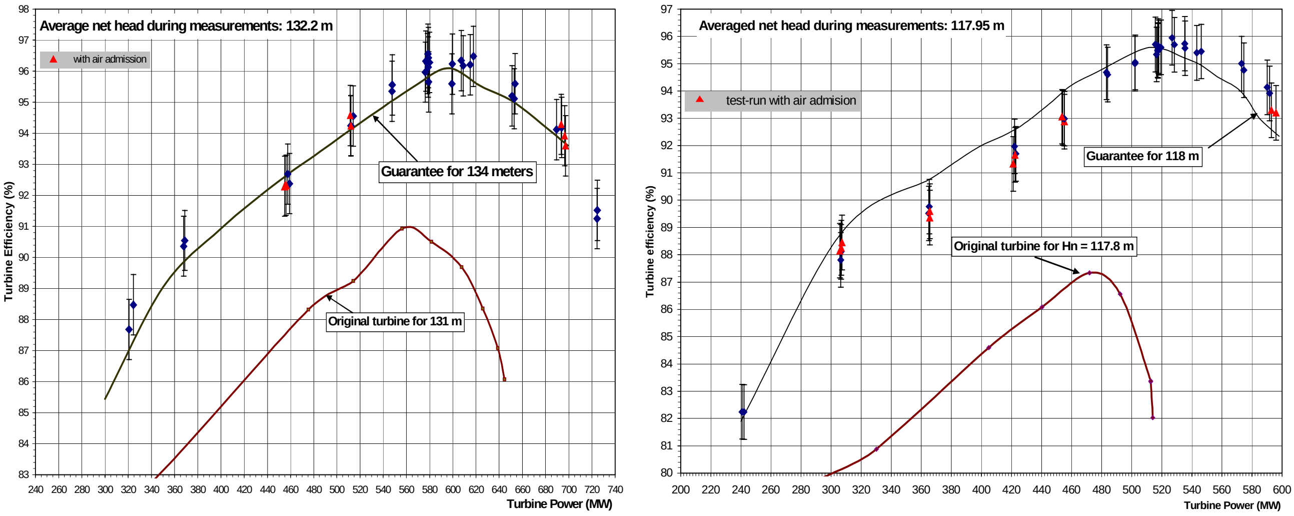


Figure 1. Prototype efficiencies curves measured at a) Net head 132 m. b) Net head of 118 m

3. DESCRIPTION OF THE MEASUREMENT (Calibration and Equipment Set-up)

The following equation gives the turbine efficiency in function of the turbine discharge, power output, net head and efficiency:

$$\eta_t = \frac{100000 \times P_{gen}}{\rho g Q \times Hn \times \eta_{gen}}$$

It is therefore important to determine with a good accuracy the discharge measurement. The Pressure-Time method was used to measure the turbine discharge and was well described in the IEC 41 Test Code [Ref. 3]. The principle of this method is based upon second Newton's law and his corollaries of variation of the cut-off pressure versus the allowed times between 2 specific sections of the penstock.

The discharge is calculated by integration of the pressure differential between two sections during the closing time of the wicket gates. The leakage flow through the wicket gates after the closure was calculated by measuring the drop of the water level in the access hole above the head gate, with an uncertainty less than ±0,2 %.

<u>Calibrating Equipment</u>

The Testing equipment was be calibrated before and after the pressure-time test, in situ and/or in a certified laboratory.

The generator output was measured with a power analyser, with an accuracy of ±0,1 %, using voltage and current transformers connected to the generator outputs. These transformers were not calibrated but classified to an accuracy of ±0,3 %. The power delivered by the turbine shaft was determined by adding generator losses. The generator efficiency was measured with the calorimetric method at four different generating loads. The turbine output was determined with an accuracy of ±0,45 %.

