University of Minnesota
St. Anthony Falls Hydraulic Laboratory

Project Report No. 285

Field Acceptance Tests of the Turbine Generator Units at the St. Cloud Hydroelectric Facility

by

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The four days in which the St. Cloud Hydroturbine Acceptance Tests were performed marked an intense period of activity, and the authors would like to thank the representatives of all parties who were present and in assistance at the site during this time. Their names are listed in the Introduction of this report.

The Acceptance Tests Project comprised more than the actual Tests themselves, and Mr. Jerry Mahon and Mr. Steve Foss of the City of St. Cloud, and Mr. Dan Coulson of M. A. Mortenson, provided helpful and needed assistance and advice in the days of preparation (and waiting, what with the delay caused by the summer's drought) that preceded the Tests. As plant operator, Mr. Daryl Stange was always on site when we were, and he was always of great help as well.

We would like to thank Mr. Larry Long and Public Utility District No. 1 of Chelan County, Washington State, for their generous provision of the Dumas–Neyrpic Currentmeters and advice and information pertaining to their use.

Finally, the Laboratory's involvement in this project extends beyond that of the authors, and includes the efforts of Mr. John MacDonald, who assisted in the data reduction and in the turbine tests; Mr. Kevin Edmunds, the Laboratory's electronics technician, who oversaw calibration of the Power/Demand analyzer and measured power output on site; the Machine Shop personnel, Milan Kalish, Dave Roberts, and others, who fabricated and assisted in the use of the testing equipment; and Diana Dalbotten, who word processed and edited the report.

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I. INTRODUCTION

As a condition of the Procurement Agreement pertaining to the supply of turbine/generating equipment for its new hydroelectric facility, the City of St. Cloud required that the equipment meet certain performance guarantees. The plant, located on the Mississippi River, houses two 3540 mm Voith Kaplan pit units, each rated at 4400 kW. This report describes the conduct and results of the Acceptance Tests wherein the guarantees associated with those units may be verified.

Construction of the St. Cloud Hydroelectric Facility was completed in May 1988, and the plant went into commercial operation June 1, 1988. Drought conditions through the spring and summer delayed the performance of the Acceptance Tests until October, when higher flows returned to the river. The formal testing program commenced on Wednesday, October 19, 1988, with the data acquisition completed Saturday, October 22, 1988.

Essentially, the Acceptance Tests called for the determination of each unit's "water–to–wire" efficiencies at three different flow rates delineating its operating range, corresponding to: 1) maximum power output; 2) peak efficiency; and 3) 40% of maximum power output. In addition, the City required that the maximum output of the two units operating together be no less than 95% of the sum of each unit's individual performance. Test results enable a verification of this "two unit versus one unit" guarantee, as well.

Prior to the Acceptance Tests, index tests of both units were conducted at the powerhouse to verify or alter the existing cam relationship (i.e., the relationship governing the position of wicket gates and runner blades relative to each other, as necessary to ensure maximum operating efficiency for any given flow), and establish operating information for the owner.

The contract governing the conduct of the Acceptance Tests largely defers to Publication 41 of the International Electrotechnical Commission (published in 1963): *International Code for the Field Acceptance Tests of Hydraulic Turbines* [1] (referred to henceforth as "IEC 41" or "the Code"). As implied, IEC 41 "[establishes] methods of testing and [ways] of measuring the quantities involved, so as to ascertain the performance of the turbine and to verify the guarantees."

Representatives of all parties with an interest in the results were invited by the City of St. Cloud to witness the Acceptance Tests. The following individuals were present at all or a portion of the tests:

Name	Party Represented
R. Voigt	SAFHL
J. Woods	SAFHL
M. Kalish	SAFHL
J. Gulliver	SAFHL
K. Edmunds	SAFHL
J. Gundhoffer	SAFHL
T. Eberly	SAFHL
J. McDonald	SAFHL
P. Rodrique	Acres
C. May	Acres
P. Carson	R.W.Beck
P. Welch	R.W.Beck
K. Favero	R.W.Beck
J. Sun	Harza
S. Larson	Warzyn
D. Coulson	MAM
S. Westby	MAM
G. Barbatos	MAM
D. Stange	MAM
S. Foss	City of St. Cloud
J. Mahon	City of St. Cloud
K. Robinson	City of St. Cloud
J. Proell	City of St. Cloud
K. Redmond	City of St. Cloud
D. Stockinger	City of St. Cloud
D. Stueve	City of St. Cloud
K. Lever	Actaeon
R. Jordon	Actaeon
M. Byrnes	Voith
S. Barnes	Voith

II. TESTING EQUIPMENT AND DATA ACQUISITION

The determination of turbine/generator efficiency requires simultaneous measurements of discharge, head, power, and the specific weight of water. Efficiency is computed as

$$E = \frac{737.5\ P}{\gamma Q H} \qquad \text{(II–1)}$$

where E = efficiency (expressed as a fraction); P = power output (kW); Q = discharge (cfs); H = net head (ft); and γ = specific weight of water (lb/ft^3).

A. DISCHARGE

As is usually the case, discharge is the most tedious of the parameters to measure. The Code specifies several methods of discharge measurement, the Currentmeter method being most appropriately suited to the large, short–length intakes characteristic of many low–head facilities. Depicted in Figs. II–1 and II–2, the intake structure of the St. Cloud facility is rectangular, comprised of a horizontal floor (el. 938.86 msl) and a sloping roof which descends at a 20° angle to an elevation of 963.21 just in front of the enclosed generator pit, where it becomes level before the contracting flow splits around the pit. A bulkhead gate slot is located about seven feet in front of the pit nose, and it circumscribes a convenient cross section through which to measure discharge.

The flow through each turbine unit was ascertained using eleven 5–inch diameter "Dumas" propeller type 2117E current meters, manufactured by Neyrpic, Inc., Grenoble, France. These meters were mounted on a transverse rack constructed primarily of 2" steel tubing, shown in Photo II–1. The ends of the rack were affixed to frames on which casters were mounted and positioned to roll up and down the vertical channels of the 31' 2-3/4"–long slot.

The slot is 2'9" wide, allowing enough room to position the meters in front of the rack with the effect that the metering plane, while in the gate slot, is only between one and two inches behind the forward wall of the slot where the cross–sectional area is closed. This area was resolved into a grid comprised of 110 metering locations, as shown in Fig. II–3. The eleven meters were spaced and mounted accordingly along the rack, and the rack itself could be positioned at any vertical location of the flow passage. Winches were mounted on steel frames straddled above the slot on both sides. Though the two winches operated independently, the cables by which

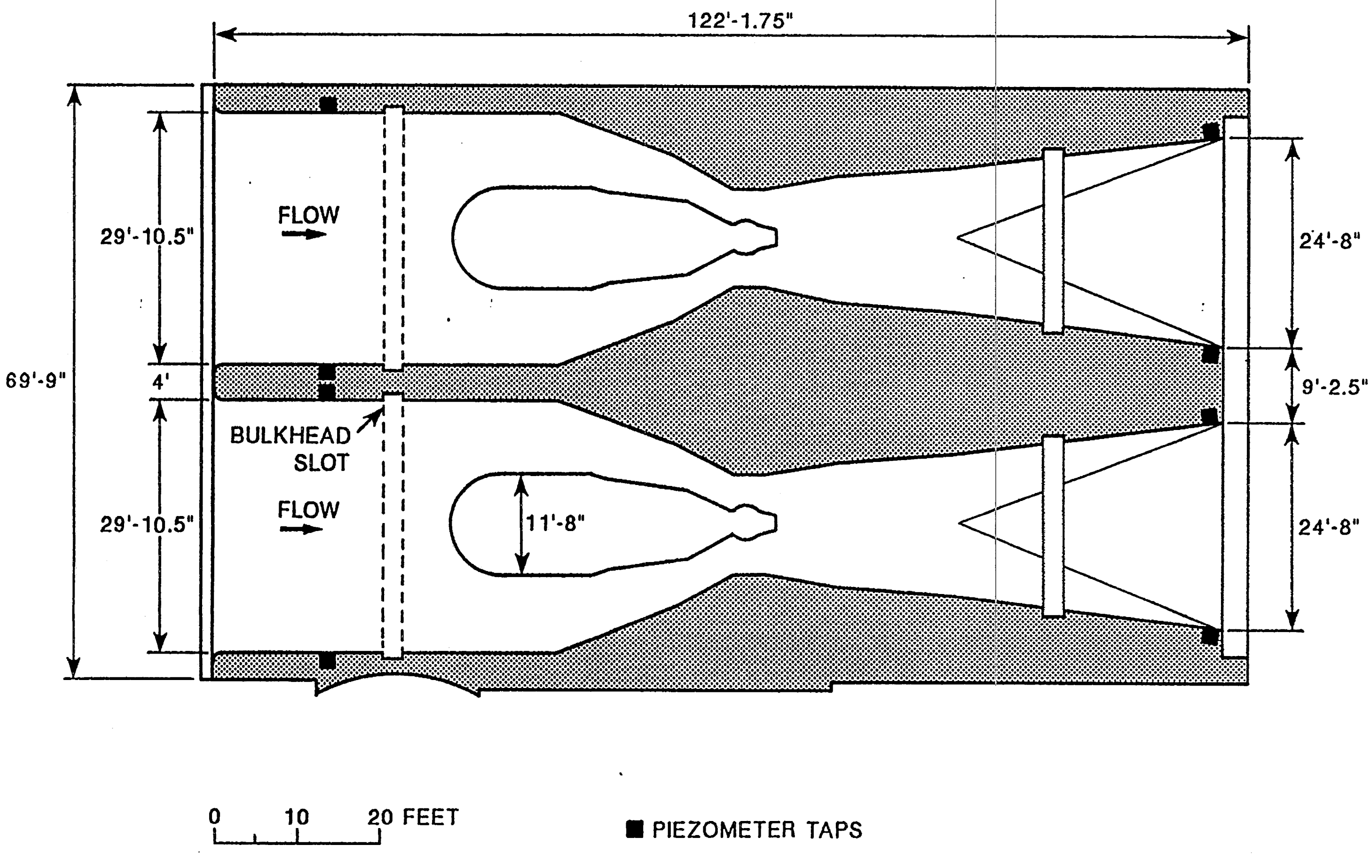


Fig. II–1. Powerhouse waterway plan.

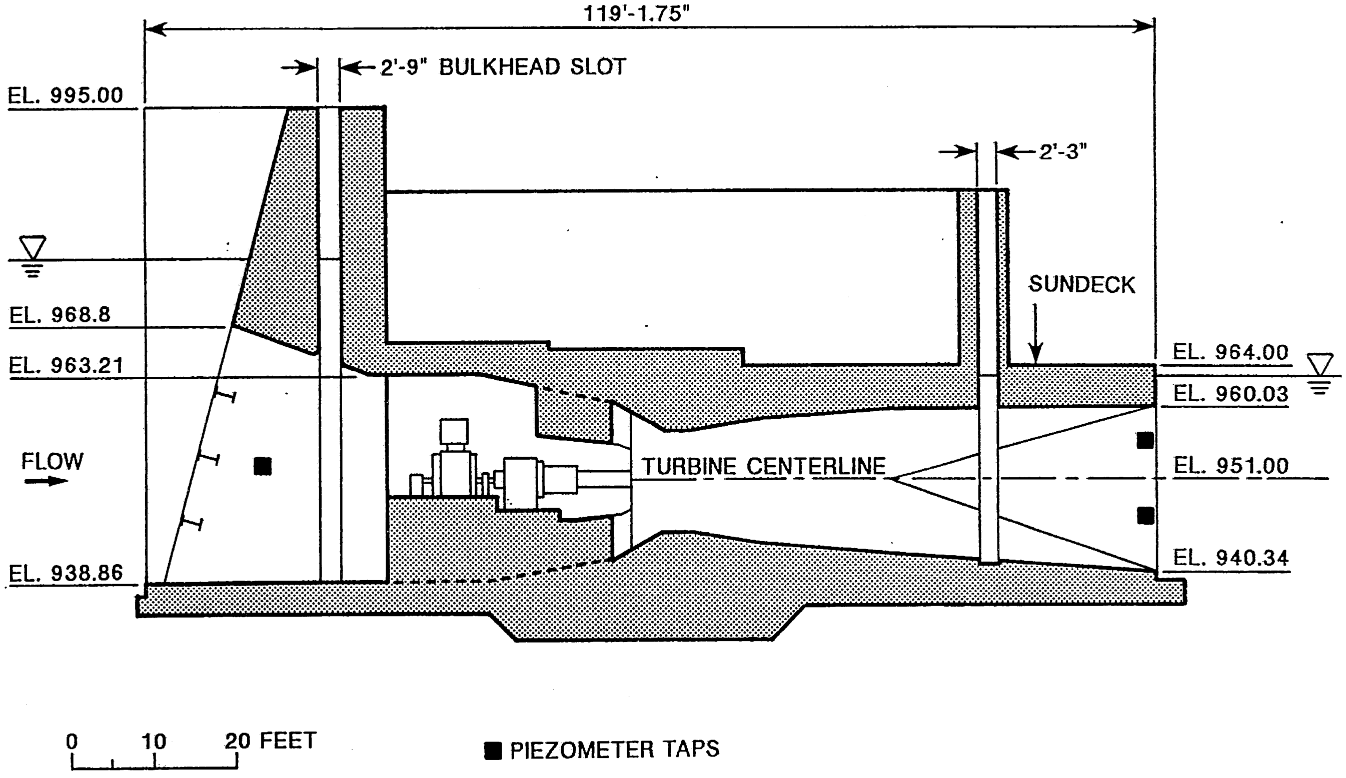


Fig. II–2. Powerhouse longitudinal section.

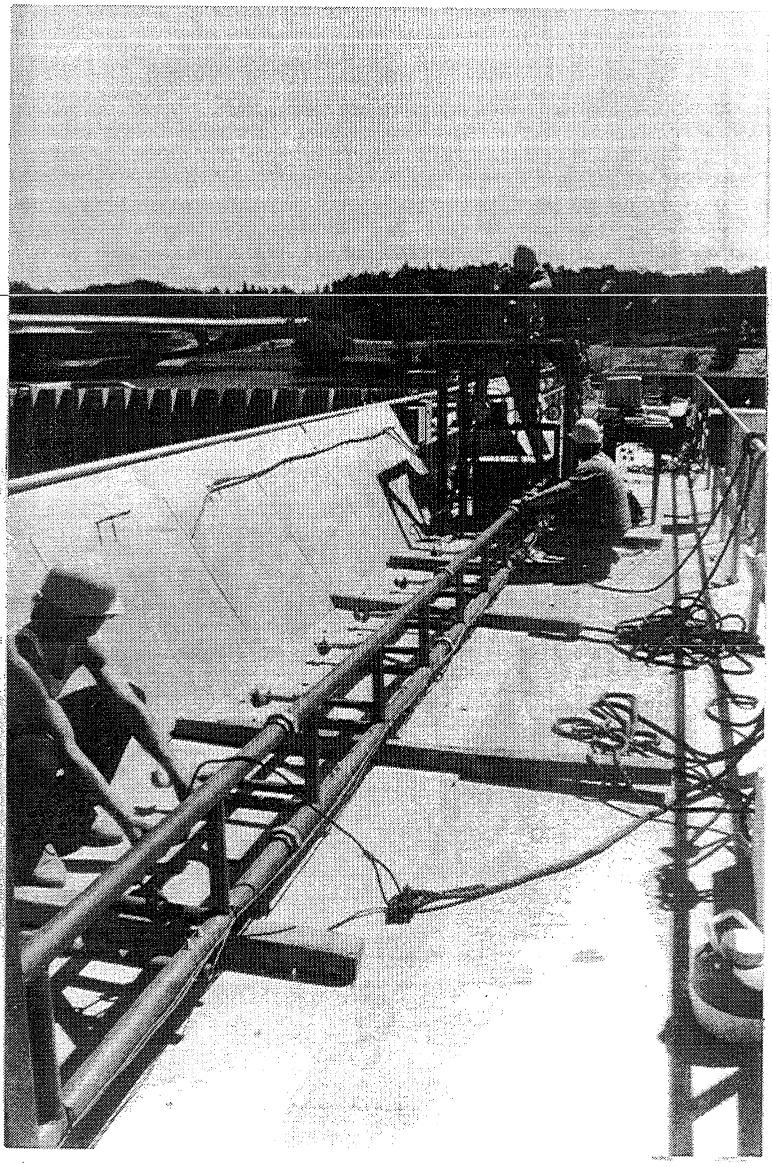


Photo II–1. Currentmeter Mounting Rack

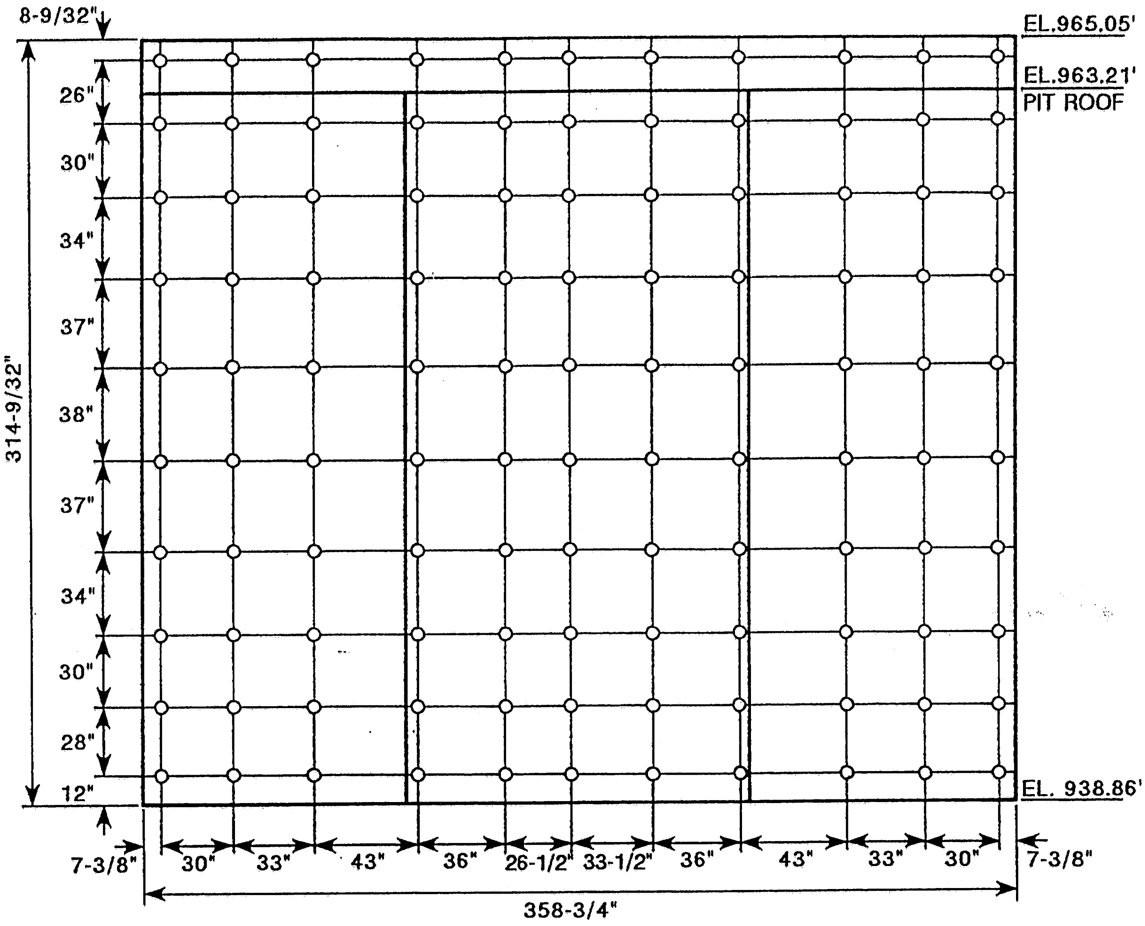


Fig. II–3. Currentmeter measurements grid.

they hoisted the end frames of the rack were marked in such a manner that the rack (and the row of meters) could be lowered and positioned in a level manner at any location in the slot.

