LAFORGE–1 COMPARATIVE TEST

J.–M. LÉVESQUE and J. NÉRON, ingénieurs
Essais et Études techniques, Hydro–Québec, 5655 de Marseille
Montréal, Canada, H1N 1J4 Telephone 514 251–7043 Telefax 514 251–7117

1. Introduction

Hydro–Québec's network includes several power plants of more than 1000 MW. Over the years, effort was made to improve turbine efficiency measurement for a better management of the hydraulic resources and turbine acceptance. At the single power plant of Churchill Falls, it was demonstrated that the prototype efficiency testing permitted to save over 70 M$CAD, see reference 1 at page 839.

We practice and possess the following four methods: acoustic, pressure–time, current meter and thermodynamic. Often, two methods are applied on the same occasion to increase the accuracy and the confidence level of the measurement. The neutral zone of the efficiency curve, for which no bonus or penalty may be applied, is adjusted accordingly but is currently between ±0.5 and ±1 %.

In June 1994, the testing department *Essais et Études techniques* obtained a grant to apply simultaneously the four above methods at a power plant. The total budget amounts to 500 k$CDA, including the acceptance test, and comes from different departments of Hydro–Québec and SEBJ. The goals were to learn about the uncertainties of these methods and manners to improve them by comparing their feasibility and applicability. Laforge–1 power plant was chosen and the main test was done in December of 1994.

2. Description of the Laforge–1 power plant

Figure 1 shows a general view of the installation. The power plant has 6 units of 145 MW each with a discharge of 280 m^3/s under a 57 meter head. The 6.65 meter diameter penstock is unpainted steel lined but the upper conduit and the elbow are made of concrete. The Francis turbines have a standard scroll case and a double draft tube.

The contractual tests already included the acoustic and pressure–time methods. The grant permitted to elaborate more the acoustic and pressure–time methods and to add the current meter and thermodynamic ones. The present article will present the preliminary results obtained up to date from the application of the four methods. The data is not completely analyzed yet, save for the acoustic method.

The authors thank G. Proulx, C.M. Tran, Alain Lefebvre and J.–P. Thivierge who participated actively in the program. Also the measurement crew composed of C. Langevin, J. Desmarais, G. Gauthier, P. Jalbert, A. Moutquin, E. DeGuise.

