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THE ST. ANTHONY FALLS
INDEPENDENT TURBINE TEST FACILITY

by

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TABLE OF CONTENTS

	<u>Page No.</u>
List of figures	iv
List of tables	vi
I. INTRODUCTION	1
II. TURBINE MODEL TESTING AND RESEARCH	3
A. Benefits	3
B. Possible uses	4
C. Facilities around the world	6
III. FACILITY DESCRIPTION	9
A. System operational capabilities	9
B. Physical description and components	9
C. Instrumentation	13
1. Flow	13
2. Torque	14
3. Differential pressure head	14
4. Suction head	15
5. Rotational speed	15
6. Temperature	15
D. Data acquisition system	15
E. Data analysis	16
1. Parameter computation	16
2. Sample output example	20

	<u>Page No.</u>
IV. SOFTWARE FOR DATA ACQUISITION, ANALYSIS AND CONTROL	23
A. Software necessary for data processing	23
B. General organization of the program package	24
1. Programs	24
V. INSTRUMENT CALIBRATION	26
A. General	26
B. Calibration of the volumetric tanks	27
C. Flow meter calibration	27
D. Load cell calibration	28
E. Calibration of the pressure transducers	29
F. RPM counter calibration	30
VI. MEASUREMENT UNCERTAINTY	32
A. Background	32
B. Theoretical approach	34
C. Methodology	37
D. Parameter uncertainty	39
1. Net head precision	39
2. Discharge precision	42
3. Torque precision	45
4. Rotational speed precision	47
5. Tail tank pressure precision	49
E. Uncertainty associated with calibration procedures	51
1. Flow meter	51
2. Load cell	54
3. Pressure transducers	54

	<u>Page No.</u>
4. RPM counter	54
F. ITTF overall measurement uncertainty	55
VII. CONCLUSIONS	57
VIII. REFERENCES	58
APPENDICES	
A : Description of Programs and Application Examples	60
B : Special Program Characteristics	86
C : How to Compile and Link the Programs	88
D : Propagation of Uncertainty	91

LIST OF FIGURES

<u>Figure No.</u>		<u>Page No.</u>
1	Independent Turbine Test Facility.	10
2	Independent Turbine Test Facility basic operating envelope curve.	11
3	Schematic of SAFHL Independent Turbine Test Facility.	12
4	Discharge coefficient versus turbine efficiency for a typical test run.	22
5	Discharge coefficient versus energy coefficient for a typical test run.	22
6	Residual plots: (a) null plot; (b) right-opening megaphone; (c) left-opening megaphone; (d) double outward bow; (e) nonlinearity; (f) nonlinearity; (g) nonlinearity and nonconstant variance; (h) nonlinearity and nonconstant variance.	35
7	Residual plot for Pressure Transducer DP 215-46 (Linear model).	36
8	Residual plot for Pressure Transducer DP 215-46 (Polynomial model).	37
9	Absolute uncertainty (95% confidence interval) for Pressure Transducer DP 215-46.	41
10	Relative uncertainty (95% confidence interval) for Pressure Transducer DP 215-46.	41
11	Absolute uncertainty (95% confidence interval) for Flow meter 10D 1435-AXAIH.	43
12	Relative uncertainty (95% confidence interval) for Flow meter 10D 1435-AXAIH.	44
13	Absolute uncertainty (95% confidence interval) for Load Cell 41-571-02.	46
14	Relative uncertainty (95% confidence interval) for Load Cell 41-571-02.	46

<u>Figure No.</u>		<u>Page No.</u>
15	Absolute uncertainty (95% confidence interval) for RPM Counter DSC-10C.	48
16	Relative uncertainty (95% confidence interval) for RPM Counter DSC-10C.	48
17	Absolute uncertainty (95% confidence interval) for Pressure Transducer DP 215-44.	50
18	Relative uncertainty (95% confidence interval) for Pressure Transducer DP 215-44.	50
A1	General organization of the program package.	63
A2	Screen display for NMENU.	64
A3	Logic structure for NDISPLAY programs.	65
A4	Screen display for the program NDISPLAY.	66
A5	Screen display for the program NDRAW.	66
A6	Screen display for the program NPLOT1.	67
A7	Logic structure for the program NPLOT1.	68
A8	Output graphic example for NPLOT1.	69
A9	Screen display for the program NPLOT2.	70
A10	Output graphic example for NPLOT2.	71
A11	Logic structure for the program NSAVEDAT.	73
A12	Screen display for the program NSAVEDAT.	74
A13	Screen display for the program NPRINT1.	75
A14	Output example for NPRINT1 program.	76
A15	Logic structure for the programs NPRINT1 and NPRINT2	78
A16	Screen display for the program NPRINT2.	79
A17	Output example for program NPRINT2.	81

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
1	Summary of various reaction turbine and pump-turbine test facilities capabilities around the world (not all-inclusive list). Facilities independent of a turbine manufacturer are noted by a (*).	7
2	Regression models and resultants Standard Error for the ITTF calibration.	39
3	Predicted precision uncertainty for the mean pressure (mean of 9 pressure measurements) with 95% confidence interval. Differential pressure transducer DP 215-46.	40
4	Predicted precision uncertainty for the mean flow (mean of 5 discharge measurements) with 95% confidence interval. Electromagnetic flow meter 10D 1435-AXAIH.	42
5	Predicted precision uncertainty for the mean torque (mean of 7 torque measurements) with 95% confidence interval. Load cell 41-571-02.	45
6	Predicted precision uncertainty for the mean RPM (mean of 7 RPM measurements) with 95% confidence interval. Magnetic pick-up DSC-10C.	47
7	Predicted precision uncertainty for the mean pressure (mean of 10 pressure measurements) with 95% confidence interval. Differential pressure transducer DP 215-44.	49
8	Estimated time delay bias uncertainty for the flow meter.	51
9	Estimated volume bias uncertainty for the flow meter.	52
10	Overall bias uncertainty for the flow meter.	54
11	Precision and overall relative uncertainties (95% confidence interval).	56

I. INTRODUCTION

In the summer of 1986, the Saint Anthony Falls Hydraulic Laboratory (SAFHL) was selected by the U.S. Department of Energy (DOE) for the development of an independent turbine test facility (ITTF). As a cost sharing project by SAFHL and the DOE, the establishment of an ITTF in the United States provides capabilities needed to the United States hydropower industry. The SAFHL ITTF will aid in the development of improved turbine designs, as well as provide a facility for cavitation, aspiration, and draft tube studies. In addition, the ITTF can provide access to model testing for small manufacturers, as well as being available for comparative model testing [1]. Finally, the ITTF is also a significant instructional tool in training of capable young hydropower engineers.

The Saint Anthony Falls Hydraulic Laboratory ITTF utilizes components taken from three test stands previously in use at Allis-Chalmer's Hydroturbine Division in York, Pennsylvania. Prior to being donated in 1981, the test facilities had been used by Allis-Chalmers for their own internal model turbine tests. Allis-Chalmers also assisted in disassembly, re-erection, and start-up of the components at the University of Minnesota and has loaned SAFHL a model turbine previously tested in this facility which was used in checkout and analysis of system capabilities. The State of Minnesota Legislative Commission for Minnesota Resources funded the initial installation and upgrade of the ITTF components.

Other equipment manufacturers have also shown an interest in the project, including the recent donation of a fabricated pump-turbine model by Escher Wyss Ltd. and Dominion Bridge-Sulzer Inc., as well as circuit breakers and a 500-kVA transformer supplied at factory cost by General Electric. Neyric and Axel Johnson Engineering have also offered operating turbine models.

The SAFHL has recently completed an upgrade of their ITTF. Partial funding for the upgrade has come in the form of a grant sponsored by the U.S. Department of Energy. This report discusses the improvements made to the Facility and its resultant overall capability.

The upgrade included enclosure of the upper portion of the test loop (head tank, tail tank, and dynamometer) to enable year-around operation. A temperature control system was constructed and installed in the test loop to provide temperature stability, necessary for cavitation testing and required by the International Electrotechnical Commission (IEC) [2] model test codes. The adaption of worm-gear jacks under the tail tank provides the needed adjustability to accommodate most draft tube and turbine/pump model configurations commonly in use. Installation of additional instrumentation provides for simpler, more efficient, data acquisition. The ITTF has been connected to the Laboratory compressed air and vacuum facilities for precise pressure control.

Instrumentation installed during the upgrade provides accurate and efficient data acquisition and analysis. All instrumentation is connected to a computerized control center. Rotational speed is measured by an electronic speed indicator. Torque measurement is provided by Sensotec Tension-Compression load cells at a known lever arm. Validyne

pressure transducers provide measurement of net head and tail tank pressures. The previously installed Fischer & Porter electromagnetic flow meter measures discharge.

The recent upgrade significantly increases the testing capabilities of SAFHL's ITTF. This report contains the resultant ITTF operating characteristics resulting from this upgrade and previous work^[1]. In addition, it briefly describes the physical attributes of the Facility. Also described herein are the data acquisition and analysis systems and the overall accuracy of the Facility, along with a corresponding component-by-component error analysis.

II. TURBINE MODEL TESTING AND RESEARCH

A. Benefits

The justification for funding the development of a research and testing facility should be based upon the expected benefits of the facility. However, it is often difficult to quantify the benefits of research, primarily because research often results in new products or methods not currently in use and hence cost data are not available. Examples abound, such as the laser, the computer chip, and hundreds of thousands of less well-known research developments. This section will attempt to identify some short-term benefits of research on a turbine testing facility.

First, consider pumped storage. Pumped storage plants in the United States are developed primarily by utilities. Each of these facilities are unique, and typically pushing the state-of-the-art. Pump-turbine research through physical model tests and numerical computer analysis of flow through the runner will increase efficiency and reduce down time caused by hydromechanical problems.

Pumped storage facilities in the U.S. are coming on line at an average of 600 MW/year, at a cost of approximately \$600 million per year. If the research program described above resulted in an overall efficiency improvement (including reduction of down time) of 0.5%, the savings to the industry would be \$3 million per year. A successful adaptation of the variable speed concept to pump-turbines could alone account for a 0.5% improvement in efficiency.

Another example is research to improve turbine operation. A recent Electric Power Research Institute (EPRI) report (EM-3435, p. 2-4) stated that "Turbine runner problems...were one of the most significant causes of unit outages identified...It is recommended that stainless steel runners be installed in new units and for units older than 20 years that have continual vibration and cavitation problems. Runner replacement is viewed as having the greatest potential for unit improvement, but it requires careful and thorough investigation, including model tests.". It is precisely this type of service which a turbine model testing facility offers to the hydropower community. In addition, significant improvements in turbine operation are possible through numerical computer simulations of the flow and model tests on existing runners to investigate various corrective measures. This research could increase both the availability and the useful life of many existing turbines with operational problems. For example, turbine runners which experience cavitation erosion may significantly benefit from a slight change in design by numerically modeling the flow with a computer program. The program would have been previously verified with model tests and therefore could be used with confidence. In many cases, modification to the runner blade geometry could be made in lieu of cavitation repair, resulting in a permanent fix to what is often a serious problem.

It is more difficult to identify the potential dollars returned on the other research topics mentioned later in this section. Many of these topics could significantly aid in hydropower plant operation. The efficient use of air injection to reduce cavitation is one topic which could have immediate application. Water quality is very important in cavitation inception. A more universal method for specifying turbine setting based upon model test results and field

conditions needs to be developed. The research on variable speed turbines has potential application in the reduction of draft tube surging and may improve the poor off design performance of the many low head Francis turbines in the United States.

Although specific economic returns cannot be currently estimated for these research topics, recent history has generally shown that the potential return on well-focused research is significant. The research topics available in the hydroturbine industry fit into this category.

B. Possible uses

Some of the possible activities and research uses of any turbine model test facility are described below.

- 1. Acceptance Model Tests:** In an acceptance model test, the client is verifying that the manufacturer's design meets the performance specifications set forth in contract documents.
- 2. Comparative Model Testing:** Comparative model testing between more than one turbine manufacturer can be performed as part of the decision-making process for equipment purchase. An independently owned and operated facility can assure an unbiased test result, directly comparing the performance of the various turbine manufacturers designs.
- 3. Prototype Testing of Micro-Generator Units:** Development and testing of low-capacity prototype turbine/generator units (micro-turbines), can also be performed.
- 4. Research and Testing of New Turbine and Pump-Turbine Concepts:** Turbine model testing facilities may be effectively used to research and test new turbine and pump-turbine concepts and innovations. There are a number of cost-effective innovations in turbine design which have been recently developed. In addition, many of the recurring hydromechanical problems of pump storage facilities need to be addressed.

Turbine aspiration concepts may also be developed and tested with the turbine test facility. Turbine aspiration is used to improve the dissolved oxygen concentration downstream from a dam where hydropower development has had an adverse impact by eliminating spillway reaeration. The current knowledge on turbine aspiration techniques is extremely limited. Model tests would be utilized to develop information on turbine aspiration efficiency and the power loss due to aspiration for turbines of various types and specific speeds.

- 5. Cavitation Scaling:** Due to the complexity of the cavitation phenomena, experimental facilities are essential for identifying and minimizing the effects of cavitation on a turbine's performance and operating lifetime. There are two basic and interrelated problems in simulating cavitation phenomena at model scale : a) viscous effects and b) the critical pressure for the onset of cavitation is strongly related to the size and number distribution of nuclei and concentration of dissolved gas in the flow. Turbine model test facility would be essential to perform research on cavitation scaling for hydraulic turbines.
- 6. Methods for Accurately Predicting Cavitation Erosion Rate:** Although a considerable amount of research effort has been expended in understanding the mechanism of cavitation erosion vis-a-vis the dynamics of bubble collapse and the resulting pressures and their impact on an adjacent surface, the research relating the erosion intensity of different types of flow patterns to cavitation erosion is not extensive. A ductile probe technique has been developed which could prove to be a very useful tool in evaluating the erosion rate as a function of performance characteristics of various turbines. A natural extension of this technique would be the correlation of erosion rate with cavitation noise. Research of this type could lead to using acoustically based diagnostic methods for determining erosion rate in an operating turbine. Such a method will allow for maintenance to be scheduled on a timely basis, providing for repair work to be carried out only when necessary and before excessive damage has occurred.
- 7. Inlet Swirl:** Hydroturbines are designed for uniform inflow conditions with zero swirl. In reality this never occurs. The amount of inlet swirl which can occur without a significant reduction in turbine performance is an important parameter in equipment warranties. Research on this topic would provide valuable information to purchasers and producers of hydroturbine equipment.
- 8. Draft Tube Design:** The draft tube is a major restriction in developing high specific speed turbines and to the development of cost-effective powerhouse designs. A turbine model testing facility could be used to investigate the advantages, disadvantages, and possibilities of an efficient, compact draft tube for high-speed propeller turbines.
- 9. Educational Training:** The use of a turbine model testing facility will aid in the development of young engineers with well-rounded backgrounds in hydropower and related areas. The flow visualization capabilities provide an unprecedented opportunity to study turbine flow and cavitation.

C. Facilities around the world

There are few independent turbine test facilities available in the world for research and testing of model hydroturbines^[3,4]. There are significantly more manufacturer-associated turbine test facilities, because of the importance of such a facility in the design process. A synopsis of operating characteristics for many hydraulic turbine (or pump/turbine) test laboratories around the world is given in Table 1. Capabilities of the different test facilities have been obtained from manufacturers catalogs^[5,6,7] and brochures^[8,9,10,11]. The list is not all-inclusive. The authors are aware of independent test facilities in Scotland, Spain, and Brazil that are not included in Table 1. In addition, there are manufacturer-associated turbine test facilities at Neyric, Tampella, and Voest-Alpine, among others.

Table 1. Summary of various reaction turbine and pump-turbine test facilities capabilities around the world (this list is not all-inclusive)
 Facilities independent of a turbine manufacturer are noted by a (*).

TEST FACILITY LOCATION		TEST CAPABILITIES				REMARKS
		Max. Head (m)	Max. Flow (m ³ / s)	Max. Power (kw)	Max. Speed (rpm)	
Independent Turbine Test Facility (*) St. Anthony Falls Hydraulic Laboratory University of Minnesota Minneapolis, Minnesota U.S.A.		32	1	75	1750	Overall precision for a typical operation point = ± 0.292%
Escher-Wyss Turbine Tests Facilities, Escher-Wyss SA Zurich, Switzerland	Low press cavitation	12	0.7	50	3000	Can be used for Kaplan and Bulb turbines
	Low press	5	1.8	35	1000	Application to low-head Kaplan and bulb turbines
	High press cavitation	100	1.1	350	3500	Application to high-head vertical axis Kaplan and Francis turbines
"Rozloch Turbine Test Stand", Escher Wyss SA, Bell Kriens, Switzerland		60	0.8	350	2500	Application to low specific speed Francis turbines
Central Water & Power (*) Research Station, Puna, India		23	3	220	2300	—————
Hitachi Hydraulic Laboratory, Hitachi, Ltd. Tokyo, Japan	M1	70	0.5	220	2000	—————
	M2	75	0.5	160	3000	—————
	M3	46	0.8	160	2500	—————
	M4R	160	1.7	1000	3000	—————
	M5R	100	0.83	1500	1500	Prot. Pumping Head Test Stand
	E1R	37	1	—	2500	—————
	R1	120	0.3	130	1500	—————
	R2	50	0.12	—	1500	—————
Hydraulic Machines Institute, (*) Federal Institute of Technology, Lausanne, Switzerland		120	1.35	300	1500	Can be used for all types of reaction machines

Table 1 (cont.).

TEST FACILITY LOCATION		TEST CAPABILITIES				REMARKS	
		Max. Head (m)	Max. Flow (m ³ / s)	Max. Power (kw)	Max. Speed (rpm)		
"Brunnenmühle" Hydraulic Research Laboratory, J. M. Voith GmbH, Heidenheim, Fed. Rep. of Germany	High Press.	200	1.2	1000	2000	Application to high-head and high-power reaction units	
	Medium Press.	100	0.9	420	1900	Horizontal and vertical shaft test rig for medium-head radial and axial turbines, and pump-turbines	
	Low Press.	30	1.5	220	1900	Application to high specific speed machines (basically axial machines)	
"S. Morgan Smith Memorial Hydraulic Laboratory", J. M. Voith GmbH York, Pennsylvania, U.S.A		134	1.6	448	3000	Overall precision for a typical operation point = ± 0.252%	
KaMeWa Hydraulic Turbine Laboratory, KaMeWa AB Axel Johnson Group Kristinehamn, Sweden	Test Stands	R-21	4	2.5	—	1500	Application to Kaplan and low-head Francis turbines
		T-24	8	1.6	45	1500	Moderate head Kaplan and Bulb turbines
		T-28	100	0.6	200	3000	Applied to low specific speed Francis turbines and Pump-turbines
Vevey Hydraulic Laboratory Vevey Engineering Works Ltd., Vevey, Switzerland		100	1.5	300	1500	New all-purpose test rig	

III. FACILITY DESCRIPTION

A. System operational capabilities

The Saint Anthony Falls Hydraulic Laboratory has designed and developed a recirculating test facility for model testing of pumps, pump-turbines, and turbines. The SAFHL Independent Turbine Test Facility, shown in Fig. 1, is available to undertake specific projects for the hydropower community.

The ITTF can be used for turbine testing and research up to a maximum power output of 100 HP, which is the limit of the dynamometer. The maximum possible rotational speed is 1750 rpm. The 300-HP main pump enables a net head up to 115 ft. and a maximum available flow of 38 cfs. The present ITTF's main capabilities are summarized in Table 1.

The ITTF's vacuum and pressure system is interconnected with the Laboratory's primary vacuum and pressure systems. Testing during the Facility shakedown period showed that the Facility is capable of reaching pressures below 4 psia, supportive of supercavitating conditions.

Fig. 2 represents the ITTF's operational envelope. Model runner diameter is in the range 10" to 18". The Facility enables testing of Francis and propeller turbines at Reynolds numbers in excess of the minimum values recommended by the International Electrotechnical Commission (IEC) test codes^[2].

The ITTF's operational capabilities enable tests performances in accordance with the IEC and the American Society of Mechanical Engineers (ASME) codes.

B. Physical description and components

The physical plant comprising the ITTF is distributed over four floors and utilizes selected components taken from stands previously in use at Allis-Chalmers' Hydroturbine Division in York, Pennsylvania. The components were refurbished and installed in the configuration shown in Fig. 3.

The ITTF enclosure shown in Fig. 1 provides year-around operational capabilities, allows easier data acquisition, and benefits the facility by promoting better security to the area and easier model test observations. The enclosure is two stories high, with primary access doors extending nearly 2/3 the width of the enclosure. The second floor consists of removable grated decking which provides for transmission of light from a skylight and upper level windows to the lower level of the enclosure. The second floor provides additional access and increases space for instrumentation and data acquisition equipment; any unused space can be used for storage of additional instrumentation and supplemental testing equipment.

The pump is located at the lowest level (Fig. 3) to provide as much head on the pump as possible for protection from cavitation. The centrifugal pump is driven by a 300-HP, constant-speed, 220-volt motor. Electrical service for the pump motor is independent of the main Laboratory electrical system.

The ITTF piping configuration consists primarily of 18 and 20-in diameter galvanized pipe (Fig. 3). Several bypass valves enable testing in either pump or turbine mode. The 20-in. downcomer pipe is connected to a penstock carrying water from the river, providing a continuous water supply for calibration purposes. The water will pass through the flow meter and be discharged into existing calibrated volumetric tanks. This procedure was adopted to provide in situ calibration of the flow meter.

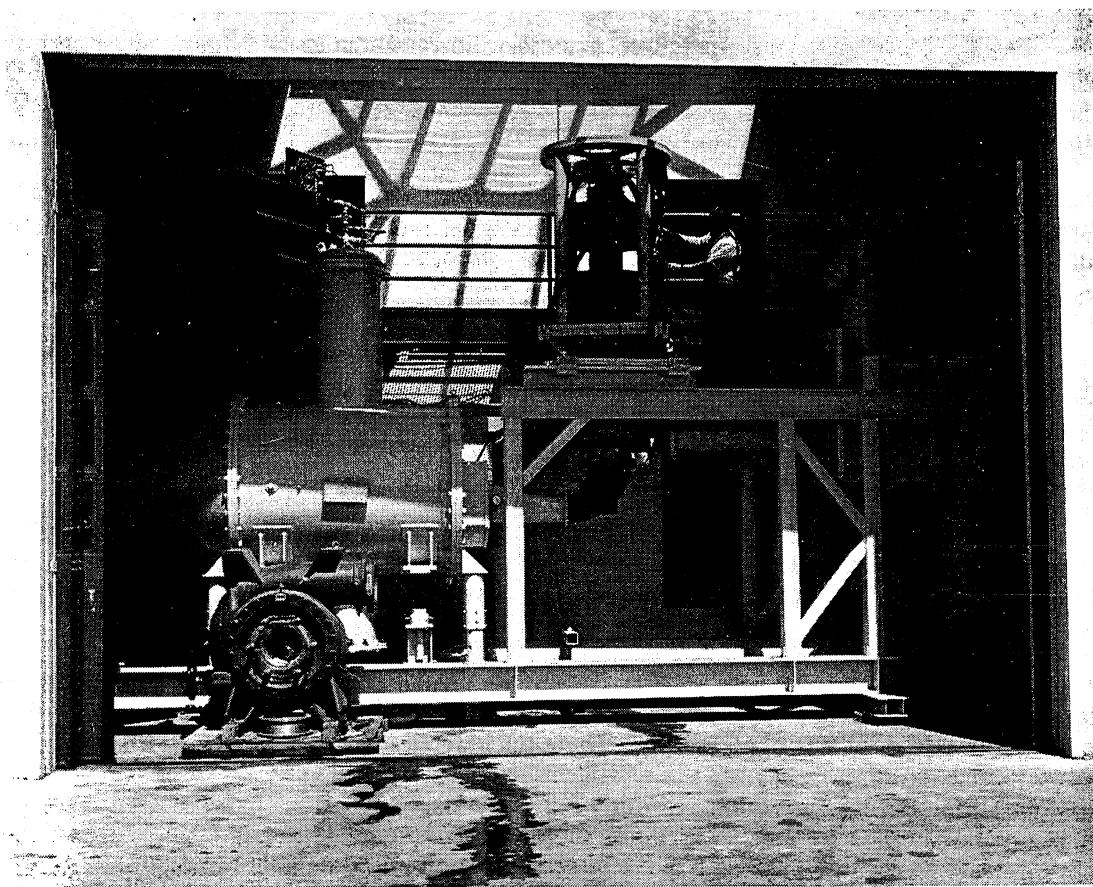


Figure 1. Independent Turbine Test Facility.