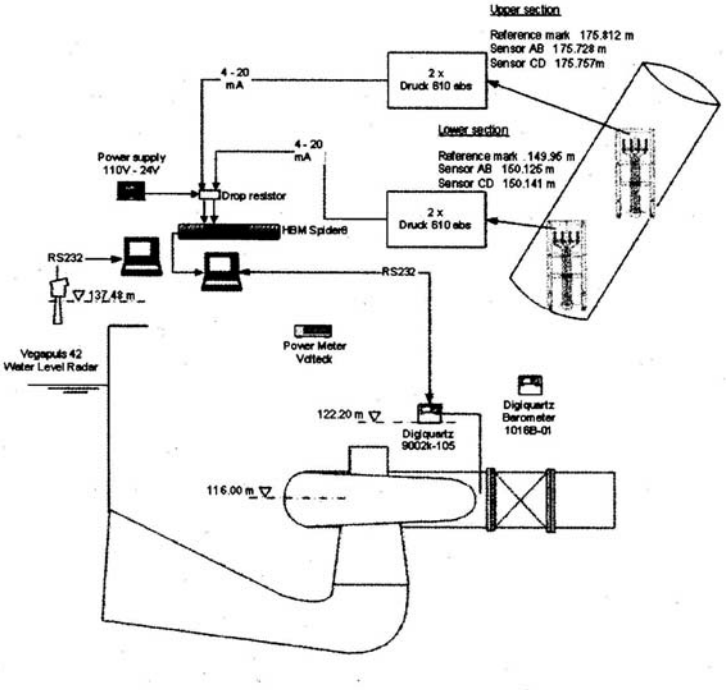


Figure 2. General equipment set-up

A dead weight balance of ±0,001 % of accuracy was the calibrating reference for pressure transducers. The calibration of these transducers using this balance permits to obtain a nominal accuracy of 0,05 % instead of their usual values of ±0,1 %.

The net head is calculated as the difference between the energy at the inlet and at the exit of the turbine. It was determined by measuring the upstream static pressure, the tailwater level, and the water discharge. The last one was measured by the pressure-time method and used for the calculation of the kinetic energies at the turbine inlet and draft-tube outlet. The pressure at the turbine inlet was measured with a transducer of ±0,001 % of accuracy. The tailwater level was determined by measuring the distance between a known reference to the tailrace using a water level radar, initially calibrated with a measuring tape. The tailwater level was determined with an accuracy of ±5 mm. By using the value of the local gravitational acceleration with the water density at the temperature of 28 °C, the effects of this accuracy on the turbine efficiency were neglected.

Benchmarks of the powerhouse were used as references to localise the elevations of the pressure transducers.

Set Up of the Water Discharge Equipment

According to the CEI 41-1991 Test Code, at least four pressure piezometers should be installed at each measuring section in a plane normal to the penstock axis. The pressure differences between the two sections of the penstock were then measured separately by four separate pressure transducers of 0,05% of accuracy, using the same length of tubing. All transducers were located in an exterior cabinet at the upper and lower section (see figure 3).

Figure 3. Set-up of the pressure equipment in the exterior cabinet

The output voltage from each transducer was measured at the rate of 150 samples/second by an analogue to digital converter. The calculations of the turbine discharge and the efficiency were done on a portable PC.

Pipe Factor

The pipe factor was calculated as 0,37087 m^{-1} from the data of the inspection sheets obtained during the tubing installation with an accuracy of ±5 mm, corresponding to an uncertainty of ±0,085 %. Using the abacus for the application of the pressure-time method, the point $\{1/g \times Q \times \Sigma L/A\}$ is located in the unfavourable zone of feasibility [Ref. 4].

Parameter Readings

The readings of the generator output, tailwater level, water temperature by thermometer, and pressure at the turbine inlet were done for 6 minutes prior to the closure of the wicket gates, at stable conditions of the unit. The power factor of the unit was adjusted close to unity.

For the Pressure-Time measurements, it was important to obtain stable condition during one minute prior to the closure of the wicket gates by closing the main servo valve of the speed governor, and to continue the measurement for one minute after the complete closure.

