

**Improvements in the dye dilution method:
Experiences in Italian power plants**

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Abstract

Dye dilution is one of the methods recognized as primary method within IEC 60041 and is very suitable in many power plants where it is not allowed to significantly affect the operation schedules.

In the last five years several tests were performed in different power plants using Rodhamine WT as dye. This experience gave the opportunity to put in evidence problems and possible solutions in order to obtain reliable results and to decrease test uncertainty to acceptable values in respect with contractual requirements.

The paper describes test results in Montjovet, Colle and Istrago power plants, where different installations have been used in order to fit different conditions.

Montjovet power plant has 2 Francis turbines with 52 m head 25 MW power 50 m³/s flow. Dye injection at penstock intake and dye sampling at the unit outlet (total 120 m mixing pattern).

Colle power plant has 1 Kaplan turbine with 35 m head 4 MW power 12 m³/s flow. Dye injection in the intake channel and dye sampling at the unit outlet (total 60 m mixing pattern).

In Colle power plant also comparative tests with current meter measurements were performed.

Istrago power plant has 2 Francis turbines with 66 m head 4 MW power 7 m³/s flow. Dye injection at penstock inlet (4000 m far from power house) and dye sampling at the unit entrance.

Finally a short description of the test devices, test procedures and calculation methods gives possible suggestions to code future revisions.

Method background

The testing methodology called “*dye dilutions method*” is included among the methods approved by international standards; however, it was not subject to developments and updates both as regards equipment and procedures. The easy implementation of these measures, the minimum impact on the management of groups under testing, the application flexibility, led WEST requested by EDISON and CVA power companies to develop the methodology to get closer, as target, to the uncertainty of other methods provided by the standards.

The improvement path of the method is the result of many years of study and comparison of the results obtained, with the aim of identifying possible error causes, and, as far as possible, to reduce weight and identify the appropriate diagnostic tools, and to evaluate the presence and influence of the errors on the measures.

The methodology focuses on three key items: the system of tracer injection - with calibration of the input solution, the system of levy of the mixture - with detection device calibration, the processing system and flow calculation.

Theoretical Outline

The dye dilutions method provided by IEC 60041 standard as the primary method for flow measuring, provides for different methods depending on specific plant conditions. WEST developed the methodology of “constant injection”.

The flow measurement, in this case, is based on the comparison between the concentration of a tracer released in the flow (injection known concentration value) and the concentration of that tracer detected from the samples probes (discrete and/or continuous) taken from the flow in a section far enough from the point of injection, in order to ensure proper mixing of the tracer.

The fluorescent tracer (preferable to saline or radioactive tracers) is a compound capable of absorbing light at a certain wavelength, re-emitting light energy at a wavelength higher and well defined. The selection of the most appropriate tracer was the subject of numerous studies, as the ideal tracer must be non-toxic, usable in small quantities, easily measurable in small concentrations and stable during the course of test. In this sense the *Rhodamine WT* is the fluorescent tracer chosen having all these requirements and also being chemically inert, extremely mixable, but not absorbed or deposited in the environment, and, therefore, suitable for applications in sensitive environmental conditions. The only attention is due to maintain the conditions of analysis controlled, because of the variability of fluorescence of Rhodamine to temperature (i.e.: variation of 2.6% per degree).

The equation, which allows to calculate the value of concentration of the tracer, is in simple form

$$Q_1 C_1 = Q_2 C_2 \qquad Q_2 = Q_1 \frac{C_1}{C_2} = R_d * Q_1$$

where

Q_1 = tracer injection flow

C_1 = tracer injection concentration

Q_2 = flow to be determined

C_2 = tracer concentration detected in the flow

$R_d = C_1 / C_2$ dye dilution ratio

Using appropriate light sources and using precision optical filters, a fluorescence-meter can measure the fluorescence rate (ratio of absorbed and emitted light) and therefore quantify the concentration of the fluorescent substance, being fluorescence linearly related to the concentration, in predetermined areas: $F = k_A C + k_B$

The dilution ratio can not be measured directly, but it can be determined by comparing the fluorescence (then proportional to the concentration) of samples taken from the flow with fluorescent solutions sample obtained for further dilution of tracer injected concentration C_1 . Note that C_1 is not note strict deadlines: usually the *Rhodamine WT* is provided in solution to

$20 \pm 2\%$. The dilution of tracer injected must lead through a dilution ratio accurately determined to a concentration

$$C_{2'} = C_1 / Rd' \quad \text{therefore} \quad C_1 = C_{2'} \cdot Rd'$$

where $C_{2'}$ is very close to the expected value of C_2

$$Q_2 = Q_1 \cdot \frac{C_{2'}}{C_2} \cdot Rd'$$

Injection system

The purpose of injection system is to provide a constant and known release of the tracer. It is fundamental to determine the injection flows because they are linearly related to the measured flow, and, therefore, are virtually source of considerable errors.