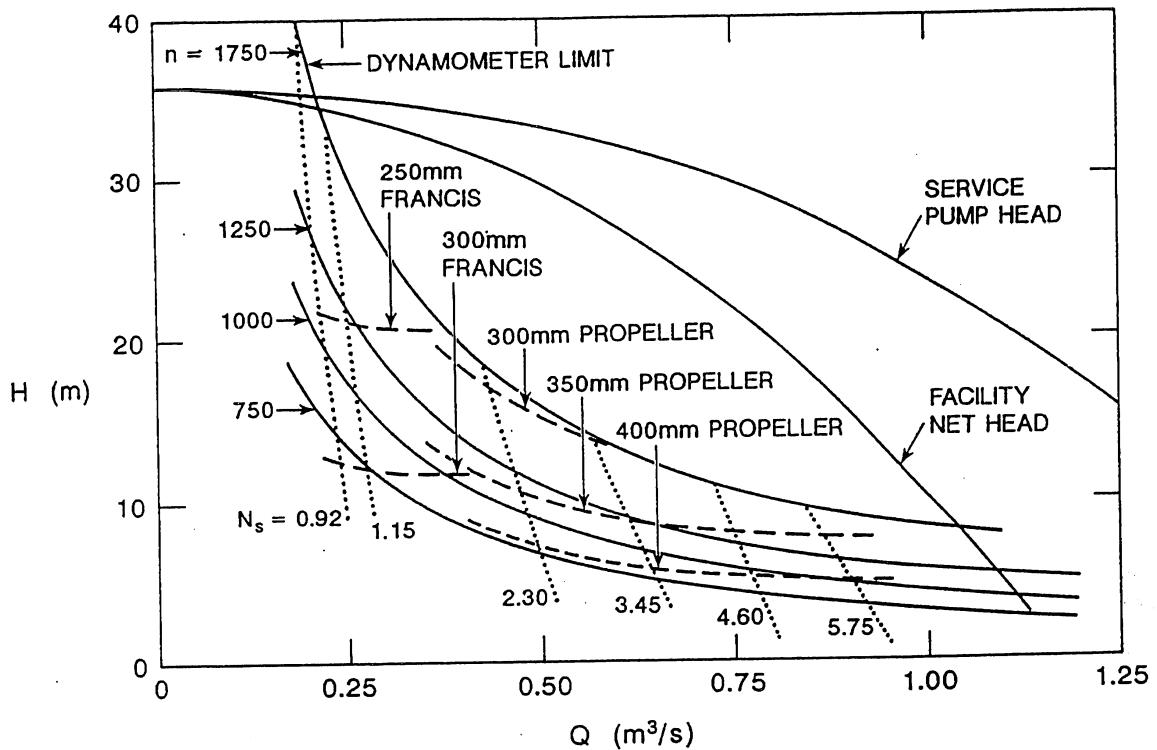


Figure 2. Independent Turbine Test Facility basic operating envelope curve.

The head tank is about 42 in. high, 44 in. wide, and 72 in. long. Baffles are provided at the inlet to reduce turbulence of the entering flow. An adapter plate is fabricated to accommodate the dimensions of the particular model to be tested. The cylindrical portion of the tail tank is 57 in. in diameter and 72 in. long and is followed with a conical transition to the downcomer. The vertical pipe at the top of the tail tank is for pressure control in the closed loop. Positive or negative pressures can be applied either from the air compressor or the vacuum pump as required for cavitation testing. Again, an appropriate adapter plate is required for a particular model test. The flange-to-flange horizontal distance between the head and tail tanks is 10 ft. The mean vertical distance between the center lines of the head and tail tanks is about 2.5 ft. The tail tank can be raised or lowered using four interconnected worm-gear jacks, which in conjunction with the tail tank blankout plate provide vertical adjustability of approximately 2 ft. This adjustability can be used to accommodate most draft tube and turbine/pump configurations commonly in use. The dome of the tail tank is connected to the Laboratory compressed air and vacuum facilities, providing pressure control for testing ranging from high tailwater simulation to severe cavitation conditions.

For water temperature control, the ITTF utilizes river water passing through the Laboratory for the coolant. The temperature control facility is basically a parallel flow heat exchanger located in the downcomer leg of the ITTF (see Fig. 3). Cooling water will be taken from the river water supply. The Facility requires no outside energy input as the natural 50 ft. drop of St. Anthony Falls provides the necessary driving force for the cooling water. Temperature control of the testing water will be accomplished by using flow control valves in the cooling water lines.

The 100-HP dynamometer, rated at 1750 rpm has undergone recent overhaul. The unit consists basically of a Westinghouse DC generator that can be used for tests with both pumps and turbines. When used in turbine testing, the generated power is dissipated in a series of air-cooled resistor banks. For pump tests, the unit serves as a DC motor which is driven with a separate motor generator set. The 100-HP dynamometer is attached to a rigid support frame between the two tanks (Figs.1 and 3).

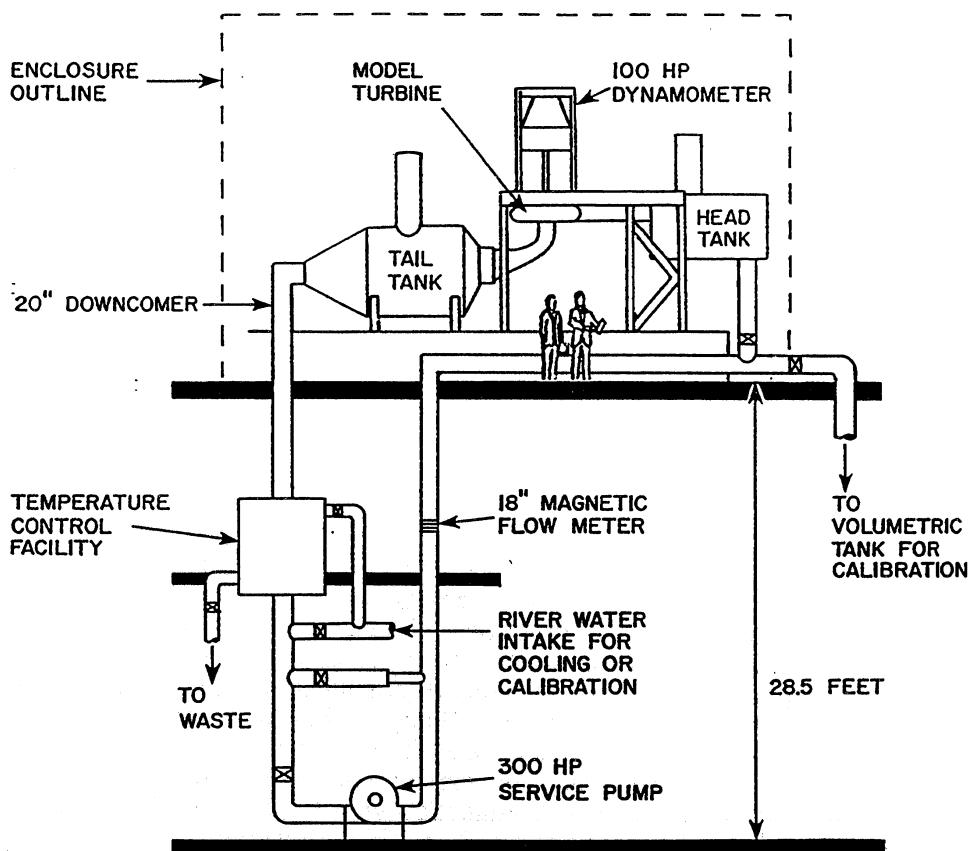


Figure 3. Schematic of SAFHL Independent Turbine Test Facility.

C. Instrumentation

To determine the model efficiency of a hydroturbine, five major parameters must be measured. They are: total head, tail water pressure, flow, torque, and rotational speed. Water temperature and barometric pressure are also measured so that the data obtained can be corrected to standard conditions. In addition, for safety considerations, pump motor temperature is continuously monitored using a temperature sensor which has been installed on its cover.

Extreme care must be taken in measuring model performance in order to obtain a high degree of accuracy and repeatability^[12]. This will be discussed later in the calibration section (section V). This section examines the Independent Turbine Testing Facility's instrumentation

1. Flow.

Flow rate in the ITTF loop is measured with a 18-in.-diameter, FISHER-PORTER electromagnetic flow meter, Model No 10D 1435-AXAIH^[13], and associated signal converter^[14]. It is installed in the vertical upcomer as shown in Fig. 3 and is capable of measuring flow in either direction up to 17,000 gpm (38 cfs). It is designed for a maximum working pressure of 165 psi at 100 °F. In the turbine testing mode of operation, the meter is preceded with a 10-diameter length of straight pipe. For pump testing with water flow in the opposite direction, the length of straight pipe is reduced to 5 diameters.

The flow meter operates according to Faraday's Law of Induction, which states that the voltage induced in a conductor moving at right angles through a magnetic field is proportional to the velocity of the conductor through that field. The magnetic field is created by electromagnets. The water flowing through the meter serves as the conductor. The induced electromotive force is measured between two electrodes placed at ends of an axis perpendicular to both the velocity of the liquid and the lines of magnetic flux. The potential sensed between the two electrodes is transmitted to a signal processor which emits a pulse-train signal with a pulse rate proportional to the flow. This pulse signal is interfaced directly into the computer.

The primary advantages of this type flow meter^[6] are :

- 1). There are no obstructions placed in the pipe-line.
- 2). Flow can be measured in either direction.
- 3). The meter generates an electrical output signal.
- 4). The meter can be easily calibrated in place using other existing Laboratory facilities.

Moreover, it is claimed by the manufacturer^[13,14] that metering accuracy is not affected by turbulence, changes in the patterns of flow velocity distribution, viscosity, or conductivity.

2. Torque.

Torque produced by the model is calculated from the force applied on a load cell located 19 in. from the center of rotation. The load cell can be operated with or without preload. In either case, the signal coming from the load cell sensor is amplified and sent to the computer. There are two reasons for a pre-loaded dynamometer. First, it promotes greater accuracy by assigning a significant portion of the load to a calibrated dead weight. Second, it diminishes the load cell vibration which generates oscillating torque readings.

The load cell used is a SENSOTEC Precision load cell^[15], Model 41 No 571-02, with a full load capacity of 250 lb. The associated amplifier is SENSOTEC SA-4 No 60-31.

This load cell exhibits the following advantages^[6,12] :

- 1). There is negligible interaction with the dynamometer because of the small deflections (.001 inches maximum).
- 2). It is highly resistant to extraneous forces such as bending, torsion, and side forces.
- 3). It has a 50% full scale overload capability with no effect on accuracy.

Moreover, the manufacturer^[15] specifies good thermal stability, linearity (only out by .1% full scale), low hysteresis (.08% full scale), and high repeatability (only out by .03% full scale).

3. Differential pressure head.

The differential pressure head between the inlet and outlet of the turbine is measured by a diaphragm type VALIDYNE Engineering Corporation pressure transducer^[16] Model DP 215-46. It has differential pressure capabilities up to 50 psi and it is connected to a VALIDYNE digital transducer indicator Model CD-23^[17] which provides direct digital display of the pressure level and an analog output proportional to pressure. Differential pressure head is obtained from a symmetrical four-tap copper manifold immediately upstream of the scroll case, and a six-tap copper manifold located symmetrically about the draft tube.

This transducer consists of a diaphragm of magnetically permeable stainless steel which is damped between two blocks of stainless steel. Embedded in each block is an inductance coil. The diaphragm, in its undeflected position, is centered with equal gaps between it and each inductance coil, which provides equal resistance for the magnetic flux path of each coil. When a pressure difference is applied, the diaphragm deflects toward the cavity with the lower pressure. This deflection decreases one gap and increases the other and therefore increases the inductance of one coil and decreases that of the other. This inductance difference is then transformed into a voltage difference. The analog voltage difference is then amplified by the transducer and conveyed into the analog/digital (A/D) converter where is digitized before going into the computer.

The basic advantages of this method of measuring differential pressure are^[4,6] :

- 1). A small volumetric displacement (full scale diaphragm deflection is only about .0013 inch) for good dynamic response.
- 2). A high overload capability because the internal cavity walls provide effective overload stops. The manufacturer specifies overload capabilities of twice design load with no effect on transducer accuracy.
- 3). A high output signal with low susceptibility to electrical noise.
- 4). The transducer diaphragm is easily changed and can be replaced with a wide variety of diaphragms of varying sensitivity for increased testing accuracy.

Moreover, it is specified by the manufacturer^[16] that this transducer exhibits a very small thermal shift, and it is not affected by humidity.

4. Suction head.

Draft tube pressure is an essential parameter when observing the cavitation performance of a turbomachine. This measurement is made by a diaphragm-type VALIDYNE pressure transducer^[16] Model DP 215-44. It has a range of up to 32 psi, and it is connected to the same type of digital transducer indicator described above^[17]. All characteristics are the same than those for Model DP 215-46. In the present model configuration, pressure is obtained using a six-tap copper manifold located symmetrically about the draft tube.

5. Rotational speed.

The rotational speed of the model runner is measured by an ELECTRO-SENSORS signal conditioner Model DSC-10C which senses rotational speed with a 16-magnet magnetic disc that is attached to the end of the dynamometer shaft. A sensing head and chassis-mounted circuit complete the rotational speed sensing instrumentation. While the shaft is rotating, the pulser disc generates an alternating magnetic field whose frequency is proportional to the speed of the shaft. This magnetic field is detected by the sensing head and is transmitted through the circuit. The signal is converted to a voltage directly proportional to the shaft speed, and then is digitized through the A/D converter.

6. Temperature.

The water temperature and pump motor temperature are measured by the use of OMEGA Engineering Inc. resistance type sensor Model F3102 platinum RTD for the water temperature sensors and Model PR-12-2-100 for the motor temperature sensor. Both of them are connected to a SENSOTEC amplifier Model SA-4 No 50-01 and are conditioned by the A/D converter for the PC-AT computer.

D. Data acquisition system

The data acquisition control center is located in a temperature-controlled room adjacent to the Turbine Test Facility's upper level. The basic data acquisition system for the ITTF consists of :

- A IBM PC-AT computer with 20-MB hard drive and 2 floppy 5 1/4 in.disk drives.
- A 12-bit, 8-channel Metrobite analog/digital (A/D) processor that uses two expansion boards^[18] called DASH-16/DASH-16F.
- Two color graphic monitors and one monochrome monitor.
- A dot matrix printer.

The DASH-16 and DASH-16F are multifunction, high-speed A/D expansion boards for the IBM Personal Computer. They are full-length boards that are installed internally in an expansion slot of an IBM PC and turn the computer into a fast high precision data acquisition and signal analysis instrument. The data sample rate for the multiplexer inside the A/D converter is up to 10,000 samples/second, or 1250 samples/second-channel when using all 8 channels in the system.

The computer has functional subroutines programmed in Assembly language with the supporting mainline programs written in Basic language to facilitate easy program modification and providing flexible data acquisition necessary in a Turbine Test Facility.

Electrical signals from the test stand instrumentation are routed to the data acquisition control center. Pulse-train signals, such as those received from the magnetic pick-up sensing rpm and those from the electromagnetic flow meter, are fed directly into the computer peripheral pulse-counter (frequency/voltage converter) where they are counted for the desired length of time to obtain a statistically significant average^[12]. Analog signals, such as those generated by the pressure transducers or load cell, pass through signal-conditioners, where required, and are then fed to the DASH-16/DASH-16F high speed Analog/digital signal-processor where they are filtered, as desired, and then converted to a digital format. Standard computer input voltage range is from -10 Volts to +10 Volts.

Following the raw data acquisition and digital integration, the integrated data are substituted into the appropriate equations to obtain processed test results. The desired output can be automatically displayed on the test stand monitor, on the computer room monitors, and/or printed out.

E. Data analysis

During data acquisition, the signal coming out of the sensors is transformed into voltage (when necessary) and then into bits (a number between 0 and 2048). This final bits number will be used by the programs for data analysis.

1. Parameter computation.

Flow

The water discharge Q_m (cfs) is given by the relation^(*)

(*) When statistically analyzing calibration data it was found that the best fitting curve was a weakly second degree polynomial. This also was the case for the rest of the calibration parameters (see section IV-C for more information).

$$Q_m = A_{dc} X_q^2 + B_{dc} X_q + C_{dc} \quad (1)$$

where

A_{dc} , B_{dc} , and C_{dc} : Flow calibration coefficients.
 X_q : Number of bits for discharge data.

Rotational speed

The rotational speed N_m is given by the second degree polynomial relation similar to the discharge equation.

$$N_m = A_{rc} X_n^2 + B_{rc} X_n + C_{rc} \quad (2)$$

where

A_{rc} , B_{rc} , and C_{rc} : rpm counter calibration coefficients.
 X_n : Number of bits for rpm data.

Torque

The value of the torque T_m (lb-ft) is given by the relation

$$T_m = L \cdot \left(A_{tc} X_t^2 + B_{tc} X_t + C_{tc} \right) - T_0 \quad (3)$$

where

A_{tc} , B_{tc} , and C_{tc} : Load cell (force) calibration coefficients.
 X_t : Number of bits for the load cell data.
 L : Arm length of dynamometer (ft).
 T_0 : Torque on bearing supporting the shaft (lb-ft).

In Eq. (3), the expression in brackets represents the calibrated force (weight) that the dynamometer is exerting on the load cell. Torque is obtained by multiplying this force by the dynamometer arm length.

In order to avoid initial static friction between bearing and shaft, the bearing is rotated by a motor capable of rotating in either direction. The estimation of the bearing torque was done running the turbine at several rotational speeds. The value of the bearing torque T_0 was found to be linearly dependent upon rotational speed.

$$T_0 = 12.2 - 0.0012 N_m \quad (4)$$

where

N_m : Rotational speed (rpm)

Pressure head

The differential pressure P (psi) is given by the relation

$$P_d = A_{pc} X_p^2 + B_{pc} X_p + C_{pc} \quad (5)$$

where

A_{pc} , B_{pc} , and C_{pc} : Differential pressure calibration coefficients
 X_p : Number of bits for differential pressure data

The pressure head H_p (ft of water) is given by the relation

$$H_p = \frac{144 P_d}{\gamma_m} \quad (6)$$

where γ_m is the specific weight of water (lb/ft^3).

A water temperature correction has been introduced in the computation of γ_m

$$\gamma_m = \gamma_{36^\circ\text{F}} + \left(14.79 \cdot 10^{-3} T - 2.2 \cdot 10^{-4} T^2 \right) \quad (7)$$

where

T : Closed circuit water temperature ($^\circ\text{F}$)

$\gamma_{36^\circ\text{F}}$: Specific weight at 36°F ($62.43 \text{ lb}/\text{ft}^3$)

The calibration equation used to compute the draft tube pressure has the same second degree polynomial format as Eq. (5). Draft tube pressure will be used when testing under cavitation conditions.

Total head

The total head is comprised of two components, the static pressure head and the velocity head at the model. The static head is measured by the differential pressure transducer, and computed by Eq. (6). The velocity head (ft of water) is computed in the following way :

$$H_v = \frac{V_i^2 - V_o^2}{2g_c} \quad (8)$$

where

V_i : Water inlet velocity (ft/s)

V_o : Water outlet velocity (ft/s)

g_c : Acceleration of gravity ($32.17 \text{ ft}/\text{s}^2$)

Traditionally, Eq. (8) is written in the following manner for hydroturbines (IEC, 1965) :

$$H_v = \frac{1}{2g_c} \cdot \left(\frac{Q_m^2}{A_i^2} - \frac{Q_m^2}{A_o^2} \right) \quad (8a)$$

where

Q_m : Total water discharge (cfs)

A_i : Cross-sectional area at pressure sensing manifold immediately upstream of the scroll case (ft^2)

A_o : Cross-sectional area located on the draft tube (ft^2)

Equation (8a) is truly correct only with a uniform velocity profile.

The total head or net head H_m (ft of water) is given by the relation :

$$H_m = H_p + H_v \quad (8b)$$

Power input and power output

The total power input PI (HP) to the turbine is computed using the relation :

$$PI = \frac{Q_m \cdot H_m \cdot \gamma_m}{550} \quad (9)$$

The total power output PO (HP) from the turbine shaft is given by the formula :

$$PO = \frac{T_m \cdot W_m}{550} \quad (10)$$

where

W_m : Angular velocity (rad./s)

Equation (10) can be also be written as :

$$PO = \frac{2\pi \cdot T_m \cdot N_m}{60 \cdot 550} \quad \text{or} \quad PO = \frac{T_m \cdot N_m}{5252.11} \quad (11)$$

where :

N_m : Measured rotational speed (rpm)

The final overall turbine efficiency η_m (%) is given by the relation :

$$\eta_m = \frac{PO}{PI} \times 100 \quad (12)$$

2. Sample output example.

The output sheets with the computed parameters and results are shown in Figs. A14 and A17 in Appendix A. The purpose was just to show the output sheet structure, and the numbers do not correspond to actual test data. More information about the programs which generate the tabular output of the results will be provided in sections A-4.8 and A-4.9 in Appendix A.

The above results in respect to head, discharge, torque, rotational speed, and power are expressed in terms of nondimensional parameters below in order to facilitate prediction of homologous prototype turbine performance^[4].

$$\text{Discharge coefficient, } Q_{1m} = \frac{Q_m}{W_m D_m^3} \quad (13)$$

$$\text{Energy coefficient, } E_{1m} = \frac{g H_m}{(W_m D_m)^2} \quad (14)$$

$$\text{Power coefficient, } PO_1 = \frac{PO}{\rho_m W_m^3 D_m^5} \quad (15)$$

$$\text{Torque coefficient, } T_{1m} = \frac{T_m}{\rho_m W_m^2 D_m^5} \quad (16)$$

where

D_m : Runner diameter (ft)

ρ_m or γ_m/g_c : Density of water (lb/ft³)

As an example, consider the following set of observations for a typical test run :

Speed, $N_m = 1000.64$ rpm

Discharge, $Q_m = 13.65$ cfs

Net head, $H_m = 37.19$ ft of water

Torque, $T_m = 248.43$ lb-ft

Runner diameter, $D_m = 0.83$ ft

Turbine guide vane opening, $\alpha_m = 45\%$

The values for the dimensionless coefficients are then :

Discharge coefficient, $Q_{1m} = 0.228$
Energy coefficient, $E_{1m} = 0.158$
Power output, PO (using equation 12) = 47.331 HP
Power coefficient, $PO_1 = 0.0296$
Power input, PI (using equation 10) = 57.632 HP
Overall efficiency, η_m (using equation 13) = 82.1 %

Results of a typical test run in respect to discharge coefficient, head coefficient, and turbine efficiency, for a guide vane setting, are shown in Figs. 4 and 5.

Values for the cavitation factor σ (Thoma's coefficient) are obtained as per IEC recommendations (IEC 193-A). For example, the IEC recommends the following formula for calculating σ for a turbine

$$\sigma = \frac{h_a - h'_s - h_{va}}{H_n} \quad (17)$$

where

h_a = Absolute pressure head in turbine outlet section referred to any convenient level.

h'_s = Suction head is equal to the height of the reference point of the runner above reference level of h_a .

h_{va} = Vapor pressure head at the actual water temperature.

H_n = Net head.

The discharge coefficients, for different guide vane openings, can be plotted against energy coefficients and contours of equal power coefficients and efficiencies superimposed on this to obtain the turbine Hill diagram. Lines of equal cavitation coefficients could also be superimposed on a plot of energy coefficient versus discharge coefficient.

Figure 4. Discharge coefficient versus turbine efficiency for a typical test run.