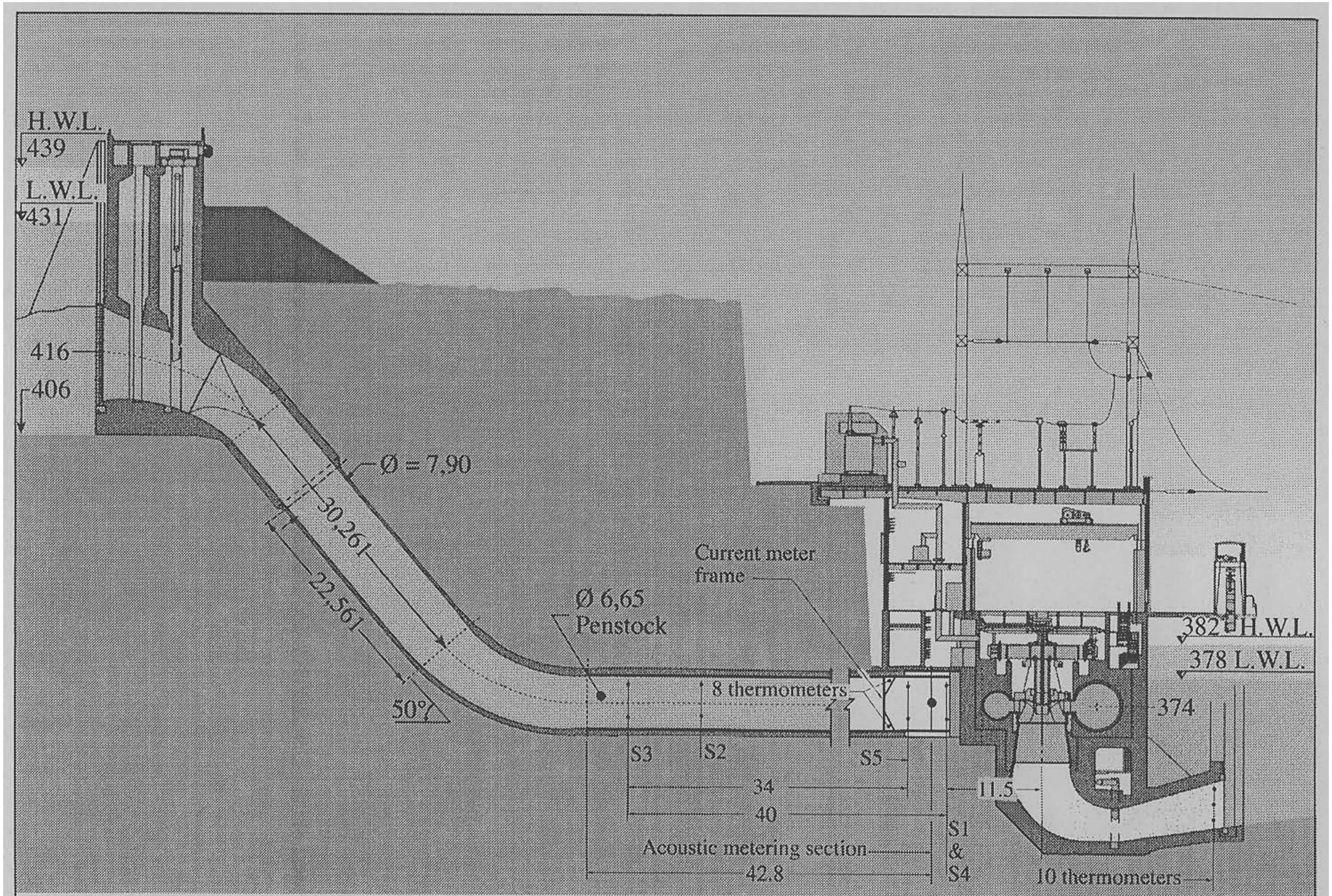

Figure 1: Laforge-1 project

3. Description of the methods

Figure 1 shows the locations of the different instruments and taps for the acoustic, current meter, pressure–time and thermodynamic methods. The highlights of each method are the following:

- 36 transducers installed on 9 levels and 18 cross–paths: 8 cross–paths for the standard flowmeter and 10 cross–paths for the study of protrusion and flow profile.
- 64 current meters on an 8–arm frame, the first ring near the liner equipped with 8 small current meters and the other 6 rings, with 56 current meters of normal size. Also, 16 other current meters on a horizontal rod in the acoustic metering section.
- 16 individual pressure taps for the pressure–time method, 2 sections of 4 taps with a good spacing for the acceptance test. Two other sections of 4 taps equipped with static and other types of taps.
- 18 thermometers for the thermodynamic method, 8 placed on braces of the current meter frame and the 10 thermometers and 10 current meters near the draft tube exit, 5 in each of the 2 passages.
- 3 watthour meters for the determination of the turbine output, with the burdens of the measurement loops completely balanced and the use of a 75 ppm instrument at site to check the power analyzer.
- the use of many pressure transducers to double and triple the measurements of the inlet, outlet and WK pressures and also the use of 0.01 % deadweight testers.
- the gate opening and the guide vane angle measured with independent transducers.

3.1 Acoustic method

The acoustic metering section was located just 1D upstream of the scroll case entrance and less than 7D downstream of a 50 degree smooth shaped elbow. The standard acoustic method consists of 8 cross–paths equipped with 16 transducers of fixed protrusion, over 4 levels. Five more levels were added for another 10 cross–paths of 20 transducers with adjustable protrusion. Figure 2 describes the location of the standard 4 levels and the 5 added levels. One may note the different path angles of the flowmeters.

Although necessary measurements were done for the installation of the standard 8 cross–path flowmeter, other measurements were also necessary for the installation of the new 10 cross–path flowmeter for the December 1994 test program, and the occasion was taken to repeat the previous measurements to ensure maximum quality control. All the measurements were checked and compared to make sure that the angle variations were compatible with the path length changes.