The pressure-time test was done at two different net heads (132 m for unit 13 and 118 m for unit 19). The same points at the same generating load were repeated twice. After the measurement, two different calculations were done to compare the results. During the tests, the pressure transducers were verified after the flow interruption by comparing their readings to the head water level.

4. COMPARATIVE DISCHARGE RESULTS

On the following figures, we have examples of the measuring signal used to determine the water discharge. All unfiltered data was computerised with the four transducers (see figure 5). The calculus was done with this data. The figure 4 gives an example of the treatment from Statkraft Gröner. In figure 6, we have the treatment of the same signals by Hydro-Québec for comparison.

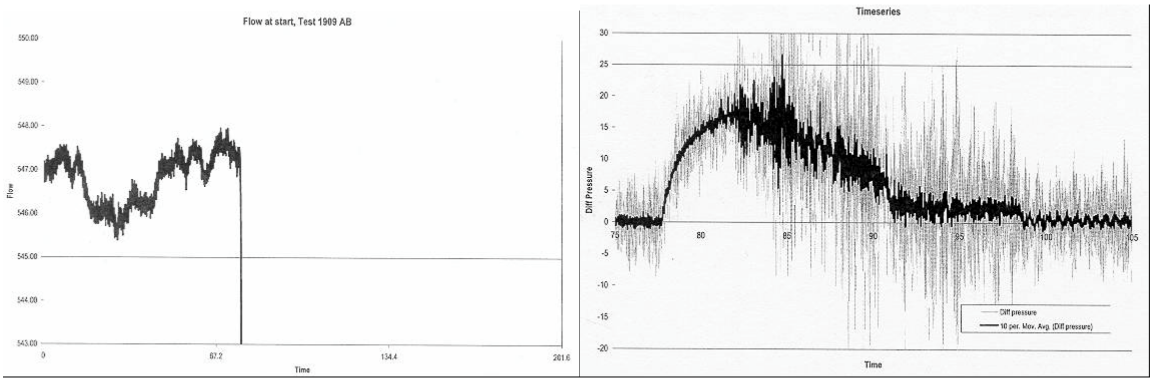
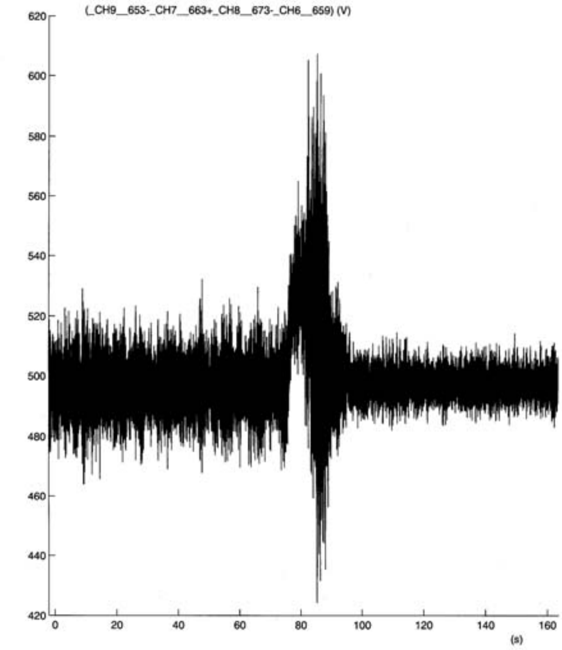