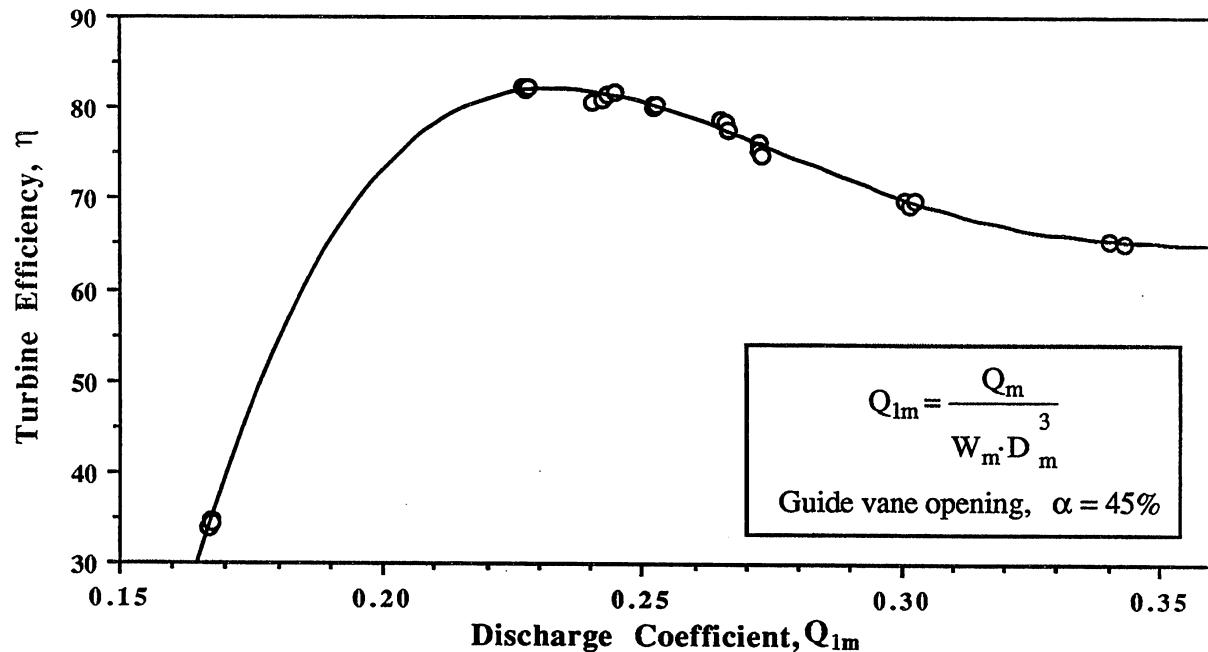
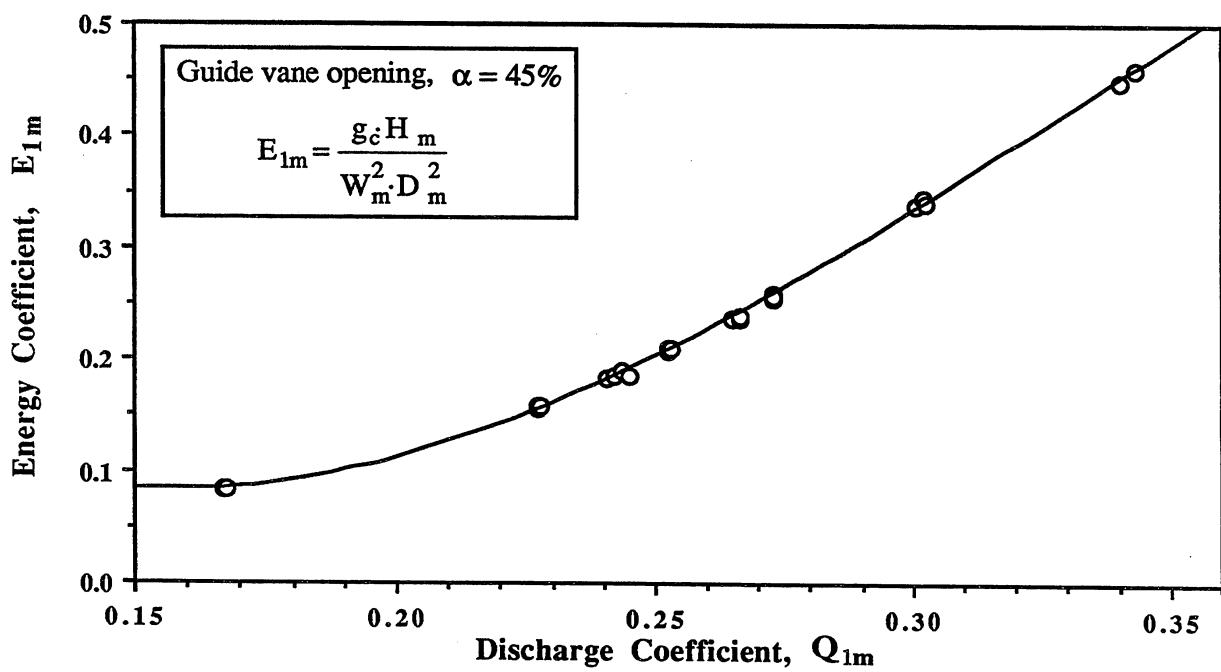


Figure 5. Discharge coefficient versus energy coefficient for a typical test run.



IV. SOFTWARE FOR DATA ACQUISITION, ANALYSIS AND CONTROL

A. Software necessary for data processing

The Turbine Test Facility's IBM A-T Personal Computer is entirely capable of all current data processing needs. However, the capability exists for interconnection to the University of Minnesota's Super Computer Institute. Data processing requires the use of software that analyzes the testing conditions into customized results. Some of the reasons that justify the creation of a software package made specific to the ITTF's objectives are :

1. The variety of parameters to be analyzed.
2. The amount of data to be processed during each run.
3. The high number of runs for a given test.
4. The necessity to save raw data and resultant parameters.
5. The complexity of the data analysis itself.
6. The ability to customize data analysis specific to a client's needs.

The parameters measured and used as input are :

1. Rotational speed (rpm)
2. Water flow (cfs)
3. Water temperature ($^{\circ}$ F)
4. Differential Head Pressure (psi)
5. Draft Tube pressure (psi)
6. Pump motor temperature ($^{\circ}$ F)
7. Force on Load Cell (lb)
8. Dynamometer preload (lb)

Other data input that are introduced by the computer operator and appear in the final tabular results as general information are :

- Turbine model
- Operator's name
- Wicket gate opening
- Blade angle, if applicable
- Atmospheric (Barometric) pressure
- Field voltage and current
- Cooling water temperature

The program's package is interactive, allowing the user to do the following :

1. Continuously display turbine parameters. Two monitors are used for the display, one in the computer room and the other next to the primary flow control valve located near the turbine model in the main turbine test Laboratory.
2. Save parameters at a rate of 10 samples/second-channel during a time interval up to 2 minutes.

3. Calculate parameters using calibration formulas, and computation of maximum, minimum and average value for each of the parameters.
4. Compute the power input, power output and efficiency using the mean value of the model parameters.
5. Compute dimensionless coefficients based on Eqns. 13, 14, 15, 16 and 17.
6. Print out tabular data and results.
7. Plot the data and results on the color monitor and on paper.
8. Check the computer input voltage corresponding to each parameter.

All these points are explained more deeply in the discussion of each program in Appendix A.

B. General organization of the program package

The total Turbine Testing package consists of 9 programs (as of April 1989) written in Basic (Version 3.0), compiled and run on a IBM PC-AT. Using Basic language facilitates program changes and allows control in data acquisition.

The package structure is organized using a branched system, complemented with options that allow the user to choose the specific turbine test run, to get results from previous runs, or to check the computer input parameters (voltage or bits).

This organization permits either implementing any program as a separate unit or improving the existing ones by adding new subroutines with minor changes in the general programming structure. More general information about software characteristics can be found in Appendix B.

1. Programs.

In order to provide an overview of how the package is structured, the purpose of each program will be discussed. The existing programs are (name without extension code) :

- **NMENU** : The link and main program. The other programs are referred to it as secondary branches.
- **NDISPLAY** : Displays the input parameter values on the screen , and offer a set of options to the user.
- **NDRAW** : Presents the plotting options in a menu format.
- **NPLOT1** : Generates a color graphic plot of any input parameter versus time. Graphic print out can also be obtained.
- **NPLOT2** : Generates a color graphic plot of any chosen pair of dimensionless coefficients. Graphic print out can also be obtained.
- **NVOLBIT** : Displays the value of each input parameter in bits.

- NSAVEDAT : Acquires and saves parameter data at a speed of 10 samples/channel-second during a variable time interval up to 2 minutes.
- NPRINT1 : Prints out the following information for a single run:
 1. General information describing the model and test conditions (i.e. Operator, Testing date, Turbine model, Runner diameter, etc).
 2. Maximum, minimum and mean for each calibrated input parameter value.
 3. Average values for power input, power output and overall efficiency.
 4. Average dimensionless coefficients (Discharge, Energy, Power, Torque, Efficiency and Cavitation).
- NPRINT2 : Prints out the mean values of speed, flow, head, torque, power input, power output, efficiency and dimensionless parameters for several runs, as specified by the test facility operator.

A more specific and detailed description of each program with application examples is given in Appendix A. All 9 programs were compiled using Quick Basic Compiler as described in Appendix C.

V. INSTRUMENT CALIBRATION

A. General

The measurement of the quantities required to determine the characteristics of a hydraulic machine have to be made with the greatest precision and accuracy. In order to ensure the accuracy of the measurements, it is often necessary to compare the quantities displayed by the facility instrumentation with those obtained with laboratory standards (National Beaureu of Standards). This is the technique of calibration.

When calibrating each instrument, it is necessary to choose a procedure which represents the actual test conditions as closely as possible. Data acquisition criteria, such as frequency and quantity, are important to allow further extrapolation of the results^[4,6,12]. Since when actually testing the turbine it is possible to repeat a test many times for given conditions (many more times than those for calibration), the results in terms of overall test precision for mean values of the input parameters computed in the next section can be considered as a maximum, whenever test sampling exceeds calibration sampling.

A set of Basic computer programs were created for data acquisition. The advantages of using these programs are :

1. Systematic data acquisition process.
2. Quick and easy calibration data analysis.
3. Possibility to handle input parameters in a separate way saving calibration time.

The general criteria under which the calibration programs were created and the calibration data acquisition was performed were :

1. If there is a natural oscillation in the parameter to be measured, the data acquisition frequency must be higher than the parameter's frequency to avoid distortion of the results and to obtain a representative value for the mean.
2. Data number per mean sample must be the same as the one used in the Data Analysis programs.
3. Calibration data acquisition time should be similar to actual testing time.

B. Calibration of the volumetric tanks

The SAFHL volumetric basins are designed to measure flows up to 300 cfs with a collecting volume of approximately 36,000 cf. and a total depth of about 19 ft. The basic structure of the measuring facility includes :

1. An approach channel conveying the inflow.
2. A diverter system to permit alternating the inflow between either of the two collecting basins.
3. A separate distribution channel and weir for each basin to disperse the flow as it passes from the diverter into the collection basin to avoid excessive waves or surging of the water surface.
4. Two independent collecting basins with known volume-stage relations.
5. A drain valve for releasing the measured water from each basin.

In addition to the above flow control structures, basic instrumentation for measuring the water stage in each basin is provided. The head-measuring instrument is a water-filled "U" tube manometer located in the control house. The minimum reading of the graduations on the manometer scale is 0.1 in. which is of the same order as the variations in pressure which may be encountered from wave action of the free surface. Since the depth of water in a filled basin is about 19 ft, a reading accuracy of 0.1 in. is equivalent to 1 part in 2280 or 0.05 % full scale.

The calibration was carried out by continually filling from a 1074.5 ft^3 (water at a temperature from 3°C to 5°C) pycnometer tank. The calibrated pycnometer tank is cylindrical with dished ends and stands with its axis vertical. It is nominally 9 ft in diameter and 15 ft high, and it is arranged to be filled from the Laboratory's city water supply. For each calibration point, the water temperature in the volumetric tank and in the pycnometer were measured, and the necessary corrections were made when the temperature was different.

After calibration, the obtained table of volumes was compared to the last calibration done in 1968. A consistent seven ft^3 positive difference was found along the calibration range (from 0 to $32,000 \text{ ft}^3$), due probably to some change in the volumetric basin bottom level. The constant difference between both calibrations suggests that the basin walls did not deform appreciably between 1968 and 1988.

C. Flow meter calibration

The calibration of the flow meter consisted of comparing the values of discharge displayed by the flow meter, with those supplied by the calibrated volumetric tank. For this purpose, the open calibration circuit shown in Fig. 3 is used. Water is drawn from the Mississippi River in two ways :

- 1) For low flows (between 5 and 15 cfs), no pump was used, taking advantage of the head difference between river intake and volumetric tanks inlet. The flow was regulated by a butterfly valve located at the pump bypass pipe while the valve at the pump inlet was kept closed (see Fig. 3)
- 2) To achieve high flows (between 15 and 35 cfs), the 300-HP pump was used. The flow was regulated using the pump inlet butterfly valve, keeping the bypass pipe valve closed.

Water is then passed through the flow meter and into the distribution channel and weir of the east volumetric tank. This continues until the flow has stabilized and the water surface in the distribution channel has reached the overflow weir. The flow is then diverted to the other volumetric tank, and everything is now set up to start calibrating. As the flow is redirected again to the east tank, the computer starts accumulating data from the flow meter (in digital format) and the stop watch is started manually. After the desired time (13 to 50 minutes depending on the flow rate), the flow is again diverted back to the west tank distribution channel. At this point, the stop watch and the computer program are stopped. After the water surface has settled, the height of the water in the volumetric tank is measured by a water-filled "U" tube manometer. From the volumetric tank calibration table, the volume is calculated and then divided by the time from the stop watch to obtain the actual flow rate. The computer simultaneously accumulates readings at a rate of 50 readings/second from the flow meter and computes an average value every 10 seconds. In the end, the program gives the mean value of all 10-second means obtained during the calibration period. This value is compared to the actual flow rate for calibration.

The chosen calibration points were approximately 5, 10, 15, 20, 25, 30 and 35 cfs, which were achieved using the butterfly valves, as described above, to control the flow, and the computer screen display to roughly check the discharge value.

The calibration was repeated five times during eight days, three of them in a systematic way from low to high discharge, and two in a random manner. The total storage time for each flow was chosen to achieve a total water volume between half and full volumetric tank capacity. This criterion minimizes the error associated with the volumetric tank, but also increases calibration time. For example, the necessary storage time was 50 minutes for the lowest flow (5 cfs). The error associated with the volumetric tanks calibration was estimated to be $\pm 0.2\%$ for volumes higher than 16,000 cubic feet and measuring times greater than 150 seconds.

D. Load cell calibration

As mentioned under section III-E.1, the measurement of the torque is reduced to measuring a force by means a tension/compression gauge load cell. The calibration of this measuring device is therefore simple and consists of replacing the force opposed by the stator of the dynamometer by a force of known magnitude. In practice, it is important not to remove the load cell so as to avoid any outside influence. For this reason, the calibration is carried out on the machine itself.

The calibration device comprises one metallic cable of 2mm. diameter, one end of which is secured to the load cell while the other is provided with a tray on which calibrated weights can be placed. The cable is guided by a low friction pulley to reduce friction to a

minimum. The weights used were from 4.022 to 30.123 lb., and the accuracy offered by the Weight and Measures Division of Minnesota Public Services was $\pm 7 \times 10^{-4}$ % for this range. After the corresponding weights have been placed on the tray and everything is settled, the computer starts accumulating data at a rate of 100 readings/second for 5 seconds. The mean value in bits is then computed and printed out. Calibration consists of making a direct comparison between this mean value and the mass of the weights on the tray. One obtains by these means the calibration coefficients which will be implemented as calibration formulas in the programs. Nine calibration points were chosen ranging from 6.368 ft-lb to 47.695 ft-lb. The calibration for these points was repeated seven times in a systematic manner from low to high values during a four day period.

The influence of temperature variation is noticeable, particularly on the load cell and its converter. This difficulty is overcome by the existence of the enclosure which maintains these devices at more or less constant temperature during operation.

Finally, it is important to point out that although the load cell is rated up to 250 lb., the actual load cell reading will be normally between 5 and 30 lb. because of the dead weight pre-load that will be installed on the dynamometer for each run. The total torque is then the summation of the one produced by the dead weight and the load cell reading. Running the ITTF without pre-load on the dynamometer requires a new load cell calibration over a wider weight range.

E. Calibration of the pressure transducers

The device used for calibrating both pressure difference and tail tank pressure transducers is a dead weight gauge tester type 1300, manufactured by Manning, Maxwell, and Moore Inc.

To start calibrating, the dead weight gauge tester is connected to the pressure transducer by a 1/4-in.-diameter copper tube, and the desired weight is placed on the weighting platform of the piston. During calibration, the weights and piston must be kept revolving by hand. Once everything is stabilized, the computer starts accumulating data coming from the pressure transducers at a rate of 100 readings/second during a 5-second period. The mean value in bits is then computed and printed out after the 5-second period. Span and zero shift were periodically checked during calibration. Amplifier output voltage and volts coming into the computer were also tabulated to check the transducer's electrical circuits and voltage variation during calibration. Calibration consists of comparing computer mean values with psi produced by the dead weight tester.

After applying the numerical procedure described in section V-C, calibration coefficients are found and implemented into the programs. The chosen calibration points were : 5, 10, 15, 20, 25, 30, 35, 40, and 45 psi for the differential pressure transducer, and 5, 10, 15, 20, 25, and 30 psi for the tail tank pressure transducer. Ten tests were done for each calibration point for the tail tank pressure transducer, and nine tests were performed for the differential pressure transducer. The calibration was undertaken over seven days.

During calibration, it was sometimes necessary to adjust the zero scale before starting a new set. Since the calibration was performed in July 88 with a daily temperature variation from approximately 80 °F in the morning to 100 °F in the afternoon, scale zero shift temperature dependence between these two values was checked. This was done leaving

transducers and amplifiers on during the day. The shift was adjusted at the beginning, and the voltage readings for zero pressure on the transducers were taken from the amplifier displays. The total span range for both amplifiers is 100 volts. The following can be concluded from these observations :

1. There is indeed zero scale point variation with increasing temperature from 80 to 100 °F. This variation is almost linear and its magnitude is approximately -0.3 volts for the differential pressure transducer/amplifier #2 circuit, and -0.6 volts for the tail tank pressure transducer/amplifier #1 circuit.
2. Direct sunlight on transducers erratically increases zero shift.
3. Pressure transducers appear to respond more sensitively to temperature changes than amplifiers do as it is inferred from the very low zero shift (+ 0.05 volts between 92 and 100 °F) obtained when the tail tank pressure transducer was kept at constant temperature (76.5 °F) and amplifier #1 was subjected to temperature variation.
4. Some experiments conducted with a spare pressure transducer and amplifier #2 confirmed points 2. and 3., although the zero shift magnitude was found to be positive (+ 0.4 volts) for the same temperature range.

When actually running the ITTF, a cover to assure that no direct sunlight falls on the transducers and a periodic check of any zero shift will be enough to guarantee the pressure transducer calibration.

F. RPM counter calibration

Calibration of the rpm counter was performed using a Hewlett-Packard frequency counter in the pulse counting mode and a DC motor to simulate the dynamometer shaft rotation. The frequency counter was installed between the magnetic pick-up sensor of the rpm counter to be calibrated and the frequency/voltage converter. After a given rotational speed has been selected and adjusted using the DC motor rheostat and the computer screen display, the computer program for rotational speed data acquisition, pulse counter, and stop watch are simultaneously started. The calibration period time extends for five minutes during which the computer continuously accumulates data (bits) at a rate of 100 data/second and takes an average every five seconds. At the end of the 5-minute period, computer, counter, and watch were stopped, and the program computed the overall mean value by averaging all 5-second means. This value was then compared to that obtained from the frequency counter.

The frequency counter only counts positive electric pulses. On the other hand, the magnetic disc has 16 alternate small magnets (8 positive and 8 negative), meaning that eight pulses represent a complete disc revolution. Dividing the total number of pulses displayed on the frequency counter after stopping it by eight and time in minutes, we get the averaged actual rpm. The chosen calibration points go from 200 rpm to 1500 rpm, with a 100 rpm step increment. The calibration procedure for the chosen points was repeated

seven times (four in a systematic manner from lower to higher rpm values and three in a random manner) during a 10-day period.

Errors associated with the frequency counter can be considered negligible. That is not the case, however, for the error related to the time lag generated when simultaneously starting and stopping by hand the counter and the stop watch (see section V-E.4). The five minute calibration time was selected as a trade off between minimizing calibration time and reducing time lag relative error to a value of little significance.

When analyzing the three first calibration data sets taken in July 1988, very high differences between computer and frequency counter readings were found for rpm values between 800 and 1500 in one data set. This generated a high rpm uncertainty for the turbine operating range. After carrying out successive new calibrations in the same operating manner as before, it was found that the rpm data acquisition electric circuit needed a 1 hour "warm up" period before giving consistent readings.

The next step was to identify the circuit component that was creating problems. Several experiments were conducted for this purpose, and the following devices were checked :

1. DC motor.
2. Frequency counter.
3. Frequency/voltage signal converter (input and output circuit).
4. Analog/digital converter.

The DC motor and frequency counter were checked separately by leaving each one of them on during a 2-hour period while the rest of the input data circuit was kept off. Readings were taken immediately after turning the circuit on again. If the problem was either the DC motor or the frequency counter, readings should have been consistent from the beginning. Neither the DC motor, nor the counter appeared to be causing the trouble. A similar procedure was followed to check the frequency/voltage converter input circuit, with the same result. This limited the investigation to the frequency/voltage converter output circuit and the A/D converter. For that purpose, the DC motor, magnetic disc, and magnetic pick-up were replaced by a constant frequency generator. Constant frequency between 40 Hz and 200 Hz was checked using the frequency counter and the stop watch. The reason for using a constant frequency generator was to ensure a constant input signal in the circuit and study its variation with time. The DC motor does not give an absolute constant rotational speed. In addition, a digital display voltmeter was placed between the frequency generator and the A/D converter. After selecting 133.3 Hz frequency and turning on the circuit without warm up, voltage readings from the voltmeter were compared to computer voltage display using the VOLTS.BAS program. Both values were observed to be identical during the checking process. On the other hand, the voltage readings value consistently decreased for about 1 hour until reaching a stable value. This eliminated the A/D converter and showed that the problem was somewhere inside the frequency/voltage converter output circuit. Other experiments have been conducted since to specifically identify and replace this piece of equipment.

VI. MEASUREMENT UNCERTAINTY

A. Background

There is an uncertainty associated with any measurement in the ITTF. This includes a bias uncertainty, accounting for systematic inaccuracies in calibration, instruments, and calibration process, and a precision uncertainty, accounting for the inability to repeat a measurement value precisely^[19]. The bias uncertainty is estimated from the calibration procedure, given in section V, and from the uncertainty associated with the various standards used. For the ITTF, the precision uncertainty will be estimated from a regression analysis of multiple measurements. The regression analysis requires fewer independent measurements of a given parameter to reduce the uncertainty to a given value. For example, three measurements at a given parameter value (say 1000 rpm) will give only two degrees of freedom and a rather large uncertainty. However, ten parameter values with three measurements each (say intervals of 100 rpm between 100 and 1000 rpm) fit to a second order equation will have 27 degrees of freedom and a marked reduction in uncertainty. The uncertainty is minimized in that more measurements will probably not significantly reduce the precision uncertainty. One must be careful, however, that the equation fits the parameter data throughout the regime of measurements.

Before going through the general procedure to find the regression curve and uncertainty associated with this regression for each input parameter, the statistical concepts and definitions that will be used will be reviewed in this section.

1. Residuals

Residuals are the observed fitting errors between the actual value of the dependent variable (y), and the predicted value for a given independent variable (x). The residual for the i th point is given by the following equation^[20]

$$\hat{e}_i = y_i - F(x_i) = y_i - \hat{y}_i \quad (i=1, 2, 3, \dots, n) \quad (18)$$

where

y_i : i th dependent variable value.

$F(x_i)$: Predicted value of the dependent variable for $x=x_i$.

n : Number of measurements.

F is the fitting curve and in general can be any kind of function, although we'll constrain our analysis to the study of linear, second and third degree-polynomials.

The residuals given by Eq. (18) provide information regarding assumptions about error terms and the appropriateness or fit of the model. Plot of the residuals versus other quantities are used to find failures of the assumptions. The most common is the plot of the residuals versus predicted values. Systematic features in this plot are of interest and will be discussed in the next section.

2. Residual sum of squares (RSS)

The residual sum of squares is based on the residuals definition, and it is formulated in the following manner^[20] :

$$RSS = \sum_{i=1}^{i=n} [y_i - F(x_i)]^2 \quad (19)$$

Based on Eqn. (19), the standard error of regression σ is defined by Eqn. (19a).

$$\sigma = \sqrt{\frac{RSS}{n - p}} \quad (19a)$$

where

n : Total number of points used in the regression.

p : Number of parameters in the model.

A good fitting curve has a low RSS (and therefore a σ low value). This is the least squares criterion where the residuals that give the vertical distance between the fitted curve and the actual y values are squared, summed, and minimized.

3. F-test

The F-test was used in the analysis to compare two regression models (ie. linear model versus second-degree polynomial model). While increasing the degree of the fitting polynomial, the RSS value will decrease. The purpose of the F-test is to show if this decrement is really significant. In other words, the F-test will indicate if increasing the polynomial degree is actually generating a better fit.

The original regression model is called null hypothesis (nh), and the new model to test is called alternative hypothesis (ah). F value is defined in the following manner :

$$F = \frac{\frac{(RSS_{nh} - RSS_{ah})}{(df_{nh} - df_{ah})}}{\frac{RSS_{ah}}{df_{ah}}} \quad (20)$$

where

df_{nh} : Degrees of freedom for the null hypothesis (total number of points - number of null hypothesis coefficients).

df_{ah} : Degrees of freedom for the alternative hypothesis (total number of points - number of alternative hypothesis coefficients).

The value of F as computed from Eq. (20) is then compared to standard tabulated F values for a 99% confidence interval (see section VI-C).

4. Prediction

The fitted equation is used to obtain values of the response (parameter) for given values of the predictor (bits). In prediction, we have a new case : we would like to know the value y_i , the corresponding response, that has not been observed. Since y_i is not available, we will use the model at the observed value of x_i to predict it^[20]. The experimental conditions during calibration were the same as during actual running conditions, and therefore we can assume that the data used to estimate the fitted curve are relevant to the prediction of the parameters, so the fitted model applies to it.

In general, the variability of the predictor has two sources : the variation in the estimates of coefficients of the fitting curve (β_0, β_1, \dots etc), and the variation due to the fact that the model is not correct. In our case, because of the high amount of points used for calibration, we will assume that our model is correct, and therefore the only remaining uncertainty associated with the estimated coefficients. Our final uncertainty will be referred to the mean parameter value (also called fitted value by some authors) for a given point in the range. In other words, the uncertainty will not be associated with a single parameter measurement, but with the mean of the measurements taken for one point. The ITTF capabilities allow numerous testing repetitions. The final uncertainty in the prediction was computed for a 95% confidence interval using Student's t-distribution table.