The Neyrpic currentmeters used in the tests were of the component propeller type especially designed to measure the axial component of the velocity. The axes of the meters were maintained in a horizontal position during all velocity measurements to facilitate computation of discharge at the vertical measuring section. The propeller shaft drives a contact cam magnetically. The meters were equipped to give one electrical impulse signal—indicating whether the contact is "open" or "closed"—for each 10 revolutions of the propeller. An analog–to–digital (A–to–D) converter was used to simultaneously read the signals of all 11 currentmeters at a rate of about 47 samples per second. A wiring harness was played out from a cable reel on one of the winch frames, connecting the A–to–D converter to each of the currentmeter terminals. The sampling period for any row of measurements (i.e., the currentmeter measurements in any given row of the grid) was slightly over two minutes, and the data was collected and processed using an IBM Personal Computer. A Basic program was written to determine the revolutions–per–second of each meter in the sampling period. Calibration curves and equations were derived individually for each meter (see Section III.A: Currentmeter Calibrations), and the velocities at the metering points were thereby computed.

Although the "component" currentmeters such as those used in the St. Cloud Acceptance Tests are designed to measure the true axial component of velocity for angles less than 10° relative to the uncertainty associated with the currentmeter method, they generally under–register this component for angles greater than 10°. For angles greater than 10°, the registered velocity may be corrected by application of the information represented in Fig. II–4. Obviously, this application requires a knowledge of the direction of flow at the point of measurement, and for this purpose a series of measurements with a two–component electromagnetic velocity meter were performed at the powerhouse prior to the commencement of the formal Testing Program (see Section III.C: Flow Angle Measurements). This meter, a Marsh–McBirney Model 511 Electromagnetic Water Current Meter, consists of (1) a transducer probe with cable, and (2) a signal processor housed in a portable case. The instrument senses water flow in a plane normal to the longitudinal axis of the electromagnetic sensor. Analog panel meters indicate the water velocity components in feet per second along the X and Y axes of the electromagnetic sensor to an accuracy of ±2%. From the two components, the direction of the velocity vector (consequently, the angle of flow) is found as

$$\theta = \tan^{-1}(v_y/v_x)$$

B. HEAD

Headwater and tailwater were each measured at three locations. The headwater was measured in the following ways:

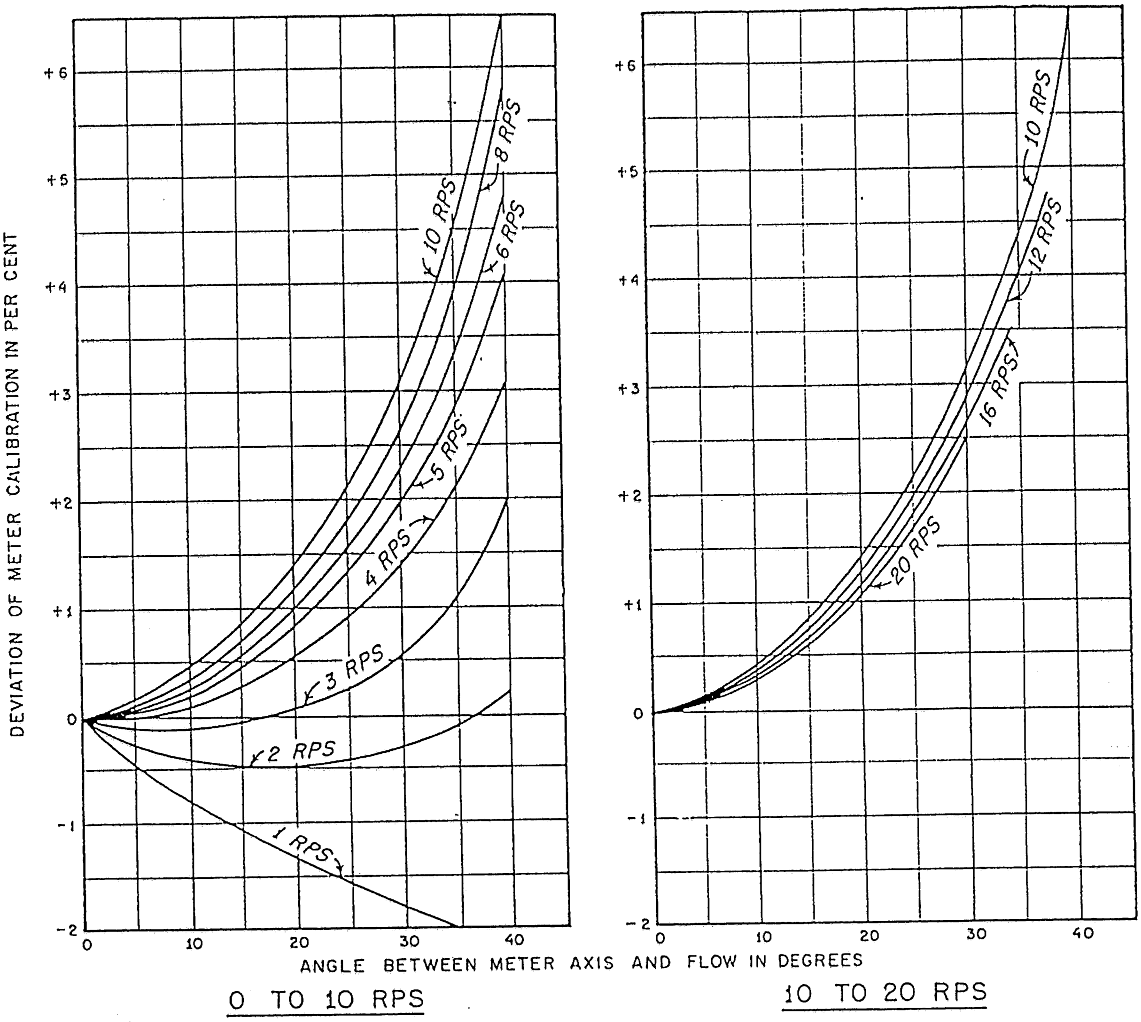


Fig. II.4. Deviation of component velocities due to flow angle.

1) An electronic point gage was mounted in a stilling well located at the junction of the first and second upstream cellular walls, as noted in Fig. II–5. Since the headwater at this location is relatively stagnant, there is no water surface "drawdown" due to velocity head, and the measurements at this location were consequently chosen in place of the location mandated by the contract for use in determining turbine/generator performance. This change was agreed upon during a monthly construction progress meeting held on site prior to the completion of construction. The actual test location coincides with the bank–side location of the lateral water surface profile labeled "A" in the St. Cloud Model Study [2]. The water surface levels measured here agree closely with measurements near the upstream end of the spillway river separation wall where it had formerly been decided to locate the stilling well.

   The point gage operates on the principal that water is a conductor, so that contact between the lowered point and the water surface essentially "closes" a circuit with the effect that a light bulb illuminates. The corresponding level is then read as indicated on the vernier and referenced to a benchmark elevation at the site to yield the elevation of the water surface. The gage is shown in Photo II–2.

2) A simple "float gage", consisting of a small, flat piece of plywood attached to a steel measuring tape, was lowered into the upstream bulkhead slot, noted in Figs. II–1 and II–2. With the plywood floating on the water surface in the slot, the vertically extended tape was read with reference to a benchmark at the ledge of the slot and the surface elevation was determined accordingly.

   Although closer to the turbine, the gate slot is at a 20° angle to the axial component of flow. Thus, the head measurement will be increased by a certain portion of the velocity head below the gate slot. It is difficult to accurately determine this velocity head component.

3) Piezometer taps are built into the turbine intake sidewalls about 6' upstream of the front edge of the slot at the level of the turbine runner centerline, as noted in Figs. II–1 and II–2. They are accessed through valves in the runner pit. Clear plastic tubing was clamped on each valve and the two tubes came together at a junction from which one tube was then suspended and clamped to a vertical board graduated according to elevation. With the valve open, the peizometric level of the water in the tube could then be read off the elevation board, as shown in Photo II–3. The location of the piezometer taps were such that they were also subject to an increase in head because of additional velocity head caused by cross–flow velocities. Again, it is difficult to determine this increase in head.

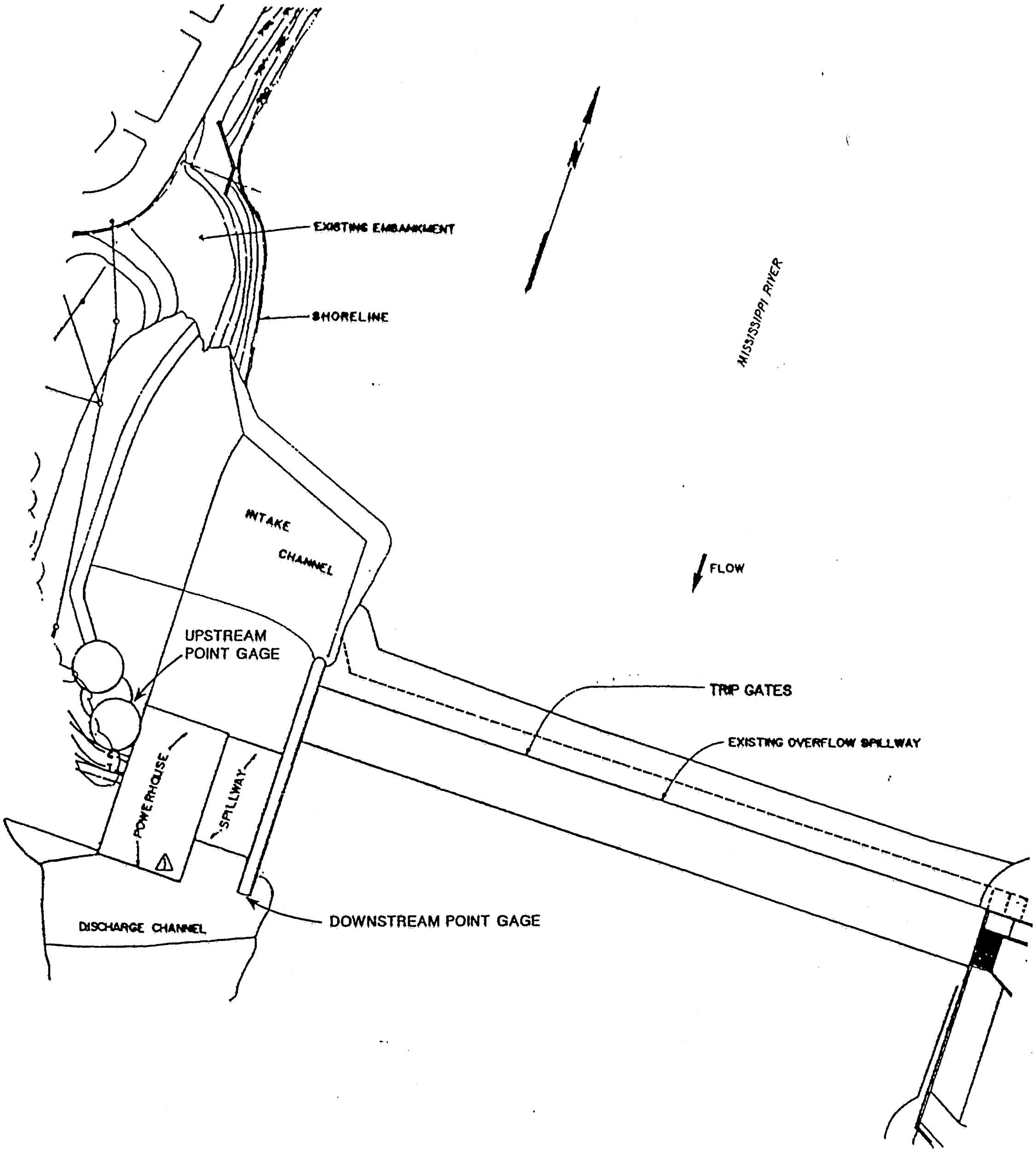


Fig. II–5. General site plan of the St. Cloud Hydroelectric Project.

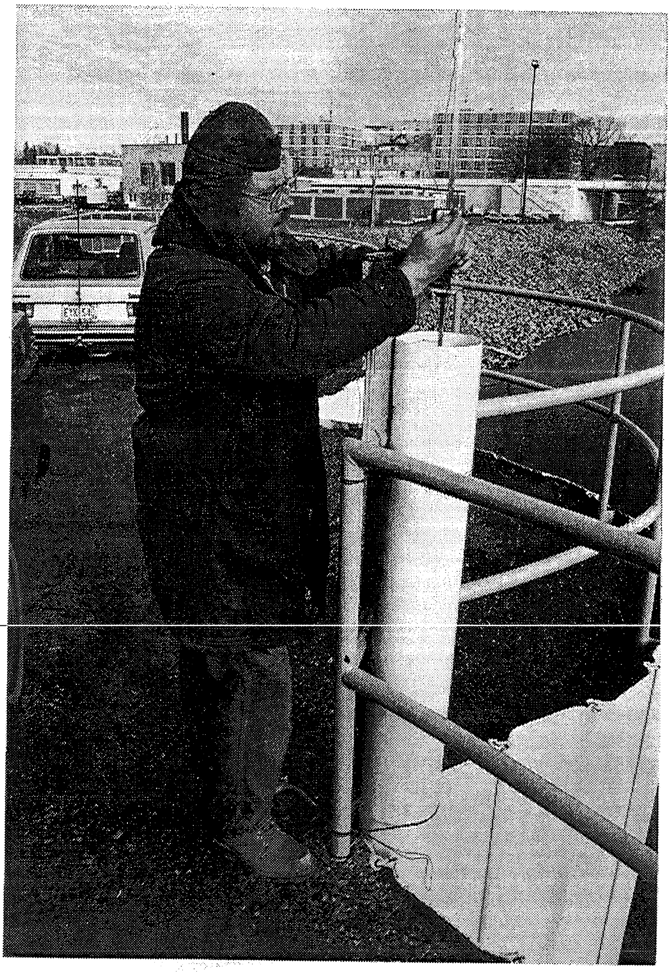


Photo II–2. Upstream Point Gage Measurement Station

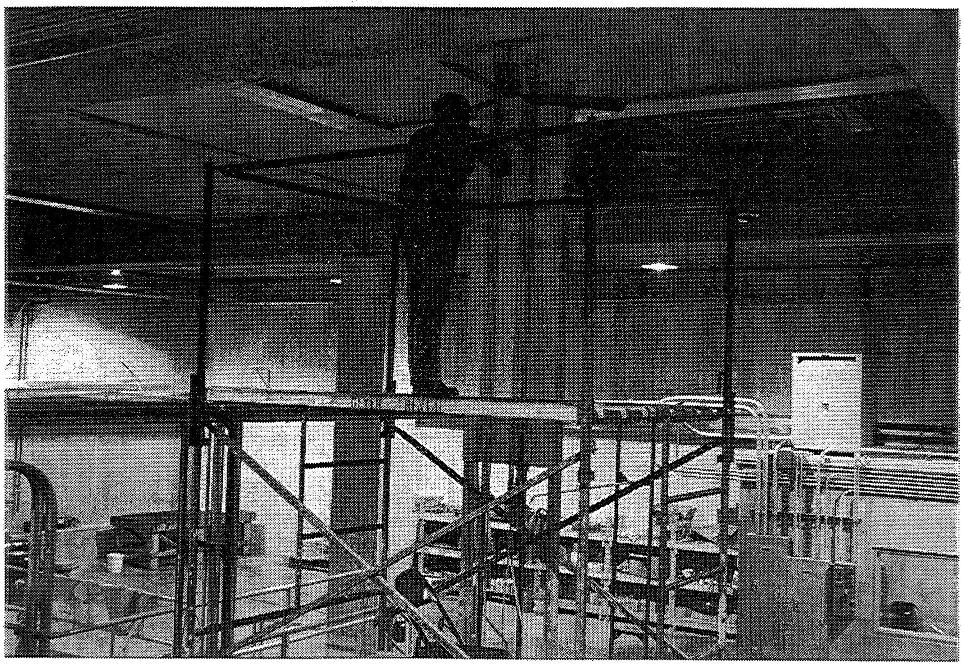


Photo II–3. Upstream Piezometer Board Measurement Station

The tailwater was measured in the following ways:

1) An electronic point gage was mounted in a stilling well located at the downstream end of the separation wall between the powerhouse complex and the main spillway (the spillway river wall; Fig. II–5), as stipulated in the contract. Operating identically to the upstream point gage, the vernier is read at the point of light bulb illumination and the water surface elevation was determined with reference to a benchmark elevation at this location. This point gage is shown in Photo II–4.

2) Similar to the measurements in the upstream bulkhead slot, a steel tape measure was extended from the sundeck at the back of the powerhouse down to the water surface in a stilling well located between the draft tube outlets, as noted in Figs. II–1 and II–2 and shown in Photo II–5. This measurement was referenced to a local benchmark elevation to determine the elevation of the water surface.

   The water surface was boiling at this location, as the flow from the draft tube exit welled up at the outlet. This is an indication of a partial conversion of velocity head to static head.

3) Four peizometer taps are built into the wall of the draft tube just inches from the outlet, as noted in Figs. II–1 and II–2. The four tubes leading up from the access valves were joined into one tube, and the piezometric level of the water in the tube could then be read off the graduated elevation board on which it was mounted, shown in Photo II–6. Again, the location of the piezometer taps were such that they were subject to a potential increase in head by the radial component of flow in the draft tube. This radial component is dependent on the operating point of the turbine and could not be measured.

The three pairs of headwater/tailwater measurements are the bases for three determinations of net head, discussed in Section IV.C: Computations and Results.