Figure 4. Treatment pressure signals with the Statkraft Gröner's software



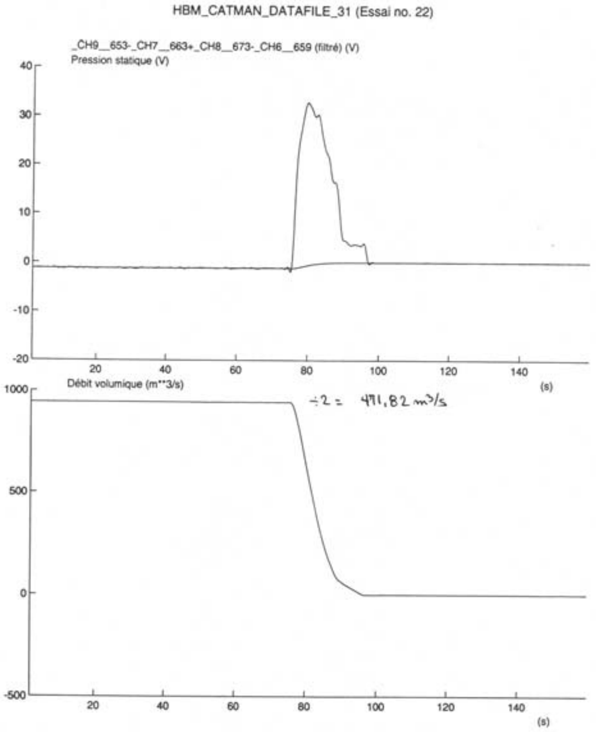


Figure 5. The 4 measuring pressure signals

Figure 6. Results from HQ's software

In conclusion, the differences on the calculated discharges are very small. These come on the specifying integrated times. We can see the main results with statistical analysis on the following table:

Table 2: Difference in the calculating discharges between Statkraft Gröner and Hydro-Québec

Piezometers section	**Unit**	**Vortex zone**	**Stable zone**	**All curve points**	
				Mean	σ
Δ[AB & CD]	13	0,05 %	0,02 %	0,03 %	0,26 %
	19	0,06 %	$0{,}00^5$ %	0,03 %	0,12 %
Δ[AB]	13	-0,05 %	0,01 %	-0,01 %	0,24 %
	19	0,01 %	-0,01 %	$0{,}00^2$ %	0,15 %
Δ[CD]	13	0,14 %	0,11 %	0,12 %	0,29 %

On both units, the results between Statkraft Gröner and Hydro-Québec were within an uncertainty of less than 0,1 %. The mean standard deviation was less than 0,3 %. The highest difference was located in the vortex zone.

We can correlate the variation of the discharges by using the Hydro-Québec's calculus: difference between the two upper taps (AB) and the lower taps (CD) in both sections; crossed difference between the superior taps of the lower section minus the inferior taps of the upper section of the penstock and the last opposite crossed difference of sections (inferior taps of the lower section minus the superior taps of the upper section).

Table 3: Dispersion between 2 different piezometer section in the calculating discharge by Hydro-Québec's method

Piezometers section	**Unit**	**Vortex zone**	**Stable zone**	**All curve points**	
				Mean	σ
$\Delta\{[AB_{lower}\text{- }CD_{upper}]\ /Q_{tot}\}$	13	0,18 %	0,01 %	0,06 %	0,30 %
	19	0,06 %	0,07 %	0,07 %	0,19 %
$\Delta\{[CD_{lower}\text{- }AB_{upper}]\ /Q_{tot}\}$	13	-0,17 %	-0,02 %	-0,06 %	0,30 %
	19	-0,06 %	-0,07 %	-0,07 %	0,19 %
$\Delta\{[AB_{lower\text{ - }upper}]/Q_{tot}\}$	13	-0,17 %	-0,10 %	-0,10 %	0,29 %
	19	-0,02 %	0,10 %	0,05 %	0,18 %
$\Delta\{[CD_{lower\text{ - }upper}]/Q_{tot}\}$	13	0,17 %	0,06 %	0,07 %	0,22 %
	19	0,02 %	-0,10 %	-0,05 %	0,18 %

We can see a small difference between the cross-calculating section (AB with CD taps) in relation with the same localisation lower or upper taps in the penstock. The estimated uncertainty is less than 0,1 % on the total discharge on both units during stable operating condition with a mean standard deviation of water discharge of less than 0,3 %. Note that these differences were calculated between the minimum and the maximum values. Calculating the discharge in absolute values with the cross section on units 13 and 19, we have a maximal difference respectively of 1,19 % and

0,69 %. With the same localisation lower or upper taps on both units, these values decrease more than 0,15 %.