Standard ORE 65^0 transducers were used for levels B, D, F and H with standard feedthrough fittings, the inside part terminated by a 62 mm Ø and 10 mm thick mount. The resulting protrusions are 25 mm for levels B and H and 14 mm for levels D and F. The transducers used for levels A, C, E and G were mounted using pipe fittings and allowed adjustment of the protrusion from 4 to 55 millimeters. The minimum protrusions were 8, 5, 5 and 3 mm for levels A, C, G and E respectively

The protrusion of the transducers was adjusted on one level only for the tests of December 1994 and all the travel time measurements were done with a newly bought recent model flowmeter completed by two satellite units borrowed from Accusonic, the system controlled by a PC computer. The measurement for the acceptance test were made at the end of November 1994 with our old 8 path flowmeter, Accusonic model 7410, during which time period, the main pressure time test was also made.

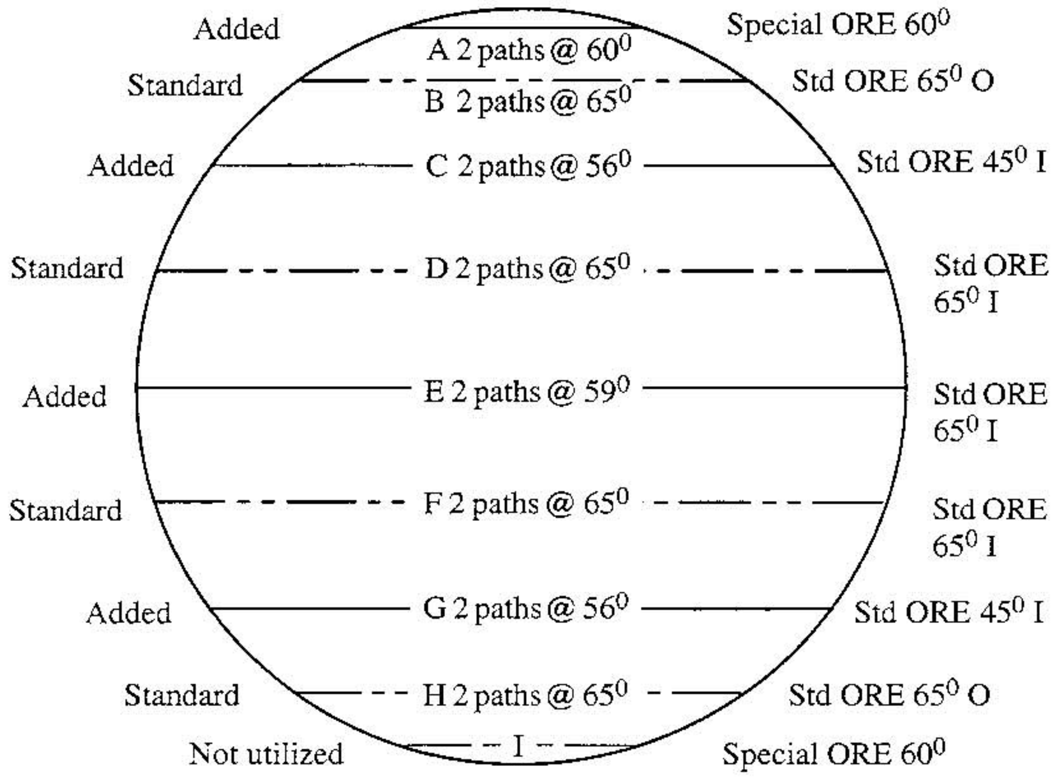

Figure 2: Arrangement of transducers and paths

More tests to identify the protrusion effect were performed in July 1995 with the protrusion adjusted on all the transducers on 4 of the 5 added levels. Two flowmeters were used, one for the 8 cross–paths consisting of levels B, D, F and H, and the other one for the 10 cross–paths consisting of levels A, C, E and G. To avoid the use of a third one, level I velocities were not measured but assumed equal to those of level A. When the testing started, both flowmeters were functioning together but we realized that interference occurred. The flowmeters were then operated separately. The tests were conducted at the discharges of 48 m^3/s and 240 m^3/s, corresponding to Reynold numbers of $7 \cdot 10^6$ and $3.2 \cdot 10^7$ respectively.