C. POWER

Power output was measured using a Dranetz Series 808 Power/Demand Analyzer, Serial Number 969116397, shown in Photo II–7. With the analyzer configured in the three wattmeter mode, power output was measured at the control panel's #PNP–3 Unit No. 3 and #PNP–6 Unit No. 6. The Dranetz 808 was connected into the Potential Transformers (PT's) and Current Transformers (CT's) through the Watt Hour Meter (Trans Data Type EMS 7000). Current was measured using three CT termination blocks, Model No. 110635–G5, and the voltage was measured directly by the

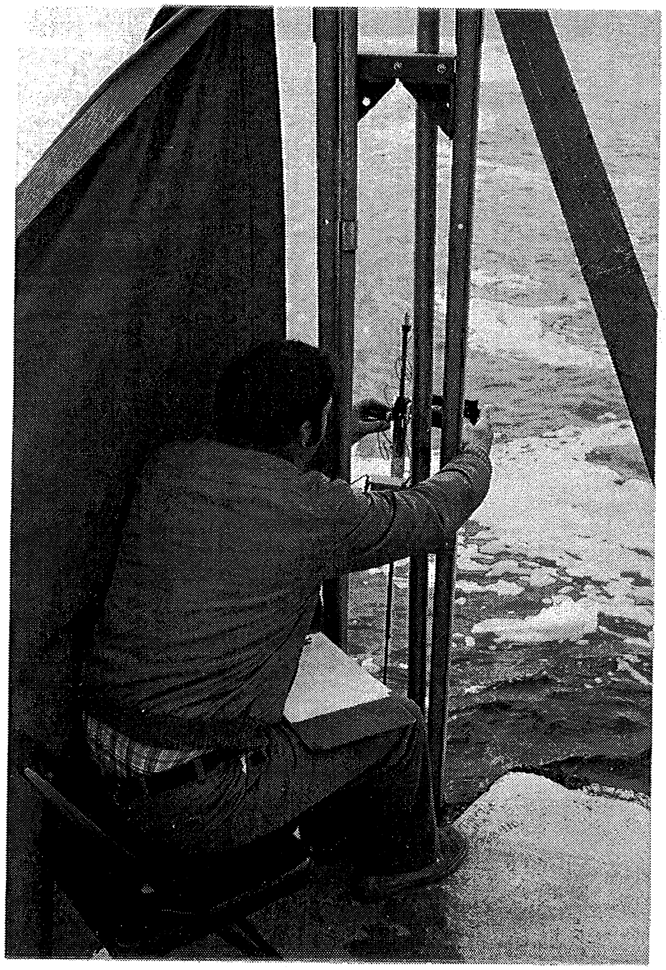


Photo II–4. Downstream Point Gage Measurement Station

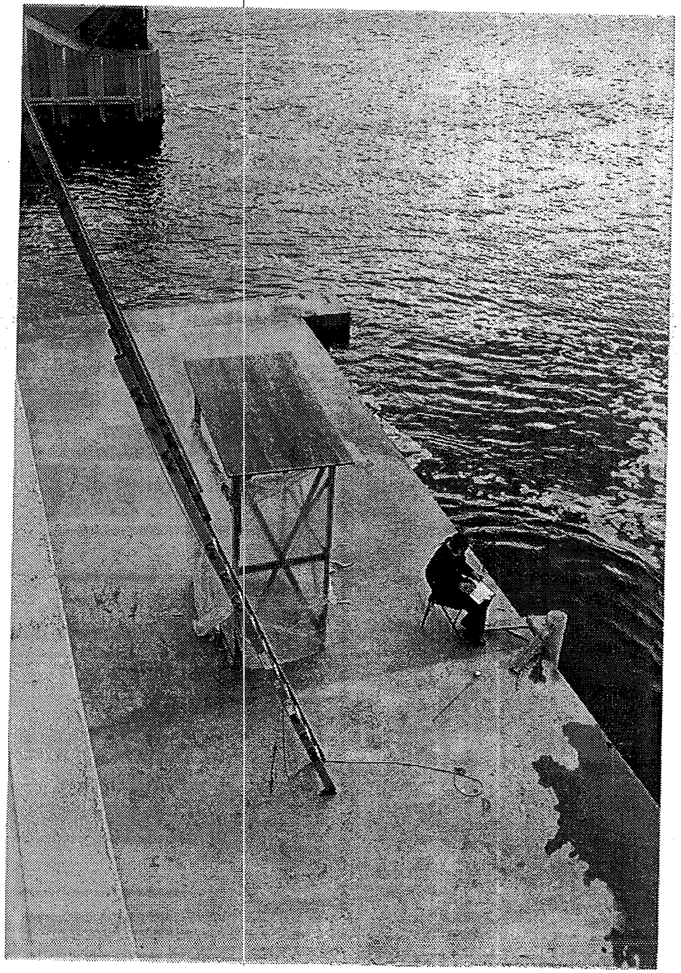


Photo II–5. Sundeck Tailwater Measurement Station

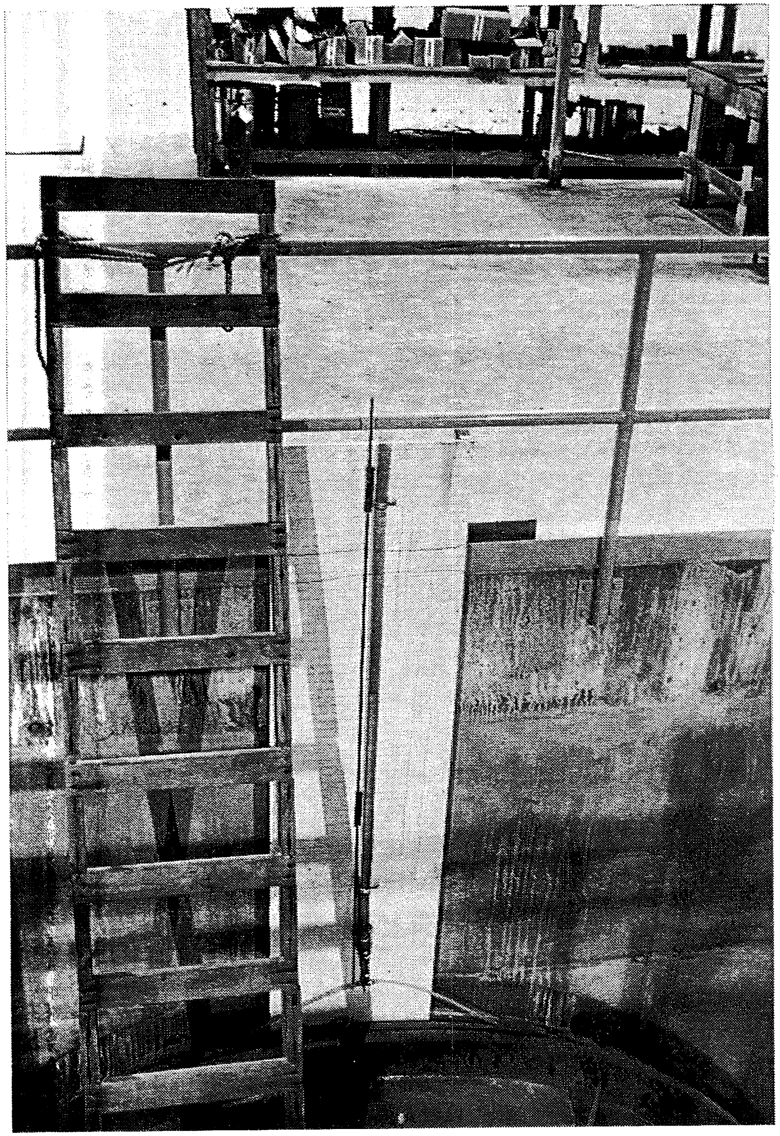


Photo II–6. Downstream Piezometer Board Measurement Station

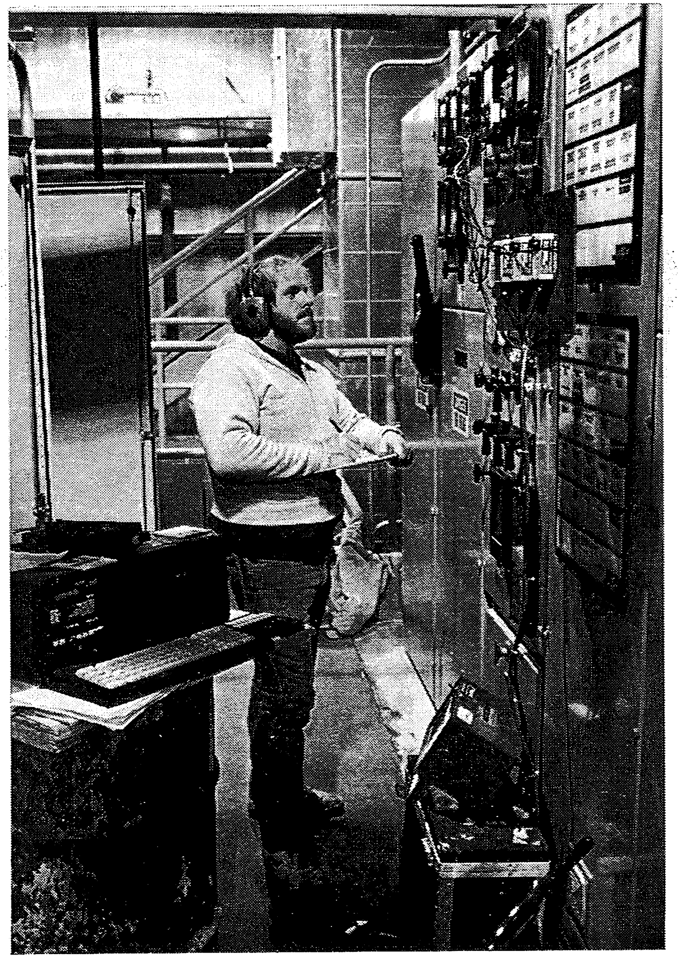


Photo II–7. Power Output Measurement Station analyzer. After programming the Dranetz with the proper CT and PT ratios (200:1 and 35:1, respectively), the analyzer would print out power and power factor on a minute–by–minute basis.

D. SPECIFIC WEIGHT OF WATER

The specific weight of water, γ, is the product of g, the local acceleration due to gravity; and the density of water, ρ, which depends on water temperature. Water temperature was recorded at the sundeck stilling well location and from this the density of water was determined from tables found in the *Handbook of Chemistry and Physics* [3] published by the Chemical Rubber Company. The local acceleration due to gravity is 32.171 ft/s^2, based on a plant latitude of 45°34' and the turbine shaft centerline elevation of 951.0 ft msl.

E. OTHER INFORMATION

Other information pertaining to unit operation, such as the blade position and wicket gate angle, were measured using the instrumentation installed on site. The blade angle was measured with the computer sensor and the angular indicator in the runner pit, while the wicket gate angle was measured with the computer and the angular indicator located on the gate ring. The wicket gate servomotor stroke was measured using a metal tape attached to the piston. The differential pressure from the relative flow taps was also measured.

III. INSTRUMENT CALIBRATION AND FLOW ANGLE MEASUREMENTS

To render test results of the accuracy required by IEC 41, the metering equipment must be calibrated to determine the relationships between the recorded data and the true values of the parameters desired. Currentmeter calibrations are performed to determine the relationship between propeller revolutions per second (n) and the velocity of water (V). The Dranetz 808 Power/Demand Analyzer must also be calibrated to determine what relationship the measured and recorded power has to the true power output. Finally, the angle of the velocity vector at each point of the flow grid must be determined in order to apply appropriate correction factors, where necessary, to the meter–registered velocities.

A. CURRENTMETER CALIBRATIONS

The currentmeters were calibrated before and after the Acceptance Tests—May 13 to May 20, 1988, and October 25 to October 28, 1988—in the main testing flume at the St. Anthony Falls Hydraulic Laboratory. The five month gap in the two sets of calibrations was the result of the lack of discharge at St. Cloud and the subsequent decision to delay testing.

A rack section, identical in construction to that used in St. Cloud, was mounted on a towing carriage equipped to run the length of the testing flume along smooth, level rails, shown in Photo III–1. Two variable–speed motors operating in a differential arrangement enable the carriage to be run at any speed from zero to about 20 feet per second. The carriage is operated from the control station at the head of the flume, and power to the carriage is transmitted through overhead electrical conductors to its wire brush pickups. After accelerating to a set speed, the carriage was designed to maintain that speed unvaryingly for the length of the run. A test length of approximately 70 ft was established for the calibrations, preceded by an adequate length of flume in which to accelerate the carriage. Since the currentmeters were calibrated on a rack section identical to that used in the field, any "frame blockage effect" was automatically incorporated into the calibration curves for each meter.

After mounting two currentmeters at a time to the rack section, river water was issued into the test flume until it completely submerged the rack (the currentmeters were about two feet underwater). The calibration of the two meters was comprised of a series of at least two runs at each of five or six carriage speeds, with enough time allowed after each run to allow the water to return to a quiescent state before continuing with the next run.

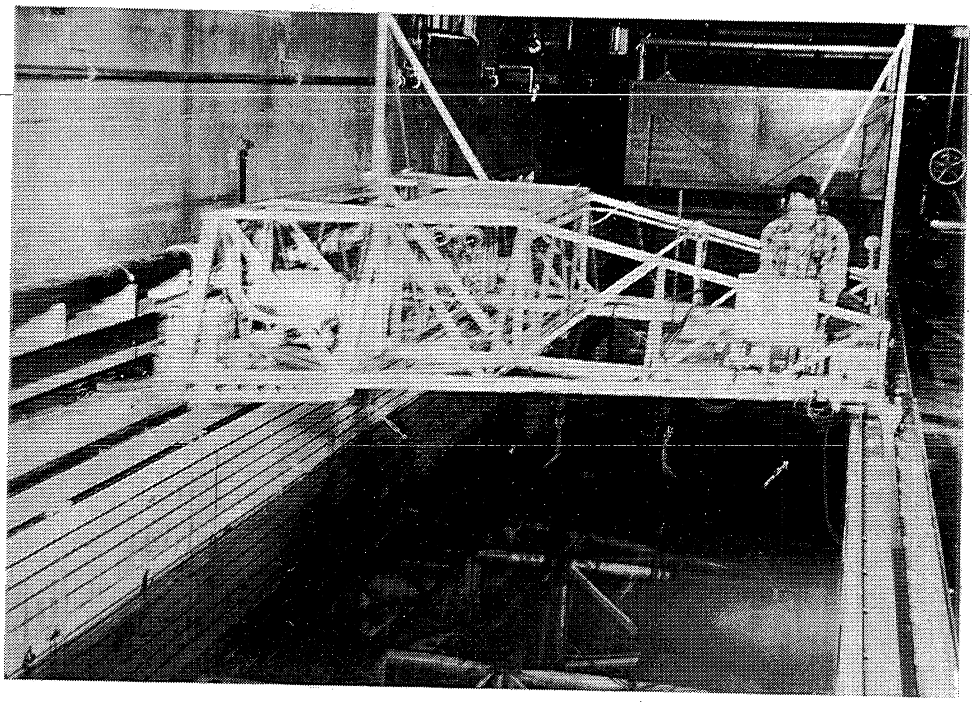


Photo III–1. Towing Carriage with Rack Mount

A personal computer and A–to–D converter similar to those used in the field were set on the carriage and wired to the currentmeters to collect and process data and compute the revolutions per second, n, of each currentmeter propeller. The PC and converter were also wired to a switch which generated an electrical impulse signal when the beginning and the end of the test length was reached. This information provided an accurate basis for computing the velocity, V, at which the carriage (and the currentmeters) had traveled over the test length.

An expanded method of plotting data points is used to magnify the normal scatter of data and to facilitate selection of the rating curve [4]. The relationship of revolutions per second to velocity may be approximated as $V^* = b^*n$, where $b^* = 0.4$, the pitch of the propeller. The difference ΔV between the observed velocity V and the velocity approximated by V^* is then expressed as $\Delta V = V - b^*n$, and this difference is plotted against n as the abscissa.

The rating curve for a given Neyrpic currentmeter is actually approximated by several straight lines rather than by a true curve. Linear regression is used to determine slopes, intercepts, and the resulting rating equations. The form of the rating equation is based on the equation for a straight line:

$$Y = mX + b.$$

Substituting $V - b^*n$ for Y and n for X, the equation becomes

$$V - b^*n = mn + b.$$

Solving for V, the equation is simplified to the form

$$V = (b^* + m)n + b,$$

where V = velocity in feet per second; b^* = meter constant (0.4 for the Neyrpic currentmeters); m = slope of the plotted line; n = revolutions per second; and b = Y–axis intercept.

Previous currentmeter rating programs, conducted in the mid–1960's by the Corps of Engineers and a consortium of utilities in Washington State [4], had established that most of the ratings for the currentmeters consist of two lines in the range between n = 1 rps and n = 16 rps. Another break usually occurred in the rating line somewhere above n = 16 rps. With this in mind, calibration runs were performed at several velocities: approximately 1 fps, 2 fps, 4 fps, 6 fps, 9 or 10 fps, and, on some of the early pre–test calibrations, about 0.4 fps. Breaks in line continuity were perceptible between n = 7 to 10 rps, and again between n = 13 to 15 rps. Generally, the first segment of the currentmeters' rating curves covered the range of velocities observed in the Acceptance Tests for flows corresponding to peak efficiency output and 40% of rated output. The second segment covered the velocities observed in the maximum output tests, and the third line segment was established for higher flow velocities than were observed in the field.

Though the field rack and flow grid were designed for the simultaneous use of eleven currentmeters, fifteen were calibrated in the pre–test calibrations in order to have four reserves available for any necessary meter replacement. As it turned out, no such replacements were required, so that only the eleven meters used were recalibrated after the tests.

The pre–test calibrations were at a water temperature of approximately 63° F. The post–test calibrations were at a water temperature of 50° F, corresponding to the water temperatures encountered in the field during the Acceptance Tests. The two sets of calibrations were consistently different (Tables III–1 and III–2; Appendix A: Pre–Test and Post–Test Calibration Curves), the post–test calibration equations yielding velocities an average of about 1.5% higher than the pre–test equations. It is believed that this is primarily due to higher oil viscosity in the currentmeters at a lower temperature, causing an increase in resistance and slight decrease in revolutions–per–second at any given flow velocity. The latter calibrations, performed immediately following the tests and at the same water temperature as the tests, were believed to be more valid than the May calibrations, and they were subsequently used to compute the test discharge values.

B. CALIBRATIONS OF THE DRANETZ 808 POWER/DEMAND ANALYZER

The Dranetz 808 Power Demand Analyzer was calibrated twice; once before the Acceptance Tests, on July 7, 1988, and once after the Acceptance Tests, on October 28, 1988.

The pre–tests calibration was performed at the laboratories of Tektronics, Inc. A known voltage and current signal were injected into the Dranetz 808, and the power value displayed by the Analyzer was compared against this known power input (the latter known simply as the product of the injected voltage and current readings over a range of voltage and current inputs. The standard for generating the voltage and current was a Fluke Model 5101 B Calibrator.

The post–tests calibration was performed at Quality Technology. This calibration made use of similar precision equipment as that used in the pre–tests calibration, and was performed in the same manner.

In both the calibrations, the readings are traceable to the National Bureau of Standards.