The release must also be constant over time and as much as possible distributed in the inlet section in order to ensure proper blending. The tracer properly diluted is taken from the supply tank and is released via closed circuit in a volumetric piston-pump of 1.5 litres capacity. The liquid is injected with a constant flow with accuracy of $\pm 0.1\%$.

The pump used was expressly designed by WEST using as drive the device of a precision machine tool.

The advancing speed is digitally set and controlled. The release of tracer is not made directly in the flow, but within a circuit of pre-mixing that pulls water from the stream (channel or penstock) in an inlet upstream section and then return to the flow mixed with the tracer, through precision pump of 10 l/s.

The pre-mixing scope is to allow a distribution of the tracer the most homogeneous as possible in the section of release. For this purpose may be adopted also the appropriate sprayers.

Along with the experience it was demonstrated essential the correct use of restraint valve, that separates the primary circuit of release from that pre-mixing, as losses or delays may result in significant measuring errors.

The section of release is selected so as to ease mixing, without the risk of reverse flow. Normally are preferable sections downstream of penstock inlet grids. It is very essential to avoid zones of dead-water or accumulation.

Sampling and measuring system

The choice of sampling section must be made to obtain the best possible mixing. The spread of the tracer is anyway both horizontal (spreading in the flow section) and axial (spreading along the axis of motion). The axial spread determines a damping of the rising/decreasing front of the measured concentration, and, thus, an excessive distance between inlet and measuring sections could make hard the definition of the plateau.

Even in the sampling section is made a pre-levy circuit, using one or more pumps which can draw from different positions of section in a balanced way (getting the sampling of average concentrations in the section measuring).

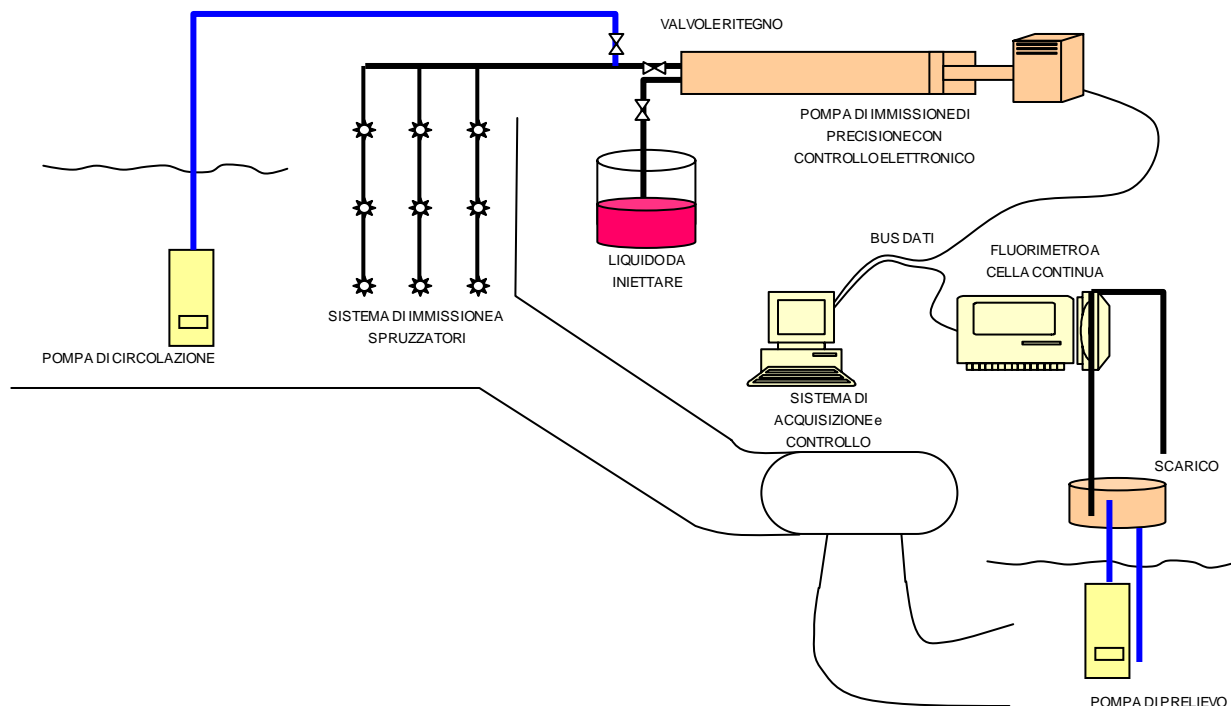
The pre-levy system configuration (number and arrangement of sampling points) is done on a case-by-case basis in order to obtain a correct measure of the average concentration in the section of measurement. Among the preliminary tests is essential to investigate the variability of concentration in the different positions of the section and over time.

