IGHEM - Montréal 96

TEST EQUIPMENT AND RESULTS FROM 25 HYDRAULIC TURBINE TESTS USING THE THERMODYNAMIC METHOD

By

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Résumé: Cette étude présente une discussion des outils et de la technologie qui oni été développés au coure de plus de quartorze ans de recherches qui out consiste en vinqt cinq experimentations pratiques sur les turbines hydroéléctriques en employant la méthode d'experimentation thermodynamique. Cette étude énumère un certain nombre d'éléments dont il est necessaire de tenis compte des le début de l'organisation du travail et de la recherche méthodologique. Un outillage portatif d'experimentation comprenant des instruments et un systeme d'acquisition de données informatisé y sont également décrits. Une attention toute particulière a été aussi consacrée à l'installation de l'outillage en particulier à l'emplacement des sondes. Les méthodes de calibrage des senseurs qu utilisent le système dont on a parlé précédenment sont énumerées. Les méthodes utilisées dans l'experimentation sont décrites et les données et les résultats représentalifs de l'experience sont démontrés et expliqués. Une discussion des procedures de correction pour le transfer de la chaleur à la turbine et a l'outillage et des effets de l'admission de l'air s'en suit, donnant lieu à une analyse des erreurs systematique et de celles qui se produisent au hasard.

Summary: This paper describes test equipment and techniques developed resulting from over 14 years of experience in conducting 25 field tests on hydraulic turbines using the Thermodynamic Test Method. It lists a number of factors that should be considered early in the planning and application of the test methodology. Portable test equipment including instruments and a computer controlled data acquisition system are described in detail. Special attention is given to the installation of equipment including the location of test probes. Procedures to calibrate the sensors using the computer controlled data acquisition system are enumerated. Procedures used to conduct the test are described and typical test data and results are shown and explained. A discussion of correction factors for heat transfer to the turbine and to the test equipment and for the effects of air admission is presented, followed by an analysis of systematic and random errors.

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INTRODUCTION

In the early 1980's, the author was a senior engineer in the Engineering Department of the Southern California Edison Company (SCE) and was responsible for a program to upgrade and modernise their hydraulic turbines and for testing the turbines. In reviewing the various testing methods, it was decided to use the Thermodynamic Method because of its simplicity, accuracy and low cost compared to other methods. At that time, we had no experience or test equipment and had to develop the necessary instrumentation and procedures using IEC Publication 607, 1978, as a guide (reference -1). In developing the test program, it was decided that it should meet the following requirements:

- o Modern electronic instrumentation should be used to eliminate taking data visually, such as reading manometers.
- o A computer controlled data acquisition system should be used to take and record data and to automatically make calculations so that results are available as the tests are being run.
- o Careful procedures must be used to calibrate sensors and to conduct the tests to minimize errors and to ensure repeatability of results.

In 1987, the author retired and has since performed turbine tests under his own Company (ENKAR). At that time, the author designed and built new test equipment to simplify the tests, improve the accuracy and to make the equipment more portable. The author also built a duplicate set of new test equipment for SCE which they continue to use to test new turbine runners. The following sections describe the the test methodology, the equipment and test procedures that have been developed based on years of testing using the Thermodynamic method.

TEST METHODOLOGY

Basic Concepts

The Thermodynamic Test Method is based on an evaluation of the total energy of the turbine and on the fact that the losses are manifested by a rise in the temperature of the water passing through the turbine. By extracting a small sample flow of water at the inlet of the turbine, it is possible to "throttle" or partially expand the sample under controlled conditions (adiabatic) and cause its temperature to rise to the same value as the temperature of the main flow of water at the discharge point. By this process, it is possible to measure efficiency without measuring the actual flow through the turbine. By accurately measuring the pressures, and the output of the generator driven by the turbine, all performance parameters of the turbine such as net head, flow and output can be accurately determined. A complete discussion of the methodology, the efficiency equation and its derivation can be found in reference -2.

Figure -1 shows a typical turbine test arrangement for a Francis turbine. An inlet probe is inserted in the penstock at the turbine inlet and is used to extract a small sample of the flow which is piped to the test chamber. Pressure, temperature and velocity sensors are mounted on a pipe assembly and inserted in the draft-tube discharge of the turbine. The symbols shown in the figure identify the sensors listed below:

- Kg - Power (Kilowatt) output of the generator
- Pd - Pressure at the turbine discharge
- Pi - Pressure at the turbine inlet, including velocity head
- Pt - Pressure in the test chamber, including velocity head of the water sample
- Qe - Flow rate of the extraction (sample) flow
- Td - Temperature of turbine discharge water
- Tt - Temperature of water sample after partial expansion
- Ta - Temperature of ambient air at the test chamber
- Vd - Velocity of turbine discharge water (used only for turbines which (have draft-tubes with more than one opening.)

The center-line elevations of the turbine inlet and discharge and of the test chamber are identified by Zi, Zd, and Zt respectively.

Application Considerations

The Thermodynamic Test Method is generally applicable to most Francis and Pelton turbines having heads of 300ft (100m) or more; however, the author has successfully tested Francis turbines with heads as low as 200ft (60m). The method normally does not require draining of the penstock, does not interfere with the operation of other units at the plant, and does not require unusual operation of the unit being tested such as repeated load rejections.

Typically, a thermodynamic test of a single unit can be completed in 4 to 5 days, and only 4 to 6 hours of unit outage time is required at the beginning of the test to install the inlet and discharge probes, and a similar time at the end to remove the probes. Typical times required to perform the test activities are listed below.

- o Setup of test equipment and calibration .... 2 days
- o Testing .... 1 to 2 days
- o Disassembly of test equipment and post calibration .... 1 day

The testing times can vary depending on how many test points are required and how long it takes for thermal conditions to stabilize during the tests. Also, Pelton turbine tests can require more time if it is desired to test the turbine under various combinations of operating nozzles.