B. Theoretical approach^[20,21,22,23]

As it was said before, the uncertainty associated with our regression model will be computed based on the variability of the curve fitting coefficients. On the other hand, uncertainty analysis for the regression model assumes that the error in the estimation is independent of the predictor (magnitude x_i) or in other words, that the variance of our data is constant in the calibration range. If the last condition is not verified for our model, its associated uncertainty based on the curve fitting coefficients will be no longer representative, and predicted values could easily lie out of the 95% confidence interval.

One way to visualize and diagnose at the same time the possible change in variance associated to a given regression is using residuals plots^[22]. If the residuals, as defined in Eq. (18), and the predicted value $F(x_i)$ are nearly uncorrelated, when residuals are plotted against predicted values, we will always have a plot with slope near zero and with scatter about the value 0. If this is not the case, our model will have a variance other than that associated with the model coefficients, and therefore the final uncertainty will not be validated. Another model must be tried then to get the desired residuals plot.

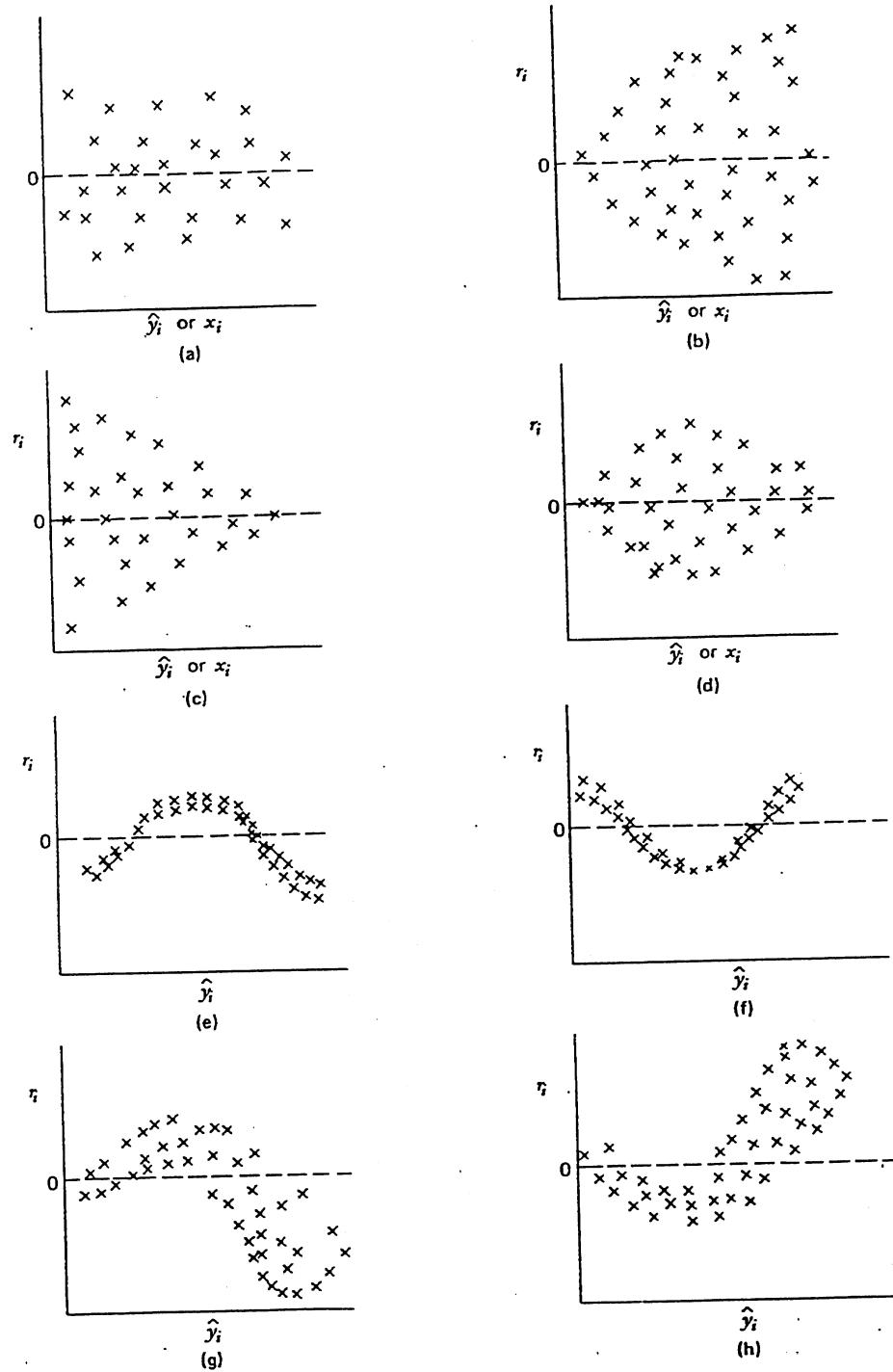


Figure 6. Residual plots: (a) null plot; (b) right-opening megaphone; (c) left-opening megaphone; (d) double outward bow; (e) nonlinearity; (f) nonlinearity; (g) nonlinearity and nonconstant variance; (h) nonlinearity and nonconstant variance. (Ref. "Applied Linear Regression" by S. Weisberg, p. 132)

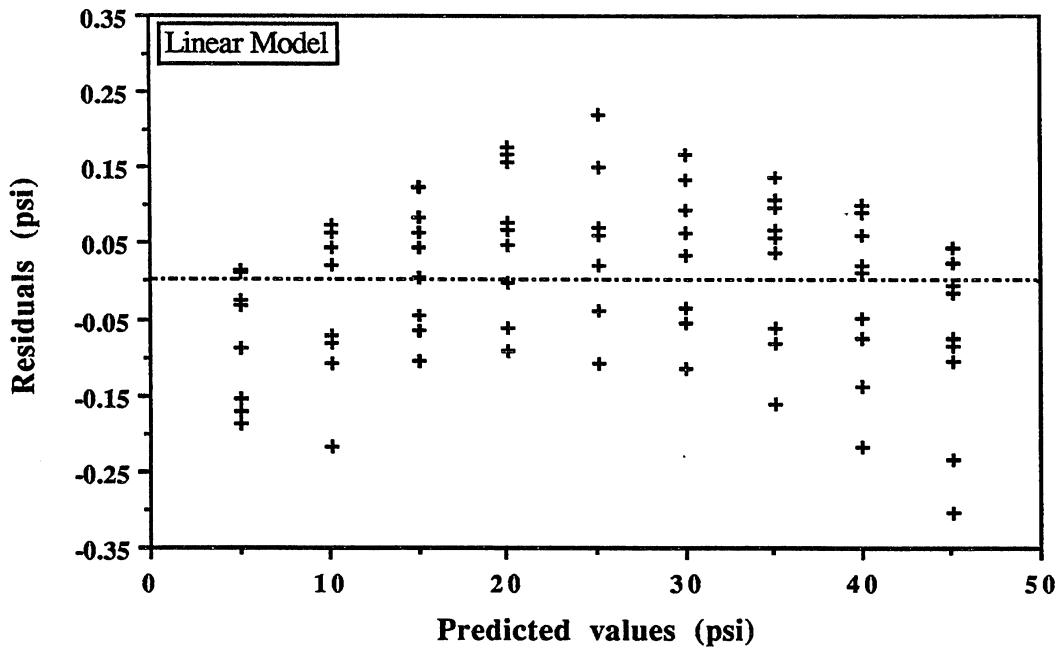
Eight idealized residual versus predicted value plots are given in Fig. 6 after applying a simple linear regression model. The first plot is as one would expect if the specified model were correct; it is a null plot. This figure is just a swarm of points without pattern. Nonconstant variance might be indicated by any of Figs. 6-b to 6-d. The right opening megaphone, Fig. 6-b, suggests variance increasing with the quantity plotted on the x-axis. The double bow of Fig. 6-d can occur if the response is constrained to lie between a minimum and a maximum value.

Figs. 6-e and 6-f suggest that the response is a nonlinear function of the quantity plotted on the x-axis, since after removing the linear trend only a nonlinear curved trend remains. This will often call for transformation of the data, either the response or the predictors, or use of nonlinear models. This nonlinear case can also be regarded as a "nonconstant bias error" case, where the bias is created by the poor fit of the curve.

The importance of this regression validation technique is pointed out in the following example for the differential pressure transducer calibration. Fig. 7. shows the residual plot after applying a simple linear regression to the data. The applied linear regression is given by Eq. (21).

$$P_d = 0.0242 \cdot X_d + 0.3411 \quad (21)$$

Figure 7. Residual plot for Pressure Transducer DP 215-46 (Linear Model).



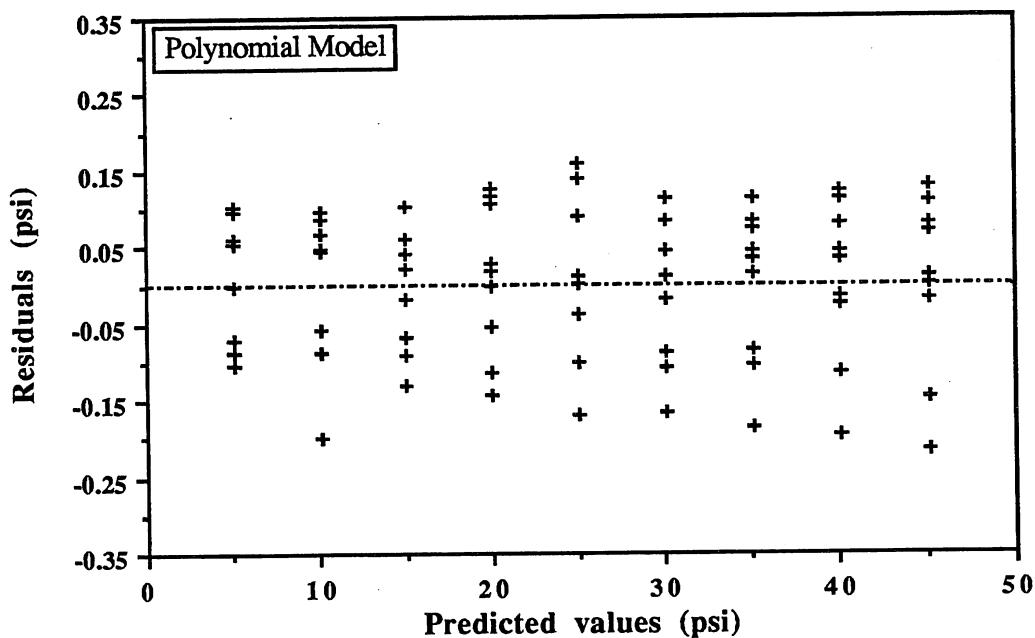
This is clearly a nonlinear case. Although the RSS is quite low (0.958), when computing and plotting the 95% confidence interval lines for the linear model, most of the points were found to lie outside of the interval. This is an example of how a slightly nonlinear behavior can invalidate a linear model assumption.

Fig. 8. shows the residual plot for a second degree regression model given by Eq. (22).

$$P_d = -2.17 \cdot 10^{-7} \cdot X_d^2 + 0.0247 \cdot X_d + 0.178 \quad (22)$$

In this case, we get a fairly nice null plot with RSS = 0.724. Although looking at the values of RSS, the result does not appear to be improved very much, the fact that we have now a random scatter residual plot validates the uncertainty analysis. Our study is then reduced to finding the best fitting curve (using the previously described F-test) that generates a null residual plot and then computing the uncertainty associated with it.

Figure 8. Residual plot for Pressure Transducer DP 215-46 (Polynomial Model).



C. Methodology

The regression and uncertainty analysis was performed using a multiregression commercial software available for a personal computer. The program allows high analysis versatility and graphic capabilities. The way this program was used to find the precision associated with each calibration parameter can be summarized in the following manner :

1. Input and plot calibration data.
2. Try linear regression, finding the two linear coefficients by using a least-squares criterion.

3. Find the analysis of variance table (anova table)^[20] for the linear model. An anova table will give us degrees of freedom and RSS values.
4. Plot and analyze the residual plot. If we are in the nonconstant or nonlinear variance case, then we must use other transformations or models until we obtain the previously described null residual plot. For the five calibrations (load cell, two pressure transducers, flow meter ,and rpm counter), a fairly clear slightly nonlinear plot was found for the residuals.
5. Try second, third, and fourth degree polynomial regressions^[22], finding coefficients and the anova table for each one, and making sure that the residual plot and RSS have been improved.
6. Use the F-test to finally select the best fitting model. We will compare the null hypothesis (lower-degree polynomial) versus an alternative hypothesis (higher-degree polynomial). Using the differential pressure transducer again as an example and applying Eq. (20) to compare the linear and second-degree models, we get a value of $F = 25.21$. If we go now through the F statistic tables for 99% confidence and the known degrees of freedom, we find a value of $F = 7$. Since $25.21 > 7$, the alternative hypothesis is found significant (we actually have 99% provable better fit) and the simple linear model is rejected.
If we now compare the second-degree polynomial versus third degree following the same procedure, we end up with a value of $F = 2.3$ which is lower than 7, and therefore the third degree model is rejected as not significantly better. For all data sets analyzed, the second-degree polynomial model was found to be the best fit.
7. Once the final model has been chosen, we use the multiregression program to find out the absolute precision associated with each parameter value in the range^[21]. As stated before, the absolute precision is referred to the mean value of the parameter for each point in the range.
8. To obtain the 95% confidence interval in the results, we multiply the values obtained in point 6. by the value taken from the Student's t-distribution table using the number of data obtained for each calibration.
9. Finally, the relative precision graphic for each calibration parameter is determined.

Once the uncertainty associated with each parameter value has been computed, we must study the propagation of uncertainty^[19,23] in finding the overall efficiency. The overall precision for the efficiency is given in section VI-F, and the theoretical analysis for the uncertainty propagation is performed in Appendix D.

D. Parameter uncertainty

After applying the analysis sequence described in section VI-C for each one of the calibrated parameters, the results are shown in this section. Table 2 summarizes some statistical variables associated with the regression model selected for each case.

Table 2. Regression models and resultant Standard Error for the ITTF calibration.

Parameter	Points #	Regression Formula	Standard Error (σ)
Net Head	81	$P_d = -2.17 \cdot 10^{-7} \cdot X_d^2 + 0.0247 \cdot X_d + 0.178$	0.096
Flow	35	$Q_m = -2.845 \cdot 10^{-7} \cdot X_q^2 + 0.0258 \cdot X_q - 9.588$	0.059
Torque	56	$T_m = 2.829 \cdot 10^{-5} \cdot X_t^2 + 0.3736 \cdot X_t + 1.169$	0.065
Rotational Speed	98	$N_m = 7.995 \cdot 10^{-6} \cdot X_n^2 + 0.9896 \cdot X_n + 0.471$	2.397
Tail Tank Head	70	$P_c = -1.31 \cdot 10^{-7} \cdot X_c^2 + 0.0173 \cdot X_c + 0.041$	0.027

All Standard Errors values are very low except for the rotational speed case. This is basically due to the relatively high value of N_m (typically 400/1200 rpm) compared to the other parameters (i.e., flow has a typical range from 10 to 20 cfs). As it was said before, the slightly second-degree polynomial function was found to be the best-fitting model for all the parameters.

Each test run of a model turbine will take the mean value of between ten and twenty measurements. Therefore, the precision uncertainty should also be based upon a number of ten-sample means, or a mean of fewer than ten samples. If fewer than ten samples are used, the precision uncertainty will be larger.

1. Net head precision.

Table 3 gives the predicted mean pressure random uncertainty for the differential pressure transducer. The predicted value is the value of the differential pressure after applying the regression formula given in Table 2. The Student's t coefficient was found using statistic tables and interpolating for our number of points.

Table 3. Predicted precision uncertainty for mean pressure (mean of 9 pressure measurements) with a 95% confidence interval. Differential pressure transducer DP 215-46.

Predicted Pressure	Estimated Absolute Precision Uncertainty ^(*)	Estimated Relative Precision Uncertainty
5.0257 PSI	± 0.0514 PSI	$\pm 1.02 \%$
10.0865 PSI	± 0.0334 PSI	$\pm 0.33 \%$
15.1290 PSI	± 0.0284 PSI	$\pm 0.19 \%$
20.1531 PSI	± 0.0306 PSI	$\pm 0.15 \%$
25.1588 PSI	± 0.0321 PSI	$\pm 0.13 \%$
30.1152 PSI	± 0.0307 PSI	$\pm 0.10 \%$
35.1152 PSI	± 0.0286 PSI	$\pm 0.08 \%$
40.0658 PSI	± 0.0337 PSI	$\pm 0.08 \%$
44.9981 PSI	± 0.0518 PSI	$\pm 0.11 \%$

(*) Student's t is 1.99 for 95% confidence interval and 81 calibration points.

Figs. 9 and 10 represent respectively the absolute and relative uncertainty intervals with 95% confidence for the differential pressure transducer. The interval curves have been obtained by interpolation of the data given in Table 3. Each one of the values plotted inside the interval is a mean of nine points. All the mean value points are randomly distributed above and below the zero error line and inside the 95% interval. As can be noticed by looking at Fig. 9, the minimum absolute precision uncertainty is generated between 15 and 35 psi. Values on the extremes of the scale have a higher absolute precision uncertainty. On the other hand, as shown in Fig. 10, the maximum relative random uncertainty is obtained for low scale values.

Figure 9. Absolute uncertainty (95% confidence interval) for Pressure Transducer DP 215-46.

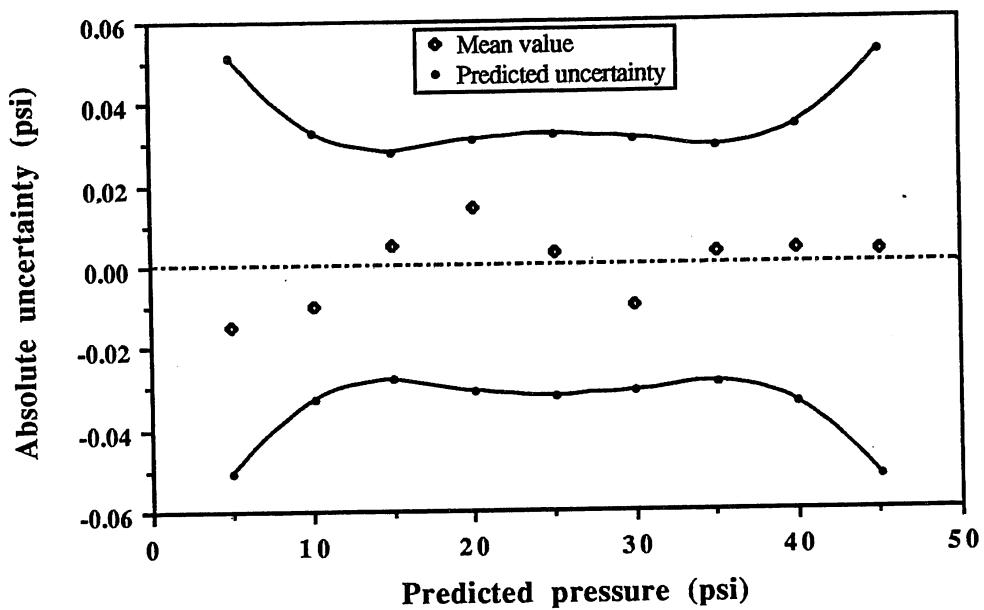
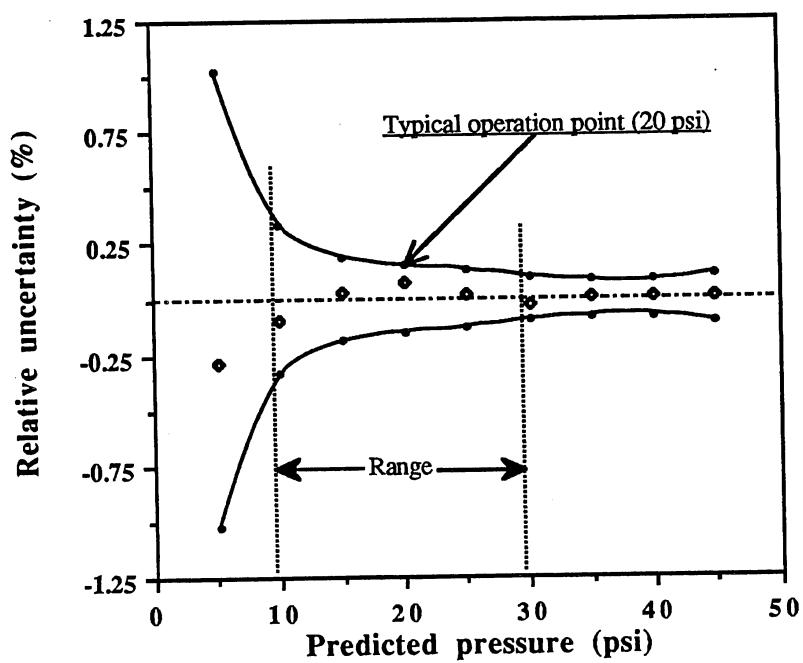


Figure 10. Relative uncertainty (95% confidence interval) for Pressure Transducer DP 215-46.



2. Discharge precision.

Table 4 gives the predicted mean discharge precision uncertainty for the electromagnetic flow meter. The predicted value shown in the first column is the flow value after applying the regression formula given in Table 2. The Student's t coefficient was found using statistic tables for 95% confidence interval and our total number of calibration points (35).

Table 4. Predicted precision uncertainty for mean flow (mean of 5 discharge measurements) with a 95% confidence interval. Electromagnetic flowmeter 10D 1435-AXAIH.

Predicted Flow	Estimated Absolute Precision Uncertainty (*)	Estimated Relative Precision Uncertainty
4.617 CFS	± 0.0525 CFS	± 1.13 %
5.955 CFS	± 0.0473 CFS	± 0.79 %
8.167 CFS	± 0.0327 CFS	± 0.40 %
11.229 CFS	± 0.0287 CFS	± 0.26 %
13.332 CFS	± 0.0275 CFS	± 0.21 %
16.479 CFS	± 0.0290 CFS	± 0.18 %
18.573 CFS	± 0.0304 CFS	± 0.16 %
21.705 CFS	± 0.0312 CFS	± 0.14 %
23.788 CFS	± 0.0310 CFS	± 0.13 %
26.906 CFS	± 0.0285 CFS	± 0.11 %
28.980 CFS	± 0.0272 CFS	± 0.09 %
32.083 CFS	± 0.0289 CFS	± 0.09 %
37.235 CFS	± 0.0462 CFS	± 0.12 %

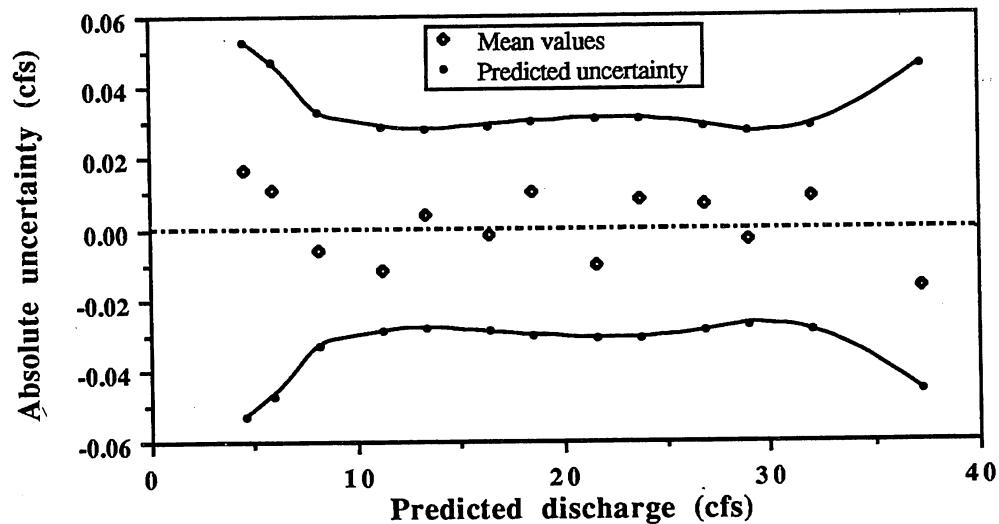
(*) Student's t is 2.04 for 95% confidence interval and 35 calibration points.

Figs. 11 and 12 represent the absolute and relative uncertainty intervals with 95% confidence for the electromagnetic flow meter. The interval curves have been obtained by interpolation of the data given in Table 4, and mean values were computed in a similar manner to those in section VI-D.1.

Again, all the mean values points are precision uncertainties distributed above and below the zero line and inside the 95% interval, although the fluctuation is now more significant than in the differential pressure transducer case. Fig. 11 shows that the minimum absolute random uncertainty corresponds to the range between 10 and 30 cfs.