The pre-levy system discharge the taken flow to a small tank, from which is derived the measuring system inlet flow. The tank has function to integrate fluctuations in concentration over time. The integral function depends on the pre-levy flows ratio (typically 10÷15 l/s) and levy (typically 1÷2.5 l/s).

The fluorescence-meter used Turner Design 10AU-005 CE - allows through specific optical kit, the continuous measurement of fluorescence and data storage. The instrument is connected to a drawing pump of 2.5 l/s max, directly suctioning from the compensation tank. The instrument also has temperature-compensation, because of the sensitivity of fluorescence of Rhodamine to temperature.

A value of constant plateau without considerable variations in the level of fluorescence is a sign of good mixing. The plateau can be considered reliable when the standard deviation of measures is in percentage less than 1% of the measure.

Fluctuation in the level of fluorescence above the allowable, requires to move the measuring section more downstream, or, to increase the sampling points taken in the section. In some cases it is necessary to increase the injection flow in order to obtain greater fluorescence values.



The injection system and measurement of dye is shown in *Figure*

During the test several samples of measuring liquid shall be taken at the plateau conditions. In order to confirm the results obtained, these samples are measured in the laboratory through cell for discrete measures (cuvette cups). The samples in this case are kept at constant temperature, through controlled bath.

Fluorescence-meter calibration and site testing

The Fluorescence-meter naturally measures the fluorescence and determines the concentration of substances of analysis (*Rhodamine* tracer) for comparison with samples with known concentrations of the same substance.

Obtaining known concentrations is get from the base substance for subsequent dilutions in distilled water. In particular, the *Rhodamine* is provided in base solution of $20 \pm 2\%$, and the fluorescence of that substance is linear between concentrations of 2 ppb to 100 ppb.

For usual applications the release will be programmed in order to obtain concentrations between 5 and 20 ppb. (e.g. with a dilution of 100 μ l per liter of the base solution is obtained a solution of 2×10^{-5} ; subsequent dilutions varying between 250 and 1000 μ l per liter allow to obtain the required concentrations).

The standard calibration scale is then realized between 0 and 25 ppb by setting the alignment of optics, in order to focus the emission frequencies and setting the sensitivity so as to obtain the 20% concentration of 20 ppb. It is necessary that the zero-point shows a fluorescence near-zero, regardless of the subtraction of white.

The method of successive dilutions has an intrinsic uncertainty of $\pm 1\%$. Each dilution was then repeated in an independent manner 10 times, in order to minimize the maximum random error; in this way it is expected to obtain a standard scale with uncertainty contained within $\pm 0.25\%$.

The calibration curve remains valid, unless evidence of problems, within the period provided by the Quality Control procedures.

Alignment of optics should never be changed unless the tracer fluid is changed. Along with periodic checks and usual operating cycles, considerable effects that necessitate sensibility variation are not expected.

The site test is performed according to the following procedure. The base solution must be mixed, in a homogeneous whole solution to be injected, during the tests, possibly diluted to obtain input speeds between 100 and 200 ml/min, with Rhodamine concentrations in the flow between 5 and 20 ppb. (In this case has proceeded to a dilution of 1/2).

Starting from this solution, operating like for the calibration, are obtained by successive dilution with plant water concentrations operationally significant.

Please note that the use of plant water can result in fluorescence that, in zero-conditions, may actually be different from zero; that offset must be subtracted to the measures.

Also the correlation between fluorescence and concentration may be different from that obtained in calibration; that may be due to dilution errors and to interactions of the environment and the water plant.

The adopted procedure allows to eliminate those effects from the error computation, for the determination of the overall uncertainty of the flow-measure, introducing an offset value, to be subtracted from all measures during testing, and determining the concentration value on the basis of fluorescence reading, corrected with an appropriate multiplicative factor.

A conversion curve is thus obtained, where the equation that allows the determination of the concentration on the basis of the values of detected fluorescence can be obtained.

This curve remains valid for the duration of the tests, until the injection solution is finished.

That is, at every new preparation, the check must be repeated and strictly adopted a new conversion curve.

Flow calculation

The implemented methodology allows to calculate the flow using two methods that serve each other verification of the result obtained: the used flow is normally the average obtained from the two different methods.

The first method is the plateau, that is determining a stable condition in which the concentration of tracer remains constant over time, for a period long enough to have a standard deviation adequately contained.

In this situation the calculation is due to the theoretical approach

$$Q_1 C_1 = Q_2 C_2 \qquad Q_2 = Q_1 \frac{C_1}{C_2} = R_d * Q_1$$

$$Q_1 C_1 = Q_2 C_2 \qquad Q_2 = Q_1 \frac{C_1}{C_2}$$

Using appropriate light sources and using precision optical filters, a fluorescence-meter can measure the fluorescence rate (ratio of absorbed and emitted light) and therefore quantify the concentration of the fluorescent substance, as said above in the theoretical outline.