Preliminary Considerations

When initially contemplating a turbine test, it is important to consider the following items at an early stage:

- o During the planning phase for the tests, make sure the tests can be scheduled for a time when there will be adequate water available and no restrictions on the operation of the unit at various power levels. If the water source is a reservoir, the reservoir should be well filled for the tests so as to avoid major changes in water levels which can otherwise cause temperature excursions due to stratified temperature regions in the reservoir.
- o When testing a unit in a multi-unit plant, it is best to maintain the total water flow through the plant at near a constant value. For example, as the flow changes in the unit being tested, the flow in other units should be changed to maintain the same total plant flow. Also, it is desirable that the plant and the units be operated continuously for several weeks before testing is begun so as to stabilize the temperatures of the structures and water system. This will help to minimize water temperature variations and make it easier to stabilize test conditions.
- o The length of penstock carrying the water to the unit should be at least 200 times the diameter to ensure uniform mixing of the water. This requirement

can be reduced if the flow velocity is high enough to produce high Reynolds numbers and good turbulence.

- o The tests should be conducted at nite to eliminate all solar radiation effects and to reduce ambient air temperatures.
- o Responsibilities of the parties involved in the test program and agreement on the test procedures and on test points should be established.
- o The Chief Test Engineer should be appointed with authority to resolve disputes.

Site Inspections

At least one site inspection should be made to obtain and verify the following:

- o Detailed plant and unit drawings showing both structure and equipment locations and dimensions.
- o Determine locations for the inlet and discharge probes and supports.
- o Determine optimum location for the test apparatus (ie, as far as possible from noise but within reach of equipment cables).
- o Determine method of supports for the test chamber at the turbine inlet.
- o Ratings of the turbine and generator and of instrument transformers used for the measurement of generator power output.
- o Generator efficiency data used for the calculation of turbine flow.
- o Identify spurious discharges such as generator cooling water and methods of re-routing them so that they do not affect the tests.

TEST EQUIPMENT

One of the basic requirements for the test equipment is that it be portable; that is, it should be of a size and weight that it can be readily transported and handled by test personnel, and it must be rugged to withstand physical abuse during transportation. Figure -2 is a photo showing the nine portable cases containing all the equipment required for performing tests and calibration of sensors, including the computer, printer,data acquisition system, sensors, probes, test chamber, cables, fittings and tools. Eight cases are identical and have dimensions of 21"x14"x11" and the one large case for the test chamber is 28"x18"x14". The total weight is approximately 700 pounds and can be carried in a standard passenger van such as a Dodge Caravan. A list of the computer system and sensors follows:

- o Computer - Hewlett Packard HP71B
- o Printer - Hewlett Packard HP2225B thinkjet
- o Data acquisition unit - Hewlett Packard HP3421A, 4 ½ digit A/D converter
- o Controller - Enkar
- o Watt transducer (Kg) - Solid-state Transdata, 3-phase,2-element
- o Pressure transducer (Pd) - Piezoresistive bridge, Ametek 57
- o Pressure transducer (Pi) - Capacitance type, Rosemount 1151
- o Pressure transducer (Pt) - "
- o Flow transducer (Qe) - Pulse wheel, Proteus 100
- o Temperature sensors (Td and Tt) - Hewlett Packard quartz thermometer
- o Temperature sensor (Ta) - Thermocouple, Omega TTC
- o Velocity sensor (Vd) - Pulse wheel, Data Industrial, 220B

Figure -3 is a photo of the three sizes of stainless steel probes which can be used for insertion in the penstock at the inlet to the turbine. The selection of which probe to use depends on the diameter and thickness of the penstock to achieve the optimum penetration distance into the flow stream.

Figure -4 is a photo of two discharge probes. The larger assembly includes a velocity sensor (Vd) and a thermowell for the discharge temperature sensor (Td), and is normally used for Francis type turbines with split draft-tubes. The smaller assembly has a thermowell for the discharge temperature sensor (Td) and is used for Pelton type turbines. The probe assembly is mounted to standard pipe sections to convey the sensor cables out of the water. The pipes and assembly are mounted to a pipe rack which must be securely held in the discharge water from the turbine. Special attention should be given to the design and installation of the rack and assembly to make certain that it can withstand the turbulence of the water. Generally, the rack and assembly is designed prior to the test based on drawings and site measurements, and is installed at the beginning and removed at the end of the test. In the case of Francis turbines, they usually have gate slots in the draft-tube openings so that the rack and pipes can be lowered into position and held in the slots. For turbines that do not have gate slots in the discharge opening or at the desired location, the probe assembly can be attached to pipes fastened to the walls and guyed, if necessary, for additional support.

Figure -5 is a photo of the special test chamber designed by ENKAR for the partial expansion of the sample flow extracted by the inlet probe. The chamber includes provisions for measuring the water temperature in the test chamber after partial expansion (Tt) and for measuring the pressure (Pt) including the velocity head. A sensor for measuring the flow rate of the extraction (Qe) is located in the discharge from the test chamber. Special motor operated valves are provided for controlling the flow rate and the partial pressure in the chamber. The flow system in the chamber is designed so that the transit time for the water extracted at the inlet probe to reach the temperature sensor (Tt) can be adjusted to be same as the transit time for the main turbine flow to reach the discharge temperature sensor (Td). This feature can be important if there are significant changes in turbine water temperature during the time that measurements are taken. The test chamber is completely insulated both internally and externally to minimize the effects of heat transfer from the ambient air to the extracted water.

INSTALLATION

Installation of Test Equipment

Figure -6 shows the test control center where the computer system, controller and quartz thermometer are setup for conducting calibrations and all tests. As can be seen, the space requirements are very modest. The location for the test control center should be selected to minimize noise levels and so that the distance to the sensors can be reached by their electrical cables. All sensors should be connected with their electrical cables during both calibration and testing.