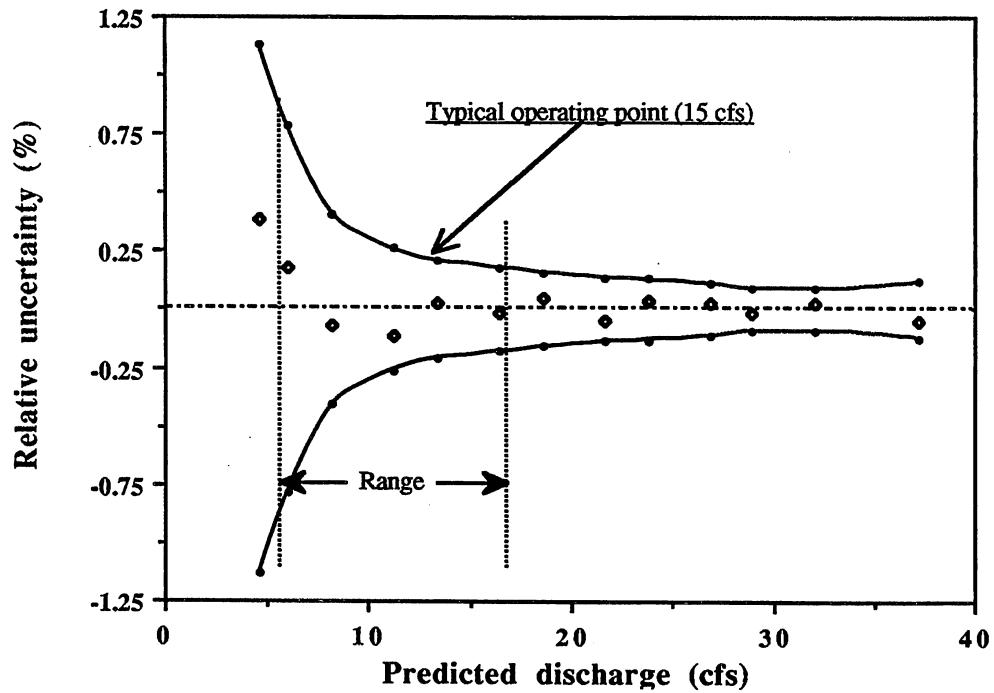
The maximum relative precision uncertainty is obtained for low-scale values of the flow (Fig. 12). For the typical operation point (15 cfs) the relative random error is about $\pm 0.2\%$.

Figure 11. Absolute uncertainty (95% confidence interval) for Flow meter 10D 1435-AXAIH.



Notice that the mean value for the relative precision uncertainty inside the typical operation range in Fig. 12 is much higher than the same mean value for the differential pressure transducer in Fig. 10, therefore the amount of uncertainty associated with the discharge measurement is greater than that associated with measuring pressure. We will see later on that the final uncertainty associated with the flow measurement is actually the most important source of error for the ITTF.

Figure 12. Relative uncertainty (95% confidence interval) for Flow meter 10D 1435-AXAIH.



3. Torque precision.

Table 5 gives the predicted mean torque precision uncertainty for the tension/compression load cell. The predicted value is the torque after using the regression formula given in Table 2. The Student's t coefficient was found in the same way than in the previous cases (for a total of 56 calibration points).

Table 5. Predicted precision uncertainty for mean torque (mean of 7 torque measurements) with a 95% confidence interval. Load cell 41-571-02.

Predicted Torque	Estimated Absolute Precision Uncertainty ^(*)	Estimated Relative Precision Uncertainty
6.074 Ft-Lbs	± 0.0428 Ft-Lbs	± 0.70 %
11.069 Ft-Lbs	± 0.0281 Ft-Lbs	± 0.25 %
16.075 Ft-Lbs	± 0.0234 Ft-Lbs	± 0.15 %
21.091 Ft-Lbs	± 0.0249 Ft-Lbs	± 0.12 %
26.117 Ft-Lbs	± 0.0265 Ft-Lbs	± 0.10 %
31.153 Ft-Lbs	± 0.0257 Ft-Lbs	± 0.08 %
36.120 Ft-Lbs	± 0.0238 Ft-Lbs	± 0.07 %
41.256 Ft-Lbs	± 0.0256 Ft-Lbs	± 0.06 %
46.322 Ft-Lbs	± 0.0370 Ft-Lbs	± 0.08 %
51.399 Ft-Lbs	± 0.0577 Ft-Lbs	± 0.11 %

(*) Student's t is 2.005 for 95% confidence interval and 56 calibration points.

Figs. 13 and 14 represent respectively the absolute and relative uncertainty intervals with 95% confidence for the tension/compression load cell. The interval curves have been obtained by interpolation of the data shown in Table 5. Fig. 13 shows that the minimum absolute precision uncertainty corresponds to the range between 15 and 40 lb-ft. Fig. 14 shows that the maximum relative precision uncertainty is obtained for values of the torque below 10 lb-ft. For the typical operation point (30 lb-ft) the relative precision uncertainty is about $\pm 0.09\%$. The average relative precision uncertainty for the operating range is $\pm 0.1\%$.

Figure 13. Absolute uncertainty (95% confidence interval) for Load Cell 41-571-02.

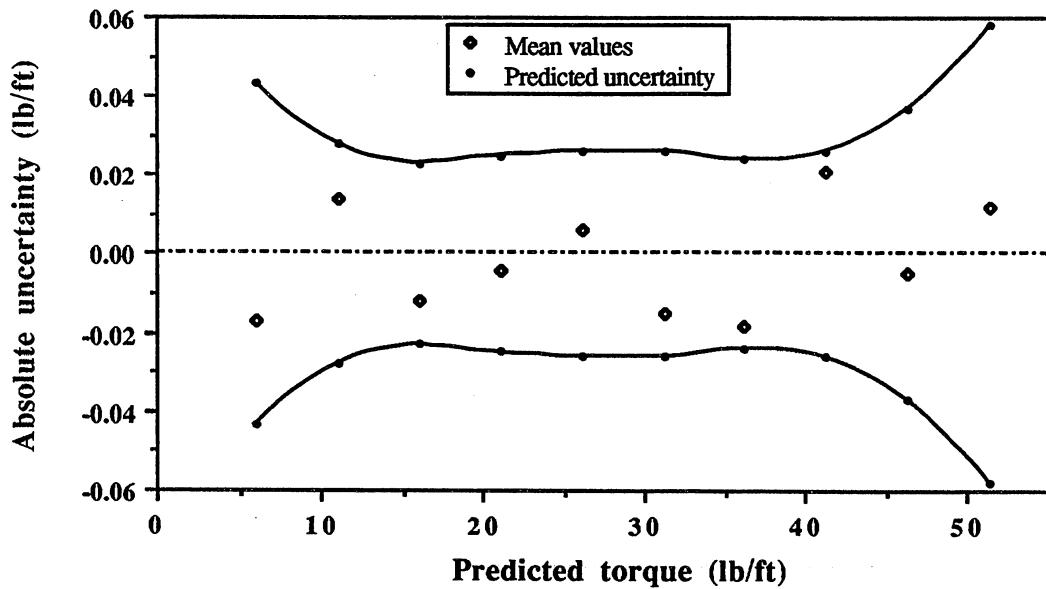
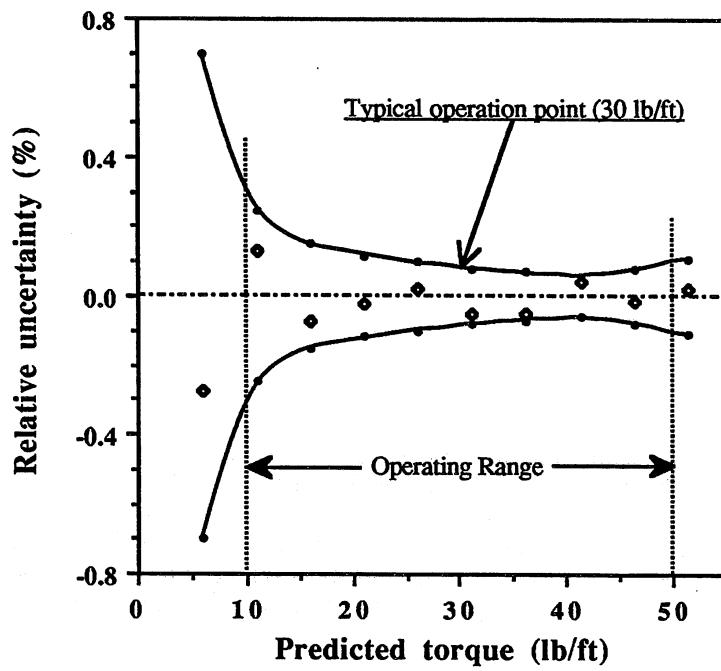


Figure 14. Relative uncertainty (95% confidence interval) for Load Cell 41-571-02.



4. Rotational speed precision.

Table 6 shows the predicted mean rotational speed precision uncertainty for the magnetic pick-up rpm counter. The predicted value is obtained after applying the regression formula given in Table 2 for several values of X_n (independent variable in bits).

Table 6. Predicted precision uncertainty for mean RPM (mean of 7 RPM measurements) with a 95% confidence interval. Magnetic pick-up DSC-10C.

Predicted RPM	Estimated Absolute Precision Uncertainty (*)	Estimated Relative Precision Uncertainty
204.7 RPM	± 1.266 RPM	± 0.62 %
303.1 RPM	± 0.943 RPM	± 0.31 %
401.4 RPM	± 0.735 RPM	± 0.18 %
500.0 RPM	± 0.649 RPM	± 0.13 %
598.8 RPM	± 0.653 RPM	± 0.11 %
697.7 RPM	± 0.690 RPM	± 0.10 %
796.8 RPM	± 0.718 RPM	± 0.09 %
896.0 RPM	± 0.719 RPM	± 0.08 %
995.4 RPM	± 0.694 RPM	± 0.07 %
1095.0 RPM	± 0.657 RPM	± 0.06 %
1194.7 RPM	± 0.648 RPM	± 0.05 %
1294.6 RPM	± 0.725 RPM	± 0.06 %
1394.6 RPM	± 0.923 RPM	± 0.07 %
1494.8 RPM	± 1.236 RPM	± 0.08 %

(*) Student's t is 1.98 for 95% confidence interval and 98 calibration points.

Figure 15. Absolute uncertainty (95% confidence interval) for RPM Counter DSC-10C.

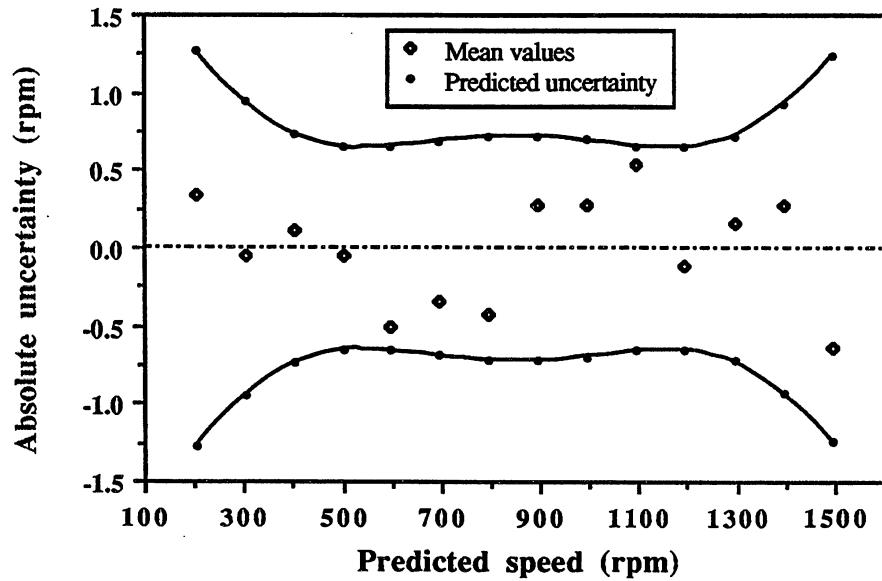
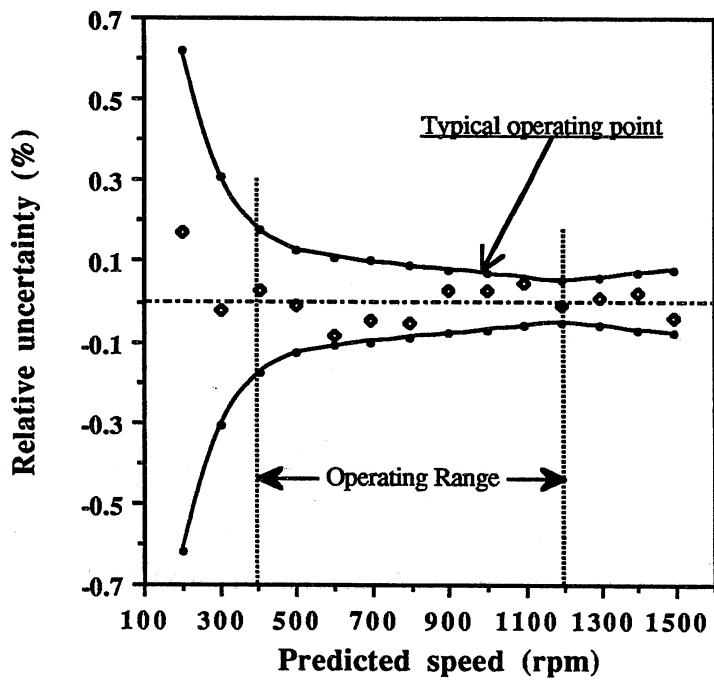


Figure 16. Relative uncertainty (95% confidence interval) for RPM Counter DSC-10C.



Figs. 15 and 16 represent the absolute and relative uncertainty intervals with 95% confidence for the magnetic pick-up rpm counter. Confidence interval curves have been obtained, as in the previous cases, by interpolation of the data given in Table 6. Mean values were computed in the way described in section VI-D.1. The minimum absolute precision uncertainty was found to be in the range between 500 and 1200 rpm. For the typical operation point (1000 rpm) the relative precision uncertainty is about $\pm 0.07\%$. The relative precision uncertainty mean value for the typical operation range (between 400 and 1200 rpm) can be estimated as $\pm 0.1\%$.

5. Tail tank pressure precision.

Table 7 gives the predicted random uncertainty for the tail tank mean pressure. This value is not used when computing the overall uncertainty associated with the efficiency, but it becomes important when performing cavitation tests. The Student's t coefficient was found as in previous cases for a total number of points of 70. As in previous cases, Figs. 17 and 18 represent the absolute and relative uncertainty intervals with 95% confidence for the tail tank pressure transducer. The minimum absolute precision uncertainty corresponds to the range from 5 to 25 psi. The mean value for the relative precision uncertainty inside the typical operation range (Fig. 18) is $\pm 0.16\%$.

Table 7. Predicted precision uncertainty for mean pressure (mean of 10 pressure measurements) with a 95% confidence interval. Differential pressure transducer DP 215-44.

Predicted Pressure	Estimated Absolute Precision Uncertainty (*)	Estimated Relative Precision Uncertainty
1.983 PSI	± 0.0121 PSI	$\pm 0.62\%$
2.994 PSI	± 0.0104 PSI	$\pm 0.35\%$
5.013 PSI	± 0.0089 PSI	$\pm 0.18\%$
8.036 PSI	± 0.0085 PSI	$\pm 0.11\%$
10.046 PSI	± 0.0089 PSI	$\pm 0.09\%$
15.057 PSI	± 0.0096 PSI	$\pm 0.06\%$
20.045 PSI	± 0.0089 PSI	$\pm 0.04\%$
25.011 PSI	± 0.0089 PSI	$\pm 0.04\%$
29.954 PSI	± 0.0145 PSI	$\pm 0.05\%$

(*) Student's t is 1.99 for 95% confidence interval and 70 calibration points.

Figure 17. Absolute uncertainty (95% confidence interval) for Pressure Transducer DP 215-44.

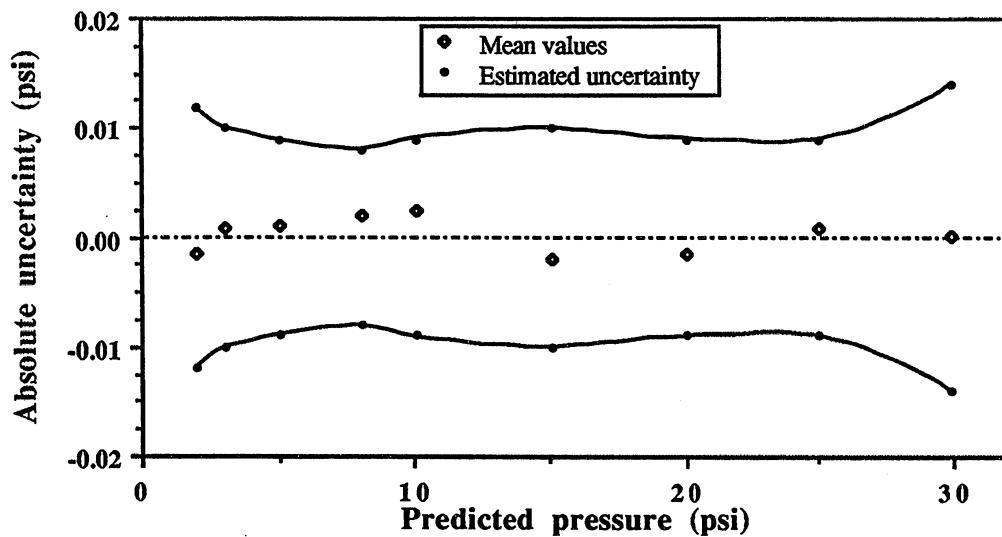
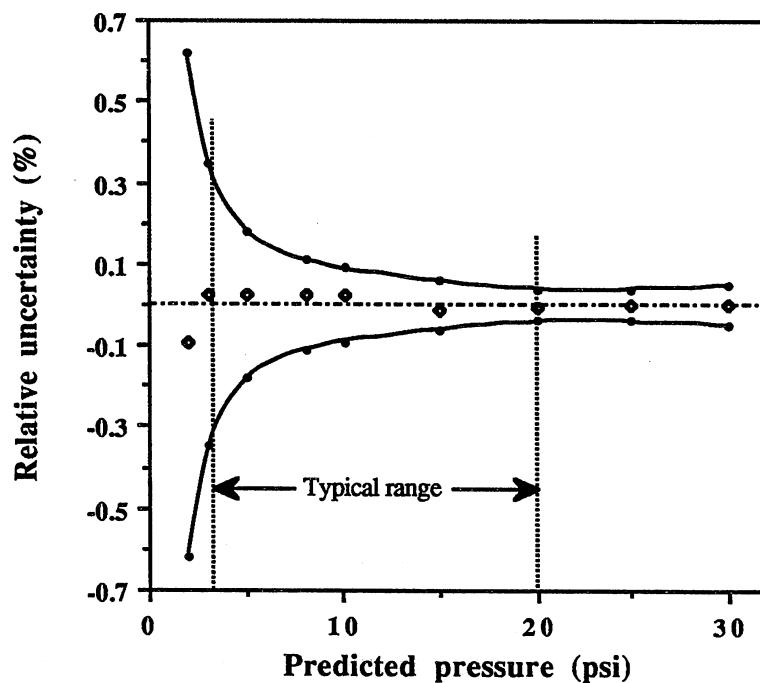


Figure 18. Relative uncertainty (95% confidence interval) for Pressure Transducer DP 215-44.



E. Uncertainty associated with calibration procedures

The electronic transducers and high-speed integration techniques associated with computerized analysis of the transducer signals provide excellent data precision, yielding data points with very little scatter. However, the accuracy of the data points depends also upon the accuracy of the calibrations of the measuring instruments, i.e., transducers and amplifiers, electromagnetic flow meter and converter, etc. This leads to a bias uncertainty in the resulting measurements.

1. Flow meter.

The bias uncertainties associated with the flow meter calibration are related to the parameters volume and time used when computing the actual discharge (discharge = volume/time).

- a). Time measurements. The accuracy of the time measurement is dependent on the accuracy of the timing device used and the accuracy of correlation between the discharge during valve opening and discharge during valve closing. The accuracy of the timing device does not pose a major problem, since a standard commercial stop watch has negligible error. However, approximately 1.5 seconds is required for valve opening and closing. A perfectly accurate calibration could occur if the volume discharged through the valve during opening is equal to the deficit of volume discharged during closing. This, in fact, does not happen. It has been assumed that an upper limit on the volume difference between opening and closing would be that which occurs with a fully opened valve over 0.75 seconds. Thus, the bias uncertainty in the timing of the valve is 0.75 seconds. Table 8 shows estimated time delay bias uncertainty for each flow and calibration time.

Table 8. Estimated time delay bias uncertainty for the flow meter.

Discharge (c.f.s.)	Time (m)	Bias Uncertainty (%)
35	13	± 0.094
30	15	± 0.085
25	20	± 0.064
20	20	± 0.064
15	20	± 0.064
10	30	± 0.043
5	50	± 0.028

- b). Uncertainty in measuring volumes. As explained before, the method for estimating volumes during calibration was by direct reading on the "U" tube manometer. Since the minimum scale reading is 0.1 in., the resolution can be considered ± 0.05 in.. Multiplying this value by $\sqrt{2}$ (we have to take two independent readings for each discharge estimation), the final resolution is ± 0.07 in.. This ± 0.07 in. represents $\pm 13.5 \text{ ft}^3$ if the water surface elevation is below the bottom of the diverter tank (volumes less than $21,500 \text{ ft}^3$) and $\pm 10.1 \text{ ft}^3$ if the surface elevation of the water volume is above the bottom of the diverter tank (volumes greater than $21,500 \text{ ft}^3$). Table 9 gives the averaged volumes used for each discharge during calibration and the percent uncertainty based on ± 0.07 in. bias uncertainty in the manometer reading.

Table 9. Estimated volume bias uncertainty for the flow meter.

Discharge (c.f.s.)	Volume (c.f.)	Bias Uncertainty (%)
35	28,500	± 0.036
30	28,000	± 0.036
25	32,000	± 0.032
20	25,000	± 0.041
15	20,000	± 0.068
10	20,300	± 0.067
5	18,000	± 0.077

In addition to these sources of uncertainty, there are others relating to the manner in which the volumetric tanks calibration was performed using the pycnometer tank.

- c). Volumetric tanks calibration. The procedure followed in 1968 was by filling and emptying the 1074.5 ft^3 pycnometer tank into the basin, measuring the total manometer increment in inches, and linearly interpolating for 0.1-in. increments. For instance, if after emptying the first pycnometer tank the total manometer increment is 5.6 in., then 1074.5 ft^3 divided by 56 will give the volume corresponding to 0.1 in. increment (in this case, 19.2 ft^3). For this linear interpolation to be accurate, no substantial change in surface area between the two water levels (before and after emptying the pycnometer tank) must be accomplished. There are three factors that can change the surface area : supporting beams, non-vertical tank walls, and the abrupt area change that occurs near the top of the volumetric tanks due to the volume occupied by the diverter tank. The third factor is the most important in computing the uncertainty associated with the linear interpolation. It will, however occur only

when the water surface is just below the bottom of the diverter tank (from 21,000 ft³ to 22,500 ft³). None of the volumes during calibration had a final volume in this zone (see Table 9) or in similar regions where the beams could affect the linear interpolation. Assuming that the walls are vertical between the points, then no bias uncertainty due to the linearly interpolated volumes during the previous calibration should be assumed. Similarly, compressed air pressure during flow meter calibration operation were kept at the same level as in 1968. Other possible differences, like small changes in tank geometry, copper transmission tube elongation due to changes in temperature, or pressure lost in the transmission tubes, are corrected by the checking of volumetric tank recalibration that was performed in December 1988. The 7 ft³. constant positive bias error found when recalibrating has already been taken into account in the flow meter calibration.

- d). Pycnometer calibration. Negligible uncertainty assumed. The pycnometer tank was calibrated using two masters weighting tanks of 100 gal. each by the State of Minnesota Department of Weights and Measures. The last increment of less than 100 gal. was measured in 5 gal., 1 gal., and pint containers. The performed calibration is valid for a water temperature between 3 °C and 5 °C, the temperature of the flow calibrations.

Finally, the bias uncertainty in flow is given as

$$B_Q^2 = B_V^2 \left(\frac{dQ}{dV} \right)^2 + B_T^2 \left(\frac{dQ}{dT} \right)^2 \quad (23)$$

for $Q = V/T$, and dividing both sides by Q^2 we get :

$$\frac{B_Q}{Q} = \sqrt{\left(\frac{B_V}{V} \right)^2 + \left(\frac{B_T}{T} \right)^2} \quad (24)$$

where

$\frac{B_Q}{Q}$: Relative overall bias uncertainty for the discharge.

$\frac{B_V}{V}$: Relative bias uncertainty for the volume measurement.

$\frac{B_T}{T}$: Relative bias uncertainty for the time measurement.

Table 10 shows the final combined bias uncertainty for the flow meter after applying Eq. (24) to compute the overall bias uncertainty.

Table 10. Overall bias uncertainty for the flow meter..