Then, reporting the reference fluorescence F_0 in the absence of tracer injection, before and after injection itself, and the fluorescence of the plateau F_p , the difference between the two measures is $F_p - F_0 = k_A C_p$, being the concentration $C_0 = 0$ by definition

$$Q_2 = Q_1 \frac{C_1}{C_2} = \frac{k_A C_1}{(F_p - F_0)} \cdot Q_1 = \frac{(F_T - F_0)}{(F_p - F_0)} R_d' \cdot Q_1$$

F_T being the fluorescence obtained during calibration from the released solution C_1 , appropriately diluted with dilution ratio R_d' , in order to be the same order of magnitude of C_2

$$C_1 = C_2 \cdot R_d' = \frac{F_T - F_0}{k_A} \cdot R_d'$$

The second method of calculation is the so-called “integral method”, for which the total volume of tracer injected must match the total volume of tracer measured in the flow. Being the injection at constant flow, the volume released is

$$V_1 = Q_1 C_1 T_1$$

where T_1 is the release total time. Conversely, the volume of tracer measured in the measuring section is

$$V_2 = Q_2 \int_{T_A}^{T_B} C_2 dT$$

then

$$Q_2 = Q_1 \frac{C_1 T_1}{\int_{T_A}^{T_B} C_2 dT} = \frac{(F_T - F_0)}{\int_{T_A}^{T_B} (F_2 - F_0) dT} Rd' \cdot Q_1$$

This second method is applicable even in absence of plateau, while gives incorrect results in presence of recirculation areas. The two analysis techniques together guarantee the absence of recirculation or unidentified secondary flows, and the achievement of measuring stationary conditions.

Measuring error evaluation

As known, the errors of measurement can be divided into two different categories: systematic and random errors.

The systematic errors are caused by calibration errors (including hysteresis and non-linearity of measuring sensors and reference instruments), from installation mistakes (elevations, sections and calculations of parameters such as water density) and specific hydraulic conditions that affect in a constant way the measure (e.g. an error caused by an incorrect positioning of a temperature sensor, that measures values consistently lower or higher than the actual temperature of fluid).

The random errors can generally be reduced by increasing the number or frequency of acquisitions and are usually due to fluctuations of the measured values (as a result of the dynamic part of the signal), to specific hydraulic conditions that affect in a variable way on the measure (e.g.: presence of vortices or pulse effects), to instability in the electrical network which produces turbine load variations.

The error introduced in the flow measurement, using the tracers in constant-injection method, may be the result of many factors.

The error due to the fluorescence-meter calibration is related to the uncertainty of determination of reference solutions, which in turn is due to uncertainty (systematic and random) of the sampling calibrated pipette, to the volumetric uncertainty of the mixing vessel, and to the intrinsic uncertainty of the instrument (this last only present as random uncertainty, being the systematic error presumably identical in both calibration and measuring). By adopting the arrangements provided in WEST test procedure, it can be normally assumed that the systematic error is $f(C_T)_S < \pm 0,25\%$ and the random error is $f(C_T)_R < \pm 0,35\%$.

The error due to uncertainty of the injection calibrated pump is related to the goodness of mechanical drive system and electronic/digital control system, according to design data and to functional periodic checks, it is reasonable to assume that the systematic error is $f(P_T)_S < \pm 0,20\%$ and the random error is $f(P_T)_R < \pm 0,25\% \cdot f(P_T)$

There is also the error due to interference with the environmental conditions and characteristics of the water. It's known, for example, and is assessed the dependence of fluorescence from temperature and pH; the measuring cell normally takes account of these parameters, both during the verification of site calibration and during the tests. The measure of discrete samples of calibration solution and the measures is also repeated in the laboratory at

constant temperature and humidity. The environment absorption of the tracer substance should be modest, and anyway measurable by the comparison between integral and plateau methods. The environmental residual error is difficult to evaluate. From the experiences made it can be assumed that the systematic error is $f(V_T)_S < \pm 0,50\%$ and the random error is $f(V_T)_R < \pm 0,25\%$.

The error due to bad mixing of the tracer in the fluid that is normally the most difficult to evaluate. It is function of the distance between the section of release and levy, and of the injection flow.

The fluctuation of the value of fluorescence (concentration) is index of mixing goodness, and then that error is manifested physically closer to a random error that not as systematic bias. The choice of injection flow and of sections of release and levy, and the number of points of injection, typically aims to reduce the fluctuation within $f(M_T)_R < \pm 1,00\%$, considering the random error range here indicated as 2σ , while the systematic error part is typically $f(M_T)_S < \pm 0,10\%$.

The error in determining the flow is for each of two components (systematic bias and random) given by

$$f(Q) = \pm (f(C_T)^2 + f(P_T)^2 + f(V_T)^2 + f(M_T)^2)^{0,5}$$

Istrago Test Case

The hydroelectric power station in Istrago, realized in the first fifties, is located in the municipality of Spilimbergo (fraction Istrago), in the province of Pordenone, and is part of Meduna hydroelectric core facilities, located precisely on Meduna river.