Location of the Inlet Probe

The installation of the inlet probe, should consider the following:

- It should be located downstream of the turbine inlet valve and as close as practical to the turbine inlet. If the inlet valve is a spherical type valve, it presents no problems; however, if it is a butterfly type valve, the probe must not be located in the plane of the valve disc.

- The depth of penetration of the probe in the flow should meet the following criteria: $0.25 \leq (Yp/R) \leq 0.33$

  where, Yp = penetration distance measured from the inside of the pipe to the center of the probe port
  R = inside radius of the penstock pipe at that point

Meeting this criteria will ensure that the inlet port in the probe will include the average velocity head of the flow, and also it will be sufficiently far from the pipe wall to avoid heat transfer effects.

Location of the Discharge Probe

The discharge probe should be installed in the center of the discharge flow and at least five runner diameters downstream from the runner to ensure adequate mixing of the water. In the case of Pelton turbines, the level of the tailwater in the discharge tunnel with the minimum flow expected during the tests should be known so that the probe location will be near the center of the flow under minimum flow conditions.

The location of the discharge probe for Francis turbines requires some special considerations. Most large Francis turbines have draft-tubes with a vertical support which results in having two discharge openings. Observations of the tailwater where the draft-tube discharges indicates that the flows often do not divide equally between the two openings and that the discharges are not uniform and are subject to surging. Often most of the turbine discharge exits from one of the opening and will even shift to the other opening as the output of the unit changes. In view of these observations, it is necessary to evaluate how is the best way of measuring the discharge parameters.

In 1987, a special test program was initiated to investigate the temperature and velocity profiles in the draft-tube openings of a Francis turbine that had previously been tested. An array of seven quartz temperature probes and velocity sensors was assembled and lowered in the each of the draft-tube openings and measurements made over a range of unit power outputs. The conclusions of these tests are listed below:

- The velocity profiles varied considerably and rapidly even when the output of the unit was constant. Sometimes the flow would concentrate in one corner and shift to another. The only point with a consistent flow velocity was at the center.

- The temperature profile varied several millidegrees C, with the probes at the top, bottom and sides being affected by the temperature of the walls and by the temperature of the tailwater into which the flow was discharged. Hence, only the temperature sensor at the center was unaffected by local temperatures at the opening and at the walls of the draft-tube.

- o The total discharge as determined by the velocity sensors showed good agreement with the total discharge determined from the actual tests which used a velocity sensor only at the center of the openings.

- o The ratio of the discharge from the draft-tube openings can be approximated by the ratio of the relative flow velocities measured at the center of the openings. Using this relationship, the turbine efficiencies measured at each opening can be combined to calculate the overall efficiency by weighting the measured values by the relative velocities measured at the center.

Handling Temperature Probes

Special care should be used in the handling of the quartz temperature probes used to measure the water temperatures as they are sensitive and relatively costly (approx. US$4000 each). In earlier tests, the author experienced a number of probe failures. The probes now used by the author have been modified and are more rugged, and no probe failures have occurred in the past 7 years; however, because of their high cost it is prudent not to subject them the physical abuse and mechanical shocks. It is also recommended that the probes be exposed to similar temperature extremes from the time they are calibrated for the tests until the post-test calibration is complete. These precautions will help to minimize differences in the pre-test and post-test calibration results.

CALIBRATION

The instrumentation and the data acquisition unit are calibrated as a system using the computer. Basically, the technique involves subjecting each primary transducer to an accurately known input and then instructing the computer to scan and convert the output of the transducer to obtain a series of readings. The computer then calculates the mean value of the A/D converted readings and the mean value then corresponds to the known primary quantity. Six calibration points are established in this manner over the operating range for each primary transducer. In addition, a number of procedural techniques are used to reduce systematic errors in the calibration, which are described below:

- The instrumentation and transducers are setup and calibrated at ambient temperatures similar to what they will encounter during the tests; thus minimizing errors due to ambient temperature during calibration and testing.

- The turbine inlet (Pi) and test chamber (Pt) pressure transducers are connected together and calibrated to the same pressure using a dead-weight tester, which substantially reduces any systematic errors in the calculated turbine efficiency due to calibration of these transducers

- The discharge pressure (Pd) transducer is calibrated by a water column with the transducer in water at a temperature approximately the same as the turbine discharge water so that there is essentially no error due to temperature. Also, the error in water column height is less than 0.1" so that the error in calculated turbine efficiency is negligible.

- The quartz probes used to measure test chamber (Tt) and turbine discharge (Td) temperatures are also used to measure the temperature difference (Td-Td). Each probe is individually calibrated with crushed distilled water in a special Dewar flask to verify its warranted accuracy of ± 0.04 deg C. The probes are also calibrated together to obtain an accurate measurement of temperature difference (Td-Tt) to within ± 0.0002 deg C. It should be realized that the temperature difference (Td-Tt) can be measured much more accurately than the absolute temperatures.

- The generator power (Kg) although not used directly in the determination of turbine efficiency is used to calculate the turbine flow rate. A 3-phase watt transducer is used to measure the generator output and is pre-calibrated prior to the tests to ± 0.25 % accuracy, which does not include instrument transformer errors which usually are in the order of less than ± 0.1%.

- The sensor used to measure turbine discharge velocity (Vd) is calibrated by connecting the assembly in which the sensor is mounted to a pipe with a flow velocity in the range of that to be expected in the draft-tube where the sensor will be mounted. This sensor is applicable only for turbines that have more than one discharge opening and is used to obtain the relative velocities at the draft-tube openings. The measurement of absolute velocity is not important.

- The sensor used to measure the extraction flow (Qe), although not used directly in the calculation of turbine efficiency, is important in determining the correction factor for heat transfer into the test chamber. The sensor Is calibrated by using the computer to measure the output voltage of the sensor at specific flow rates determined by measuring the time required to accumulate a known volume of water.