Discharge (c.f.s.)	Overall Bias (%)
35	± 0.101
30	± 0.092
25	± 0.072
20	± 0.078
15	± 0.097
10	± 0.080
5	± 0.082

2. Load cell.

The most significant sources of uncertainty associated with the load cell calibration are :

- a). Uncertainty associated with dead weights. The Weights and Measures Division of Public Services provides the following precision :

For 1 lbm the estimated error is ± 0.3 mg ($\pm 7 \times 10^{-5}\%$)
 For 50 lbm the estimated error is ± 0.15 g ($\pm 7 \times 10^{-4}\%$)

- b). Thermal elongation that will affect the uncertainty in the length of the dynamometer arm. Typical standard uncertainty found for similar dynamometer size is ± 0.006 in. due to a possible 50 °F variation. This represents only $\pm 0.03\%$ relative uncertainty.

Total bias uncertainty = $\pm 0.03\%$.

3. Pressure transducers.

The only significant uncertainty associated with the pressure transducers is due to the dead weight gauge tester itself and was estimated by the manufacturer to be $\pm 0.025\%$.

Total bias uncertainty = $\pm 0.025\%$.

4. RPM counter.

There are two possible sources of uncertainty in the rpm counter calibration :

- a). Uncertainty due to the frequency counter. Assumed to be negligible. The frequency counter in the pulse counting mode can really be considered an absolutely precise device.
- b). Time delay uncertainty. It is associated with human imprecision when starting and stopping frequency counter and stop watch at the same time. After several trial repetitions recording the results, the estimated time delay due to human error for one operation was ± 0.06 seconds maximum. Since for each reading we needed to start and stop frequency counter and stop watch, the maximum total uncertainty for the complete process was ± 0.12 seconds. During the five-minute calibration time this represent a maximum $\pm 0.04\%$ relative uncertainty.

Total bias uncertainty = $\pm 0.04\%$.

F. ITTF overall measurement uncertainty

The partial and final precision for each one of the parameter values and the overall efficiency precision of the test are summarized in Table 11. The statistical procedure followed to compute the table values is described in Appendix D.

Table 11. Precision and overall relative uncertainties (95% confidence interval)

Parameter	Full scale	Parameter Value	Precision uncertainty	Overall relative uncertainty	Typical operating point
Net Head	50 PSI	10 PSI	$\pm 0.334 \%$	$\sqrt{.334^2 + .025^2} = \pm 0.335 \%$	
		15 PSI	$\pm 0.190 \%$	$\sqrt{.190^2 + .025^2} = \pm 0.192 \%$	
		20 PSI	$\pm 0.153 \%$	$\sqrt{.153^2 + .025^2} = \pm 0.155 \%$	20 PSI ($\pm 0.155 \%$)
		25 PSI	$\pm 0.129 \%$	$\sqrt{.129^2 + .025^2} = \pm 0.131 \%$	
		30 PSI	$\pm 0.102 \%$	$\sqrt{.102^2 + .025^2} = \pm 0.105 \%$	
Flow	38 CFS	7 CFS	$\pm 0.423 \%$	$\sqrt{.423^2 + .082^2} = \pm 0.431 \%$	
		10 CFS	$\pm 0.287 \%$	$\sqrt{.287^2 + .080^2} = \pm 0.298 \%$	
		12 CFS	$\pm 0.229 \%$	$\sqrt{.229^2 + .088^2} = \pm 0.245 \%$	
		15 CFS	$\pm 0.187 \%$	$\sqrt{.187^2 + .097^2} = \pm 0.216 \%$	15 CFS ($\pm 0.216 \%$)
		17 CFS	$\pm 0.179 \%$	$\sqrt{.179^2 + .086^2} = \pm 0.199 \%$	
		20 CFS	$\pm 0.156 \%$	$\sqrt{.156^2 + .078^2} = \pm 0.175 \%$	
Torque	400 Lbs-Ft	10 Lbs-Ft	$\pm 0.281 \%$	$\sqrt{.281^2 + .03^2} = \pm 0.283 \%$	
		20 Lbs-Ft	$\pm 0.125 \%$	$\sqrt{.125^2 + .03^2} = \pm 0.129 \%$	
		30 Lbs-Ft	$\pm 0.086 \%$	$\sqrt{.086^2 + .03^2} = \pm 0.091 \%$	30 Lbs-Ft ($\pm 0.091 \%$)
		40 Lbs-Ft	$\pm 0.064 \%$	$\sqrt{.064^2 + .03^2} = \pm 0.071 \%$	
		50 Lbs-Ft	$\pm 0.115 \%$	$\sqrt{.115^2 + .03^2} = \pm 0.119 \%$	
Rotational Speed	2000 RPM	400 RPM	$\pm 0.184 \%$	$\sqrt{.184^2 + .04^2} = \pm 0.188 \%$	
		600 RPM	$\pm 0.109 \%$	$\sqrt{.109^2 + .04^2} = \pm 0.116 \%$	
		800 RPM	$\pm 0.090 \%$	$\sqrt{.090^2 + .04^2} = \pm 0.098 \%$	
		1000 RPM	$\pm 0.069 \%$	$\sqrt{.069^2 + .04^2} = \pm 0.08 \%$	1000 RPM ($\pm 0.08 \%$)
		1200 RPM	$\pm 0.056 \%$	$\sqrt{.056^2 + .04^2} = \pm 0.069 \%$	
Tail Tank Head	30 PSI	3 PSI	$\pm 0.347 \%$	$\sqrt{.347^2 + .025^2} = \pm 0.348 \%$	
		5 PSI	$\pm 0.178 \%$	$\sqrt{.178^2 + .025^2} = \pm 0.180 \%$	
		8 PSI	$\pm 0.107 \%$	$\sqrt{.107^2 + .025^2} = \pm 0.110 \%$	—
		10 PSI	$\pm 0.089 \%$	$\sqrt{.089^2 + .025^2} = \pm 0.092 \%$	
		15 PSI	$\pm 0.064 \%$	$\sqrt{.064^2 + .025^2} = \pm 0.069 \%$	
Overall efficiency uncertainty for a typical operation point = $\pm 0.292 \%$					

VII. SUMMARY AND CONCLUSIONS

The U.S Department of Energy partially sponsored upgrade of the Independent Turbine Test Facility at the St. Anthony Falls Hydraulic Laboratory significantly improved the operating capabilities, automated data acquisition, and markedly enhanced data analysis of the facility. The upgrade enabled four-season all-weather test scheduling and provided increased model and equipment security. A complete range of cavitation testing can be accomplished with the upgraded vacuum and pressure system.

Shakedown testing using a Francis model indicate capacity and size capabilities exceed International Electrotechnical Commission (IEC) requirements for the model testing of Francis and Propeller Turbines.

The automated data acquisition and analysis system provides for efficient assimilation of model test data.

Upon thorough evaluation, testing accuracy meets or exceeds IEC recommendations and is comparable with similar testing facilities in existence. Based on the shakedown testing and instrument calibration, the measurement uncertainty of the ITTF is computed to be $\pm 0.29\%$ (95% confidence interval) under typical operating conditions.

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APPENDIXES

APPENDIX A

DESCRIPTION OF PROGRAMS AND APPLICATION EXAMPLES

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A-1. Program versions

Since two different program versions are introduced in the package (the Basic version and the compiled version), it is necessary to differentiate them in some way. The extension code added to the programs' names is as follows :

- PROGRAM NAME.C : Code used to name the Basic source of the executed programs. These programs cannot be run. They are only the Basic written source of executed versions using machine language.
- PROGRAM NAME.EXE : Name for all executed programs, that means Basic source programs that have been compiled and linked. The execution of these programs is very fast, and they can only be run from the Disk Operative System (DOS).

All these programs are copied inside a subdirectory called PROGRAMS, which will be explained in section A-3.

A-2. Data files organization

The generated data files are named by the user. The user also access to data and results files to print or to plot them. Therefore, special attention must be paid to the way we name our files. The following must be taken into consideration :

1. A file name of 8 characters maximum.
2. No extension code is manually introduced. The program automatically places the extension depending on the type of file.
3. The last part of the name should be a number (from 1 to 99) to identify the run. For instance, a file named T18 means that contains data from the 18th run of the T test.

If condition number 3 is not taken into account, there will be no way of getting an automatic print out of the results (i.e. from T1 to T20).

The four differents kinds of files depending on the extension code are :

- FILE NAME.DTP : Extension DTP means that the file contains raw input data for one run.
- FILE NAME.INF : File containing general information about the turbine test run (i.e. field voltage, atmospheric pressure, operator's name etc).

- **FILE NAME.T1** : File containing mean values of speed, flow, head, torque, power input, power output and efficiency for one run.
- **FILE NAME.T2** : File containing the dimensionless coefficients values (i.e. Energy, Torque, Efficiency etc) for one run.

All these programs are directly created inside a subdirectory called DATA, which will be explained in section A-3.

A-3. Directories structure

Two subdirectories have been created to store the programs and the files generated when running the package :

- **C:\TTEST\PROGRAMS** : The subdirectory named PROGRAMS is inside the subdirectory TTEST (Turbine Test), which belongs to the main directory C:\ of the computer hard disk.
As was stated before, PROGRAMS contains the Basic source of the executed programs (extension .C), and the executed programs (extension .EXE).
- **C:\TTEST\DATA** : DATA subdirectory has the same structure as PROGRAMS. It contains the four kinds of data files that have been mentioned before.
DATA subdirectory only contains data files.

In addition to programs mentioned earlier, there are three very important pieces of software inside the directories' structure that have to be implemented to assure proper operation of the package :

- **BRUN30.LIB** : This is a quick Basic compiler program that allow to run the executed programs' executed version.
BRUN30.LIB must be copied in the PROGRAMS subdirectory.
- **C1.INF** : This is a numerical file containing the conversion coefficients used when computing the turbine performance parameters value, such as flow, pressure, speed, etc. The user has to be careful not to name any file as C1.
C1.INF must be copied in the DATA subdirectory.

A-4. Programs description

Before describing how to run the package, a description of the purpose, the input, and the output of each program will be described.

All the programs are interrelated, and once one program is run the access to any other is available simply by following the branched system shown in Fig.A1. Additional information about general programs characteristics can be found in Appendix B.

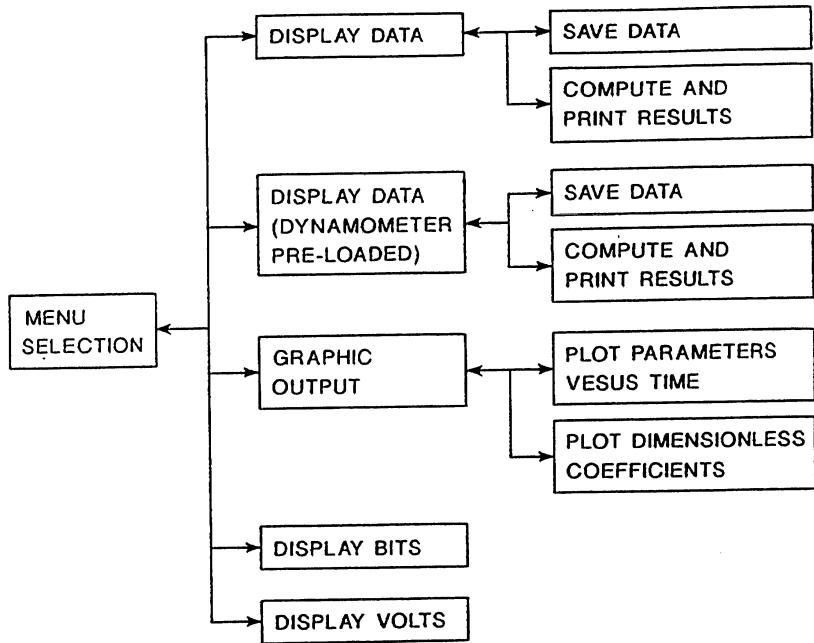


Figure A1. General organization of the program package.

A-4.1 NMENU

NMENU is the main program, linking all of the secondary programs. The others are referred to it as secondary branches.

Screen display : The six screen display options are shown in Fig. A2.

Input : The only inputs that NMENU has are :

- a. Option number (from 1 to 6)
- b. The yes/no inkey to confirm the option.

Output : The user may chose an option number and run a program (see Fig. A1). For instance, first option runs NDISPLAY (displays data on screen), third option runs NDRAW (offers the graphic output options), etc.

A-4.2 NDISPLAY

The purpose of the program is to display on the computer screen the input parameters value, and to offer a set of options to the user. If the dynamometer is pre-loaded, an additional input parameter (channel #7) is displayed with the value of this constant load.

The logic structure is shown in Fig. A3. The program starts initializing the analog/digital converter. Once the converter is initialized, one datum is taken from each one of the 8 channels (named from 0 to 7). The datum in bits is converted to the channel unit (rpm, cfs, etc) using calibration functions.

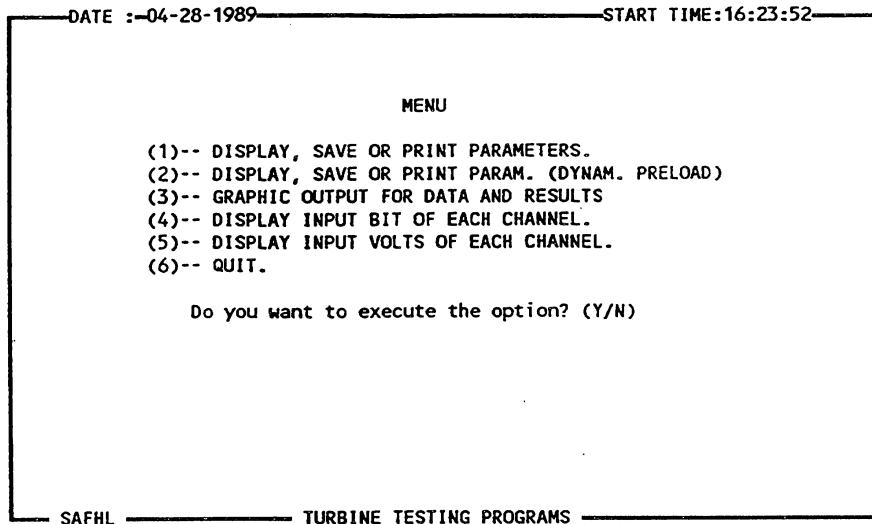


Figure A2. Screen display for NMENU.

The power output of the dynamometer (PO) and the overall efficiency of the turbine (η), are given by Eqs.(12) and (13) in section III-E.1.

After computing the efficiency, channels values are displayed on the screen for approximately one second (delay loop in Fig. A3). Then, if one of the options is chosen, the corresponding program will run. If no option number is pressed, the program returns to take another data set and starts the process again.

Screen display : The screen displays for NDISPLAY is shown in Fig. A4, and it includes :

- a. Parameters values
- b. Computed power output and efficiency
- c. Options
- d. Reference time, present time and date

Input : The inputs for NDISPLAY are :

- a. External input data coming through the channels from the turbine test instrumentation
- b. Option number (from 1 to 4)
- c. Pre-load (weight) on the dynamometer.
- d. Yes/no inkey to confirm the chosen option

Output : The user may output all items that appear on the screen display, plus running a program depending on the option number pressed (see Fig. A1). For instance, first option runs NSAVEDAT (save data at 10 samples/channel-second), second option runs NPRINT1 (print data and results), etc.

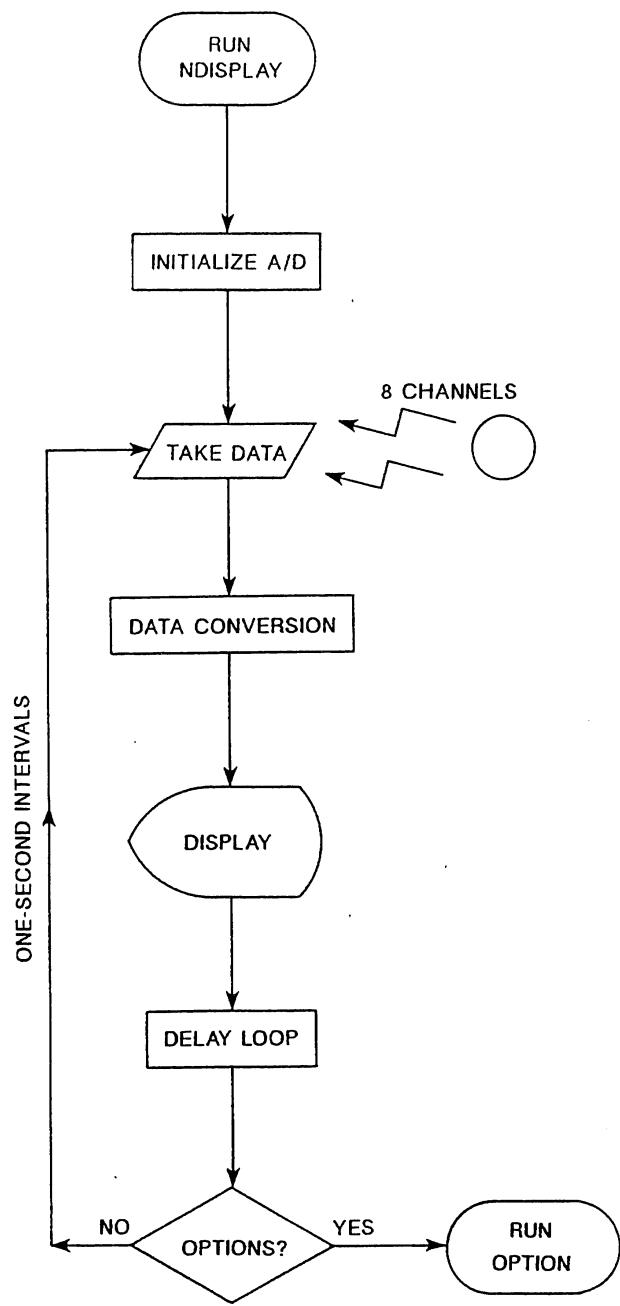


Figure A3. Logic structure for NDISPLAY programs

DATE :--04-28-1989 START TIME:16:34:54

CHANNEL	VALUES
(0) SPEED,	RPM 0.0
(1) FLOW,	CFS 0.00
(2) WATER TEMP.,	F 31.4
(3) DIFF. PRES.,	PSI 0.00
(4) TAIL T. PRES.,	PSI 0.01
(5) SER. MOTOR TEMP.,	F 30
(6) TORQUE,	FT-LBS 0.00
(7) WEIGHT,	LBS 0.00
OUTPUT OF DYNAM.,	H.P. 0.00
EFFICIENCY OF TURBINE,	% 0.0

OPTIONS Date / Time : 04-28-1989 / 16:35:09

(1)-- SAVE DATA (Rate = 10 Samples/Channel-Sec.)
 (2)-- PRINT RESULTS FOR 1 RUN (Mean values and Dimensionless Coeff.)
 (3)-- PRINT MEAN RESULTS AND COEFFICIENTS FOR SEVERAL RUNS.
 (4)-- RETURN TO MENU.

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Figure A4. Screen display for the program NDISPLAY.

A-4.3 NDRAW

NDRAW presents the two plotting options using menu format. It has the same function as NMENU but for the plotting programs.

Screen display : The 3 screen display options are shown in Fig. A5.

Input : The inputs are :

- a. Option number (from 1 to 3).
- b. The yes/no inkey to confirm or cancel the option.

Output : The user may choose an option number and run a program (see Fig. A1).

First option runs NPLOT1 (plots parameters versus time), second option runs NPLOT2 (plots dimensionless coefficients).

DATE :--04-28-1989 START TIME:16:41:16

CHOOSE THE PLOTTING OPTION YOU WANT

(1)-- PLOT INPUT PARAMETER VERSUS TIME
 (2)-- PLOT DIMENSIONLESS COEFFICIENTS
 (3)-- RETURN TO MENU

SAFHL TURBINE TESTING PROGRAMS

Figure A5. Screen display for the program NDRAW.

A-4.4 NPLOT1

This program permits to display on the medium resolution color monitor any input parameter (turbine speed, water temperature, pressure difference, pressure head, water discharge, etc) versus time. Also allows to obtain a draft printout (using the dot matrix printer) of the graphic.

Incoming data time distribution must be periodically checked during the test. A tailored graphic software is a powerfull tool that also permits identify unstabilities in the data aquisition process, and save time and money avoiding unwanted runs.

Screen display : The screen display for NPLOT1 is shown in Fig. A6. In the lower right corner there is a quit option to return to NMENU at any time by pressing the F1 key. By pressing F2 key, the DATA subdirectory is displayed.

Input : The inputs are :

- a. Name of an already created file (8 characters max. with no extension).
- b. Channel (parameter) number to plot. From 0 to 6 (i.e. 0= rpm, 3= differential pressure, 5= motor temperature, 6= torque, etc.)
- c. F1 and F2 keys.

Output : The outputs are :

- a. Parameter versus time plot on color monitor.
- b. Parameter versus time printout.
- c. Run NMENU when pressing F1 key.
- d. Display DATA subdirectory when pressing F2 key.

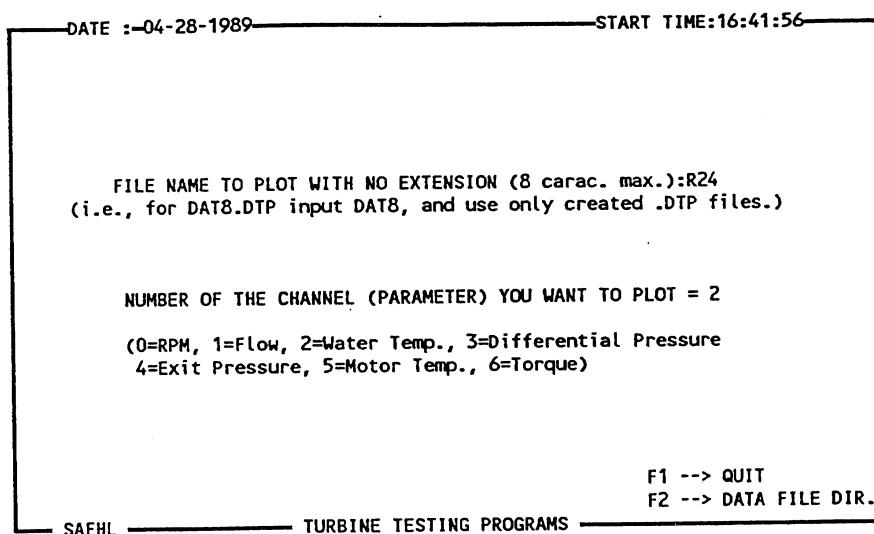


Figure A6. Screen display for the program NPLOT1.

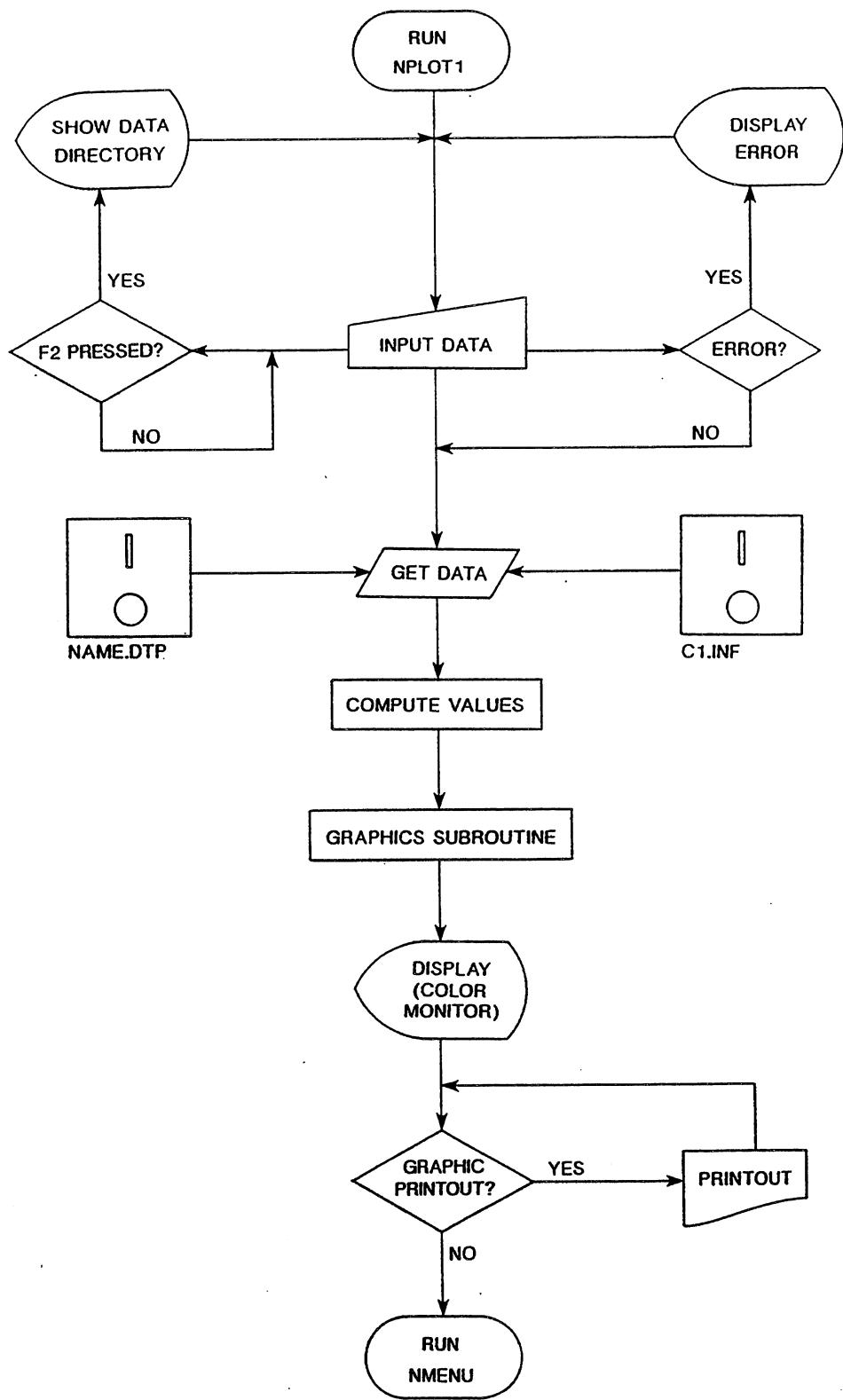


Figure A7. Logic structure for the program NPLOT1.