Table III–1. Currentmeter Calibration Equations on St. Cloud Rack Section; Conducted May 13 to May 20, 1988, 5 (Five) Months Prior to the Acceptance Tests.

Meter No.	Equations	Limits
695	$V = 0.4241n + 0.0778$	$n = 0.75$ to $n = 7.224$
	$V = 0.4474n - 0.0901$	$n = 7.224$ to $n = 14.175$
	$V = 0.4707n - 0.4209$	$n = 14.175$ to $n = 24$
725	$V = 0.4389n + 0.0592$	$n = 0.75$ to $n = 8.242$
	$V = 0.4561n - 0.0819$	$n = 8.242$ to $n = 13.860$
	$V = 0.4592n - 0.1255$	$n = 13.860$ to $n = 24$
738	$V = 0.4365n + 0.0707$	$n = 0.75$ to $n = 7.708$
	$V = 0.4624n - 0.1286$	$n = 7.708$ to $n = 13.659$
	$V = 0.4679n - 0.2047$	$n = 13.659$ to $n = 24$
741	$V = 0.4334n + 0.0725$	$n = 0.75$ to $n = 7.796$
	$V = 0.4558n - 0.1021$	$n = 7.796$ to $n = 13.872$
	$V = 0.4801n - 0.4396$	$n = 13.872$ to $n = 24$
747	$V = 0.4302n + 0.0767$	$n = 0.75$ to $n = 7.275$
	$V = 0.4492n - 0.0622$	$n = 7.275$ to $n = 14.056$
	$V = 0.4771n - 0.4543$	$n = 14.056$ to $n = 24$
748	$V = 0.4371n + 0.0627$	$n = 0.75$ to $n = 8.324$
	$V = 0.4603n - 0.1304$	$n = 8.324$ to $n = 13.612$
	$V = 0.4618n - 0.1509$	$n = 13.612$ to $n = 24$
750	$V = 0.4347n - 0.0752$	$n = 0.75$ to $n = 7.711$
	$V = 0.4601n - 0.1206$	$n = 7.711$ to $n = 13.723$
	$V = 0.4661n - 0.2025$	$n = 13.723$ to $n = 24$
752	$V = 0.4329n + 0.0896$	$n = 0.75$ to $n = 7.146$
	$V = 0.4606n - 0.1087$	$n = 7.146$ to $n = 13.829$
	$V = 0.4862n - 0.4615$	$n = 13.829$ to $n = 24$
753	$V = 0.4387n + 0.0684$	$n = 0.75$ to $n = 7.872$
	$V = 0.4627n - 0.1205$	$n = 7.872$ to $n = 13.806$
	$V = 0.4756n - 0.2982$	$n = 13.806$ to $n = 24$
755	$v = 0.4434n + 0.0795$	$n = 0.75$ to $n = 7.593$
	$V = 0.4711n - 0.1307$	$n = 7.593$ to $n = 13.583$
	$V = 0.4870n - 0.3472$	$n = 13.583$ to $n = 24$
757	$V = 0.4346n + 0.0731$	$n = 0.75$ to $n = 7.455$
	$V = 0.4557n - 0.0842$	$n = 7.455$ to $n = 13.890$
	$V = 0.4746n - 0.3471$	$n = 13.890$ to $n = 24$

Table III–1 (cont.)

Meter No.	Equations	Limits
765	$V = 0.4424n + 0.0727$ $V = 0.4592n - 0.0491$ $V = 0.4876n - 0.4386$	$n = 0.75$ to $n = 7.267$ $n = 7.267$ to $n = 13.672$ $n = 13.672$ to $n = 24$
770	$V = 0.4332n + 0.0952$ $V = 0.4543n - 0.0530$ $V = 0.4808n - 0.4214$	$n = 0.75$ to $n = 7.023$ $n = 7.023$ to $n = 13.864$ $n = 13.864$ to $n = 24$
772	$V = 0.4348n + 0.0559$ $V = 0.4515n - 0.0958$ $V = 0.4641n - 0.2745$	$n = 0.75$ to $n = 9.097$ $n = 9.097$ to $n = 14.105$ $n = 14.105$ to $n = 24$
775	$V = 0.4360n + 0.0687$ $V = 0.4583n - 0.1220$ $v = 0.4695n - 0.2782$	$n = 0.75$ to $n = 8.534$ $n = 8.534$ to $n = 13.956$ $n = 13.956$ to $n = 24$

Table III–2. Currentmeter Calibration Equations on St. Cloud Rack Section; Conducted October 25 to October 28, 1988, the Week After the Acceptance Tests.

Meter No.	Equations	Limits
725	$V = 0.4340n + 0.1126$	$n = 0.75$ to $n = 8.143$
	$V = 0.4592n - 0.0929$	$n = 8.143$ to $n = 13.832$
	$V = 0.5077n - 0.7628$	$n = 13.832$ to $n = 24$
738	$V = 0.4390n + 0.1086$	$n = 0.75$ to $n = 8.453$
	$V = 0.4584n - 0.0556$	$n = 8.453$ to $n = 13.774$
	$V = 0.5114n - 0.7859$	$n = 13.774$ to $n = 24$
747	$V = 0.4315n + 0.1092$	$n = 0.75$ to $n = 9.120$
	$V = 0.4480n - 0.0416$	$n = 9.120$ to $n = 14.081$
	$V = 0.5054n - 0.8496$	$n = 14.081$ to $n = 24$
748	$V = 0.4400n + 0.1060$	$n = 0.75$ to $n = 9.881$
	$V = 0.4532n - 0.0242$	$n = 9.881$ to $n = 13.887$
	$V = 0.5152n - 0.8852$	$n = 13.887$ to $n = 24$
750	$V = 0.4319n + 0.1600$	$n = 0.75$ to $n = 8.494$
	$V = 0.4582n - 0.0630$	$n = 8.494$ to $n = 13.837$
	$V = 0.5189n - 0.9035$	$n = 13.837$ to $n = 24$
752	$V = 0.4389n + 0.1132$	$n = 0.75$ to $n = 9.515$
	$V = 0.4553n - 0.0424$	$n = 9.515$ to $n = 13.867$
	$V = 0.5149n - 0.8697$	$n = 13.867$ to $n = 24$
753	$V = 0.4422n + 0.0957$	$n = 0.75$ to $n = 8.928$
	$V = 0.4589n - 0.0531$	$n = 8.928$ to $n = 13.704$
	$V = 0.5177n - 0.8584$	$n = 13.704$ to $n = 24$
755	$v = 0.4498n + 0.0909$	$n = 0.75$ to $n = 9.506$
	$V = 0.4633n - 0.0373$	$n = 9.506$ to $n = 13.533$
	$V = 0.5243n - 0.8625$	$n = 13.533$ to $n = 24$
770	$V = 0.4296n + 0.1704$	$n = 0.75$ to $n = 7.765$
	$V = 0.4588n - 0.0563$	$n = 7.765$ to $n = 13.716$
	$V = 0.5185n - 0.8742$	$n = 13.716$ to $n = 24$
772	$V = 0.4294n + 0.1148$	$n = 0.75$ to $n = 7.912$
	$V = 0.4501n - 0.0487$	$n = 7.912$ to $n = 13.964$
	$V = 0.5050n - 0.8147$	$n = 13.964$ to $n = 24$
775	$V = 0.4380n + 0.1179$	$n = 0.75$ to $n = 8.151$
	$V = 0.4561n - 0.0300$	$n = 8.151$ to $n = 13.783$
	$v = 0.5186n - 0.8908$	$n = 13.783$ to $n = 24$

C. FLOW ANGLE MEASUREMENTS

A series of flow angle measurements were performed in each unit before proceeding with the Acceptance Tests. The sensing probe of the electromagnetic water current meter was mounted in successive positions along the rack and lowered into the flow passage so as to measure the axial and cross–flow components of the velocity at various points of the flow grid. The cross–flow component was either horizontal or vertical, depending on the orientation of the probe. In each unit, and for each of the three flowrates encountered in the Acceptance Tests, horizontal cross–flows were investigated in one series of measurements, and vertical cross–flows were investigated in another. The angle that the velocity vector makes with the line normal to the metering plane is determined as

$$\theta v = \tan^{-1} \{(v_y^2 + v_z^2)^{1/2}/v_x\},$$

where v_x, v_y, and v_z are the component velocities in the x (axial), y (cross–flow horizontal), and z (cross–flow vertical) directions, respectively.

Figure II–4 indicates that at the typically measured revolutions–per–second of between 3 rps and 15 rps, the deviation in meter calibration at a flow angle of 10° varies between –0.15% and +0.45%. Measurements were recorded and flow angles determined only at those points of the grid where the angle was greater than 10°. Generally, the angles of at least half of the grid points were insignificant (i.e., less than 10°).

The information gathered in these series of measurements was applied in the data analysis that followed the Acceptance Tests (see Section IV.C: Computations and Results).

IV. TESTING PROGRAM AND RESULTS

The conduct of the Acceptance Test was subject to the conditions and agreements of all parties with a vested interest in its outcome. Such conditions and agreements were stipulated primarily in the Contract Documents which, as already mentioned, deferred largely to IEC 41. In addition, some on–site discussion and agreement was necessary to accommodate field conditions not anticipated or specifically dealt with in the contract. Representatives of all parties were present at the test site to resolve issues of concern.

A. THE TESTING PROGRAM

The formal data acquisition of the Acceptance Tests was commenced Wednesday, October 19, 1988, and completed Saturday, October 22, 1988. Parties present at the test site were positioned at the various gaging/metering stations and all pertinent data were collected at five–minute intervals for the duration of time required to ascertain the turbine discharge.

Since Kaplan turbines are double–regulated, their operating efficiency at a given discharge will depend not just on the wicket gate opening but on the relationship between the wicket gate opening and the adjustable blade angle. The turbines could have been tested "on cam" using the wicket gate opening and blade angle relationship developed from the index tests. However, the Voith/M.A. Mortenson contract specified that three tests be run near each discharge point. Since small headwater and tailwater changes could be significant at this low–head facility during the time span required for one test run, the consensus of all parties present at the initiation of testing was to set constant gate and blade angles near each discharge point for each of the three runs. Each unit in St. Cloud was therefore tested three times at each of the prescribed flow rates, each test constituting a [relatively slight] change in the relationship between the gate opening and blade angle of the unit. The cam curve and the gate and blade settings for the acceptance test runs are shown in Figs. IV–1 and IV–2. The previously conducted index tests helped to ensure that the optimum relationship (corresponding to the maximum efficiency at the given flow rate) would be circumscribed by the three tests. One of the three efficiencies subsequently computed was retained for performance evaluation and the verification of guarantees. A total of eighteen runs were completed for the two units operating individually—nine for each unit, consisting of the three runs just alluded to at each of the three flow rates. A nineteenth run involved the measurement of plant output with both units full open, pertinent for the "two versus one" guarantee. Discharge was not measured for this nineteenth run.

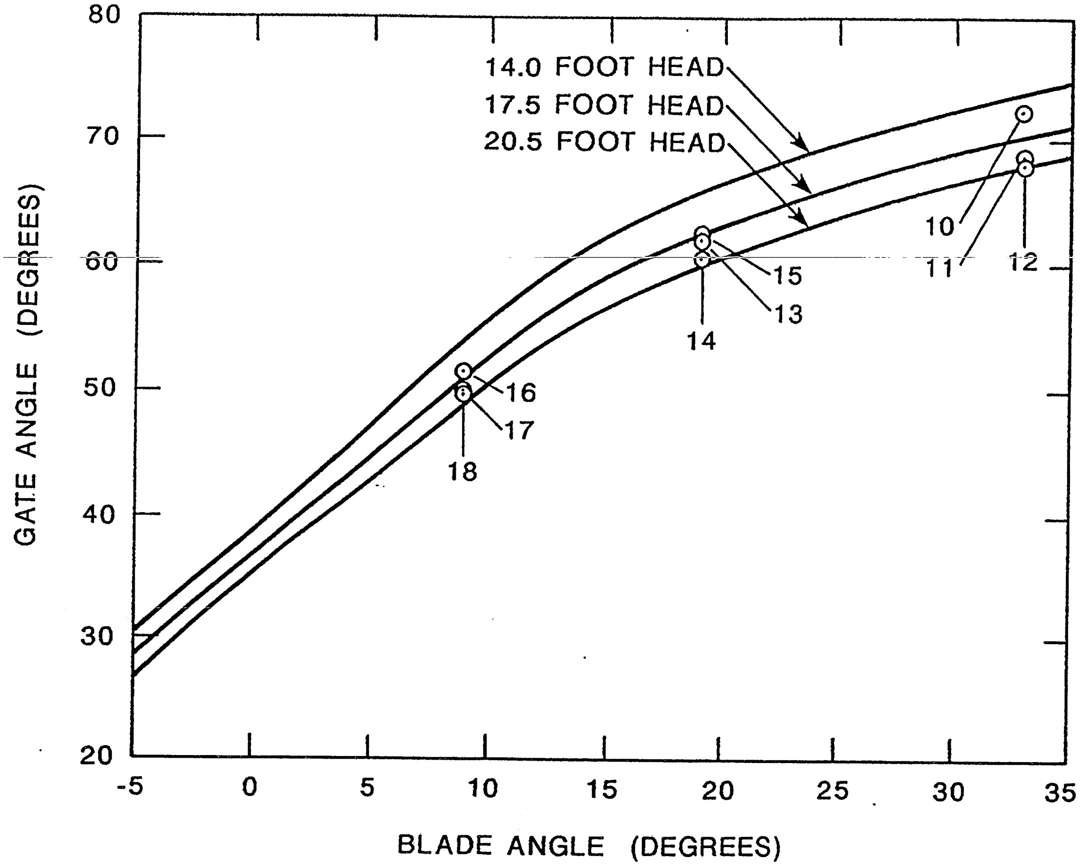


Fig. IV–1. Cam curves and actual acceptance test gate/blade settings for Unit 1.

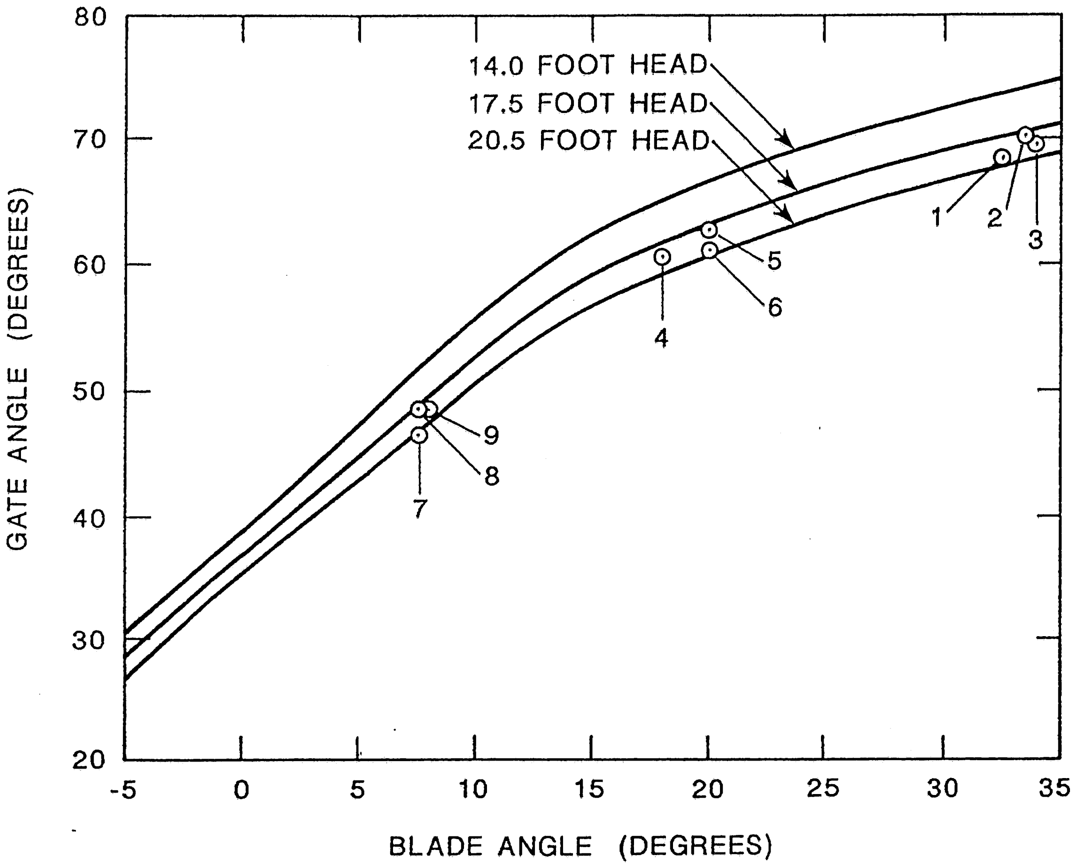


Fig. IV–2. Cam curves and actual acceptance test gate/blade settings for Unit 2.

The following events occurred during a test run:

1) The currentmeters were mounted on the rack and checked with the PC/A–to–D converter to ensure the proper operation of the system. The rack was then lowered in the bulkhead gate slot to the location of the first row of measurements.

2) The Dranetz 808 Power/Demand Analyzer and other powerhouse instrumentation were checked and activated, and test personnel stood by at the gaging/metering stations ready to begin recording data. The Power/Demand Analyzer was set up to print out the average power (to a thousandth of a Megawatt) and power factor for every minute of the run.

3) Prior to bringing the plant on–line for maximum output runs, the headwater level and tailwater level were recorded. The turbine unit was then run up to full capacity and testing could begin after the initial surging (drawdown in the headwater, rise in tailwater) was past.

4) Communication was facilitated by two–way radios, and the Chief of Test initiated the formal commencement of a run.

5) Currentmeter measurements at each designated position of the flow grid lasted slightly over two minutes. At each position the PC Data Acquisition Program compiled and recorded such pertinent information as revolutions per second (RPS) of the currentmeter; samples per second (SPS) of the A–to–D converter; samples–per–pulse (SPP), or the number of A–to–D samples recorded for every electrical pulse generated by the revolving meter (one pulse cycle signifies ten revolutions of the meter); and the values of velocity (FPS) computed using the pre–test calibration equations, unadjusted for flow angles and time–of–test conditions.

6) After processing the data and saving the results in computer memory or on disks, the rack was positioned at the next level of the grid and the process was repeated. Because of time constraints, the "raw" data—consisting of the actual electrical signal sampling record of each currentmeter—was saved only for one of the three runs performed at a given flowrate. This record was only necessary to aid troubleshooting in the event of a currentmeter or wiring malfunction.

7) One head– or tail–water measurement was derived from the average of a rapid succession of five measurements. This rapid succession of measurements was performed at all stations (for point gage readings, steel tape measurements in the gate slot and sundeck, piezometer readings) and was repeated every five minutes or with each row of currentmeter measurements. At any given station, the head– or tail–water measurement for the run was computed as the average of the readings at that station.