The July 1995 testing included: 12 hours of measuring time, the waiting time to stabilize the discharges, at least one hour each time for a complete change of protrusion of the transducers, and the time for 70 change–overs from one flowmeter to the other. For each 5 minute run , the discharge and the different velocities of each path, were measured at a rate of one measurement per 2 seconds. For the two studied small and large discharges, measurements were done for protrusions of about 4, 17, 30, 42 and 55 mm, 7 runs with each flowmeter, for a grand total of nearly 140 test runs.

3.2 Current meter method

The current meter frame was located 4.9 meters upstream from the center of the acoustic metering section. The frame was made of 75x35 mm hollow ovoid rod and from 65x25 mm solid ovoid rod, welded as necessary to the liner. The frontal area of the current meter rods was 2 % of the metering section and the rod braces area was of 0.7 %. Figure 3 shows the location of the currents meters.

All the current meters were supported by special holders that produce an offset between the axis of the current meter and the axis of the supporting rod. This holder decreases by half the interference effect of the rod on the current meter as it was demonstrated in laboratory. All the current meters were calibrated recently before the test. The calibrations were done at Berne in Switzerland, in 28 points from velocity of zero to 8 meters per second, always with the special holders. The calibration certificate establishes at 0.3 % the typical uncertainty to 95 % confidence limit.