After calibration of the sensors and before conducting test runs to determine turbine efficiency at specific power values, it is necessary to perform a series of tests to determine correction factors to account for the effects of heat transfer to the extraction system. To perform these tests, the unit is operated at a constant output and for a sufficient time to stabilize water temperatures. Under these constant conditions, a series of tests are conducted to calculate the efficiency for various extraction flow rates (Qe). Data points are plotted for efficiency vs the reciprocal of Qe and a straight line fit to the data points. The line is extended to the vertical axis where (1/Qe) is zero, and the efficiency at that point compared to the efficiency at the various extraction flow rates gives the correction factor for the heat transfer effects. Since the heat transfer is also a function of the temperature difference between the extracted water (Tt) and the ambient air (Ta), it is important to record the air temperature during these tests. The slope of the straight line and the ambient air temperature are input to the computer so that the correction factor for heat transfer to the extraction system is automatically computed in the efficiency calculations. After this series of tests is completed, the actual turbine tests are begun.

TESTS

The following steps describe the procedures for conducting each test run:

1. The extraction flow (Qe) of the water sample taken from the inlet probe is adjusted to the desired value. The valve in the test chamber used for partial expansion or throttling of the extracted flow is adjusted to obtain a small temperature difference (may be positive or negative) between the water in the test chamber (Tt) and the water at the turbine discharge (Td).

2. When conditions are stabilized as indicated by stable readings of the temperature difference, the computer is instructed to take readings of all parameters which is called a scan. The computer takes 20 readings of the parameters, computes the average, stores the data and prints the values. Each scan takes approximately 30 seconds. Several scans are repeated for these conditions.

3. The valve in the test chamber used to control the partial expansion is adjusted to increase (or decrease) the water temperature to obtain a temperature difference (Tt-Td) opposite in sign to the previous scans. The computer is instructed to make several scans under these new conditions.

4. The data from each scan is printed (a typical printout and explanation of data is shown in Appendix -A). Typically, two or three scans are made for the positive and negative temperature differences; however, more scans may be made if spurious temperature differences were observed which can be caused by short-term temperature excursions in the turbine water flow. Scans which exhibit this condition should be considered suspect and may be deleted from the calculation of turbine efficiency as discussed later.

TEST RESULTS

Calculation of Results

When all the scans have been completed, the computer is instructed to calculate the results. A typical printout and explanation of terms is shown in Appendix -B. As shown in the turbine efficiency equation derived in reference -2, one of the fundamental parameters to be determined by the tests is the pressure (Pto) in the test chamber at which the temperature difference (Tt -Td) is zero. Since a number of scans are conducted with both positive and negative temperature differences, it is possible to compute the pressure (Pto) by interpolation for all possible combinations of the scan data. In other words, three positive and three negative temperature difference scans can be combined to provide nine values of turbine efficiency, from which the mean value of efficiency (ET) and the standard deviation from the mean (SDM) can be calculated. This approach provides a high level of confidence that the calculated efficiency is the true efficiency as it is based on a large number of data points with a random error indicated by the standard deviation (SDM).

As previously mentioned, it is possible to encounter a short-term unexpected change in turbine water temperature during a scan which produces a large temperature difference. When this condition is observed, the data from that scan is suspect and may cause unusually large variations in calculated efficiency. When the results are computed and printed, scan combinations which use the suspected data can be discarded (and so indicated in the printout) and not included in the calculation of mean values. This approach has been developed as the result of experience derived from performing a large number of tests in which short-term temperature excursions have occasionally been observed, and provides a means of detecting this condition when they occur during a scan and of documenting when the data is discarded.

Correction Factors

As shown in the typical printout of results in Appendix -B, the computer calculates two correction factors (CF1 and CF2). Correction Factor -1 accounts for the heat transfer to the test chamber and is based on the extraction flow rate (Qe) and the ambient air temperature (Ta), and on the heat transfer parameters determined in the preliminary tests described in the section on calibration.

The second correction factor (CF2) accounts for the heat transfer to the turbine water from the location of the inlet probe to the location of the discharge probe, including the exposed portion of the turbine inlet pipe and through the concrete structures around the flow path. The parameters used to calculate CF2 are computed from the physical dimensions of the turbine and from plant drawings using standard heat transfer formulae to determine an overall transfer coefficient. These calculations are made prior to starting the tests.

Since air is often admitted to the turbine runner, it is necessary to discuss the possible effect that it has on the calculation of efficiency. For Francis turbines, the amount of air admitted is generally very small (in the order of 3 to 5% of the turbine flow) and numerous calculations on the sensible heat transferred to the water have shown that it has a negligible effect on the calculated turbine efficiency and no correction factor is needed for it. It is important to note the distinction that the sensible heat transferred has a negligible effect on the calculations but the admission of the air does affect the operation of the turbine.

In the case of Pelton turbines, the admission of air to the discharge pit has two results that need to be evaluated. First, the air will absorb a portion of the turbine windage losses and will be discharged above the tailwater; thus, a portion of the windage losses are unaccounted for which produces an error that increases the calculated turbine efficiency. Second, the moisture in the air can result in the transfer of sensible heat to the water which produces an error that decreases the calculated turbine efficiency. Fortunately, both of these effects are negligible and produce off setting errors so that no correction factor is needed for them.

Even though the above paragraphs indicate that air admission can be disregarded, it is our practice to measure air volumes, temperature and relative humidity at the site to verify that the effects are negligible.

Typical Test Results

Table -1 is a list of turbines that have been tested by the author using the methodology and techniques described in the preceding paragraphs. The last five tests were conducted using the new test equipment shown in the photos. The table shows the measured peak efficiency of the turbines many of which were equipped with modern turbine runners. Although the peak efficiency of the new runners may be only 1 or 2 percentage points higher than the original runners, the efficiency curve was often shifted to the right so that at full output the efficiency was often 6 to 8 percentage points greater.