8) Water temperature was recorded during a run at the sundeck stilling well location. The water temperature remained virtually

constant at 10° C for the first three days of the tests, and on Saturday, October 22, it fell to between 9° C and 8° C.

9) A run was completed when the results from the last row of currentmeter measurements were compiled and the flow grid was replete with RPS [and unadjusted velocity] measurements. Generally, one run took from about 45 minutes to 1–1/2 hours to complete, depending on whether or not "raw" data was saved.

10) Upon completion, all the data for the run was collected and approximate values of preliminary efficiency were computed on–site.

B. TESTING AGREEMENTS

The following testing agreements were made by most parties prior to initiation of the Acceptance Tests:

1) The headwater elevation used in performance evaluation would be measured by the electronic point gage at the location given in Fig. II–1, upstream of the intake at a point determined from intake model tests, as mentioned in Section II.B.

2) The tailwater elevation used in performance evaluation would be measured by the electronic point gage at the downstream end of the spillway river separation wall, as shown in Fig. II–1 and discussed in Section II.B.

3) Net head in the performance guarantee is defined as the difference in head between a location immediately behind the trash rack and the draft tube outlet. IEC 41 specifies a means of converting tailwater elevation to draft tube outlet head. To get the head immediately behind the trashracks, measured headwater elevation was adjusted according to the results of the St. Cloud hydraulic model study and subsequent analysis. This is included in a letter from John S. Gulliver to Mr. Douglas Spaulding, Warzyn Engineering, appended to this report as Appendix B.

The following testing agreements were made immediately prior to or during the Acceptance Tests by all parties present:

4) Unit 2 was tested at an operating power factor of 1.0. However, the guarantees for the turbine/generator equipment are predicated upon a power factor of 0.8. Consequently, all parties present during the tests agreed that for Unit 2 the power output computed from the record of the Power/Demand Analyzer should be adjusted to a power factor of 0.8, using Figure 15 in the Index Test Report issued by Voith Hydro, Inc. [5]. Unit 1 was tested at a power factor of 0.8, so that no adjustment was required.

5) It was also agreed to by the attendant parties to measure power during the two–turbine combined output tests using the station watt meters for each unit. Further, since headwater elevation was

expected to fall significantly during the two–unit test due to insufficient river discharge, it was difficult to set the wicket gate and blade angle at a specified value for Unit 1, both Units, and Unit 2 in sequence. It was therefore agreed that the two–unit test would be run at the "best estimate" gate setting and blade angle and compared with the output of the full output tests performed individually for Units 1 and 2.

The following decision has been made by the Chief of Test and would require agreement by all pertinent parties if it affected the contract in any way:

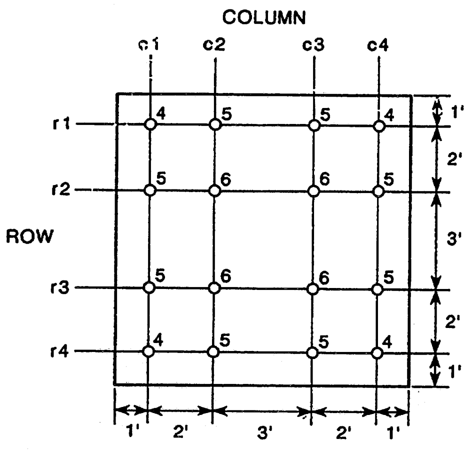
6) IEC 41 states that the arithmetic mean of pre– and post–test calibrations shall be used if they lie inside of normal limits. If not, a special agreement must be made. The differences between the pre– and post–test currentmeter calibrations, already discussed in Section III.A, were consistent and attributable primarily to water temperature differences. Since the water temperature for the post–test calibrations equaled that encountered in the field during the Acceptance Tests, the latter calibrations alone were used.

C. COMPUTATIONS AND RESULTS

The results are tabulated in Table IV–1.

1. Discharge

The discharge was computed using the grid of velocity measurements consisting of 11 points across and 10 points down, as shown in Fig. II–3. The methodology used to compute Q is exhibited in the following simplified example:



(velocities in fps, denoted at grid points)

$v_{c1,r1} = 4$ fps

$v_{c2,r1} = 5$ fps

⋮

$v_{c2,r2} = 6$ fps

⋮

etc.

At the boundaries, the seventh root law shall be used as follows:

$$v_x = VX^{1\ 7}$$

Table IV–1. Data Summary Sheet

Run	Unit	Pretest calibration flow	Post–test calibration flow	g	HWpg	TWpg	Trash rack losses	Exit velocity head	Hn_{pg}
		cfs	cfs	ft/s^2	ft	ft	ft	ft	ft
1	2	3039	3098	32.171	981.308	963.237	0.500	0.639	16.932
2	2	3205	3265	32.171	980.805	963.176	0.500	0.709	16.420
3	2	3200	3259	32.171	980.488	963.194	0.500	0.707	16.087
4	2	1977	2023	32.171	981.662	963.081	0.240	0.272	18.069
5	2	2083	2130	32.171	981.671	963.140	0.240	0.302	17.989
6	2	2087	2134	32.171	981.557	963.076	0.240	0.303	17.938
7	2	1226	1265	32.171	981.713	962.894	0.180	0.106	18.533
8	2	1234	1272	32.171	981.827	962.981	0.180	0.108	18.558
9	2	1271	1309	32.171	981.853	963.007	0.180	0.114	18.552
10	1	3370	3411	32.171	981.475	963.454	0.420	0.774	16.827
11	1	3222	3263	32.171	981.553	963.455	0.420	0.708	16.970
12	1	3107	3148	32.171	981.495	963.394	0.420	0.659	17.022
13	1	2013	2057	32.171	981.653	963.205	0.200	0.282	17.966
14	1	2005	2050	32.171	981.790	963.274	0.200	0.280	18.036
15	1	2050	2095	32.171	981.799	963.300	0.200	0.292	18.007
16	1	1336	1374	32.171	981.467	962.763	0.170	0.126	18.408
17	1	1322	1359	32.171	981.607	962.890	0.170	0.123	18.424
18	1	1323	1361	32.171	981.677	962.933	0.170	0.123	18.451

HW_{pg} = headwater elevation measured by point gage
TW_{pg} = tailwater elevation measured by point gage
Hn_{pg} = net head using point gage measurements

Table IV–1 (cont.)

Run No.	HW_{gs}	TW_{sd}	Intake velocity head at gate slot	Gate slot velocity head vertical	Hn_{gssd}	HW_{pz}	TW_{pz}	Inlet piezometric velocity head	Exit piezometric velocity head	Hn_{pz}
	ft	ft	ft	ft	ft	ft	ft	ft	ft	ft
1	980.939	963.289	0.282	0.011	17.282	980.934	963.246	0.205	0.639	17.254
2	980.295	963.224	0.312	0.011	16.663	980.387	963.176	0.227	0.709	16.729
3	979.978	963.230	0.310	0.011	16.340	980.047	963.177	0.226	0.707	16.389
4	981.495	963.146	0.114	0.000	18.191	981.494	963.128	0.087	0.272	18.180
5	981.471	963.223	0.125	0.003	18.068	981.514	963.203	0.097	0.302	18.106
6	981.349	963.133	0.125	0.003	18.035	981.399	963.103	0.097	0.303	18.090
7	981.639	962.896	0.044	0.000	18.681	981.674	962.883	0.034	0.106	18.719
8	981.743	963.035	0.045	0.001	18.644	981.790	962.989	0.034	0.108	18.727
9	981.747	963.073	0.048	0.001	18.607	981.790	963.025	0.037	0.114	18.688
10	981.038	963.436	0.318	0.011	17.135	981.098	963.466	0.248	0.774	17.106
11	981.140	963.460	0.287	0.007	17.252	981.199	963.451	0.227	0.708	17.267
12	981.079	963.442	0.270	0.007	17.241	981.132	963.388	0.211	0.659	17.296
13	981.491	963.240	0.116	0.001	18.084	981.514	963.240	0.090	0.282	18.082
14	981.597	963.328	0.115	0.001	18.103	981.629	963.319	0.090	0.280	18.120
15	981.603	963.367	0.120	0.001	18.063	981.646	963.364	0.094	0.292	18.084
16	981.396	962.784	0.051	0.002	18.535	981.424	962.760	0.040	0.126	18.579
17	981.543	962.906	0.050	0.002	18.562	981.549	962.900	0.039	0.123	18.565
18	981.613	962.954	0.049	0.002	18.583	981.610	962.957	0.039	0.123	18.568

HW_{gs} = headwater elevation at the gate slot
TW_{sd} = tailwater elevation at the sundeck
Hn_{gssd} = net head using HW_{gs} and TW_{sd}

HW_{pz} = headwater elevation at piezometric taps
TW_{pz} = tailwater elevation at piezometric taps
Hn_{pz} = net head using HW_{pz} and TW_{pz}

Table IV–1 (cont.)

Run No.	Temp. deg C	Specific weight of water psf	Unadjusted power MW	Pre–test calibration power MW	Post–test calibration power MW	Guaranteed overall efficiency at 17.5 ft net head	Guaranteed transformer efficiency at 17.5 ft net head	Power factor adjustment	Blade Angle Computer %	Wicket Gate Angle Computer %
1	10.0	62.393	3.961	3.959	4.055	86.89%	99.28%	0.991	90%	91%
2	10.0	62.393	3.935	3.933	4.028	86.89%	99.28%	0.991	93%	93%
3	10.0	62.393	3.825	3.823	3.915	86.89%	99.28%	0.991	95%	93%
4	10.0	62.393	2.816	2.817	2.875	88.53%	99.18%	0.993	57%	82%
5	10.0	62.393	2.943	2.943	3.006	88.62%	99.19%	0.992	60%	85%
6	10.0	62.393	2.898	2.899	2.959	88.62%	99.19%	0.992	60%	83%
7	10.0	62.393	1.709	1.712	1.734	86.21%	99.03%	0.995	31%	66%
8	10.0	62.393	1.711	1.714	1.736	86.07%	99.02%	0.995	30%	68%
9	10.0	62.393	1.786	1.789	1.814	86.35%	99.04%	0.995	32%	68%
10	10.0	62.393	4.204	4.202	4.305	86.89%	99.28%	1.000	95%	96%
11	10.0	62.393	4.109	4.107	4.207	86.89%	99.28%	1.000	94%	92%
12	10.0	62.393	3.990	3.988	4.085	86.89%	99.28%	1.000	94%	91%
13	10.0	62.393	2.915	2.916	2.977	88.62%	99.19%	1.000	60%	84%
14	10.0	62.393	2.905	2.906	2.967	88.62%	99.19%	1.000	59%	83%
15	10.0	62.393	2.935	2.935	2.998	88.62%	99.19%	1.000	60%	86%
16	9.0	62.398	1.884	1.887	1.915	86.64%	99.04%	1.000	34%	73%
17	8.5	62.400	1.871	1.874	1.901	86.64%	99.04%	1.000	34%	72%
18	8.0	62.402	1.866	1.869	1.896	86.64%	99.04%	1.000	34%	72%

Table IV–1 (cont.)

	Measured Efficiencies Computed using Hn_{pg}			Measured Efficiencies Computed using Hn_{gssd}			Measured Efficiencies Computed using Hn_{pz}		
Run No.	Guaranteed efficiency at Hn	Measured efficiency*	Overall efficiency*	Guaranteed efficiency at Hn	Measured efficiency*	Overall efficiency*	Guaranteed efficiency at Hn	Measured efficiency*	Overall efficiency*
1	86.67%	89.06%	89.02%	86.89%	87.03%	87.91%	86.80%	87.26%	87.94%
2	86.37%	86.86%		86.51%	85.46%		86.55%	85.07%	
3	86.17%	86.55%		86.32%	85.06%		86.35%	84.77%	
4	88.70%	90.46%		88.72%	89.83%		88.72%	89.88%	
5	88.78%	90.13%		88.79%	89.72%		88.80%	89.53%	
6	88.76%	88.85%		88.79%	88.34%		88.80%	88.05%	
7	86.56%	85.25%		86.59%	84.54%		86.59%	84.38%	
8	86.42%	84.76%		86.44%	84.35%		86.46%	83.95%	
9	86.69%	86.08%		86.70%	85.81%		86.72%	85.42%	
10	86.61%	87.25%	90.25%	86.76%	85.54%	89.38%	86.75%	85.69%	89.28%
11	86.69%	88.30%		86.80%	86.75%		86.80%	86.67%	
12	86.72%	88.57%		86.79%	87.38%		86.82%	87.07%	
13	88.77%	93.32%		88.80%	92.68%		88.80%	92.69%	
14	88.79%	92.94%		88.80%	92.58%		88.81%	92.48%	
15	88.78%	92.03%		88.79%	91.74%		88.80%	91.61%	
16	86.93%	87.68%		86.96%	87.05%		86.97%	86.83%	
17	86.93%	87.95%		86.96%	87.27%		86.96%	87.25%	
18	86.94%	87.45%		86.97%	86.79%		86.96%	86.87%	
			89.64%			88.65			88.61

*Adjusted to a net head of 17.5 ft, computed via Eqs. IV–5 and IV–7.

where

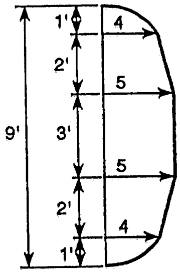
X = distance from the boundary to the point being plotted, in fractional portion of the total distance from boundary to first metering point (X = 1 at first metering point),

V = velocity at first metering point, and

v_x = velocity at any point X.

Note: The average velocity between the last measuring point and the boundary is mathematically determined under the seventh root law to be 7/8 of the velocity at the first metering point V.

Then, for each vertical column of measurements, the average velocity for that column shall be determined as follows:



$$\bar{v}_{c1} = \left\{1' \cdot \frac{7}{8} \cdot v_{c1,r1} + 2' \cdot \left[\frac{v_{c1,r1} + v_{c1,r2}}{2}\right] + 3' \cdot \left[\frac{v_{c1,r2} + v_{c1,r3}}{2}\right]\right.$$

$$\left. + 2' \cdot \left[\frac{v_{c1,r3} + v_{c1,r4}}{2}\right] + 1' \cdot \frac{7}{8} \cdot v_{c1,r4}\right\} / 9' \text{ (height)} = 4.44 \text{ fps}$$

Similarly,

$$\bar{v}_{c2} = 5.42 \text{ fps}$$

$$\bar{v}_{c3} = 5.42 \text{ fps}$$

$$v_{c4} = 4.44 \text{ fps}$$

Then, these vertically–averaged velocities are themselves averaged horizontally to get the areally–averaged velocity for the cross section:

$$\bar{v} = \left[1' \cdot \frac{7}{8} \cdot \bar{v}_{c1} + 2' \cdot \left[\frac{\bar{v}_{c1} + \bar{v}_{c2}}{2}\right] + 3' \cdot \left[\frac{\bar{v}_{c2} + \bar{v}_{c3}}{2}\right]\right.$$

$$\left. 2' \cdot \left[\frac{\bar{v}_{c3} + \bar{v}_{c4}}{2}\right] + 1' \cdot \frac{7}{8} \cdot \bar{v}_{c4}\right] / 9' \text{ (width)} = 4.86 \text{ fps}$$

Finally, $Q = \bar{v} \cdot A = 4.86 \cdot 9' \cdot 9' = 393.66$ cfs.

"Pre–test calibration flow" denotes the discharge as computed in the field using the pre–test calibration equations, without flow angle adjustments.

As discussed in Sections III.A and IV.B, the post–test calibration equations for the currentmeters were subsequently judged to be most applicable to the field measurements, and velocities at the grid points were calculated using these equations. For each unit, at each flowrate tested, there is associated with each grid point a flow angle previously determined from the flow angle measurements. There is consequently a correction factor associated with each grid point which is applied to the velocity determined from the post–test calibration. The correction factor depends on the meter RPS and angle of flow, in accordance with Fig. II–4, and its application yields the true axial component of the velocity. Post–test calibration flow (Q_{adj}) denotes the discharge computed using these velocities. This is the discharge used to compute the unit efficiency during a run.

2. Head

"HW_{pg}" and "TW_{pg}" denote the run–averaged headwater and tailwater readings at the electric point gages, respectively. "HW_{gs}" and "TW_{sd}" denote the run–averaged headwater measured in the gate slot and the run–averaged tailwater measured at the sundeck above the draft tube outlet, respectively. "HW_{pz}" and "TW_{pz}" denote the run–averaged piezometer readings of the headwater and tailwater, respectively.

"Trash rack headloss" (hl_{tr}) denotes headloss across the trash rack. These are contractually agreed upon values which were estimated using information from Idelchick's *Handbook of Hydraulic Resistance* [6], and measurements performed in the hydraulic model study of the St. Cloud Hydroelectric Facility (SAFHL Project Report No. 255) [2]. These are given in Appendix B.

"Exit velocity head" (hv_{exit}) denotes the velocity head at the exit of the draft tube. It is computed as specified by IEC 41 to be

$$hv_{exit} = \frac{\left[\frac{Q_{adj}}{A_{exit}}\right]^2}{2g} \qquad \text{(IV–1)}$$

where A_{exit} is the cross–sectional area of the piezometer taps located immediately upstream of the draft tube exit (483.33 ft^2 in the Voith Hydro, Inc. Index Test Report [5]).

"Intake velocity head at gate slot" (hv_{gs}) denotes the velocity head at the gate slot in the metering plane, approximated as

$$hv_{gs} \approx \frac{1}{110} \sum_{\substack{grid\\points}}^{110} \frac{V^2}{2g} \qquad \text{(IV–2)}$$

where V is the magnitude of the velocity vector at a point. V_a, the axial component, is known from the currentmeter measurements. The "angle" of the vector, ∠, is also known from the flow angle measurements, so

$$V = \frac{V_a}{\cos(\angle)}$$

"Gate slot velocity head correction" (hv_{gsv}) denotes the velocity head correction to be applied at the gate slot. This parameter is meant to account for the component of the velocity vectors in the top row of measurements that is normal to the plane of the gate slot. This plane is oriented at a 20° angle to horizontal. The ratios of vertical to axial components of flow, V_v/V_a, are known at the top row grid points, and the gate slot velocity head correction is then computed as

$$hv_{gsv} = \frac{1}{11} \sum_{\substack{top\\row}}^{11} \frac{\left\{V_a * \left[\sin 20° + \left[\frac{V_v}{V_a}\right] * \cos 20°\right]\right\}^2}{2g} \qquad \text{(IV–3)}$$

"Inlet piezometric velocity head" (hv_{pz}) is the velocity head computed at the location of the upstream (intake) piezometer tap and is computed similar to hv_{exit}, using A_{intake} = 853.83 ft^2, as determined in the as built survey of the intake.