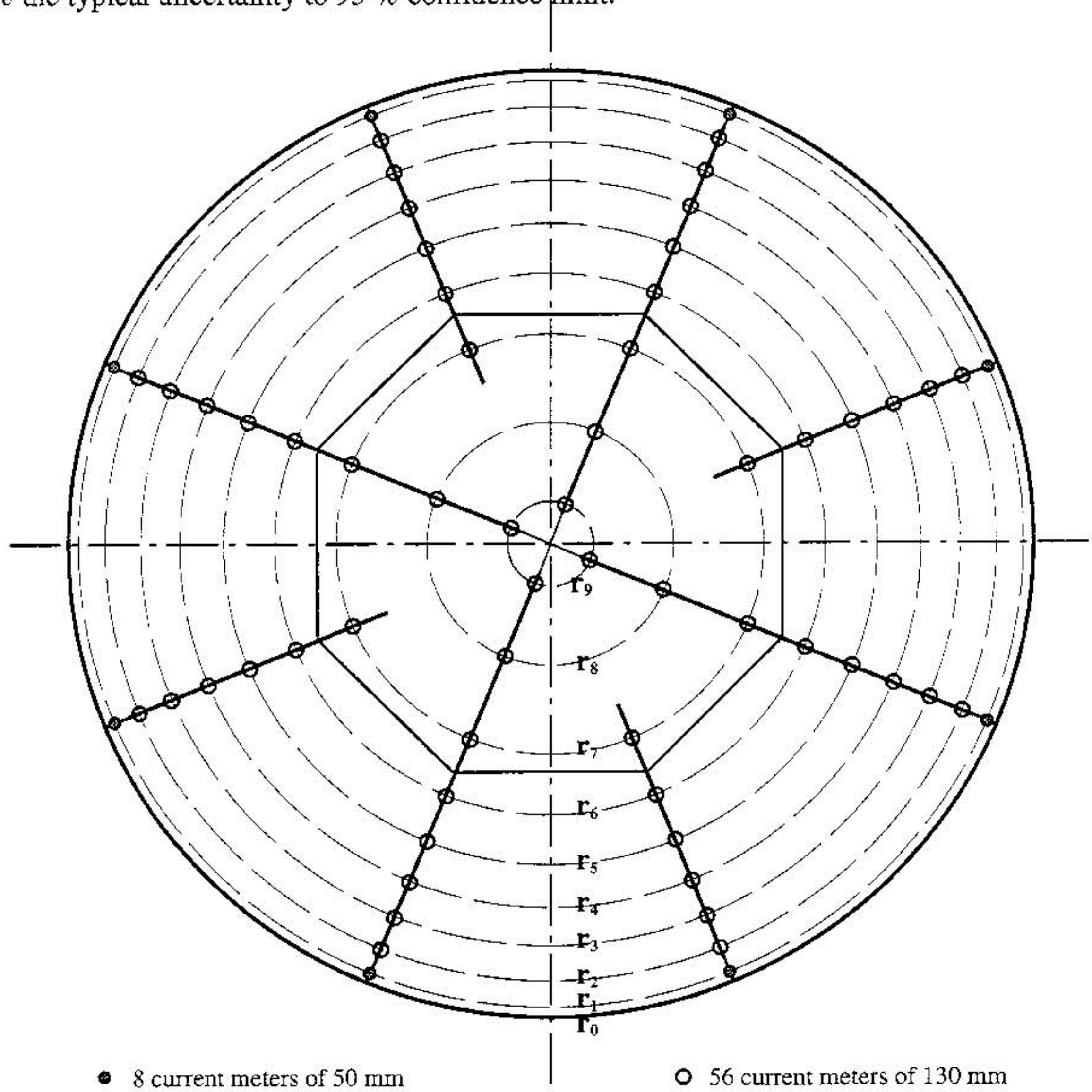

Figure 3: Current meter layout

At site, all the measurements were done to ensure a high quality control. The angle from the horizontal of each current meter was also measured. The small current meters were placed at 69 mm from the liner. The four central current meters were used to measure the flow velocity at the center rather than to use a sole current meter at the center which would have required a special calibration. The rings $\mathbf{r}_2$ to $\mathbf{r}_8$ were spaced to obtain rings of equal area. All the electrical wires were passed inside the rods. The results of the current meters placed on acoustic path G are not yet analyzed and so it will not be treated in this article.

3.3 Pressure time method

The penstock was already equipped with 3 sections of 4 static taps (S_1, S_2 and S_3) for the pressure time method in a 40 meter long run with one section in common for the measurement of static pressure at the turbine inlet. All pressure taps are independent with tubing ending in the power station. A tap section S_4 was added near S_1 for the measurement of the static pressure to separate that measurement for the pressure time ones. Another tap section S_5 was added only 1D upstream of S_1 for the pressure time method.

This article will report only the results obtained from two L/A factors. The contractual one, comprising sections S_1 and S_2 spaced by 27 meters and giving the good L/A of 0.78 m^{-1}. The second factor with a greater L/A of 0.99 m^{-1} and included between sections S_3 and S_5. The first L/A in an acceptable zone while the second lies in an excellent zone of the abacus of pressure time application presented at page 2211 of reference 2. The sections S_3 and S_5 include non–standard taps and the spacing is 34 meters.

The pressure difference between each pair of analogous taps were measured by an independent electronic transducer. For the medium and large L/A only, eight transducers were utilized and measured separately and simultaneously at a rate of 100 samples per second by an analog to digital 16–bit converter. The medium and large L/A were calculated from dimensional site measurements of the penstock and yielding an uncertainty of 0.05 %. All the transducers were calibrated in our laboratory with high accuracy 0.005 % deadweight tester, and most of the transducers offer a better than 0.05 % uncertainty.

The acceptance pressure time test was made according the normal procedure and using water to air separators on all usual transducers. Additional testing was done with another type of transducer without water to air separator and with different closure time of the wicket gates. These last results will not be reported since they are not analyzed. From the preliminary results obtained at site, the measured discharges were in concordance with those measured with the usual procedure and transducers.

The discharges are calculated using a special software developed by *Essais et Études techniques* over the past 20 years. The recovery line assumes an exponent of 2. The calculation includes many goodies as described in different papers, see reference 2.

3.4 Thermodynamic method

The analysis of this method has not progressed since the site results obtained in December and for that reason, little will be reported here. However, for those who were not present at Laforge–1 during the site test of December 1994, we will summarize the situation.

During the installation, one upstream thermometer was dropped and the sensor apparently damaged. It was however installed and it seemed to work correctly but no further checks were made. The thermometers and the current meters for the weighting of the temperatures, installed in the left passage of the draft tube were damaged during the turbine starts and nearly no data will be obtained there.