It is a flowing water-type power plant, located downstream Colle power station, downstream the crossing of Meduna riverbed. Near Sequals, from the canal, water fills an upstream basin, and through grilles and head valve passes in the underground penstock about 3 km long.

Near the power plant, downstream of an inspection man-door, the penstock connects to an expansion tower about 30 m high, downstream of which depart the two pipelines that feed the two units of the power plant and the lower reservoir.

The units, vertical axis-type, consist of two Francis turbines, with synchronous-relief valve and rotational inlet valves, coupled to two salient-poles-type generators. Specific feature of the plant is the length of the rotational shaft which requires the presence of an intermediate bearing.

TURBINE DATA

head:	H	=	66	m
max. flow:	Q	=	7	m ³ /s
power:	P _r	=	4182	Kw

The tests were carried out under a constant flow and substantially with a balance between inlet flow and power absorbed by the turbine.

The release of tracer is made at the entrance to the tunnel under pressure for a duration of about 300 seconds, in order to define with sufficient precision the plateau of concentration, within the time required to flow measuring.

For each hydraulic point were made three acquisitions identified by the letters “a”, “b” and “c”. The acquisition “a” is simultaneous to the tracer injection.

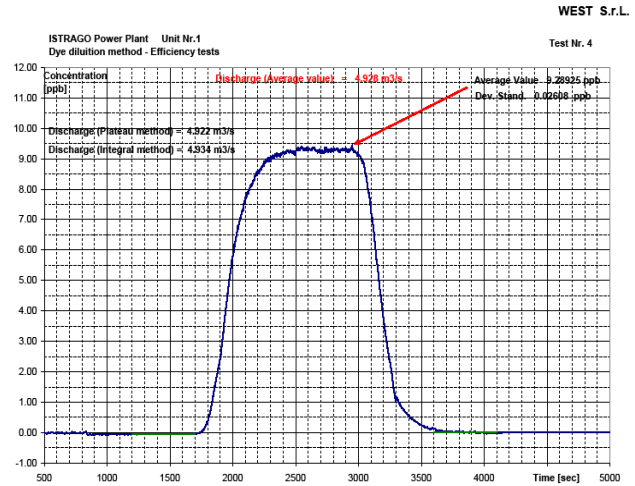
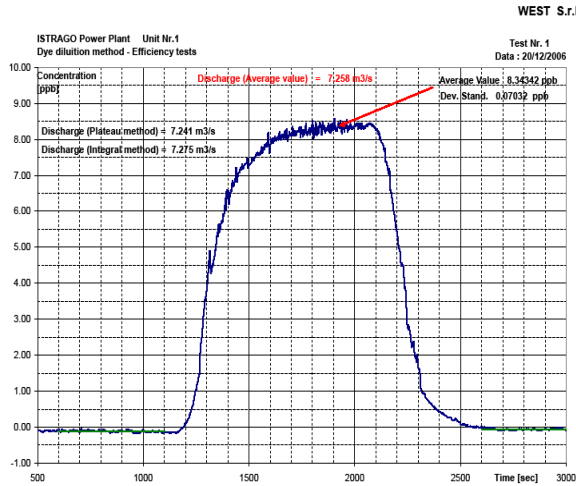
The acquisitions “b” and “c” are respectively carried out during the transit of Rhodamine through the penstock and during the measurement of the plateau concentration, at the transit of tracer in the section of detection (in fact the distance between sections of input and detection leads to a time of several tens of minutes between injection and measurement, during which it is essential that the hydraulic conditions remain constant).

The verification of measure and operating conditions constancy was determined by the power measurement and differential pressure of Venturi-cone taps taking into account their respective coefficients derived from tests with tracers. The tests have regarded the full operational range of the unit, within 5 and 10 tenths of the rated load.