Three methods are used to compute H_n, the net head. "Hn_{pg}" is net head using the point gage measurements, and is computed as

$$Hn_{pg} = HW_{pg} - hl_{tr} - TW_{pg} - hv_{exit}$$

"Hn_{gssd}" is net head using the gate slop and sundeck measurements, and is computed as

$$Hn_{gssd} = HW_{gs} + (hv_{gs} - hv_{gsv}) - TW_{sd} - hv_{exit}$$

"Hn_{pz}" is net head using the piezometric taps, and is computed as

$$Hn_{pz} = HW_{pz} + hv_{pz} - TW_{pz} - hv_{exit}$$

Hn_{pg} is the contractually stipulated value used to verify the guarantees. The other two values are provided as additional information, and were used to check and verify the point gage readings.

3. Power

"Unadjusted power" (P_{unadj}) denotes the mean power recorded by the Power/Demand Analyzer during a run:

$$P_{unadj} = \frac{1}{n} \sum^{n} P_{m} \qquad \text{(IV–4)}$$

where there are n measurements of power output, P_m, during the run.

"Pre–test calibration power" (P_{precal}) is computed as

$$P_{precal} = P_{unadj} * C_{1_{pre}} + C_{0_{pre}}$$

where the pre–test calibration of the Dranetz is reflected in the values of the constants, $C_{1_{pre}} = .997718$ and $C_{0_{pre}} = 7159.317$. Similarly, "Post–test calibration power" ($P_{postcal}$) is computed as

$$P_{postcal} = P_{unadj} * C_{1_{post}} + C_{0_{post}}$$

where the post–test calibration constants are $C_{1_{post}} = 1.030390$ and $C_{0_{post}} = -26706.3$. For the above calibration equations, power is expressed in units of Watts. As per IEC 41, the arithmetic mean of P_{precal} and $P_{postcal}$ was used to compute efficiency.

4. Efficiency

The "guaranteed efficiencies" are those found in Tables 1 through 4 of Appendix C, taken from Guarantees and Performance Data of the Conformed Technical Provisions and Related Data for Generating Equipment [7], prepared by Warzyn Engineering, October 1986. For Unit 2, a "power factor adjustment" was applied to reference the data measured at 1.0 power factor to 0.8 power factor, using Figure 15 in the Voith Hydro, Inc. Index Test Report [5].

Individual run efficiency, adjusted to 17.5 ft net head, was computed using the following formula:

$$\text{Eff} = \frac{737.5 * \dfrac{(P_{\text{precal}} + P_{\text{post cal}})}{2} \begin{bmatrix}\text{Guaranteed}\\ \text{efficiency}\\ \text{at 17.5 ft.}\end{bmatrix} \begin{bmatrix}\text{Transformer}\\ \text{efficiency at}\\ \text{17.5 ft, rated power}\end{bmatrix} \begin{bmatrix}\text{Power}\\ \text{factor}\\ \text{adjustment}\end{bmatrix}}{(Q_{adj})(H_n)(\gamma)(\text{Guaranteed efficiency at } H_n)} \qquad \text{(IV-5)}$$

Hn_{pg} was used as net head as per contractual agreement. For additional information, Hn_{gssd} and Hn_{pz} were also used in the formula to yield efficiencies based on those net head values.

5. Maximum Unit Power Output

Maximum Unit Power Output was computed using the following formula:

$$\begin{matrix}\text{Maximum}\\ \text{Unit}\\ \text{Power}\\ \text{Output}\end{matrix} = \left[\frac{\begin{matrix}\text{Pre-test calibrated}\\ \text{power output}\end{matrix} + \begin{matrix}\text{Post-test calibrated}\\ \text{power output}\end{matrix}}{2}\right]$$

$$\times \left[\frac{\begin{matrix}\text{Guaranteed efficiency}\\ \text{at 17.5 net head}\end{matrix}}{\begin{matrix}\text{Guaranteed efficiency}\\ \text{at net head}_{pg}\end{matrix}}\right] \times \left[\frac{17.5}{\text{net head}_{pg}}\right]^{1.5} \qquad \text{(IV-6)}$$

The above equation was also used for computation of the power outputs in the two unit versus sum of individual units test, Run 19, with the lone modification being the replacement of Hn_{pg} with Hn_{gssd}.

6. Weighted Average Efficiency

The weighted average efficiency of each unit was computed as follows:

$$E = \frac{(2\ E_{100} + 2\ E_{max} + E_{40})}{5} \qquad (IV\text{–}7)$$

where

E_{100} = efficiency at 100 percent of rated output at 17.5 ft head

E_{max} = maximum efficiency at 17.5 ft net head, and

E_{40} = efficiency at 40 percent of rated output at 17.5 net head

Of the three tests at each operating point, one was chosen as yielding an E value (i.e., E_{100}) for use in the equation. The E_{100} value was selected as the best efficiency of the three runs because the guaranteed maximum output at 17.5 ft net head was exceeded in all three runs, as seen in Table IV–2. The E_{max} was selected as the best efficiency of the three runs, by definition. The E_{40} was selected as the run with power output (corrected to 17.5 ft net head) closest to 1670 kW, the 40% guaranteed output.

Table IV–2. Maximum Unit Outputs

Unit	Run	Pre–Test Calibration Adjusted Power	Post–Test Calibration Adjusted Power	Guarantee Listed Efficiency at 17.5 ft Net Head	Net Head Ptg	Guarantee Listed Efficiency at Net $Head_{pg}$	17.5 ft Power Output (kw)
1	10	4.206	4.305	86.89	16.827	86.61	4528
	11	4.111	4.207	86.89	16.970	86.69	4365
	12	3.988	4.085	86.89	17.022	86.72	4216
2	1	3.963	4.055	86.89	16.932	86.67	4223
	2	3.937	4.028	86.89	16.420	86.37	4408
	3	3.827	3.915	86.89	16.087	86.17	4428

Based on the above criteria, the computations were based on the following runs:

	Unit 1	Unit 2
E_{100}	Run 12	Run 1
E_{max}	Run 13	Run 4
E_{40}	Run 18	Run 9

D. UNCERTAINTY ANALYSIS

Every measurement is attended by unavoidable uncertainty in accuracy and precision. The uncertainty in a given measurement should be provided by an uncertainty analysis. If a result, R, is related to measurements $x_1, x_2, \ldots x_n$ by the function f,

$$R = f(x_1, x_2, x_3, \ldots, x_n),$$

then the uncertainty in that result, for the same confidence limit as the parameter uncertainties, is

$$\delta R = \left\{ \left[\frac{\partial R}{\partial x_1} \delta x_1 \right]^2 + \left[\frac{\partial R}{\partial x_2} \delta x_2 \right]^2 + \ldots + \left[\frac{\partial R}{\partial x_n} \delta x_n \right]^2 \right\}^{1\ 2} \qquad \text{(IV-8)}$$

This is true if each of the variable parameter values, x_i, is considered to be 1) unrelated (i.e., independent of each other), 2) from a Gaussian population of possible values, and 3) the uncertainty interval quoted for each variable must be quoted for the same "odds". Thus, the equation

$$x_i = \hat{x}_i + \delta x_i \qquad (P = 95\%) \qquad \text{(IV-9)}$$

means that the expected value of x_i is $\hat{x}_i$, and there is a 19 out of 20 chance that the actual value of x_i will lie within $\delta\hat{x}_i$ of that value. In fractional, nondimensional form, the uncertainty may be expressed as

$$\left[\frac{\delta R}{R} \right]^2 = \left[\frac{\partial \ln R}{\partial \ln x_1} \frac{\delta x_1}{x_1} \right]^2 + \left[\frac{\partial \ln R}{\partial \ln x_2} \frac{\delta x_2}{x_2} \right]^2 + \ldots + \left[\frac{\partial \ln R}{\partial \ln x_n} \frac{\delta x_n}{x_n} \right]^2$$

$$= \left[\frac{\delta x_1}{R} \frac{\partial R}{\partial x_1} \right]^2 + \left[\frac{\delta x_2}{R} \frac{\partial R}{\partial x_2} \right]^2 + \ldots + \left[\frac{\delta x_n}{R} \frac{\partial R}{\partial x_n} \right]^2 \qquad \text{(IV-10)}$$

For the special case where the result R can be written as a product of terms, each raised to some power

$$R = x_1^a x_2^b x_3^c \ldots x_N^n$$

this Relative Uncertainty, $\delta R/R$, can be found as

$$\left[\frac{\delta R}{R}\right]^2 = \left[a\ \frac{\delta x_1}{x_1}\right]^2 + \left[b\ \frac{\delta x_2}{x_2}\right]^2 + \ldots + \left[n\ \frac{\delta x_n}{x_n}\right]^2 \qquad \text{(IV-11)}$$

Since unit operating efficiencies are the primary subject of Acceptance Tests, it becomes necessary to determine the uncertainty associated with the computed values. Essentially,

$$E = f(P,Q,H), \text{ and}$$

$$\frac{\delta E}{E} = \left\{\left[\frac{\delta P}{P}\right]^2 + \left[\frac{\delta Q}{Q}\right]^2 + \left[\frac{\delta H}{H}\right]^2\right\}^{1\ 2} \qquad \text{(IV-12)}$$

The uncertainties for 95% confidence limits associated with the determination of P, Q, and H are derived in the following analysis.

1. Power

For each run, as specified by IEC41,

$$P = x\bar{P}_{pre} + (1 - x)\ \bar{P}_{post} = x\left\{\left[\frac{1}{n}\ \overset{n}{\Sigma}\ P_m\right]\ C_{1_{pre}} + C_{0_{pre}}\right\}$$

$$+ (1 - x)\left\{\left[\frac{1}{n}\ \overset{n}{\Sigma}\ P_m\right]\ C_{1_{post}} + C_{0_{post}}\right\} \qquad \text{(IV-13)}$$

where x is a weighting factor between 0 and 1; where n is the number of power output measurements during a run; P_m is a value of power recorded by the Power/Demand Analyzer; $C_{1_{pre}}$ and $C_{0_{pre}}$ are coefficients derived from the pre–test calibration of the Analyzer; and $C_{1_{post}}$ and $C_{0_{post}}$ are derived from the post–test calibration.

$$\delta P^2 \approx \left\{\left[\frac{1}{60}\overset{60}{\Sigma}\ P_m\right]C_{1_{pre}}\ \delta x - \left[\frac{1}{60}\overset{60}{\Sigma}\ P_m\right]C_{1_{post}}\ \delta x\right\}^2$$

$$+ \left\{\left[\frac{x}{60}\overset{60}{\Sigma}\ P_m\right]\delta C_{1_{pre}}\right\}^2 + \left\{\left[\frac{1-x}{60}\overset{60}{\Sigma}\ P_m\right]\delta C_{1_{post}}\right\}^2$$

$$60\left\{\frac{xC_{1_{pre}}}{60}\ \delta P_m + \frac{(1-x)C_{1_{post}}}{60}\ \delta P_m\right\}^2$$

$$\approx \{(\bar{P}_{pre} - \bar{P}_{post})\delta x\}^2$$

$$+ \{x\bar{P}_m \delta C_{1_{pre}}\}^2 + \{(1-x)\bar{P}_m \delta C_{1_{post}}\}^2$$

$$+ \frac{1}{60}\{xC_{1_{pre}}\delta P_m + (1-x)C_{1_{post}}\delta P_m\}^2 \qquad \text{(IV–14)}$$

The Code implicitly sets $x = 0.5$, but the two calibrations are sufficiently divergent that an uncertainty of $\delta x = 0.5$ is assigned to it.

From regression analyses of the calibration data,

$C_{1_{pre}} = 0.997718;$ $\delta C_{1_{pre}} = 0.003309;$

$C_{1_{post}} = 1.030390;$ $\delta C_{1_{post}} = 0.010287.$

The Power/Demand Analyzer records power output to the nearest Kilowatt, so $\delta P_m = 0.0005$ MW.

The following values are compiled for power output (in MW)

Operating Point	$\bar{P}_m$	$\bar{P}_{pre}$	$\bar{P}_{post}$	$\bar{P}_{test}$
Full Capacity	4.004	4.002	4.099	4.051
Peak Eff.	2.902	2.903	2.964	2.934
40% Capacity	1.805	1.808	1.833	1.821

Then using Eq.
V–14, we derive the following uncertainties

Operating Point	$\frac{\delta P}{P}$
Full Cap y	± 1.31 %
Peak Eff.	± 1.17 %
40% Cap y	± 0.87 %

2. Discharge

$$Q = A_{cs} \cdot v_{av} \tag{IV–15}$$

where A_{cs} = area of metering cross section; v_{av} = average cross–sectional velocity = f(calibrations; number of pulses, p, in time, t; time of measurement, t; boundary law; shape of profile between grid points; flow angles; flow angle correction factors). <u>Calibration, pulse count, and time of measurement uncertainties</u> are dealt with first. We may approximate v_{av} in any of a number of ways, such as

$$v_{av} \approx \frac{1}{110} \sum_{\substack{\text{grid}\\ \text{points;}\\ \text{i–rows,}\\ \text{j–columns}}}^{110} v_{ij} \approx \frac{1}{110} \sum_{\substack{\text{eleven}\\ \text{current–}\\ \text{meters;}\\ \text{j–columns}}}^{11} c \sum^{10} \frac{P}{t}$$

$$\approx \frac{1}{110} \sum_{\substack{\text{ten}\\ \text{times;}\\ \text{i–rows}}}^{10} \frac{1}{t_i} \sum^{11} \frac{p_{ij}c}{t} \approx \frac{1}{110} \sum_{\substack{\text{pulses}\\ \text{recorded}\\ \text{at grid}\\ \text{points in}\\ \text{time t}}}^{110} \frac{p_{ij}c}{t} \tag{IV–16}$$

where c is a meter–dependent constant derived from the currentmeter calibrations. Then

$$\delta v_{av}^2 \approx \sum_{j}^{11} \left[\frac{\delta c_j}{11}\, pt^{-1}\right] + \sum_{i}^{10} \left[\frac{\delta t_i}{10}\, t_i^{-2}\, cp\right]^2 + \sum^{110} \left[\frac{\delta p_{ij}}{110}\, ct^{-1}\right]^2$$

$$\approx \frac{(\delta c\ pt^{-1})^2}{11} + \frac{(\delta t\ t^{-2}cp)^2}{10} + \frac{(\delta p\ ct^{-1})^2}{110} \tag{IV–17}$$

so that

$$\left[\frac{\delta v_{av}}{v_{av}}\right]_{cal,p,\&t} \approx \frac{1}{11}\left[\frac{\delta c}{c}\right]^2 + \frac{1}{10}\left[\frac{\delta t}{t}\right]^2 + \frac{1}{110}\left[\frac{\delta p}{p}\right]^2 \qquad \text{(IV–18)}$$

The number of pulses for a propeller meter may be derived as

$$p \approx \left[\frac{v_{av}}{4}\right] t \ ,$$

and

$$\delta p \approx \frac{\left[\frac{v_{av}}{4}\right]}{SPS} \ ,$$

where SPS is the samples per second. Therefore,

$$\frac{\delta p}{p} = \frac{1}{(t)(SPS)} = \frac{1}{(127)(46.9)} = 1.68\times10^{-4} \ ,$$

which is independent of v. Also, the time of measurement is

$$t = 127 \text{ seconds},$$

and from the computer and associated circuitry,

$$\delta t = .05 \text{ seconds},$$

so

$$\frac{\delta t}{t} \approx 3.94\times10^{-4} \ ,$$

which is also independent of v.

Regression analyses applied to the post–test currentmeter calibrations yield the results shown in Table IV–3. With only three calibrations per meter, the standard deviation of the calibration coefficient, c, is multiplied by a fairly large student's t value to get the 95% confidence interval. $\delta c/c$

Table IV-3. Currentmeter Coefficient Uncertainty from Post-Test Calibrations. Three Tests Result in Two Degrees of Freedom.

Meter No.	c at 40% output and peak	S_c $(\times 10^3)$	degrees of freedom	t at 95%	t S_c $(\times 10^3)$	c at full output	S_c $(\times 10^3)$	degrees of freedom	t at 95%	t S_c $(\times 10^3)$
725	.43	1.31	2	4.303	5.64	.46	0.42	2	4.303	1.81
738	.44	0.23	2	4.303	0.99	.46	0.75	2	4.303	3.23
747	.43	1.84	2	4.303	7.92	.45	0.70	2	4.303	3.01
748	.44	2.06	2	4.303	8.86	.45	1.01	2	4.303	4.35
750	.43	0.21	2	4.303	0.90	.46	0.06	2	4.303	0.26
752	.44	2.10	2	4.303	9.04	.46	1.16	2	4.303	4.99
753	.44	3.85	2	4.303	16.57	.46	1.09	2	4.303	4.69
755	.45	4.89	2	4.303	21.04	.46	0.38	2	4.303	1.64
770	.43	3.36	2	2.776	9.33	.46	0.65	2	4.303	2.80
772	.43	2.14	2	2.776	5.94	.45	1.14	2	4.303	4.91
775	.44	1.69	2	4.303	7.27	.46	2.22	3	3.182	7.06
mean	.44				8.50	.46				3.52

$\frac{\delta c}{c} \approx 0.850/0.44 = 1.93\%$ $\frac{\delta c}{c} \approx 0.352/0.46 = 0.77\%$

S_c = standard deviation of the coefficient c determined by calibration.

t = student's t

$\delta c = t\ S_c$

was determined for each of the three flows measured, and Eq. IV-20 is used to get $(\delta v_{av}/v_{av})_{cal,p,\&t}$:

Operating Point	$\frac{\delta c}{c}$	$\left[\frac{\delta v_{av}}{v_{av}}\right]_{cal,p,\&t}$
Full	0.0077	± 0.23%
Peak	0.0193	± 0.58%
40%	0.0193	± 0.58%

The mean velocity v_m in the zone between the boundary and the first metering point is given by the relation

$$v_m = \frac{7}{8} v_1$$

corresponding to the application of a "1/7th law" for the boundary layer profile. This is uncertain, however, and the actual profile may exhibit between a 1/5th law and a 1/10th law. This will impact the calculated discharge, and the uncertainty in v_{av} resulting from the uncertainty in the boundary law application is found to be

$$\left[\frac{\delta v_{av}}{v_{av}}\right]_{\substack{\text{boundary}\\ \text{law}}} = \pm\ 0.40\ \%$$

This uncertainty is independent of v_{av}.

In the discharge computations, a linear velocity profile is assumed between the grid points. The actual profile will, of course, be differentiable, and the uncertainty inherent in the linear profile assumption was estimated by hand fitting a curve to a portion of the data to be

$$\left[\frac{\delta v_{av}}{v_{av}}\right]_{\text{profile}} = \pm\ 0.08\%$$

This uncertainty is also independent of v_{av}.