The other instruments worked quite well but the site results indicate a good precision of the results, in the order of the other methods, but accompanied by a shift, or systematic bias of 1.5 %. We hope to have the time at the end of this year or next year to complete the analysis of the measurements.

3.5 Other measurements

The net head was deduced from the discharge measurement for the kinetic energy and from the pressure measurements at the inlet and outlet of the turbine. Each of the four static taps at the inlet and the two tail race levels were measured individually by a 0.05 % transducer, compared to the line pressure which was measured by a 0.01 % deadweight tester. These basic measurements were backed by other measurements with transducers installed in other fashion to duplicate the measurements. From these results, we are convinced that the uncertainty on the net head determination is better than 0,05 %.

The turbine output was deduced from measurements taken at the generator terminals using calibrated current and voltage transformers to an accuracy of 0.02 %, an analyzer of 0.05 % verified at site by a 75 ppm instrument, all the measurement loops balanced to a known burden, all the separated generator losses measured or calculated from measured parameters. The final result being a total uncertainty of 0.1 % on the turbine output. A typical calculation appears at page 82 of ASME PTC 18–1992.

4. Results

Before presenting the results, one must note the following

- The discharge measurements for the acceptance test permitting to compare the standard 8 path flowmeter to the pressure time method were done at the end of November 1994.
- In December 1994, the comparative test was done with the standard 8 path flowmeter, the 10 added path flowmeter, the current meter and the thermodynamic methods. Additional runs were also done with the pressure time method.
- In July 1995, more tests were done specifically to quantify the protrusion effect of the transducers on the acoustic flowmeter by applied measurements with the 8 and 10 path flowmeters. Detailed results on protrusion effect are scheduled to be given at IARH Symposium in Valencia in September of this year. So, no detailed results on the protrusion effect will be presented here.
- All the acoustic measurement results presented here are corrected for the protrusion effect as measured during the July 1995 test campaign.
- The current meter measurements include no blockage effect correction but a small one to take into account the angle of each current meter in the penstock. The discharge was calculated using the "Numerical Integration of Velocity Area" method described at paragraph 9 of ISO 3354, to which refers Standard IEC 41.
- The thermodynamic results are the most preliminary and uncompleted.

The discharge comparisons are presented in tables 1 and 2. The first table gives the discharges measured by the 8 and 10 path acoustic flowmeters and current meter method during the comparison test of December 1994. The second table shows the discharges measured by the 8 path flowmeter and the pressure time method during the acceptance test in November of 1994.

From the corrected discharges, we would like to point out the following preliminary results.

- From table 1, the mean 8 path discharge agrees with the mean 10 path discharge within 0.13 %. The differences between the 8 path and the 10 path mean discharge, from the current meter mean discharge, are –0.12 and 0.01 %. The most reliable acoustic discharge is probably with 18 paths and the mean compares with the current meter mean discharge within 0.06 %.

- From table 2, the mean discharges of both pressure time L/A factors agree within 0.09 %. The differences between the mean of the pressure time discharges from the 8 path flowmeter mean discharges are 0.04 and 0.14 respectively for the 0.78 and 0.99 L/A.

- By combining results of tables 1 and 2, it is deduced that the current meter method measures less discharge than the acoustic by 0.06 % and the pressure time method more discharge than the acoustic by 0.09 %. These bias are however of the same magnitude as the uncertainties.

- From the different runs of table 1, the standard deviation σ of the discharge differences are 0.17, 0.12 and 0.13 % respectively. It can be deduced that, if the standard deviation σ of all methods are assumed equal, the standard deviation σ of each method is 0.099 %.

- From the different runs of table 2, the standard deviation σ of the discharge differences are the following: 0.29, 0.31 and 0.20 %. Using the same assumption as before but taking into account that σ of the acoustic is 0.099 %, the standard deviation of each of the pressure time application is 0.24 %.

- We believe that the uncertainty of the mean discharge, to a 95 % confidence limit, for each of the three methods can be 0.1 % in many instances.