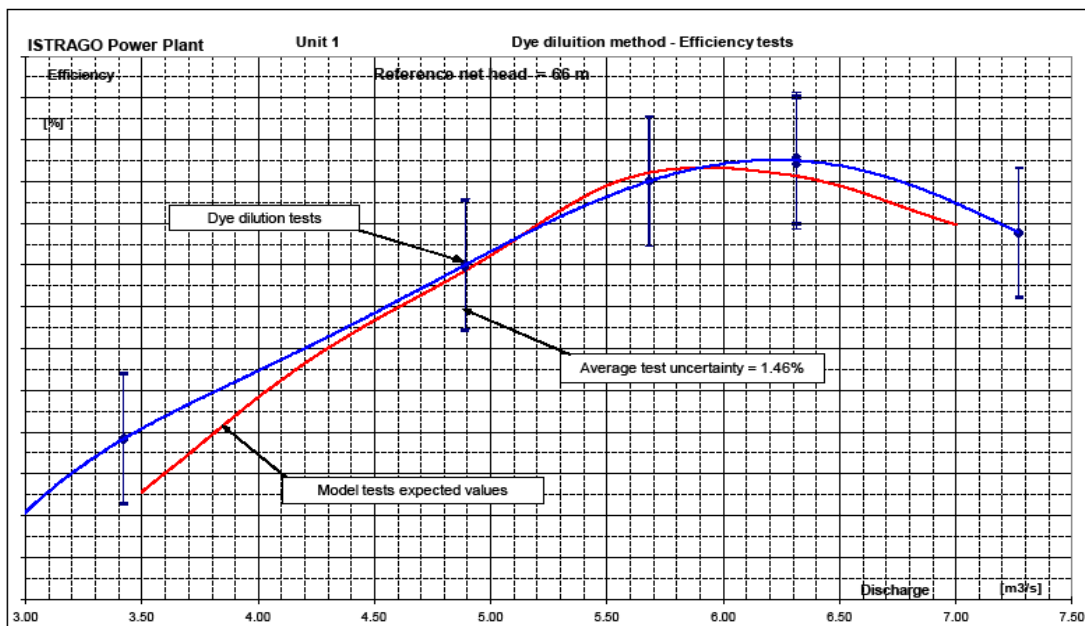
The levy section was identified at a man-door on the upstream penstock, several meters before the surge well near the power house.

It has been inserted a sampling probe to take mixed water in the central area of the penstock. The good mixing found at the end of the mixing trail (through the whole 3 km penstock length) did not need to take mixed water from many points.

The following charts show the concentration trend over time



It is noted that the raise ramp lasts about 400 seconds, however the plateau condition average of 400 is all the way present, for which a good definition of the reached concentration value is achievable. Even at the maximum flow, corresponding to the minimum concentration of tracer, fluctuations of the measure are sufficiently contained. On average the measurement uncertainty remains contained within $\pm 1.43\%$. The results obtained show a good correlation between the measurements made with tracers and forecasts, with deviation still lower than the measurement uncertainty.



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Montjovet Test Case

Montjovet hydroelectric power plant is located in the municipality of Montjovet, in the province of Aosta, and is part of Chatillon hydroelectric core facilities, located precisely on Dora Baltea river.

It is a flowing-water type power plant with a catchment area of 2,414 sq km, which uses the waters of the Dora Baltea and fits between St. Clair and Hone1 plants, having a yearly average productivity of 221 GWh.

The work of derivation, located in the town of St. Clair, is a cross with four openings, closed by flat gates.

From the upper basin starts a penstock with two pipelines that feed two units with a total flow of 110 cubic meters/sec and 52.8 m head, that can provide efficient power of 50 MW.

TURBINE DATA

head:	H	=	51.60	m
max. flow:	Q	=	55	m ³ /s
power:	P _r	=	25860	Kw

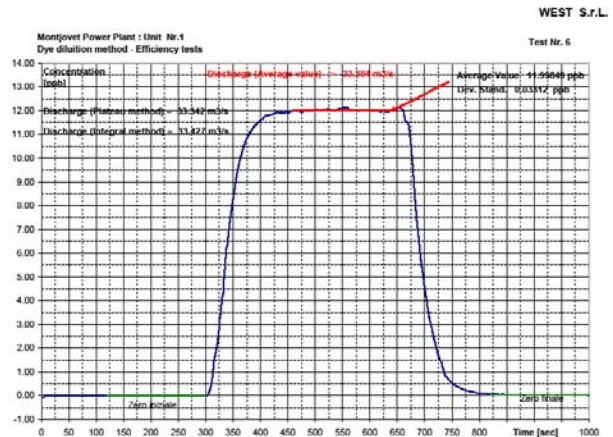
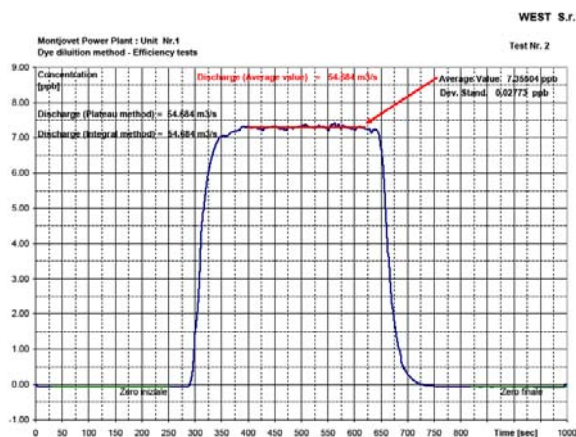
The flow was measured with tracers method, injecting Rhodamine WT through nine calibrated sprayers mounted on a metal structure, properly installed at the penstock entrance, immediately downstream grids.

The levy section was identified downstream from the draft tube elbow, in the discharge channel, several meters before reunification with the discharge channel of the second unit, and re-entering of waters in Dora riverbed.