Analysis of Errors

Inaccuracies in the calculated turbine efficiency can be caused by systematic and random errors. Systematic errors depend on the accuracy of the calibration of the sensors and on possible changes (drift) in the performance of sensors during the tests. Careful calibration procedures and the use of high quality sensors can minimize the systematic errors. Changes in the performance of sensors (drift) can be detected by comparing the calibration data taken at the beginning of the tests with the data taken during the post test calibrations. Based on experience of many tests using the equipment and procedures described herein, the systematic errors generally fall within the curve shown in Figure -7.

Random errors due to the divergence of parameters during the tests can be minimized by taking a large number of readings and by making sure that stable conditions have been reached before attempting to take readings. The test equipment and the computer controlled data acquisition system make it possible to accomplish these objectives. Usually, the mean value of calculated turbine efficiency has a standard deviation of less than 0.1%.

CLOSING REMARKS

It has been a privilege to participate in this Seminar and it is hoped that the information presented in this paper will be of value and help advance the use of the Thermodynamic Method for testing hydraulic turbines.

REFERENCES

1. International Electrotechnical Commission (IEC Standard) Publication 607, First Edition, 1978, "Thermodynamic Method for Measuring the Efficiency of Hydraulic Turbines, Storage Pumps and Pump-Turbines."

2. Karlicek, Robert F.. "Testing of Hydraulic Turbines by the Thermodynamic Method," ASME International Hydro-Power Symposium, Anaheim, California, December, 1986.

Table -1: List of Turbines Tested by The Thermodynamic Method

Rated Capacity (Hp)	Rated Head (Ft.)	Type Turbine (Note-a)	Peak Efficiency (%)
69,400	2200	I/H	89.5
41,300	740	F/V	92.5
41,300	740	F/V	91.5
41,300	740	F/V	92.6
49,500	750	F/V	91.82
50,600	737	F/V	94.67
69,400	383	F/V	92.2
69,400	383	F/V	91.9
69,400	383	F/V	92.3
36,500	680	F/V	92.24
52,500	690	F/V	93.05
100,000	945	F/V	94.7
100,000	1004	F/V	93.8
28,700	800	F/V	89.8
28,700	800	F/V	88.9
2,500	1600	I/H	83.3
14,750	210	F/V	94.4
3,500	250	F/H	80.6
3,500	250	F/H	80.0
8,800	260	F/V	93.59
57,685	1245	I/V	90.53
50,000	587	F/V	89.34
18,000	240	F/V	92.34
136,730	2192	I/V	90.78
93,500	2230	I/V	90.12

Note -a: F/V = Francis turbine/Vertical shaft
F/H = Francis turbine/Horizontal shaft
I/V = Impulse (Pelton) turbine/Vertical shaft
I/H = Impulse (Pelton) turbine/Horizontal shaft