The use of these last piezometers in calculus was considered as a better choice. On other testing units, the dispersion on the water discharge must be verified with more individual pressure transducers. The water dispersion in both measuring sections was changed with the increase of the water net head. The measuring accuracy was increased principally in the vortex zone and stayed negligible in operating stable zone.

5. HYDRO-QUÉBEC’S INFLUENCE ON THE UNCERTAINTY WITH THE INTEGRATION TIME LIMITS

To determine the influence of the integration time limits on the turbine discharge, we calculate the water discharge with different time intervals.

To compare the discharge, calculations were done by means of two different software. The main difference between them is the filtering method used to evaluate the signal and to limit the time intervals during the closing of the wicket gates. The first one, a Statkraft Gröner’s homemade software, permits to calculate the flow with equal time intervals sufficiently small to avoid a good numerical integrating result. The starting and ending times of the wicket gates displacement were evaluated and given manually by the software’s operator.

In the second treatment, the discharge was computerised automatically using a correction based on the convergence criteria of the differential pressure at zero value. Furthermore, it was possible to adjust the integrating times of the four different time limits. These one are: (t_1) starting time of the test under stable condition, (t_2) time at the beginning of the wicket gate displacement, (t_3), time at the end of the wicket gate displacement and (t_4), ending time of the running test point. These limits, which include all cycles of pressure oscillation, were defined at negative or positive peaks. It was possible to filter the signal numerically at high frequencies, before the calculation, in order to reduce the influence of the positioning limits.

From these results, we can determine the influence of the integration times for the calculation of the discharge and the corresponding uncertainty.

6. ANALYSING RESULTS AT REFERENCE POWER OUTPUT

On unit 13, we calculate the variation on the integrating times for 5 comparative points at the same generating unit load of 571,3 ±1,4 MW. For the unit 19, the mean generating load was 571,1 ±1,0 MW with 7 reference points.

On the following figures, we see with the limitation of times t_1 and t_2, their uncertainties are higher than with t_3 and t_4 interval times.