- A brief overview of the thermodynamic temperature measurements indicates that the draft tube left passage has twice the discharge than the right one. Before the wreck of the instruments in that passage, the thermometers were indicating a lower temperature in this passage by 2 mK compared to the temperature of the right passage, thus affecting the efficiency by 1 %.

- Due to lack of time before the test and at site, the work involve for the whole program, difficulties with some instruments and partial controls and analysis, the benefits of the thermodynamic method application will be reduced.

- Our intention was not to demonstrate that the thermodynamic method is the best choice to measure the efficiency of a 60 meter head machine. Our conclusion is however that it is possible to do it within an uncertainty of better than 1 %.

From the analysis of other data, particularly by looking at the turbine efficiency, many other recommendations can be drawn but evidence will not be supplied here due to limitation and other reasons.

- The acoustic procedure, using weighting coefficient for path, was applied to the measured flow profile by the current meters. The standard 8 path calculations overestimated the discharge by 0.4 % while the 10 path calculations under estimated the discharge by 0.4 %. For the Laforge–1 case, 18 paths are therefore necessary to overcome the flow profile distortion without error.

- If the paths are placed vertically instead of horizontally, the error will be significantly decreased. That observation was derived from the current meters with mathematical rotation of the paths.

- Using the measured current meter velocity profile, the 18 path calculations as the 36 path ones yield exactly the same discharge than the ISO procedure, hence demonstrating that the calculations can be made with a high degree of accuracy and confidence.

- A 0.5 % must be anticipated to take in account the flow distortion when using an 8 path flowmeter.

- The thermodynamic site results have a bias error and we will report on that situation later.

Table 1: Discharges of the current meter method compared with the acoustic

Run No	Q 8 m3/s	Q 10 m3/s	Q 18 m3/s	Q c.m. m3/s	Q 8 - Q 10 %	Q c.m. - Q 8 %	Q c.m. - Q 10 %
105	188.8	189.1	188.9	188.7	-0.12	-0.08	-0.20
106	205.3	205.0	205.2	205.0	0.13	-0.14	0.00
107	212.3	212.0	212.1	212.0	0.15	-0.15	0.01
103	222.4	222.1	222.2	222.2	0.15	-0.08	0.07
102	223.7	223.0	223.4	223.2	0.31	-0.23	0.09
108	230.1	229.5	229.8	229.7	0.24	-0.16	0.08
114	239.4	239.2	239.3	239.2	0.11	-0.10	0.01
104	239.7	239.3	239.5	239.6	0.15	-0.04	0.10
110	245.7	246.1	245.9	245.4	-0.14	-0.12	-0.27
109	246.0	246.3	246.1	246.1	-0.12	0.05	-0.07
123	186.1	185.4	185.8	185.3	0.38	-0.42	-0.04
124	205.1	205.2	205.1	205.3	-0.05	0.09	0.04
125	221.7	220.9	221.3	221.3	0.39	-0.21	0.18
126	238.2	237.6	237.9	238.1	0.26	-0.05	0.21
Q 8 = 8 path discharge				**mean:**	**0.13**	**-0.12**	**0.01**
Q 10 = 10 path discharge				**standard deviation:**	**0.17**	**0.12**	**0.13**
Q c.m. = current meter discharge				**uncertainty at 95 %:**	**0.10**	**0.07**	**0.07**