The logic structure for NPLOT1 is shown in Fig. A7. The input is complemented with an error subroutine to prevent input file errors and a F2 option that enables to display the data file directory.

Once the file name is recognized, the program gets data from the input parameters' file (NAME.DTP) and from the conversion coefficients' file (C1.INF), and computes the final mean parameters value.

The graphics subroutine selects the x-axis and y-axis range based upon the total running time and the maximum and minimum parameter's value. Values are plotted using screen coordinates (x-axis = 250 points, y-axis = 140 points). The total computer running time for this graphics subroutine is around five seconds.

After displaying and printing out the graphic (if this is the case), the program automatically returns to NMENU.

During the all running process, the user is enabled to quit NPLOT1 just by pressing F2 key as defined at the beginning of the program.

The final graphic is plotted on the medium resolution color monitor screen. By pressing "Shift / Print screen" keys, we obtain the printout in Fig. A8. Higher resolution output requires higher quality printer and special graphic interface.

*** Input Data Variation versus Time ***

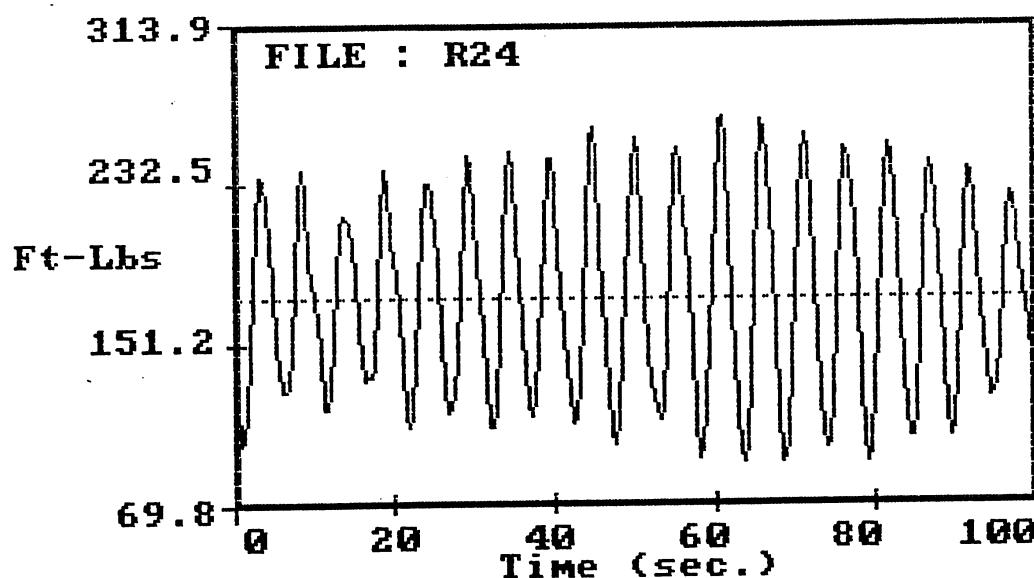


Figure A8. Output graphic example for NPLOT1.

A-4.5 NPLOT2

This program permits to plot on the color monitor the characteristic turbine test dimensionless parameters. A total of six options are offered to the user (see Fig. A9). As for the previous program NPLOT1, it is also possible to obtain a draft graphic printout (using the dot matrix printer).

Screen display : The screen display for NPLOT2 is shown in Fig. A9. In the lower right corner there is a quit option to return to NMENU at any time by pressing the F1 key. There is another input data screen very similar to that used in program NPRINT2 (see section A-4.9).

Input : The inputs are :

- a. Data file name using no extension and no extension number. For instance, if R12 to R25 are the files we want to print out, then we must only input R (see example at the end of the section).
- b. Number of the first run to print out (using the example above, this number is 12).
- c. Number of the last run to print out (in the example the number is 25).
- d. Data from mean values files.
- e. F1 and F2 keys.

Output : The outputs are :

- a. Dimensionless parameter plot on color monitor.
- b. Dimensionless parameter printout.
- c. Run NMENU when pressing F1 key.
- d. Display DATA subdirectory when pressing F2 key.

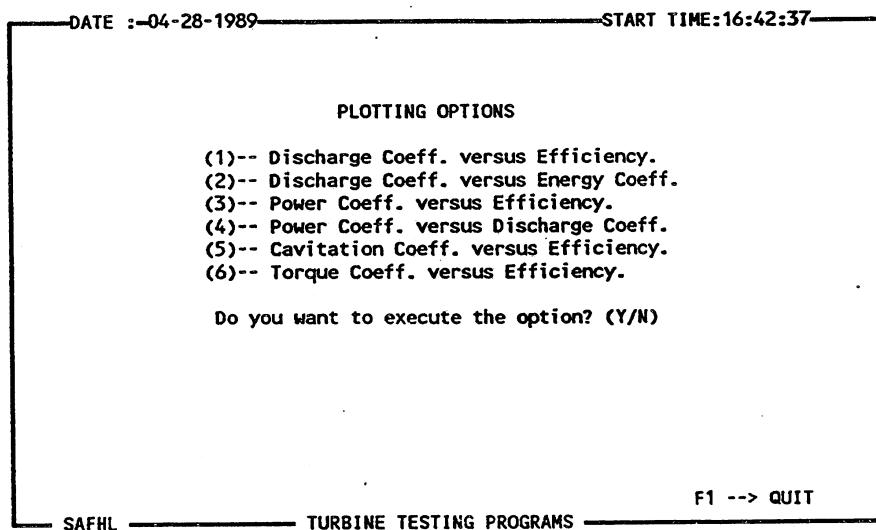


Figure A9. Screen display for the program NPLOT2.

The logic structure for NPLOT2 is similar to that already discussed for NPLOT1 in Fig. A7. The only difference is that once the file name is recognized, the program gets data from the NAME.T2 file (file containing mean values of the dimensionless coefficients).

The graphics subroutine selects the x-axis and y-axis range based upon the maximum and minimum dimensionless coefficients value. Again, values are plotted using screen coordinates (x-axis = 250 points, y-axis = 140 points).

The final graphic is plotted on the medium resolution color monitor screen. By pressing "Shift / Print screen" keys, we obtain the printout in Fig. A10.

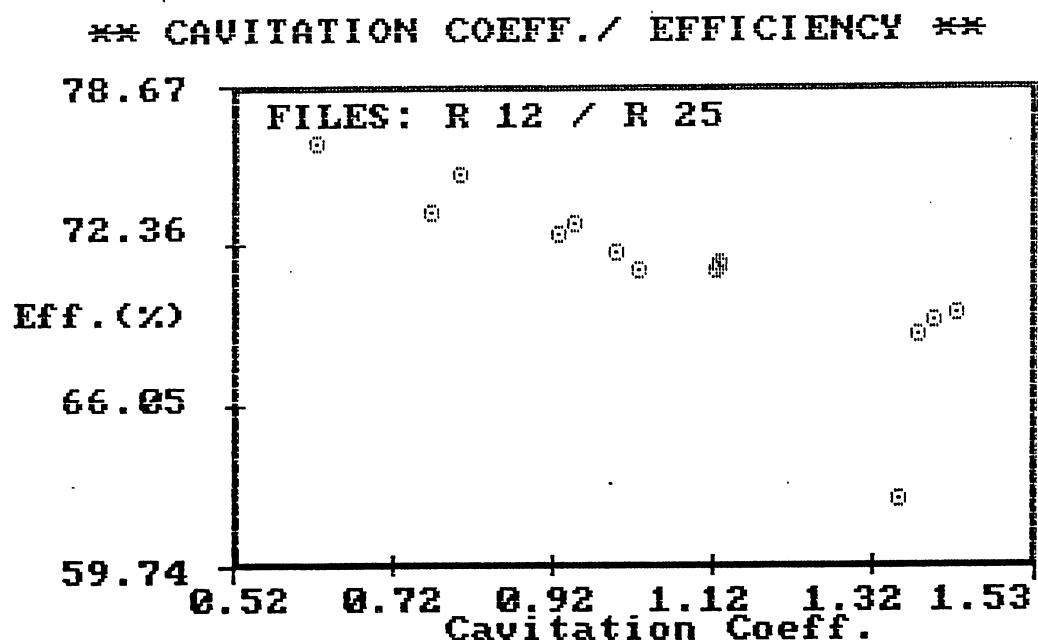


Figure A10. Output graphic example for NPLOT2.

A-4.6 NVOLBIT

This program displays the value of each channel in bits or volts. It is useful to check the input signal coming into the computer. Volts/bits conversion is given by Eq.(A1).

$$B_{in} = V_{in} \cdot 204.8 \quad (A1)$$

where : B_{in} = Input bits.

V_{in} = Input Volts.

Screen display : The screen display for NVOLBIT is just a simple continuous display of the incoming bits or volts per channel.

Input : Inkey input to run NMENU (just by pressing any character).

Output : Run NMENU.

A-4.7 NSAVEDAT

NSAVEDAT saves raw input data at a speed of 10 samples/channel-second. It has the logic structure shown in Fig. A11. All numerical input data are checked using an error subroutine. Only numerical inputs (when needed) within certain values will be allowed (i.e. field voltage has to be a number within 0 and 250 Volts).

Once the analog/digital conversion has been performed (Fig. A11), the program takes data from the channels at a speed of 10 samples/channel-second. The computer has a buffer capacity of 10,000 pieces of data per run, i.e. since we use 8 channels (or parameters), the maximum data amount per channel and run is 1250. In the program we can control the taking data time (from 1 to 120 seconds). That gives us a maximum of 1200 data per channel for a 2-minutes run, inside our data capacity limit.

In order to select the speed at which data are going to be taken, two integer variables are used : N_1 and N_2 . The software package for data adquisition and control uses Eq. (A2) to specify the speed.

$$\text{Sample rate} = \frac{1000000}{N_1 N_2 N_{ch}} \quad (\text{A2})$$

where : N_{ch} = Number of channels.

If $N_1=100$ and $N_2=125$, since the number of channels is 8, the sample rate will be 10 samples/channel-second.

Once the data have been taken, they are saved into C:\TTESTDATA subdirectory. The manual input data are saved as an information file (FILE NAME . INF), and the input raw data are saved as data file (FILE NAME . DTP). When the saving process is done, NDISPLAY is automatically run.

Screen display : The screen display for the saving data programs is shown in Fig. A12. All the input data displayed are saved in the information file.

Input : The manual input data are :

- a. Data file name using no extension code (8 characters maximum).
- b. Field volts. Units = Volts
Maximum value allowed = 250 V
Minimum value allowed = 0 V
- c. Armature volts. Units = Volts
Maximum value allowed = 250 V
Minimum value allowed = 0 V
- d. Armature current. Units = Amperes
Maximum value allowed = 700 A
Minimum value allowed = 0 A
- e. Water temp. Units = Degrees Farenheit
Maximum value allowed = 100 °F
Minimum value allowed = 30 °F

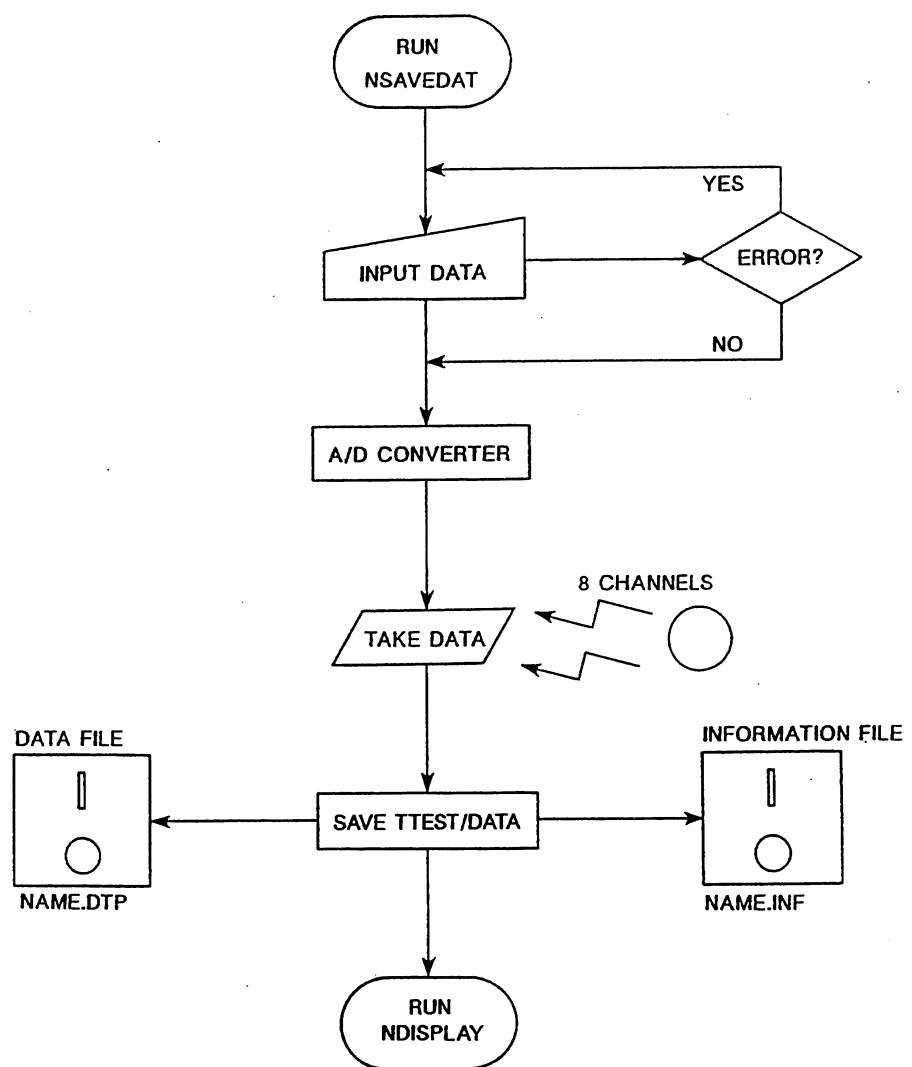


Figure A11. Logic structure for the program NSAVEDAT.

- f. Open wicket gate. Units = percent
Maximum value allowed = 100 %
Minimum value allowed = 1 %
- g. Operator's name (14 characters maximum)
- h. Model type (6 characters maximum)
- i. Atm. pressure. Units = Inches of Mercury
Maximum value allowed = 32 Hg-in.
Minimun value allowed = 28 Hg-in.
- j. Runner diameter. Units = Feet
Maximum value allowed = 1.5 ft.
Minimun value allowed = .5 ft.
- k. Running time. Units = Seconds
Maximum value allowed = 120 sec.
Minimun value allowed = 1 sec.

Output : The outputs are :

- a. Creates general information file (FILE NAME.INF).
- b. Creates data file.(FILE NAME.DTP).
- c. Run NDISPLAY.
- d. General written information about the created files like starting saving date and time, finshing saving date and time, data file name and information file name.
- e. Display DATA subdirectory when pressing F2 key.

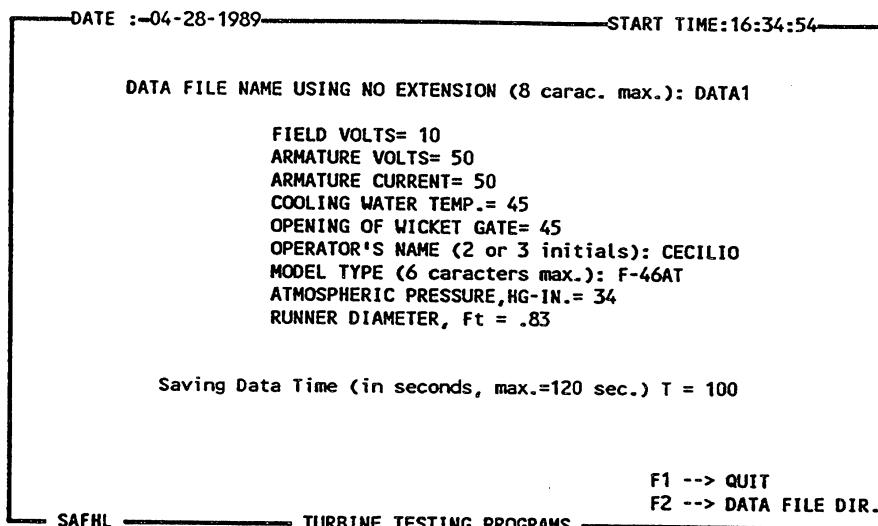


Figure A12. Screen display for the program NSAVEDAT.

A-4.8 NPRINT1

The purpose of the program is to print out the following general information and results :

1. Maximum, minimum and average for each input parameter.
2. General information, such as field voltage, armature current, closed-circuit cooling water temperature, etc.

3. Averaged values for the pressure head, velocity head, power input, power output and overall efficiency.
4. Dimensionless coefficients table (i.e. Energy, Power, Efficiency, etc).

Screen display : The screen display for NPRINT1 is shown in Fig. A13.

Input : The programs' inputs are :

- a. Data file name using no extension (8 characters maximum).
- b. Data from data file (FILE NAME.DTP).
- c. Data from conversion coefficient file (C1.INF).

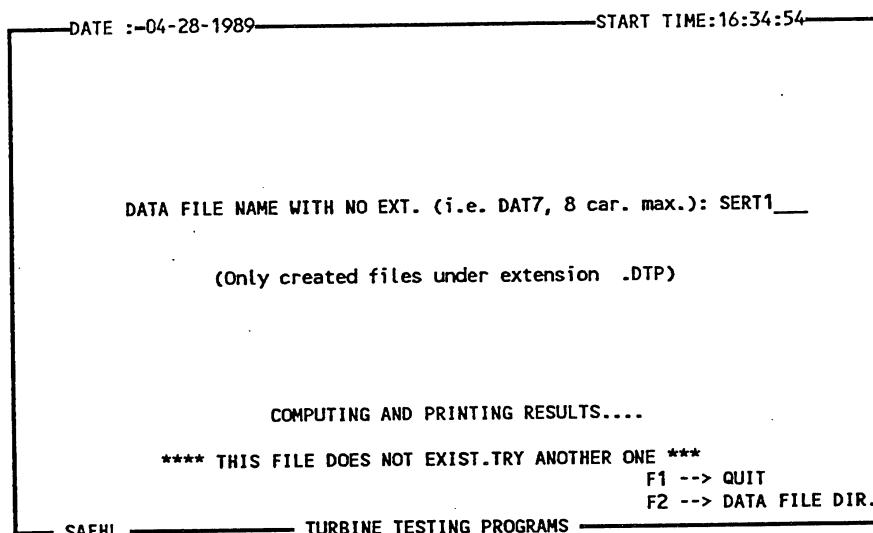


Figure A13. Screen display for the program NPRINT1.

Output : Programs' outputs are :

- a. Creation of the mean value files (FILE NAME.T1 and FILE NAME.T2).
- b. Print output as it is shown in Fig. A14. It includes :
 - File name, operator, testing date and testing time.
 - General testing information, including turbine model type, runner diameter, gate opening, etc.
 - Average, maximum and minimum values for speed, flow, water temperature, pressure differential, draft tube pressure, motor temperature and load (torque).
 - Summary table with averaged values for rotat.speed, torque, flow, velocity and pressure head, power input, power output and efficiency.
 - Summary table containing dimensionless coefficients averaged values (Discharge, Energy, etc).
- c. Run NDISPLAY.
- d. Display DATA subdirectory when pressing F2 key.

=====
DATA FILE NAME = R12
=====

Operator : TING Testing Date :03-02-1988 Testing Time :15:43:45

Test General Information

TURBINE MODEL TYPE : F RUNNER DIAMETER, Ft : .83
 FIELD VOLTS : 65 ARM. VOLTS : 107 ARM. CURRENT : 205
 WICK. GATE OPENING,% : 36 COOL. W. TEMP.,F : 32 ATM.PRES.,IN.HG : 30

MEAN VALUES

SPEED	FLOW	W.TEMP.	D.PRESS.	T.PRESS.	M TEMP.	LCELL	LOAD
RPM	CFS	F	PSI	PSI	F	FT-LBS	LBS
821.55	13.20	89.59	13.92	0.53	110.42	250.52	0.00
					AVERAGE	MAXIMUM	MINIMUM
SPEED		821.55	823.59	816.09			
FLOW		13.20	13.37	12.99			
W.TEMP.		89.59	89.66	89.49			
D.PRESS.		13.92	14.43	13.26			
T.PRESS.		0.53	0.61	0.42			
M TEMP.		110.42	127.63	109.42			
LCELL		250.52	346.85	159.89			
LOAD		0.00	0.00	0.00			

FINAL RESULTS

SPEED	FLOW	VEL.HEAD	PRE.HEAD	NET HEAD	TORQUE	PI	PO	E
RPM	CFS	FT	FT	FT	FT-LB	H.P.	H.P.	%
821.55	13.20	1.24	32.47	33.72	239.30	49.93	37.43	74.97

DIMENSIONLESS COEFFICIENTS

Discharge	Energy	Power	Torque	Efficiency(%)	Cavitation
0.27	0.21	2.57	0.04	74.97	0.80

Figure A14. Output example for NPRINT1 program.

The simplified logic structure for these programs is shown in Fig. A15. The program starts checking the input data using two subroutines, one for the numerical values and the other one for file's name. An error message will appear on the screen in case the input conditions are not correctly specified.

Once the input has been accepted, the program opens the data file (FILE NAME . DTP) and the conversion coefficients' file (CI . INF) and combines them to find the data actual value in the given units (depending on the parameter, units will be different, i.e. rpm, cfs, etc). Then maximum, minimum and average values are found as well as variables such as power input, power output, and efficiency. These results are printed out, and the program returns to NDISPLAY.

Before printing results and after computing mean values, two mean value parameters files are created (FILE NAME.T1 and FILE NAME.T2), which will be used when running NPRINT2 (Fig. A15).

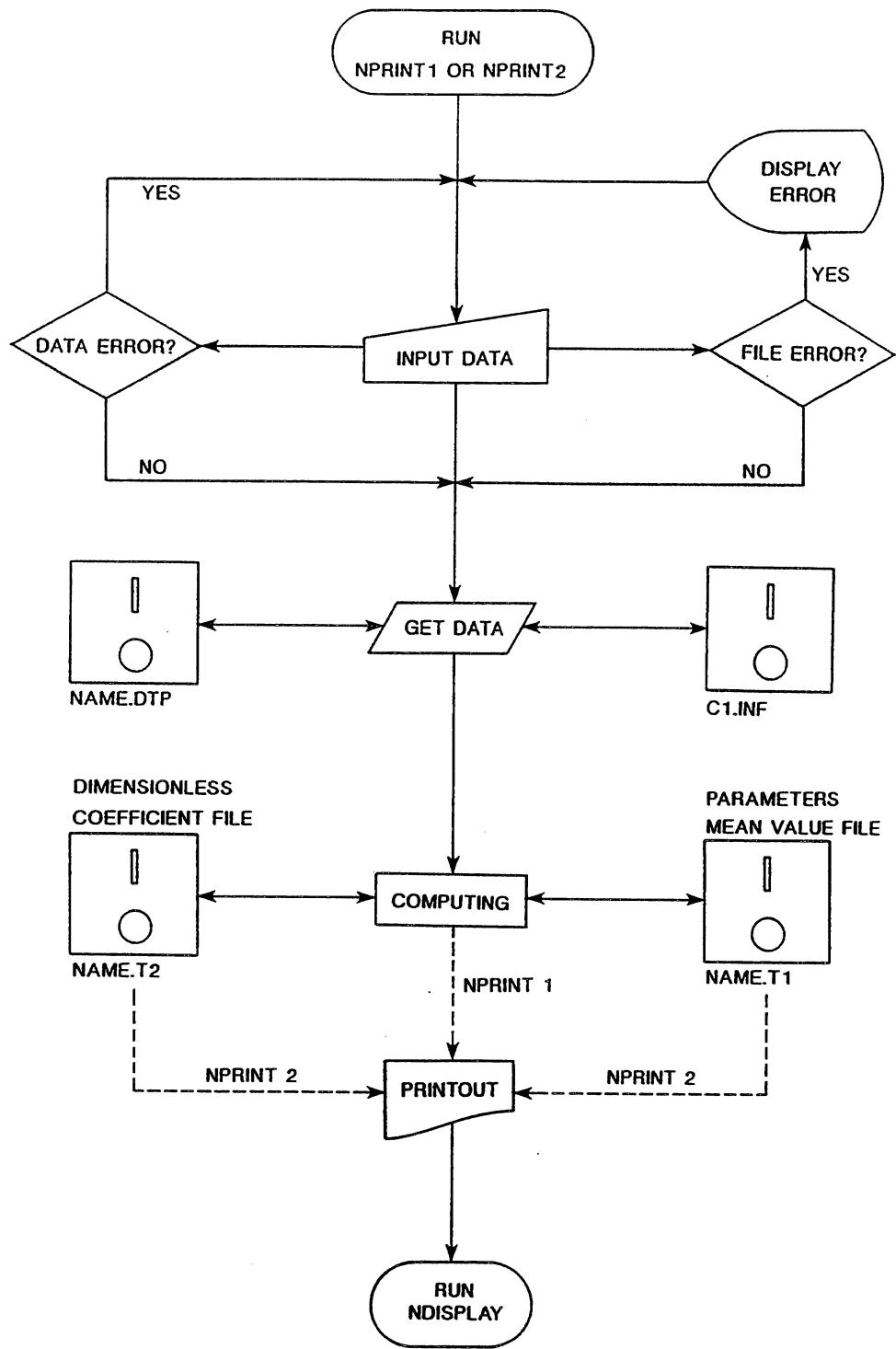


Figure A15. Logic structure for programs NPRINT1 and NPRINT2.