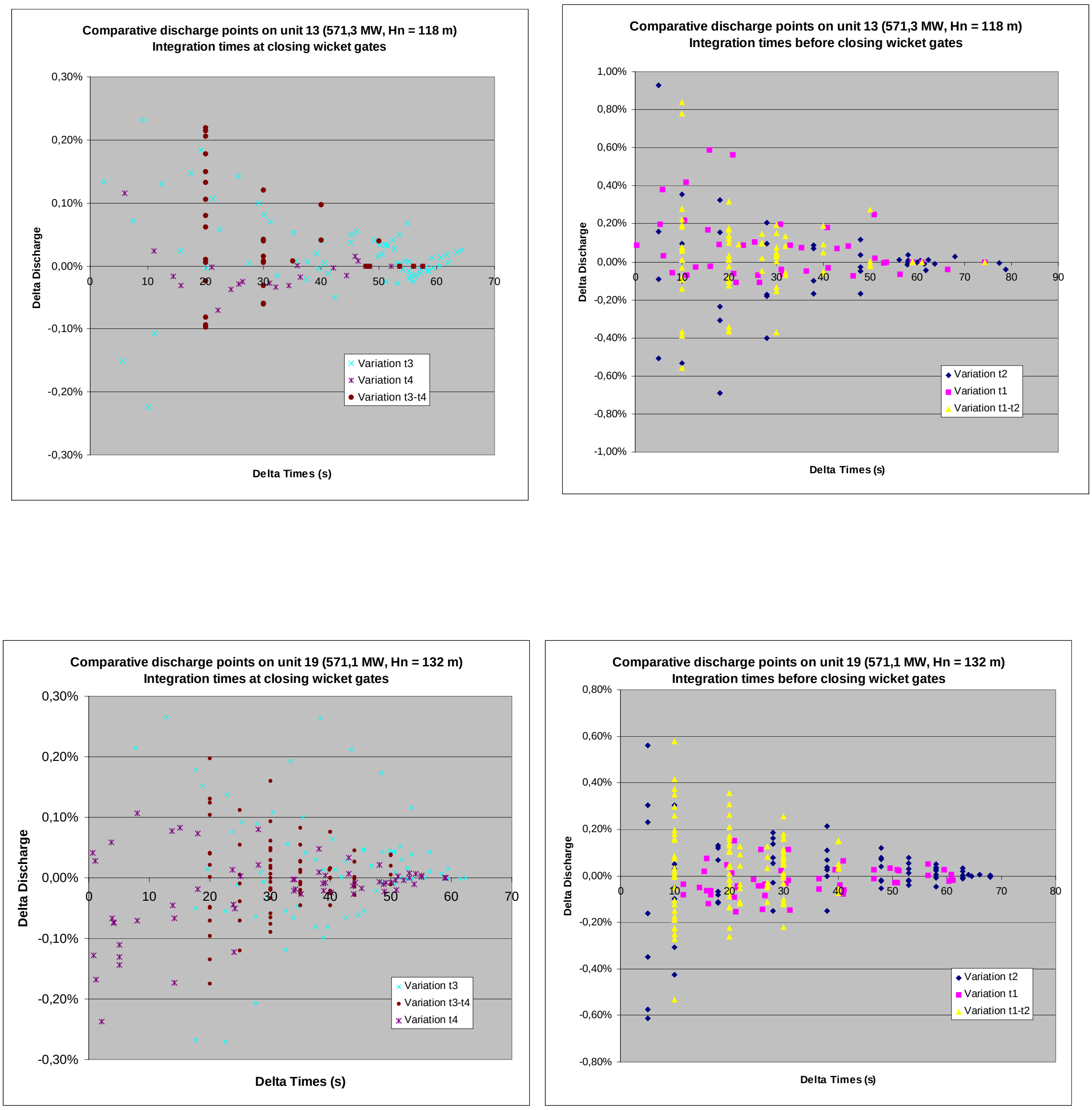


Figure 7. Influence of different integration time limits on the calculated turbine discharge

According the IEC 41 Test Code, the recording times before the beginning and after the end of the wicket gate movement shall be not less than 20 sec. With these 12 reference points, the 20-sec accuracy is higher than 0,2 %. By using the interval times calculated by the software (higher than 30 sec), the uncertainty was decreased to less than 0,1 %.

It is therefore important to use a time interval before and after the wicket gate closure sufficiently high to minimise the calculation uncertainty.

7. CONCLUSION

The development of a high performance prototype is difficult. At first, a comparative model test permits the best selection of the new runner and other parts. At the end of the project, the determination of the prototype turbine efficiency using an absolute pressure-time test permits to confirm without doubt the necessity of the refurbishing project at Guri. The turbine efficiency was determined on two refurbished Guri's units at two different net heads by the pressure-time method with separated diagrams.

At nominal net head, the possible gain in peak efficiency with the runner change replacement is 5,4 %. The measured weighted efficiency is then 0,54 % higher than the guaranteed weighted efficiency from the model test.

Two different software were used to calculate the discharges, both using the same test data. The difference between them was less than 0,1%. The mean standard deviation was less than 0,3 %. The calculation was done with the piezometers located between the downstream and upstream sections of the penstock.

It was well noticed, that during measurements near to vortex zone or when suitable features of the machine (i.e.: tailwater level variation or unstable response of speed governor) are not totally controllable, it is quite important to increase the integrating time before and after closure of wicket gates in order to diminish dispersion on discharge calculation, and therefore, on the total uncertainty.

Finally, the measurements in Guri on both units were done successfully to obtain the turbine discharge within an accuracy of less than 0,9 % with a random error lesser than 0,23 %.

8. REFERENCES

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