Table 2: Discharges of the pressure time method compared with the acoustic

Run No	Q 8 m3/s	Q 10 m3/s	Q 78 m3/s	Q 99 m3/s	Q 78 - Q 99 %	Q 78 - Q 8 %	Q 99 - Q 8 %
55	46.4	----	46.8	46.8	-0.10	0.72	0.82
54	82.9	----	83.1	82.7	0.44	0.29	-0.15
35	136.2	----	135.8	136.3	-0.34	-0.28	0.06
44	152.6	----	152.7	152.8	-0.08	0.01	0.08
34	171.3	----	171.2	171.8	-0.34	-0.05	0.29
26	187.3	----	187.5	187.9	-0.21	0.09	0.30
39	195.9	----	197.1	195.7	0.67	0.59	-0.08
33	203.6	----	203.4	203.5	-0.05	-0.10	-0.05
38	211.4	----	212.5	212.0	0.25	0.51	0.26
27	223.2	----	223.4	223.7	-0.14	0.08	0.22
37	230.4	----	230.3	230.6	-0.13	-0.01	0.12
48	242.5	----	243.1	243.1	0.03	0.25	0.23
53	243.9	----	243.5	243.8	-0.13	-0.16	-0.03
36	247.5	----	247.6	247.9	-0.12	0.06	0.18
42	253.4	----	253.2	253.7	-0.20	-0.06	0.14
49	256.3	----	256.9	257.1	-0.07	0.26	0.33
50	261.8	----	261.2	261.7	-0.20	-0.24	-0.04
52	269.6	----	270.6	269.8	0.28	0.36	0.08
51	271.6	----	271.4	271.5	-0.02	-0.07	-0.05
41	272.2	----	271.2	272.2	-0.38	-0.38	0.00
43	278.8	----	277.6	279.3	-0.58	-0.42	0.16
30	278.6	----	277.4	279.0	-0.60	-0.46	0.14
Q 99 = pressure time discharge, 0.99 of L/A				**mean:**	**-0.09**	**0.04**	**0.14**
Q 78 = pressure time discharge, 0.78 of L/A				**standard deviation:**	**0.29**	**0.31**	**0.20**
				uncertainty at 95 %:	**0.13**	**0.14**	**0.09**

- The current meter method gives more information that any other method and should be favored whenever possible and specially to obtain the flow profile. Also, if applied correctly with a small obstruction of the frame, there is no reason to correct the results for blockage effect.
- The comparison between current meter discharges and pressure time discharges was made using the acoustic method but not exactly in the same manner. Since important discrepancies in turbine efficiency were observed (obviously not real), presently and subject to confirmation by further analysis, it is concluded that compared to the acoustic method, the pressure time measures more discharge by 0.25 % and the current meter method less discharge by 0.25 %.

5. Conclusions

The PTC and IEC Test Codes (reference 6) recommend to locate the metering section more than 25D to 10D (current meter and acoustic methods) from an elbow followed by a 3D or longer straight section before the scroll case entrance. These distances were 7D and 1D respectively for our test at the Laforge–1 power plant. Nevertheless, we are convinced that the absolute error of each of the three discharge methods was well within 0.5 % and the uncertainty better than 0.25 %. We thus believe that the uncertainties of 1 to 2 % as mentioned in PTC and IEC publications can be very well compensated by a careful application of the methods.

Taking into account the uncertainty on any of the three discharge methods, the uncertainties on the head and turbine output, the resulting uncertainty on the efficiency becomes 0.3 %, which is a result on prototype nearly comparable to one achievable on the model in the laboratory (references 3, 4 and 5).

The goals of the comparative test of Laforge–1 were met on three of the four methods used and we therefore conclude that this test met the original purpose of the grant. Many direct and indirect consequences are already foreseen, concerning the placing of the acoustic transducers, the choice of the method, the neutral band for acceptance purposes, the step–up between the model and the prototype, the possibility to demonstrate the benefits of runner changes with small gain expected, etc.

References

- 1– J. M. Lévesque and C. Tran, *The Importance of Prototype Efficiency Testing*, 16th Symposium of the IARH 1992, São Paulo, Brazil.
- 2– J. M. Lévesque, J. Néron and C. Tran, *Pressure–time Method Using Modern Practices*, WaterPower 91, Denver, Colorado, USA.
- 3– T. Ida, *New Formula for Efficiency Step–up of Hydraulic Tirbines*, 17th Symposium of the IARH 1994, Beujing, China.
- 4– J. Marcinkiewicz and L Svensson, *Modification of the Spiral Casing Geometry in the Neighborhood of the Guide Vanes and its Influence on the Efficiency on a Kaplan Turbine*, 17th Symposium of the IARH 1994, Beujing, China.
- 5– P. Henry and H.–P. Mombelli, *Hydraulic Machinery Model Testing IMHEF test Facilities*, WaterPower 93, Nashville, Tennessee, USA.
- 6– Standards IEC 41 of 1991 and ASME–PTC 18 of 1992.