A-4.9 NPRINT2

The program prints out mean values for speed, flow, head, torque, power input, power output, efficiency and all the dimensionless coefficients for several runs to compare them.

The logic structure for these programs is the same as that used for NPRINT1, and it is given in Fig. A15. The final printout is taken from the mean value files (FILE NAME.T1 and FILE NAME.T2) created when running NPRINT1.

Screen display : It is given in Fig. A16.

Input : The inputs are :

- a. Data file name using no extension and no extension number. For instance, if R12 to R25 are the files we want to printout, then we must only input R (see example at the end of the section).
- b. Number of the first run to print out (using the example above, this number is 12).
- c. Number of the last run to print out (in the example, the number is 25).
- d. Data from mean values files.

```
DATE :-04-28-1989 START TIME:16:34:54
_____
DATA FILE NAME USING NO EXTENSION AND NO EXTENSION NUMBER:SERT_____
(i.e. DAT___. for DAT12.T1, use existing files with .T1 or .T2 extension.)

NUMBER OF FIRST RUN (FILE) YOU WANT TO PRINT = 1
(i.e., start printing DAT1.T1 results; input 1)

NUMBER OF LAST RUN (FILE) YOU WANT TO PRINT = 8
(i.e., stop printing results at DAT8.T1; input 8)

***** THESE FILES DO NOT EXIST.TRY ANOTHERS ***
F1 --> QUIT
F2 --> DATA FILE DIR.

SAFHL TURBINE TESTING PROGRAMS
```

Figure A16. Screen display for the program NPRINT2.

Output : The programs output are :

- a. Prints out file name.
- b. Prints out data from mean value files (FILE NAME.T1) as average speed, average flow, etc.
- c. Prints out data from mean value files (FILE NAME.T2) as discharge, energy, etc.
- d. Runs NDISPLAY.

An illustrative printout example is given in Fig. A17, which is the mean value output files from R12.T1 to R25.T1, and from R12.T2 to R25.T2. For this example, if we want to print out mean values from run 12 to run 25, we must write the following :

Data file name with no extension and no number = R

Number of the first run to print = 12
Number of the last run to print = 25

FILES FROM R 12 TO R 25
=====

MEAN RESULTS

SPEED	FLOW	VEL. HEAD	PREL. HEAD	NET HEAD	TORQUE	PI	PO	K
RPM	CFS	FT	FT	FT	FT-LB	H.P.	H.P.	%

---(RUN # 12)---								
821.549	13.198	1.243	32.474	33.716	239.303	49.930	37.432	74.969
---(RUN # 13)---								
1022.347	15.230	1.655	42.217	43.872	293.830	75.045	57.195	76.215
---(RUN # 14)---								
764.544	13.643	1.328	36.889	38.217	296.978	58.877	43.231	73.426
---(RUN # 15)---								
761.777	10.401	0.772	26.525	27.297	157.565	32.071	22.854	71.260
---(RUN # 16)---								
769.438	13.371	1.275	28.753	30.028	224.985	45.335	32.961	72.705
---(RUN # 17)---								
826.388	13.426	1.286	27.905	29.191	205.409	44.240	32.320	73.056
---(RUN # 18)---								
816.926	13.985	1.395	26.105	27.500	200.613	43.398	31.204	71.902
---(RUN # 19)---								
844.321	10.689	0.815	20.519	21.334	99.498	25.718	15.895	62.194
---(RUN # 20)---								
608.759	10.817	0.835	19.458	20.293	148.574	24.751	17.221	69.578
---(RUN # 21)---								
609.913	10.885	0.845	19.540	20.385	149.283	25.006	17.336	69.327
---(RUN # 22)---								
609.808	10.891	0.846	19.725	20.571	149.316	25.245	17.337	68.675
---(RUN # 23)---								
714.252	12.051	1.036	23.742	24.778	176.598	33.630	24.016	71.413
---(RUN # 24)---								
715.382	12.047	1.035	23.726	24.761	175.726	33.591	23.935	71.255
---(RUN # 25)---								
715.586	12.044	1.035	23.624	24.658	175.475	33.437	23.908	71.502

DIMENSIONLESS COEFFICIENTS

Discharge	Energy	Power	Torque	Efficiency(%)	Cavitation

---(RUN # 12)---					
0.27	0.21	2.57	0.04	74.97	0.80
---(RUN # 13)---					
0.25	0.18	2.03	0.03	76.21	0.62
---(RUN # 14)---					
0.30	0.28	3.66	0.06	73.43	0.76
---(RUN # 15)---					
0.23	0.20	1.95	0.03	71.26	1.03
---(RUN # 16)---					
0.29	0.22	2.73	0.05	72.71	0.92
---(RUN # 17)---					
0.27	0.18	2.17	0.04	73.06	0.95
---(RUN # 18)---					
0.29	0.18	2.16	0.04	71.90	1.00
---(RUN # 19)---					
0.21	0.13	1.01	0.02	62.19	1.35
---(RUN # 20)---					
0.30	0.23	2.89	0.05	69.58	1.43
---(RUN # 21)---					
0.30	0.23	2.89	0.05	69.33	1.40
---(RUN # 22)---					
0.30	0.24	2.90	0.05	68.68	1.38
---(RUN # 23)---					
0.28	0.21	2.50	0.04	71.41	1.13
---(RUN # 24)---					
0.28	0.21	2.48	0.04	71.26	1.12
---(RUN # 25)---					
0.28	0.21	2.47	0.04	71.50	1.13

Figure A17. Output example for program NPRINT2.

A-5. How to start running the programs

Once the computer has been turned on, go to the PROGRAMS subdirectory. The way to do it from the main directory in DOS is as follows :

C>cd\TTEST\PROGRAMS (Press return key)

There are two kinds of programs that can be used : the non-executed programs (or Basic source version) and the compiled programs.

A-5.1 Using the non-executed version.

The Basic source version is not as quick as the executed version but it is very useful when checking or modifying programs because each modification can be run immediately.

In using the Basic source programs, the procedure is as follows :

1. Call BASICA from DOS

C>BASIC (Press return key)

2. Load desired program (including ".BAS" extension)

i.e. : **LOAD "NMENU.BAS"** (Press return key)

3. Run the program just by pressing F2 key, or by writing :

RUN (Press return key)

A-5.2 Using the executed version.

The executed version is substantially faster. In using the executed programs the user must write the file's name (without including extension ".EXE") while in DOS.

i.e. : **C>NPRINT1** (Press return key)

In running both programs versions, the color monitor screen is used as a parameters' display and the monochrome monitor is employed to input data. The purpose of that is to keep track of the running procedure by continuously displaying the previous screen.

A-6. Running turbine testing programs

Using the branched system organization shown in Fig. A1 is the best and quickest way to run the program. The boxes represent program's units. Each specific program is run by pressing the corresponding option number.

Starting with NMENU (section A-4.1), we have six possible options :

Option (1) : Runs NDISPLAY (section A-4.2), and offers four other secondary options to the user which are :

1. Save data with a speed of 10 samples/channel-second (NSAVEDAT program, section A-4.7).
 2. Compute and print mean results for one run (NPRINT1 program, section A-4.8).
 3. Print mean results for several runs (NPRINT2 program, section A-4.9).
 4. Return to NMENU program.

To run the option, just press the desired number. See Figs. A1, A2 and A4 to clarify the process.

Option (2) : Runs NDISPLAY (section A-4.2) in the pre-loaded dynamometer case and offers four secondary options in the same manner as Option (1). If option (2) is selected, the user will be asked to input the value of the dynamometer load and then run NDISPLAY.

Option (3) : Runs NDRAW and displays 3 options (Fig. A5).

1. Plot parameters versus time (program NPLOT1; section A-4.4).
 2. Plot dimensionless coefficients (program NPLOT2; sect. A-4.5).
 3. Return to NMENU.

Option (4) : Runs NVOLBIT (section A-4.6) and displays the value in bits of each channel.

Option (5) : Runs NVOLBIT (section A-4.6).and displays the value in volts of each channel.

Option (6) : Returns to DOS.

Some general examples follow about how to run the branched system.

A-6.1 Example 1.

Suppose that the turbine testing stand is running steady and we want to display the parameters' values, get mean values and efficiency each 15 minutes during 2 hours, and finally print out a table containing main parameters and results for the 2 hours running process. Assume no load on the dynamometer. The procedure, assuming that we already are inside PROGRAMS subdirectory, is as follows :

- a). Call NMENU from DOS. We'll use the executed programs. If using the Basic source programs we must follow the instructions given in section A-5 1

C>NMENU (Press return key)

The screen shown in Fig. A2 will appear.

- b). Press number 1 to choose option (1). The option title will then be colored to show the user the chosen option. Then press Y key to admit and execute the option.
The screen display shown in Fig. A4 will appear, and the parameter values will be re-displayed each second.
- c). Press option (1), and press Y key to execute the option. Now, the screen display shown in Fig. A12 will appear.
- d). Type in the user-supplied input data (data file name, field volts, etc) pressing return each time also select taking data time (maximum = 2 minutes). If you want to come back to the previous screen (Fig. A4), press F1 key. If you want to take a look to the DATA subdirectory in order not to assign the same to an already created file, press F2 key.
- e). Once all the information data have been introduced, the label "SAVING THE FILE" will appear. After saving the file, the program will return to the previously displayed screen (Fig. A4). Repeat steps c). and d). each 15 minutes, looking at the continuous display time on the screen.
- f). After finishing saving data, press option (2), and press Y key to execute the option. In doing this, we can compute and print mean results. Screen display shown in Fig. A13 will appear.
- g). Enter the required data file name and press the return key. Again, if you want to come back to the previous screen (Fig. A4), press F1 key.
- h). After entering the data, a label saying "COMPUTING RESULTS" will be displayed, and the results printed out. If there is any problem (such as incorrect file name or disconnected printer), a label will inform the user about the kind of error, and the input must be typed again.
Fig. A4 will be displayed again after the printing process is finished.
- i). Repeat steps f). and g). for the rest of the 7 created files, (You have saved a file each 15 minutes during 2 hours). The final printout format will be the same as the one shown in Fig. A14.
- j). Now, to print out the summary table, press option (3) and Y key to execute the option. The screen display shown in Fig. A16 will appear.
- k). Fill up the input data (see end of section A-4.9 for details). If you want to come back again to Fig. A4 screen, press F1 key.
- l). After introducing the data, a table as shown in Fig. A17 will be printed out. Then, Fig. A4 will be displayed again.
- m). Press option (4) to return to NMENU when the test is done.

A-6.2 Example 2.

Let's now take the same case as Example 1 but assume that the dynamometer is pre-loaded and that we want to check periodically the computer input voltage while waiting 15 minutes in between save routines. The procedure is as described above but with the following variations :

- 1). We are now in the pre-loaded case, so in step b). of Example 1 we must chose option (2).
- 2). In between saving sets of data, we have to press option (4) (see Fig. A4) to come back to NMENU. Then, once we are running NMENU, press option (5) (see Fig. A2). The screen display showing channels voltage will appear.
Hit any key to return to NMENU, and press option (2) again.

A-6.3 Example 3.

Finally, suppose we want to find out the turbine speed and torque time variation during the saving data process without load on the dynamometer. The procedure is as follows :

- a). The first two steps are the same as those in Example 1.
- b). Press option (1).
- c). Repeat steps d). and e). in Example 1 .
- d). Return to NMENU by hitting option (4).
- e). Press option (3). The screen display shown in Fig. A5 will appear.
Press option (1) to run NPLOT1.
- f). Input the data (data file name and channel number to plot versus time). For this particular example, the channels numbers to plot are 0 (turbine speed) and 6 (turbine torque). Input only one of them at a time.
- g). Run NPLOT1 and plot the graphic on the color monitor.
- h). If you want a draft printout of the graphic, press "Shift / Print screen" keys.
- i). Return to NMENU and repeat steps e)., f). and g).with the other channel number.

APPENDIX B

SPECIAL PROGRAM CHARACTERISTICS

APPENDIX B : SPECIAL PROGRAM CHARACTERISTICS

As a final complement to the programs' description, some comments about the input data routines and versatility should be made :

1. The text portions of the user-supplied input is introduced using text subroutine which allows the user to choose the maximum number of characters for a given text. This method avoids input errors, especially when dealing with file names limited to 8 characters.
2. All input numerical values are introduced using an "only number checking subroutine", which forces the user to input only numerical values. When a number is required, the user cannot input anything but numbers. If the input value is out of a given range predetermined in the program (i.e. voltage never greater than 1000 volts), the input will be erased and the user will be asked again.
3. All decisions made are protected by a yes/no option that enables the user to avoid undesirable runs.
4. The ON KEY statement has been introduced in all programs in such a way that permits the user to go to the previous program stage by pressing F1 key.
5. Finally, in order to avoid input/output file errors when trying to access a nonexistent or incorrectly named file, a set of ON ERROR subroutines have been created. These subroutines enable the user to keep running the program without going out to DOS. An error statement informing the user about the kind of mistake is displayed on the screen.

APPENDIX C

HOW TO COMPILE AND LINK THE PROGRAMS

APPENDIX C : HOW TO COMPILE AND LINK THE PROGRAMS

For data acquisition and control, we use DASH 16/16. In running the original Basic programs (.BAS), there are two statements that must be introduced to get data :

1. CALL "DASH16.BIN"
 2. DEF SEG(*)

Now, when a Basic program is compiled, the significance of DASH16 in the CALL statement is no longer the same. DASH16 is not interpreted by the compiler as a variable. It becomes the public name of the subroutine that you wish to call. Therefore, before compiling the program, the lines that contain the DASH16.BIN routine and all DEF SEG statements that control the location of the routine have to be removed.

When compiling, statements 1 and 2 are not required as the linker will locate the DASH16 routine in memory automatically.

Having said this, the steps to create an executed version (compiled+linked) from the original source Basic version using the IBM Microsoft Quick Basic are :

- a). Copy the program you are going to compile and link into the Quick Basic subdirectory (C:\TTEST\QB).
 - b). Go to the Quick Basic subdirectory using the following statement :

C>CD C:\TTEST\QB (Press return key)

- c). Compile the program using the following statement :

C>QB PROGRAM NAME.EXT [options]; (Press return key)

The options that can be introduced are :

/e : This option must be used when the statement ON ERROR GOTO with RESUME is written on the program to compile.

/q : Optimizes the program to be as fast as possible. It is highly recommended to use it when compiling all the programs.

/x : This option has to be used under the presence of ON ERROR GOTO with RESUME in the program to compile.

(*) See Basic programs print out.

/w : This option has to be used when the statement ON KEY GOSUB is written on the program to compile.

i.e. C>QB SPEED100.C /w/x/e/q ; (Press return key)

After the compiling session, the object program is already created.

d). Link the created object program in this way :

C>LINK PROGRAM NAME.OBJ + DASH16.OBJ (Press return key)

If DASH16.OBJ is not in the Quick Basic subdirectory, we have to use the following statement :

C>LINK PROG.NAME.OBJ+C:\DIR.NAME\ DASH16.OBJ (Return)

where DIR. NAME is the subdirectory's name in which DASH16.OBJ is copied.

After the linking process, the executed version of the program is already created.

APPENDIX D

PROPAGATION OF UNCERTAINTY

APPENDIX D : PROPAGATION OF UNCERTAINTY

D-1. Equation for the efficiency

We want the overall efficiency η_m (%) as a function of the four input parameters :

T_m = External torque (lb-ft)

N_m = Rotational speed (rpm)

P_d = Pressure difference between turbine inlet and outlet (psi)

N_m = Discharge (cfs)

$$\eta_m = \frac{\text{Power out (PO)}}{\text{Power in (PI)}} \times 100 \quad (\text{D1})$$

The power output PO (HP) is :

$$PO = \frac{T_m N_m 2\pi}{33000} \quad (\text{D2})$$

The power input PI (HP) is :

$$PI = \frac{\gamma_m H_m Q_m}{550} \quad (\text{D3})$$

where :

γ_m = Specific weight (62.42 lbs/ft³)

H_m = Total head (ft)

On the other hand :

$$H_m = H_p + H_v \quad (\text{D4})$$

where :

H_p = Pressure head (ft)

H_v = Velocity head (ft)

$$H_p = \frac{144 \cdot P_d}{\gamma_m} \quad ; \quad H_v = \frac{V_i^2 - V_o^2}{2g_c} = \frac{\frac{Q_m^2}{A_i^2} - \frac{Q_m^2}{A_o^2}}{2g_c} \quad (\text{D5}, \text{D6})$$

where :

$$\begin{aligned} V_i &= \text{Inlet mean velocity (ft/s)} \\ V_o &= \text{Outlet mean velocity (ft/s)} \\ A_i &= \text{Inlet area (1.36 ft}^2\text{)} \\ A_o &= \text{Outlet area (3.5 ft}^2\text{)} \\ g_c &= \text{Acceleration of gravity (32.17 ft/s}^2\text{)} \end{aligned}$$

Replacing Eqs. D2, D3, D4, D5, and D6 into Eq. D1 we obtain the following expression :

$$\eta_m = \frac{T_m N_m}{aQ_m P_m + bQ_m^3} \quad (D7)$$

where :

$$\begin{aligned} a &= 1375 \\ b &= 4.232 \end{aligned}$$

Eq. D7 gives the efficiency as a function of the measurands :

$$\eta_m = F(T_m, N_m, P_d, Q_m) \quad (D8)$$

D-2. Propagation of uncertainties into results

Differentiating Eq. D8, and expanding this differentiation, we obtain Eqs. D9 and D10.

$$d\eta_m = \frac{\partial F}{\partial T_m} dT_m + \frac{\partial F}{\partial N_m} dN_m + \frac{\partial F}{\partial P_d} dP_d + \frac{\partial F}{\partial Q_m} dQ_m \quad (D9)$$

$$\begin{aligned} d\eta_m = & \frac{N_m}{aQ_m P_d + bQ_m^3} dT_m + \frac{T_m}{aQ_m P_d + bQ_m^3} dN_m - \frac{T_m N_m (aP_d + 3bQ_m^2)}{(aQ_m P_d + bQ_m^3)^2} dQ_m - \\ & - \frac{a T_m N_m Q_m}{(aQ_m P_d + bQ_m^3)^2} dP_d \quad (D10) \end{aligned}$$

Dividing both sides of Eq. D10 by the efficiency, we get :

$$\frac{d\eta_m}{\eta_m} = \frac{dT_m}{T_m} + \frac{dN_m}{N_m} - \frac{aP_d + 3bQ_m^2}{aQ_m P_d + bQ_m^3} dQ_m - \frac{aQ_m}{aQ_m P_d + bQ_m^3} dP_d \quad (\text{D11})$$

Let W be the uncertainty with the subscript indicating the variable. Replacing the differentials in Eqs.D10, and D11 with the uncertainty in the measurands, we get

$$W_{\eta_m} = \sqrt{\left(\frac{\partial\eta_m}{\partial T_m} W_{T_m}\right)^2 + \left(\frac{\partial\eta_m}{\partial N_m} W_{N_m}\right)^2 + \left(\frac{\partial\eta_m}{\partial Q_m} W_{Q_m}\right)^2 + \left(\frac{\partial\eta_m}{\partial P_d} W_{P_d}\right)^2} \quad (\text{D12})$$

and dividing again by the efficiency :

$$\frac{W_{\eta_m}}{\eta_m} = \sqrt{\left(\frac{\partial \ln\eta_m}{\partial \ln T_m} \frac{W_{T_m}}{T_m}\right)^2 + \left(\frac{\partial \ln\eta_m}{\partial \ln N_m} \frac{W_{N_m}}{N_m}\right)^2 + \left(\frac{\partial \ln\eta_m}{\partial \ln Q_m} \frac{W_{Q_m}}{Q_m}\right)^2 + \left(\frac{\partial \ln\eta_m}{\partial \ln P_d} \frac{W_{P_d}}{P_d}\right)^2} \quad (\text{D13})$$

In general, Eq. D13 can be derived from Eq. D12, as it shown in the following example for one of the terms :

$$\begin{aligned} \frac{\partial\eta_m}{\partial T_m} &= \frac{\partial \ln\eta_m}{\partial \ln T_m} \frac{\partial \ln T_m}{\partial T_m} \quad \frac{\partial\eta_m}{\partial \ln\eta_m} = \frac{\partial \ln\eta_m}{\partial \ln T_m} \frac{\eta_m}{T_m} \quad \left(\text{Since } \frac{\partial\eta_m}{\partial \ln\eta_m} = \eta_m \right) \\ \therefore \quad \frac{\partial \ln\eta_m}{\partial \ln T_m} &= \frac{T_m}{\eta_m} \frac{\partial\eta_m}{\partial T_m} \end{aligned}$$

Expanding Eq. D13 we get :

$$\frac{W_{\eta_m}}{\eta_m} = \sqrt{\left(\frac{W_{T_m}}{T_m}\right)^2 + \left(\frac{W_{N_m}}{N_m}\right)^2 + \left(-\frac{aP_d + 3bQ_m^2}{aQ_m P_d + bQ_m^3} W_{Q_m}\right)^2 + \left(-\frac{aQ_m}{aQ_m P_d + bQ_m^3} W_{P_d}\right)^2} \quad (\text{D14})$$

with the same coefficients than in Eq. D11.

Eq. D14 is applied in the following way :

1. To compute the propagation of precision uncertainty and bias separately for specific values of the measurands and measurands' uncertainty.
2. The total combined precision is found using the rms (root mean square) method in the following way :

$$\left(\frac{W_{\eta_m}}{\eta_m} \right)_{\text{Total}} = \sqrt{\left(\frac{W_{\eta_m}}{\eta_m} \right)_{\text{Precision}}^2 + \left(\frac{W_{\eta_m}}{\eta_m} \right)_{\text{Bias}}^2}$$

Eq. D14 can be rewritten as follows :

$$\frac{W_{\eta_m}}{\eta_m} = \sqrt{\left(K_1 \frac{W_{T_m}}{T_m} \right)^2 + \left(K_2 \frac{W_{N_m}}{N_m} \right)^2 + \left(K_3 \frac{W_{Q_m}}{Q_m} \right)^2 + \left(K_4 \frac{W_{P_d}}{P_d} \right)^2} \quad (\text{D15})$$

where :

$$K_1 = K_2 = 1$$

$$K_3 = - \frac{aP_d Q_m + 3bQ_m^2}{aQ_m P_d + bQ_m^3}$$

$$K_4 = - \frac{aQ_m P_d}{aQ_m P_d + bQ_m^3}$$

D-3. Analysis

Let's analyze the value of the coefficients K_1 , K_2 , K_3 , and K_4 in the range of the measurands to find which one is going to be more significant, and if there is some one comparatively small that we can neglect.

- a. In computing K_3 and K_4 , only two measurands have influence: P_d (pressure) and Q_m (flow).
- b. Typical pressure and flow ranges are :
 - Pressure (From 5 to 40 psi)
 - Flow (From 5 to 30 cfs)

c. For the above ranges, the results are :

$$\begin{aligned}1 &< K_3 < 1.5 \\1 &> K_4 > 0.5\end{aligned}$$

d. Since the relative precision uncertainties for a typical point are :

- Rotational speed (rpm) = 0.08%
- Output torque (lbs-ft) = 0.09%
- Pressure differential (psi) = 0.16%
- Flow (cfs) = 0.22%

All four are quite similar, although the rotational speed sometimes could be negligible compared to the other three values of the input parameters.