The section was explored horizontally and vertically, during preliminary tests, in order to evaluate the homogeneity of mixing, were used three levy points.

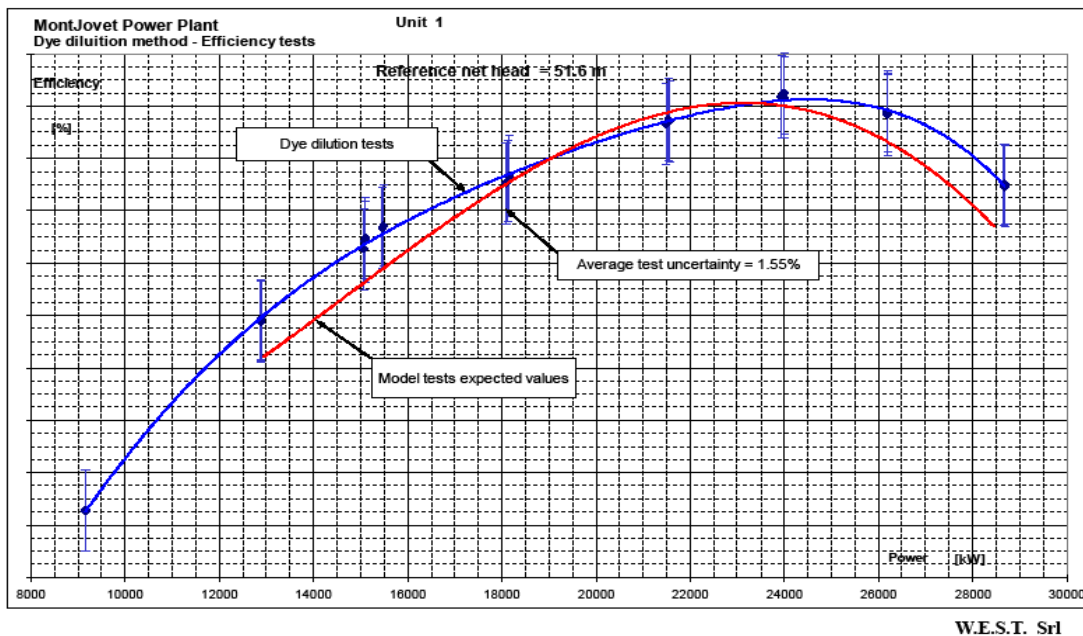
The verification of measure and operating conditions constancy was determined by the power measurement and differential pressure of Venturi-cone wells taking into account their respective coefficients derived from tests with tracers. The tests have regarded the full operational range of the unit, within 5 and 10 tenths of the rated load.

The following charts show the trend in concentration over time.



In this case the raise ramp lasts about 40 seconds, and the plateau condition average of 400 is extremely stable, for which a good definition of the reached concentration value is achievable. At the maximum flow, corresponding to the minimum concentration of tracer, fluctuations of the measure are sufficiently contained.

On average the measurement uncertainty remains contained within $\pm 1.55\%$. The results obtained show a good correlation between the measurements made with tracers and forecasts, with deviation still lower than the measurement uncertainty.



Colle Test Case

The hydroelectric plant of Colle, use water from the river Meduna derived with the taking of Maraldi and conveys to a load basin through a channel length of over 4.5 km, with trapezoidal section for 4.3 km. On the left side of the basin there are the intake grids to a prestressed concrete underground penstock with diameter of 2.5 m and 65 m length. The turbine discharges the water into the free hair tunnel that conveys water in the tub load the next plant Istrago after 3.5 km.