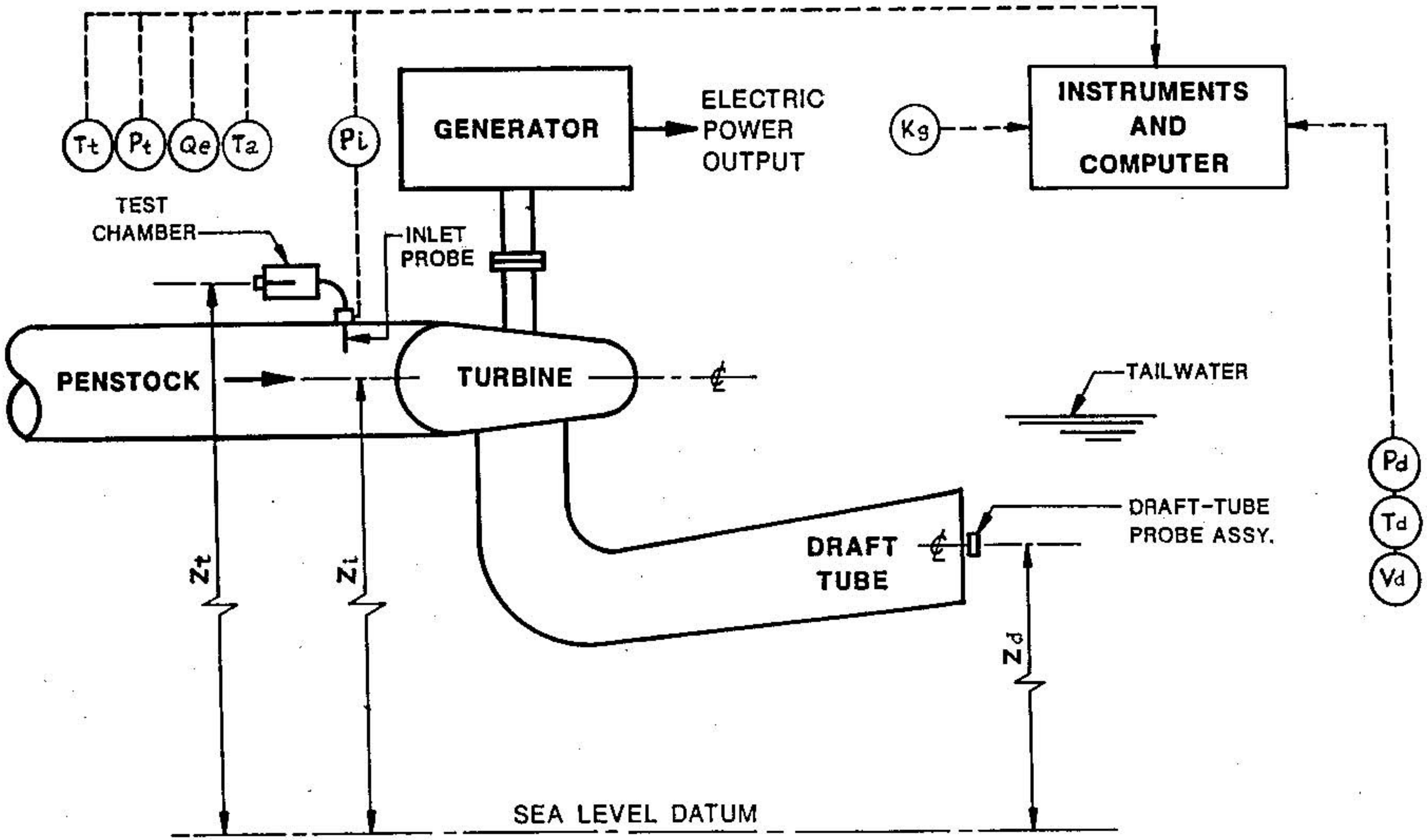

Figure -1: Typical Turbine Test Arrangement of Sensors

Figure -2: Photo of Complete Set of Test Equipment

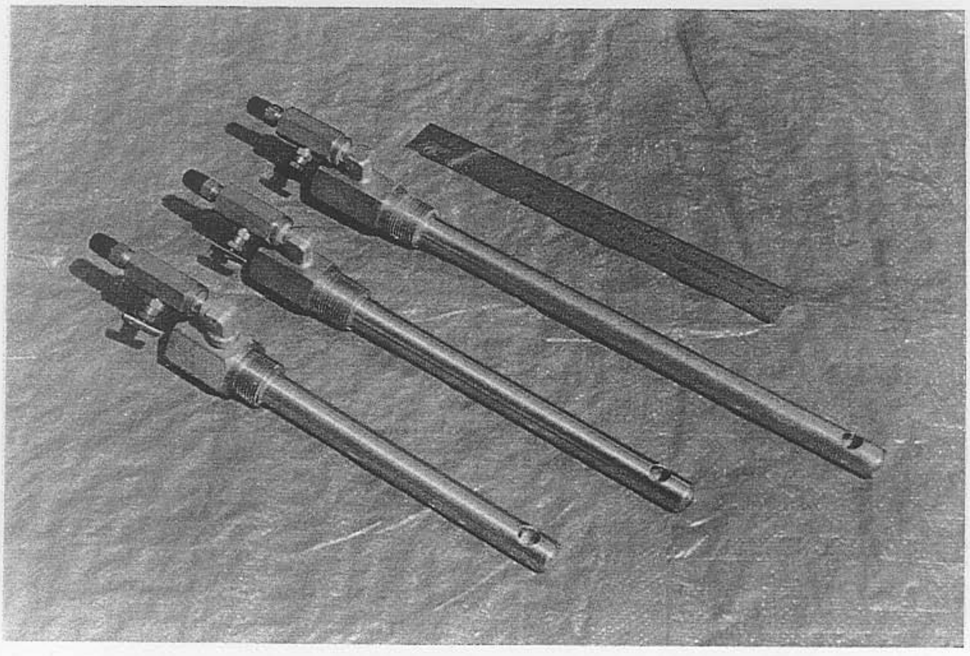

Figure -3: Photo of Several Sizes of Inlet Probes

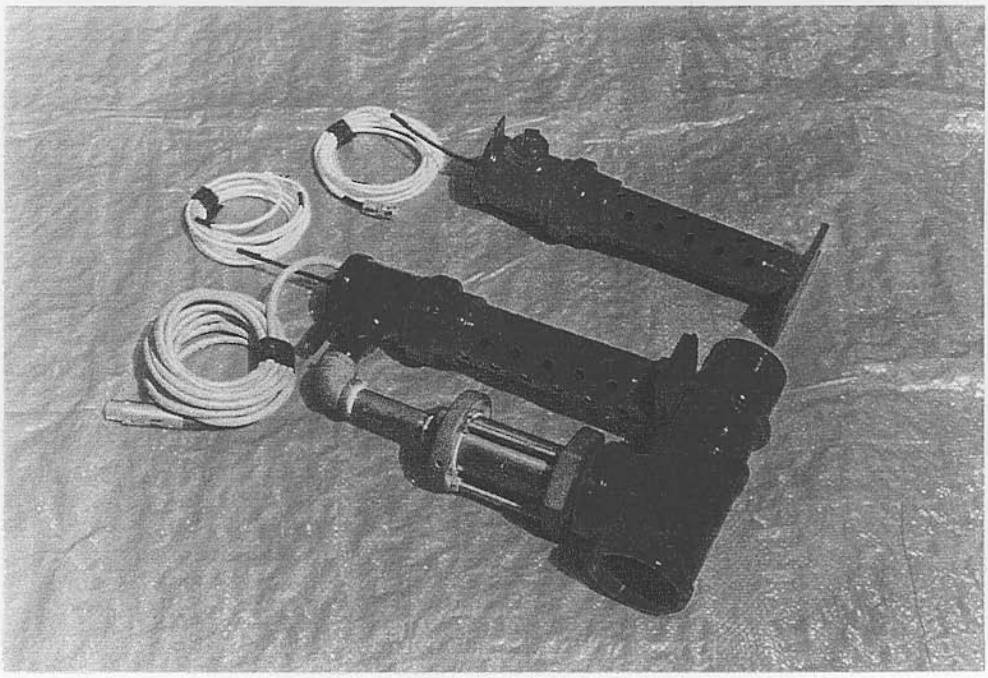

Figure -4: Discharge Probe Assembly

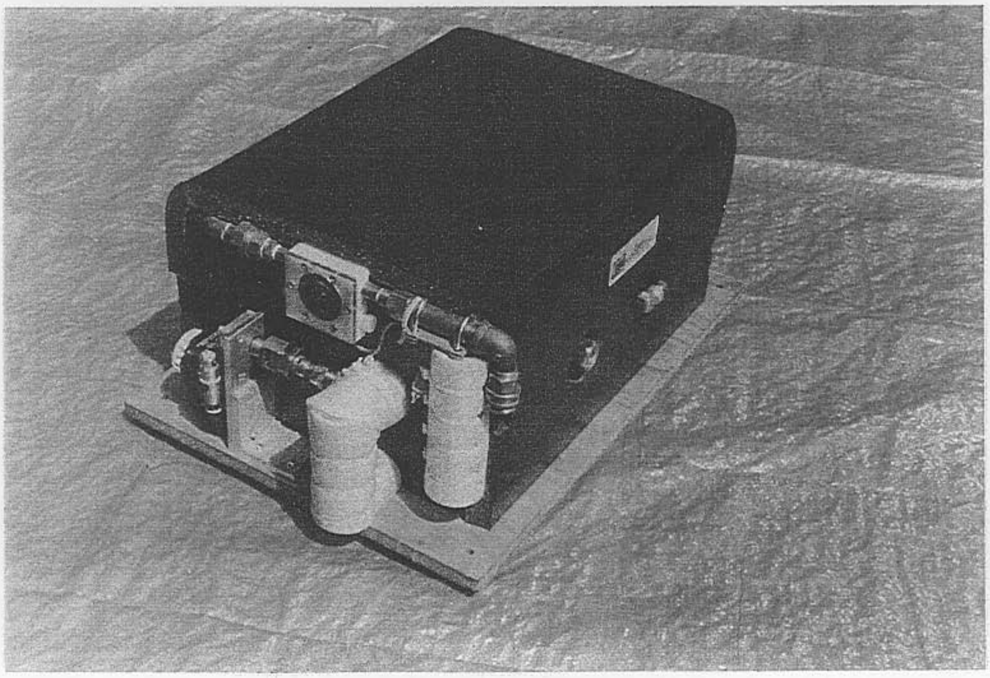