It is estimated that the angle of flow at any given grid point may actually be ± 10° from what it is measured to be. However, the effect of this random uncertainty over the entire cross–section (110 grid points) is such that a perturbation of $\delta\angle^\circ = 10^\circ/\sqrt{110} \approx 2^\circ$ may be applied to every grid point flow angle to determine the uncertainty δv_{av} associated therewith. These are tabulated as follows:

Operating Point	$\left[\frac{\delta v_{av}}{v_{av}}\right]_{\angle^\circ}$
Full, Unit 1	± 0.06%
Full, Unit 2	± 0.09%
Peak, Unit 1	± 0.04%
Peak, Unit 2	± 0.05%
40%, Unit 1	± 0.01%
40%, Unit 2	± 0.02%

There is also an uncertainty $\delta C\angle^\circ$ in the correction factors $C\angle^\circ$ which are applied to grid point velocities to account for the flow angles. The uncertainty $\delta C\angle^\circ$ is found from the CDE/PUD report (2) to be a function of $\angle^\circ$, such that

$$\delta C\angle^\circ \approx 4.27\times10^{-2}(\angle^\circ)$$

The correction factors at each grid point were perturbed so that

$$v_{a_{i,j}(C\angle^\circ+\delta C\angle^\circ)} = v_{i,j_{unadj}}\,[1 + .01(C\angle^\circ + \delta C\angle^\circ)]$$

where $C\angle^\circ$ and $\delta C\angle^\circ$ denote percentage corrections to the velocity, and from resulting uncertainties in δv_{av} the table below is constructed:

Operating Point	$\left[\frac{\delta v_{av}}{v_{av}}\right]_{C\angle^\circ}$
Full, Unit 1	± 0.28%
Full, Unit 2	± 0.49%
Peak, Unit 1	± 0.22%
Peak, Unit 2	± 0.40%
40%, Unit 1	± 0.16%
40%, Unit 2	± 0.36%

The uncertainties are combined as follows:

$$\left[\frac{\delta v_{av}}{v_{av}}\right]^2 = \left[\frac{\delta v_{av}}{v_{av}}\right]^2_{cal,p,\&t} + \left[\frac{\delta v_{av}}{v_{av}}\right]^2_{\substack{\text{boundary}\\ \text{law}}}$$

$$+ \left[\frac{\delta v_{av}}{v_{av}}\right]^2_{profile} + \left[\frac{\delta v_{av}}{v_{av}}\right]^2_{\angle^\circ} + \left[\frac{\delta v_{av}}{v_{av}}\right]^2_{C\angle^\circ}$$

resulting in the following overall uncertainties for average velocity:

Operating Point	$\left[\frac{\delta v_{av}}{v_{av}}\right]$
Full, Unit 1	± 0.55%
Full, Unit 2	± 0.68%
Peak, Unit 1	± 0.74%
Peak, Unit 2	± 0.82%
40%, Unit 1	± 0.73%
40%, Unit 2	± 0.80%

There is an <u>uncertainty in A_{cs}</u> attributable primarily to construction tolerances and the fact that the roof "point" is actually the intersection of the vertical gate slot front wall and the roof tangent. Vertically, the uncertainty is estimated to be .1', and horizontally, it is estimated at 1/2". Then since $A_{cs} = L_h \cdot L_v$,

$$\frac{\delta A_{cs}}{A_{cs}} = \left\{\left[\frac{\delta L_h}{L_h}\right]^2 + \left[\frac{\delta L_v}{L_v}\right]^2\right\}^{1\ 2} \approx \left\{\left[\frac{.5}{358}\right]^2 + \left[\frac{1.2}{314}\right]^2\right\}^{1\ 2} = 0.51\%$$

Finally, since $Q = A_{cs} \cdot v_{av}$

$$\frac{\delta Q}{Q} = \left\{\left[\frac{\delta A_{cs}}{A_{cs}}\right]^2 + \left[\frac{\delta V_{av}}{V_{av}}\right]^2\right\}^{1\ 2}$$

and the following results are derived for <u>flow rate uncertainty</u>:

Operating Point	$\left[\frac{\delta Q}{Q}\right]$
Full, Unit 1	± 0.69%
Full, Unit 2	± 0.79%
Peak, Unit 1	± 0.85%
Peak, Unit 2	± 0.92%
40%, Unit 1	± 0.84%
40%, Unit 2	± 0.90%

3. Head

The net head on the turbine generator unit is calculated from the equation

$$H_n = HW_{pg} - h\ell_{tr} - TW_{pg} - hv_{exit}$$

Intake head losses , $h\ell_{tr}$, are calculated as per contractual agreement, and thus do not have an associated uncertainty. Therefore,

$$\frac{\delta H_n}{H_n} = \frac{\{\delta HW_{pg}^2 + \delta TW_{pg}^2 + \delta hv_{exit}^2\}^{1\ 2}}{H_n}$$

HW_{pg} and TW_{pg} are each averaged from about 50 measurements, each measurement having an uncertainty of about ± 0.01 ft. Then

$$\delta HW_{pg} = \delta TW_{pg} \approx \frac{0.01}{\sqrt{50}} = \pm\ 0.00141 \text{ ft}$$

Since

$$hv_{exit} = \frac{\left[\dfrac{Q}{A_{exit}}\right]^2}{2g}$$

then

$$\frac{\delta hv_{exit}}{hv_{exit}} = \left\{\left[2\ \frac{\delta Q}{Q}\right]^2 + \left[2\ \frac{\delta A_{exit}}{A_{exit}}\right]^2\right\}^{1\ 2}$$

where $\delta Q/Q$ has been previously estimated and $\delta A_{exit}/A_{exit}$ will be computed similar to $\delta A_{cs}/A_{cs}$:

$$\frac{\delta A_{exit}}{A_{exit}} \approx \left\{2\ \left[\frac{\delta L}{L}\right]^2\right\}^{1\ 2} = \left\{2\ \frac{\delta L^2}{A_{exit}}\right\}^{1\ 2} = \left\{2\ \frac{5^2}{483.33 \cdot 144}\right\}^{1\ 2} = \pm\ 0.27\%$$

Then, a table is again constructed:

Operating Point	$\frac{\delta hv_{exit}}{hv_{exit}}$	hv_{exit}	δhv_{exit}	H_n	$\frac{\delta H_n}{H_n}$
Full, Unit 1	± 1.48%	.71	± 0.0105	16.94	± 0.06%
Full, Unit 2	± 1.67%	.69	± 0.0115	16.48	± 0.07%
Peak, Unit 1	± 1.78%	.28	± 0.0050	18.00	± 0.03%
Peak, Unit 2	± 1.92%	.29	± 0.0056	18.00	± 0.03%
40%, Unit 1	± 1.76%	.12	± 0.0021	18.43	± 0.02%
40%, Unit 2	± 1.88%	.11	± 0.0021	18.55	± 0.02%

4. Efficiency

Having compiled the relative uncertainties $\delta P/P$, $\delta Q/Q$, and $\delta H/H$, also denoted in the Code as f_P, f_Q, and f_H, the relative uncertainty in efficiency f_E is computed as:

$$f_E = \sqrt{f_P^2 + f_Q^2 + f_H^2}$$

These values are tabulated in Table IV–4.

Table IV–4. Efficiency and Parameter Uncertainties for the Acceptance Tests and IEC 41.

	f_p,%	f_Q,%	f_H,%	f_η,%
Full,1	1.31	.69	.06	1.48
Full,2	1.31	.79	.07	1.53
Peak,1	1.17	.85	.03	1.45
Peak,2	1.17	.92	.03	1.49
40%,1	.87	.84	.02	1.21
40%,2	.87	.90	.02	1.25
CODE "probable"	.8	1.0	.2	1.30

V. CONCLUSIONS

A. GUARANTEED EFFICIENCY

The test results of each unit are summarized in Table IV–1, except for those listed below.

The weighted average efficiency of Unit 1 at 17.5 ft net head, E_1 = 90.25%.

The weighted average efficiency of Unit 2 at 17.5 ft net head, E_2 = 89.02%.

The Overall Combined Effective Efficiency of the Generating Equipment, $E_{Eff} = (E_1 + E_2)/2 = 89.64\%$ at 17.5 ft net head.

The guaranteed E_{Eff} was 87.2% at 17.5 ft net head.

B. GUARANTEED MAXIMUM OUTPUTS

The maximum individual outputs are summarized in Table IV–2. The maximum output of Unit 1 (adjusted to 17.5 ft net head) was 4528 kW at the generator terminals. The maximum output of Unit 2 (adjusted to 17.5 ft) was 4428 kW at the generator terminals. Guaranteed maximum output was 4175 kW.

C. TWO UNIT VERSUS ONE UNIT GUARANTEE

The two unit versus one unit guarantee is summarized in Table V–1. The results are as follows:

Two Unit Test. Run 19, power adjusted to 17.5 ft net head

Unit 1 (100% Gate, 95% Blade)	4471 kW*
Unit 2 (95.5% Gate, 96% Blade)	4422 kW*
Total Output	8893 kW

Each Unit Individually. Power adjusted to 17.5 ft net head.

Unit 1 (Run 10, 96% Gate, 95% Blade)	4399 kW*
Unit 2 (Run 3, 93% Gate, 95% Blade)	4326 kW*
Total Output	8725 kW

---

*Adjusted using net head as measured between the gate slot and sundeck because water level variation during Run 19 rendered the pt. gage measurements useless.

Table V–1. Two Unit vs Combined Individual Unit Output Test

Run	Unit	H.W.$_{gs}$	T.W.$_{sd}$	Horizontal Gate Slot Velocity Head	Vertical Gate Slot Velocity Head	Exit Velocity Head	Net Head$_{gssd}$	Guarantee Listed Efficiency at 17.5 ft Net Head	Guarantee Listed Efficiency at Net Head$_{gssd}$	Unadjusted KW	Adjusted KW
19	1	980.975	964.177	.318	.011	.774	16.331	86.89	86.31	4004	4471
19	2	980.884	964.177	.310	.011	.707	16.299	86.89	86.30	3948	4422
10	1	981.038	963.436	.318	.011	.774	17.135	86.89	86.76	4256	4399
3	2	979.978	963.230	.310	.011	.707	16.340	86.89	86.17	3871	4326

$$\frac{\text{Two Unit Output}}{\text{Unit 1 + Unit 2 Output}} = \frac{8893}{8725} = 1.019$$

The two unit combined output is 1.9% higher than the sum of each unit individually. This is probably due to differences in wicket gate setting.

VI. REFERENCES

1. International Electrotechnical Commission, Publication 41: *International Code for the Field Acceptance Tests of Hydraulic Turbines*, 1963.

3. Gulliver, J. S., Dahlin, W. Q., and Woods, J. L., "Intake Model Study for the St. Cloud Hydroelectric Project," Project Report No. 255, St. Anthony Falls Hydraulic Laboratory, April, 1987.

3. *Handbook of Chemistry and Physics*, 54th Ed., the CRC Press, 1973.

4. "Columbia River Turbine Discharge Rating Program," North Pacific Division, Corps of Engineers, Portland, Oregon; Public Utility District of Grant County, Ephrata, Washington; and Public Utility District No. 1 of Chelan County, Wenatchee, Washington; March 1967.

5. Byrne, M., "Voith Hydro, Inc. Index Test Report," Voith Hydro, Inc., June 1988.

6. Idel'Chik, I. E., *Handbook of Hydraulic Resistance*, Hemisphere Publishing Corp., Washington, D.C., 1986.

APPENDIX A

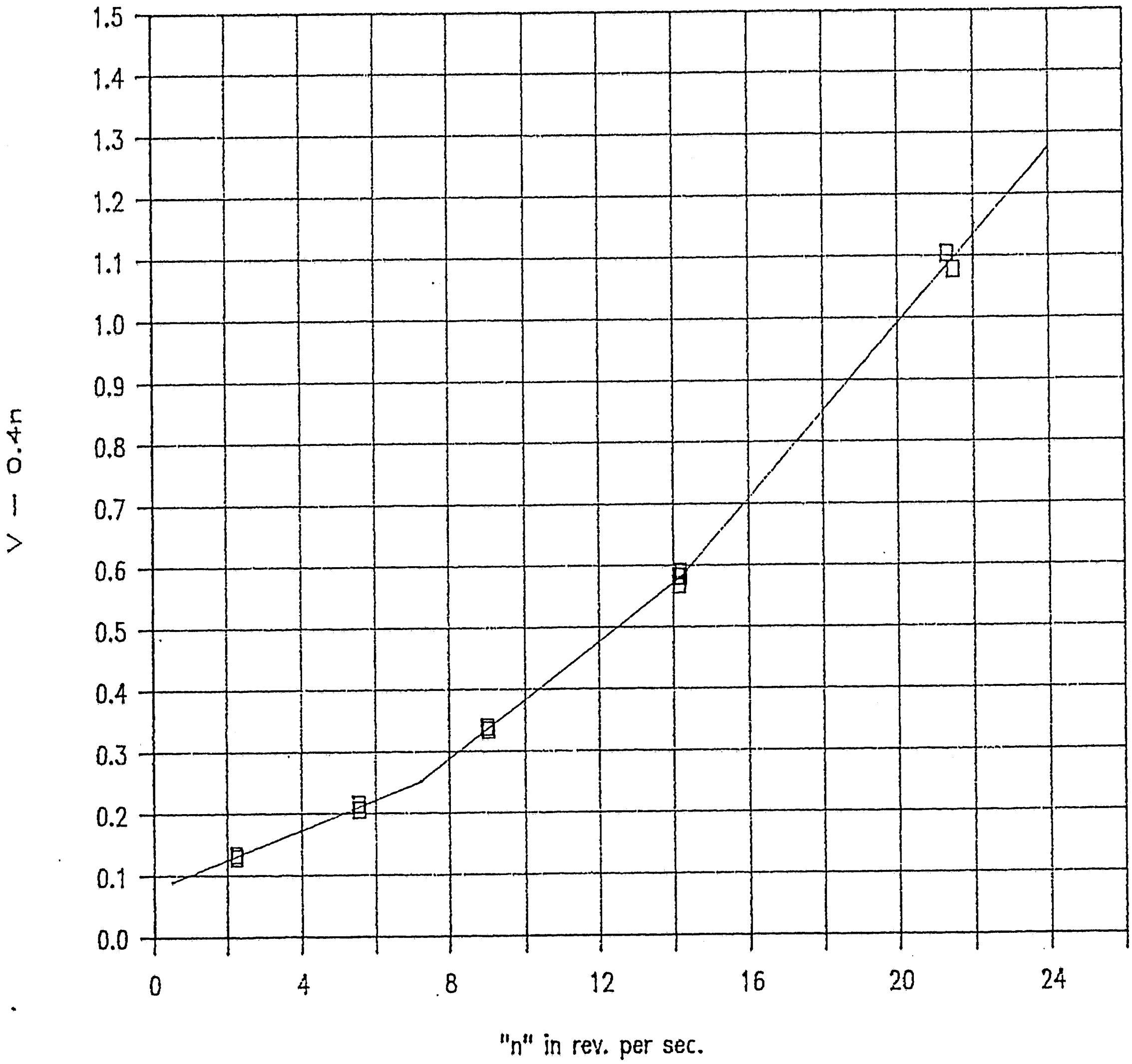
Pre–Test and Post–Test Currentmeter Calibration Curves

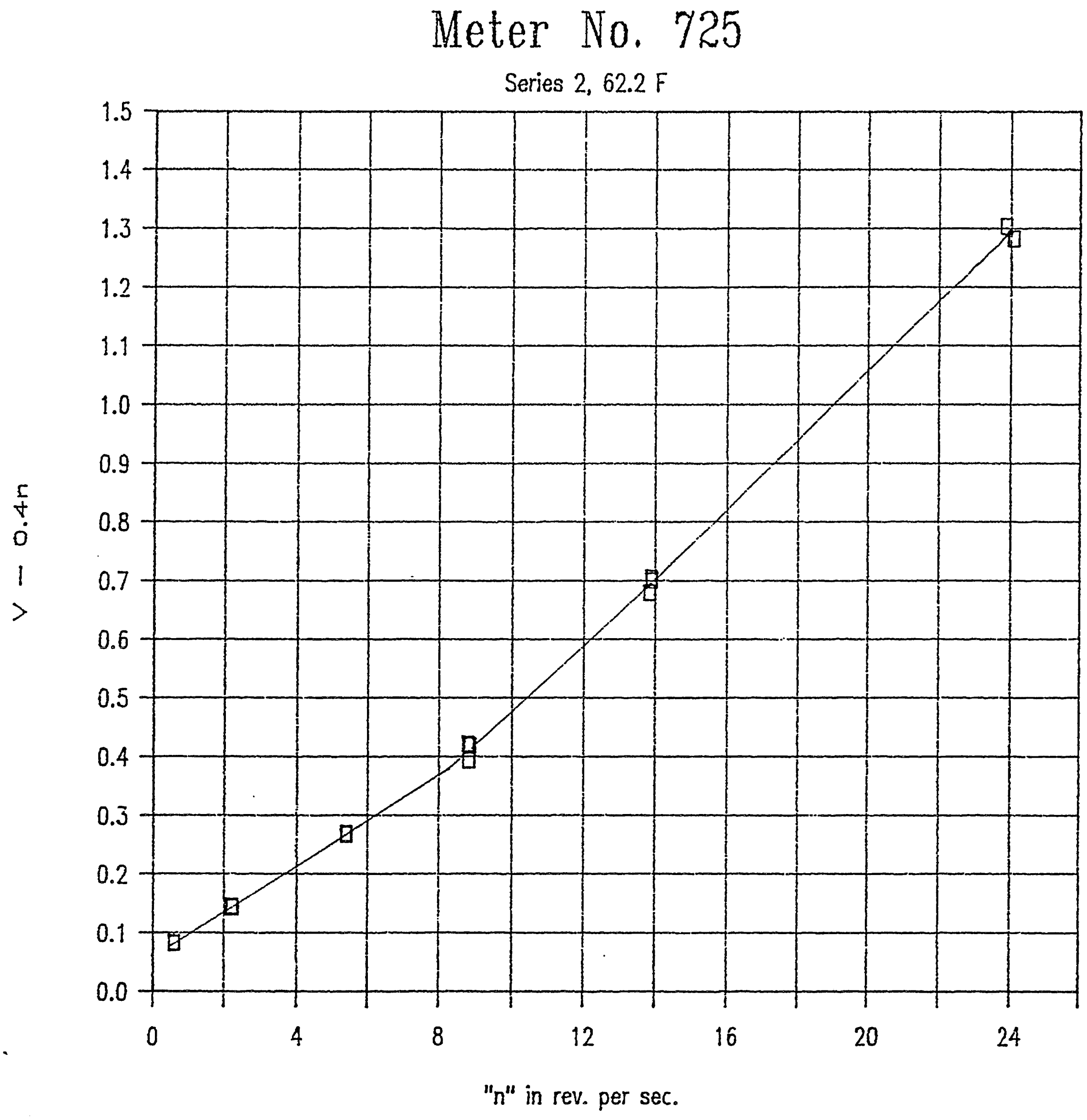
Pre-Test Currentmeter Calibration Curves