TURBINE DATA

head:	H	=	32	m
max. flow:	Q	=	14	m ³ /s
power:	P _r	=	3950	Kw

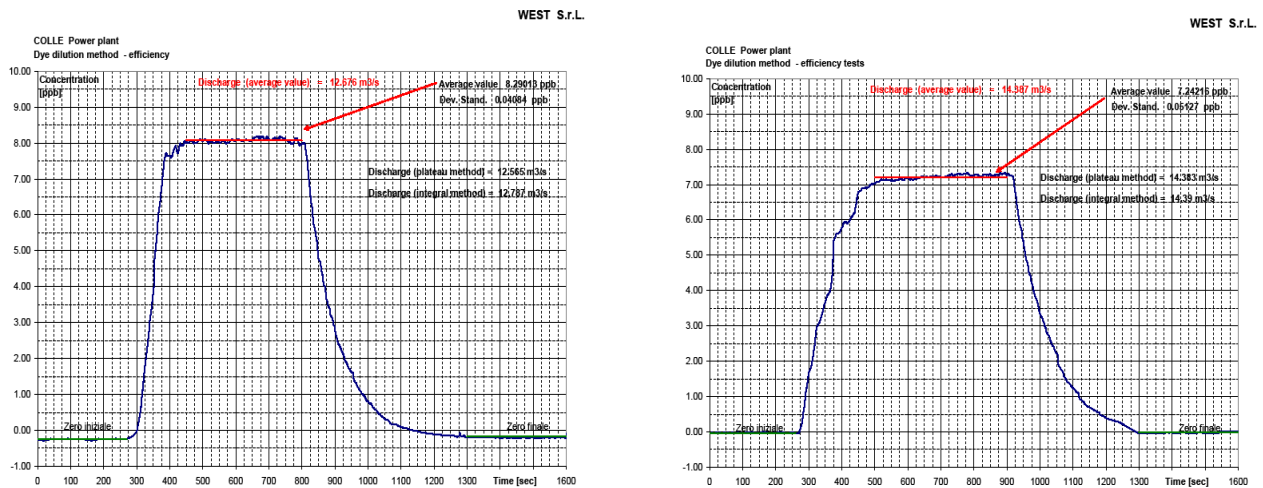
The flow was measured with dye dilution method, injecting Rhodamine WT through six calibrated sprayers mounted on a metal structure, properly installed at the penstock entrance, immediately downstream the intake grids

The levy section was identified downstream from the draft tube elbow, in the discharge channel.

The section was explored horizontally and vertically, during preliminary tests, in order to evaluate the homogeneity of mixing, were used three levy points.

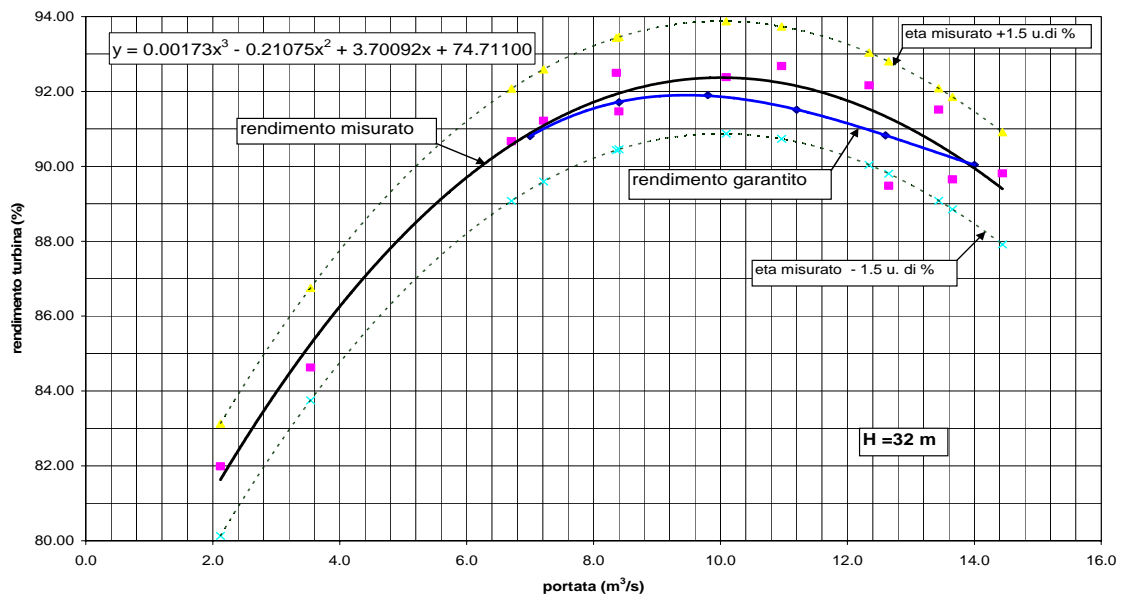
Current meter tests were performed in parallel with dye dilution method. The tests have regarded the full operational range of the unit, within 5 and 10 tenths of the rated load.

The following charts show the trend in concentration over time.



In this case the raise ramp lasts about 100 seconds, and the plateau condition average of 400 is extremely stable, for which a good definition of the reached concentration value is achievable. At the maximum flow, corresponding to the minimum concentration of tracer, fluctuations of the measure are sufficiently contained.

On average the measurement uncertainty remains contained within $\pm 1.45\%$. The results obtained show a good correlation between the measurements made with tracers and forecasts, with deviation still lower than the measurement uncertainty.



Conclusions

The improvement of measuring equipment, test procedures and diagnostic methods have made it possible to considerably improve the credibility and reliability of the tracers method. The two cases shown, corresponding to plants with different characteristics and dimensions, with installation and test modes substantially different, have given extremely positive and encouraging results. In the three cases examined the error of measurement resulted of about $\pm 1.50\%$.

While recognizing that further improvements and refinements should be made, it is believed that the work done so far may allow to do performance tests with total error reasonably lower than $\pm 1.75\%$.

In addition, the investigation to identify the errors of measurement is a valuable tool of data analyzing and to assess further improvements to implement.

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