Figure -5: Test Chamber

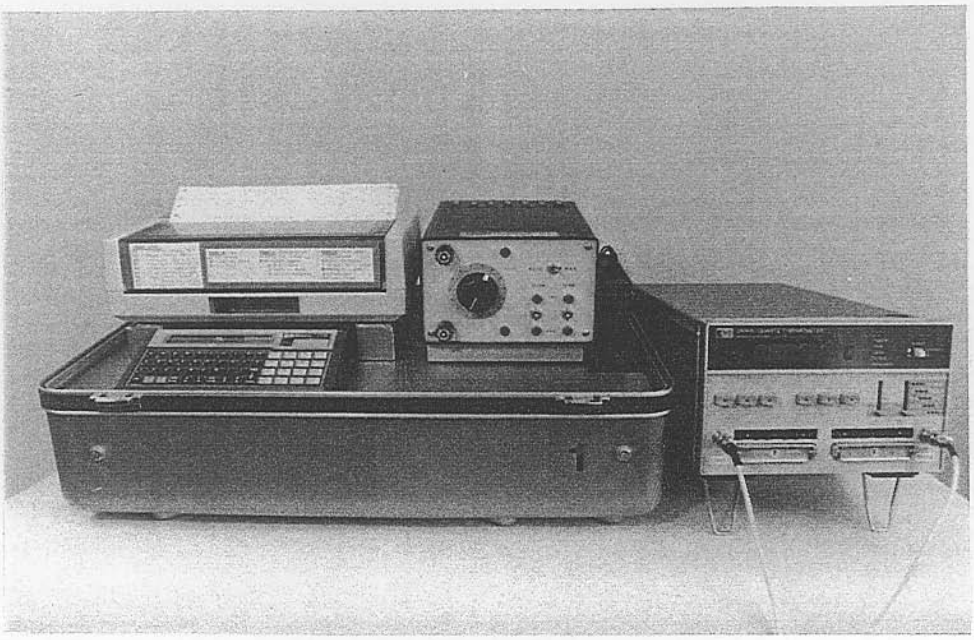

Figure -6: Test Control Center

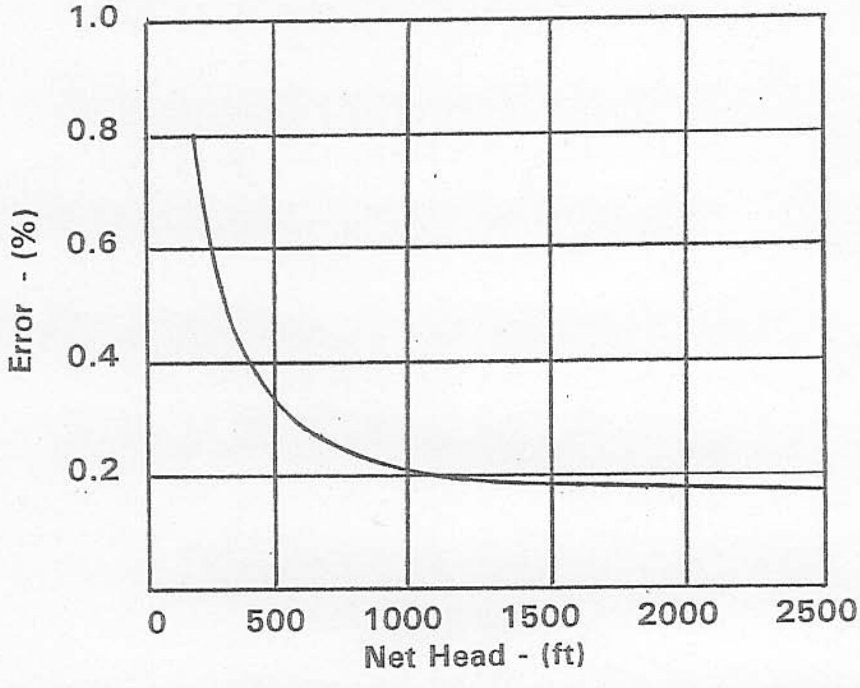

Figure -7: Typical Systematic Error in Turbine Efficiency

Appendix -A : Typical Scan Data

The following page is a copy of scan data from an actual turbine test of a Pelton turbine. An explanation of the terms and data follows:

Run # and Date	= self-explanatory
Probe Pos. #	= position of the discharge probe assembly (position 1 is at the center of the discharge)
Probe Ass. #	= identifying no. of the assembly (only #1 was used)
Probe Setting	= thumbwheel setting of the discharge temperature probe
Generator Output	= generator kW output at the start of the test run
Turbine Flow Est.	= estimated turbine flow
Optimum Ext Flow	= extraction flow rate for equal water transit times

Readings:

Scan	= self-explanatory
KG (kW)	= generator output
PI (ft)	= pressure at the inlet probe, including velocity head (note -1)
PT (ft)	= pressure in the test chamber, including velocity head (note -2)
PD (ft)	= pressure due to tailwater above the center of the discharge
VD (fps)	= velocity at discharge probe (not measured for this test; hence =0)
QE (gpm)	= extraction flow rate (note -3)
TA (C)	= temperature of ambient air at test chamber
TD (C)	= temperature of water at discharge probe
DT(mC)	= temperature difference between the water in the test chamber and the water at the discharge probe (note -4)

Notes:

1- The penetration distance of the probe into the flow may not be exactly at the point where it measures the total velocity head of the flow, and the computer calculates a velocity head adjustment for PI. Also, the probe has a calibrated pressure loss equation for calculating the internal pressure loss due to the extraction flow. These adjustment are included in the values on the second line of each scan.

2- Same velocity head adjustment for PI as described in note-1 is also applied to PT.

3- Since temperature measurements were very stable, it was not necessary to adjust the extraction flow for equal transit times. A larger extraction flow is desirable as it means a smaller correction factor for heat transfer effects.

4- The thumbwheel settings on the probes are held constant and it is necessary to include an adjustment based on the calibration data as shown in the second value.

RUN #= 1 , DATE= 93/03/02
PROBE POS.#= 1
PROBE ASS.#= 1 , PROBE SETTING = 458
GENERATOR OUTPUT = 76105. KW
TURBINE FLOW EST.= 453.78 CFS
OPTIMUM EXT FLOW = 1.43 GPM

SCAN	KG (KW)	PI (FT)	PT (FT)	PD (FT)	VD (FPS)	QE (GPM)	TA (C)	TD (C)	DT (mC)
1	76072	2234.9	2057.5	2.9	0.0	2.9	17.5	4.28	-46.8
		2238.8	2058.8						-47.4
2	76080	2233.9	2050.7	2.9	0.0	2.9	17.5	4.28	-47.0
		2237.9	2051.9						-47.6
3	76129	2233.9	1970.3	2.9	0.0	3.1	17.5	4.28	12.0
		2238.2	1971.5						11.4
4	76157	2233.9	1973.8	2.9	0.0	3.0	17.5	4.28	13.9
		2238.2	1975.1						13.3

Appendix -B : Typical Test Results

The following page is a copy of actual test results from the scan data shown in Appendix -A. An explanation of the terms and data follows:

Scan Comb	=	scan combinations use to compute the results (for example, 1:1-3 means that the computed results on line 1 are based on the data from scans 1 and 3.)
KT (kW)	=	calculated turbine output
HT (ft)	=	calculated net head
QT (cfs)	=	calculated turbine flow rate
VD (fps)	=	velocity at discharge probe (not calculated and set = 0)
CF1 (%)	=	correction factor -1 for heat transfer to test chamber
CF2 (%)	=	correction factor -2 for heat transfer to turbine flow
ET (%)	=	calculated turbine efficiency
QR (cfs)	=	calculated turbine flow rate corrected to rated head
KR (kW)	=	calculated turbine output corrected to rated head

Disregard Lines: Lines, if any, which are listed here are not included in the calculation of mean values due to unstable conditions observed during one of the scans associated with that combination.

<u>Calculated Mean Values:</u>

KR (kW)	=	turbine output corrected to rated head /SDM *
QR (cfs)	=	turbine flow rate corrected to rated head /SDM *
ET (%)	=	turbine efficiency /SDM *
VD (fps)	=	velocity at discharge probe (not used in this test)
QE (gpm)	=	extraction flow rate
TA (C)	=	temperature of ambient air
TD (C)	=	temperature of the water at discharge probe
PD (ft)	=	pressure due to tailwater above the center of the discharge
HT (ft)	=	net head of turbine
QT (cfs)	=	turbine flow rate

* SDM is the standard deviation of the mean.

RUN # 1 RESULTS

SCAN COMB	KT (KW)	HT (FT)	QT (CFS)	VD (FPS)	CF1 (%)	CF2 (%)	ET (%)	QR (CFS)	KR (KW)
1:1-3	77544	2237.0	460.9	0.0	-.20	.00	88.80	460.2	77181
2:1-4	77559	2237.0	459.9	0.0	-.20	.00	89.02	459.2	77197
3:2-3	77548	2236.5	461.3	0.0	-.20	.00	88.76	460.6	77209
4:2-4	77563	2236.5	460.3	0.0	-.20	.00	88.97	459.6	77225

DISREGARD LINES: NONE

MEAN KR= 77203 KW /SDM= 9
MEAN QR= 459.90 CFS /SDM= .32
MEAN ET= 88.89 % /SDM= .06
MEAN VD= 0.00 FPS
MEAN QE= 2.95 GPM
MEAN TA= 17.47 DEG-C
MEAN TD= 4.28 DEG-C
MEAN PD= 2.89 FT
MEAN HT= 2236.75 FT
MEAN QT= 460.60 CFS