May 12 to May 20, 1988

Meter No. 695

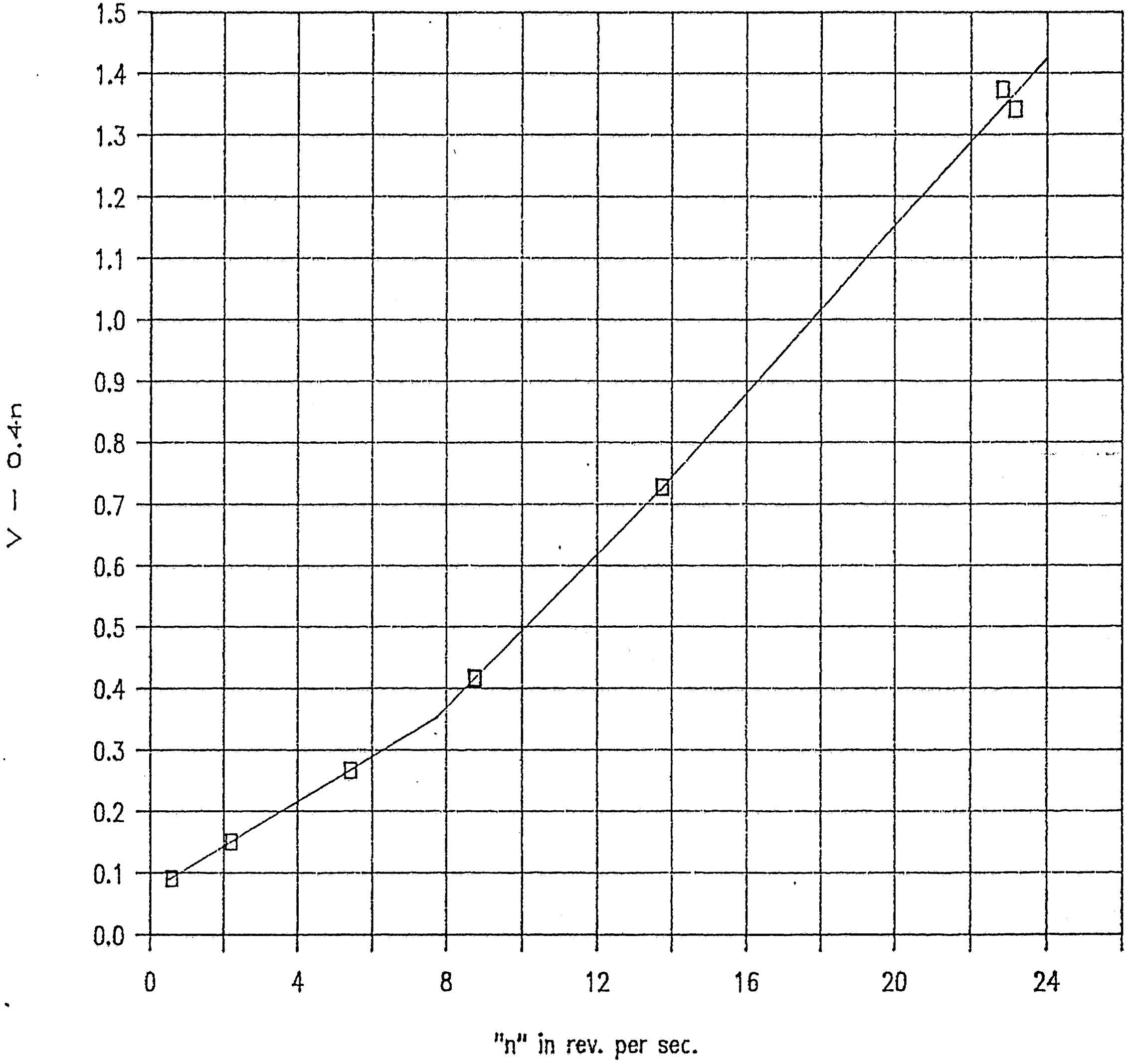
Series 4, 61.2 F




Meter No. 725
Series 2, 62.2 F
V − 0.4n
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
4
8
12
16
20
24
"n" in rev. per sec.

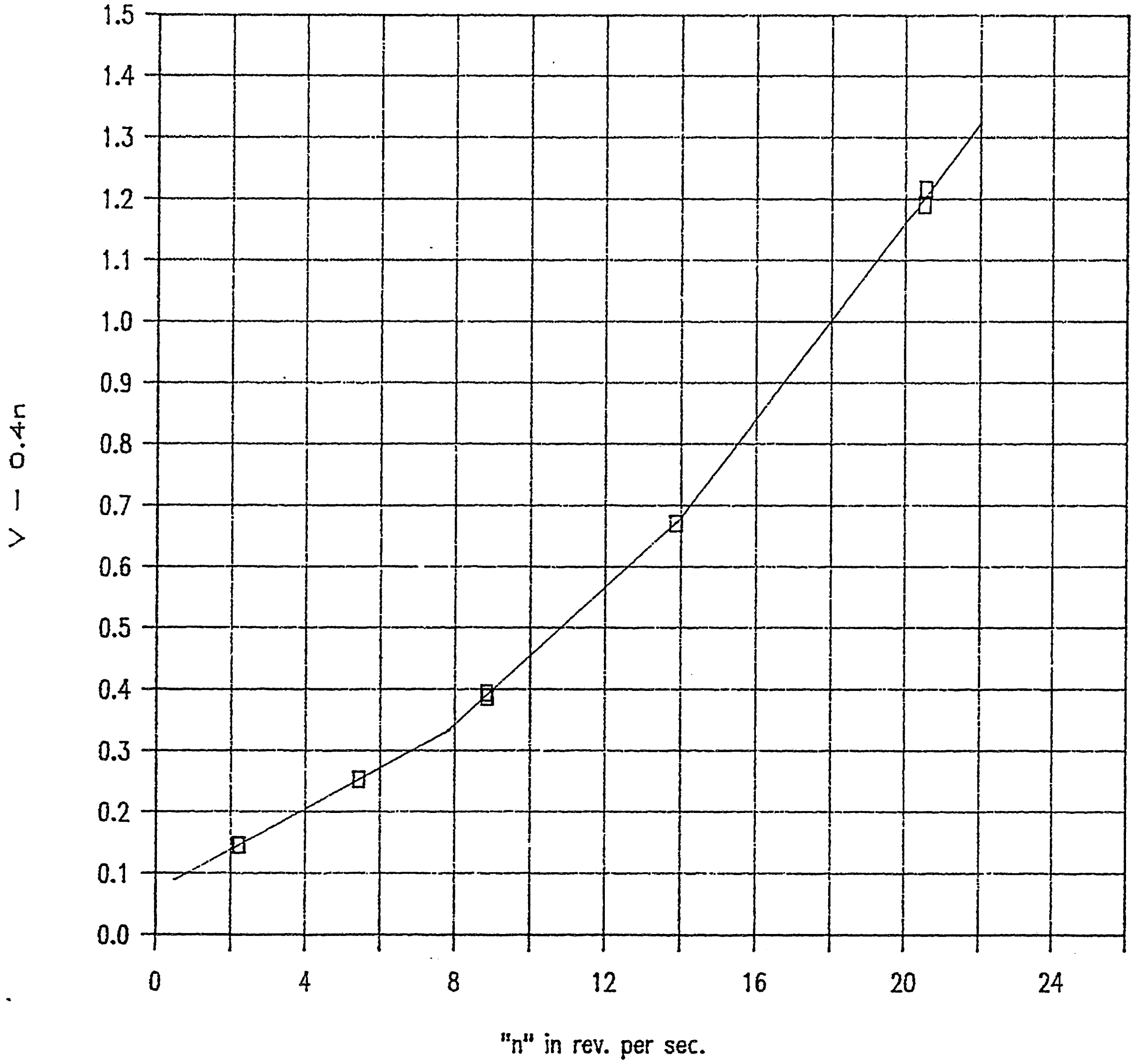
Meter No. 738

Series 1, 63.5 F



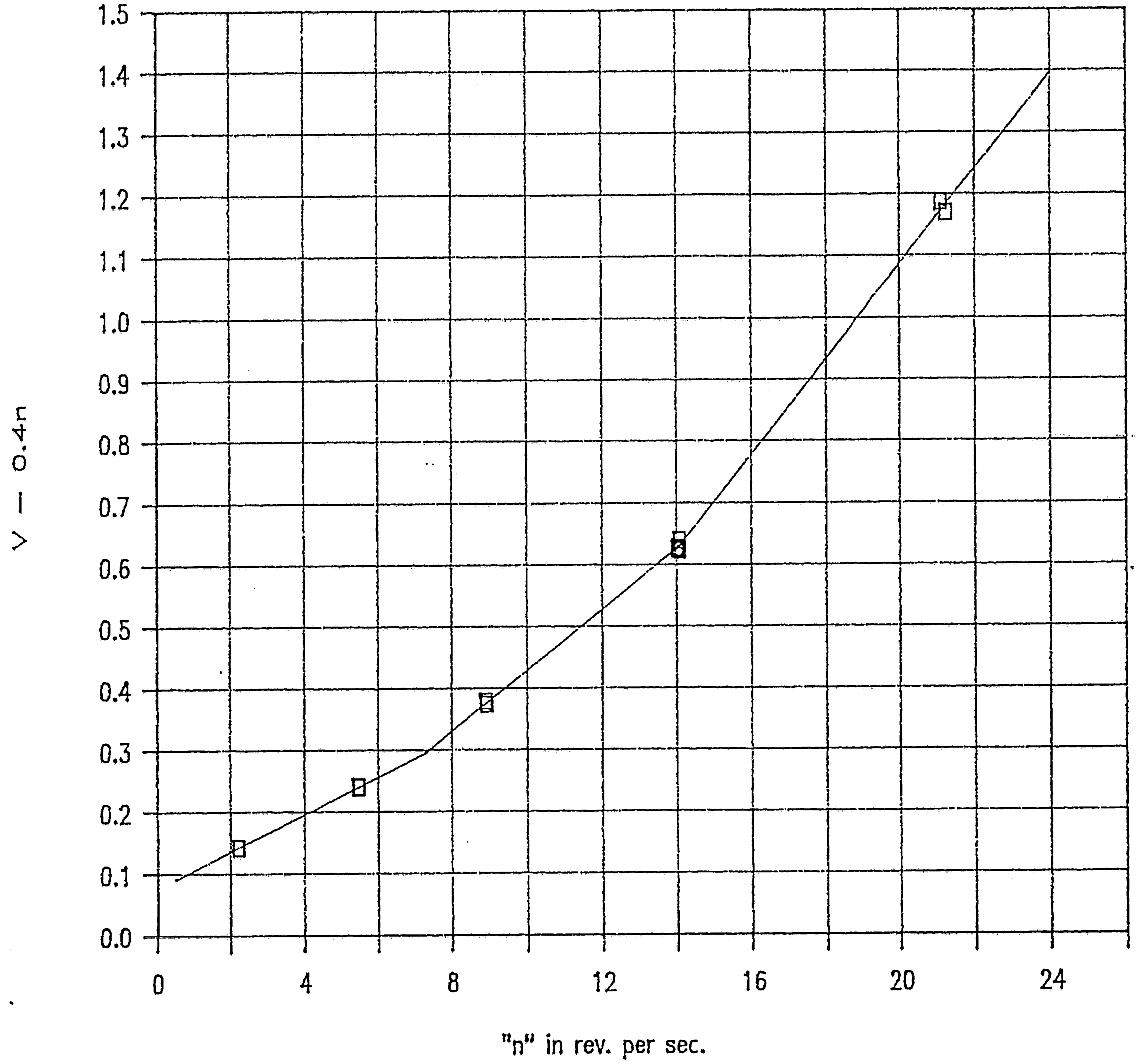
Meter No. 741

Series 7, 63.3 F



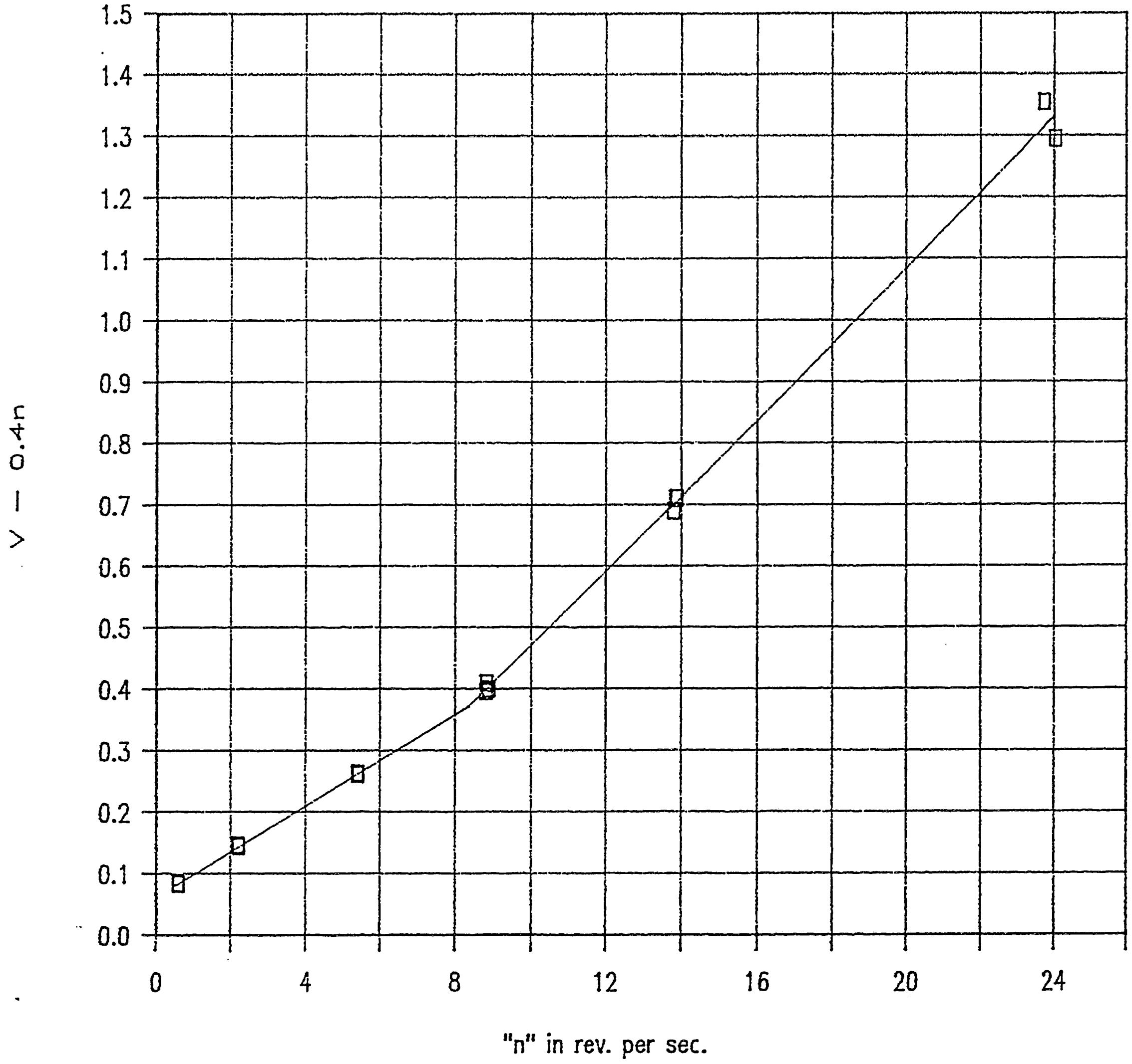
Meter No. 747

Series 4, 61.2 F



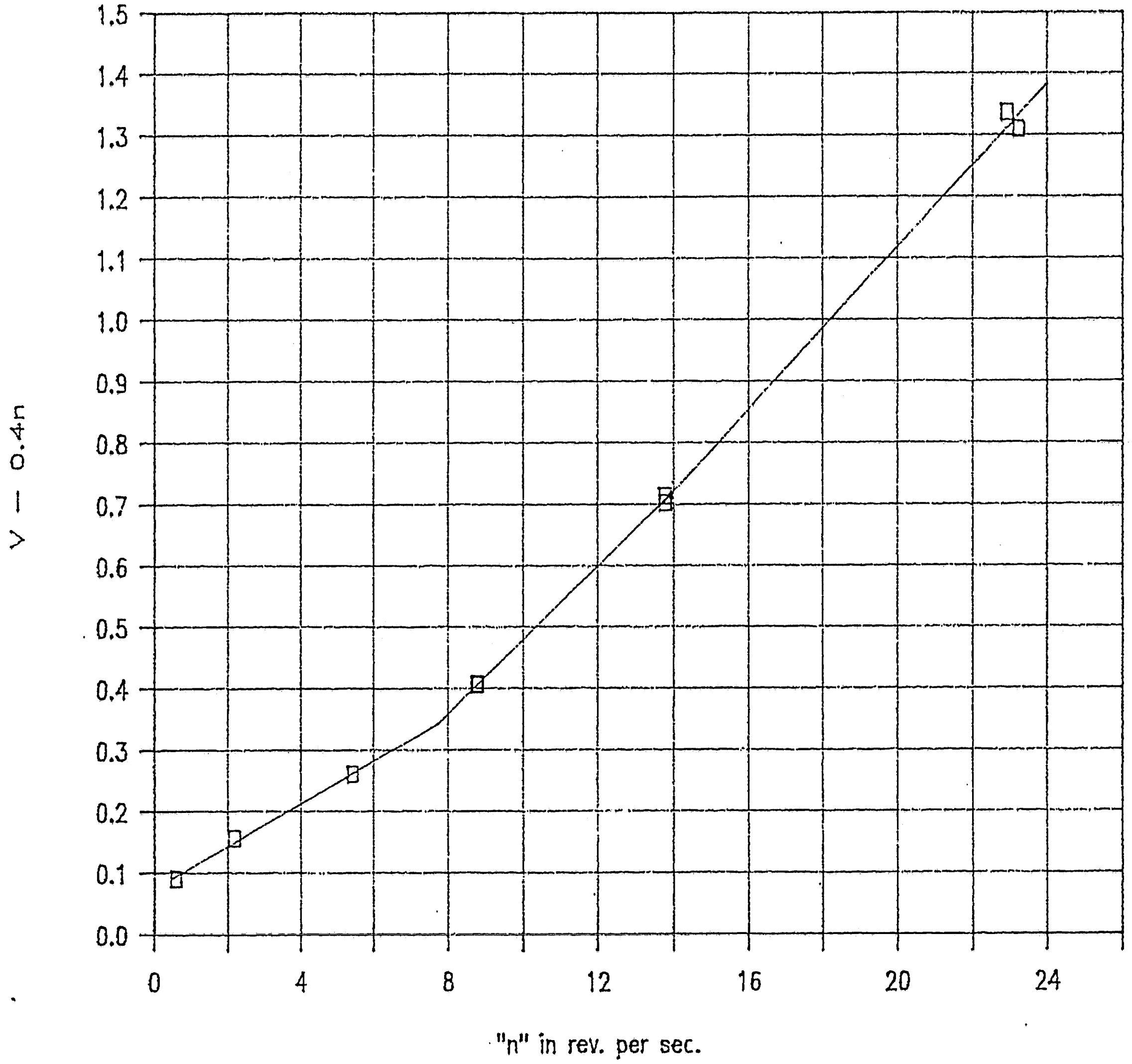
Meter No. 748

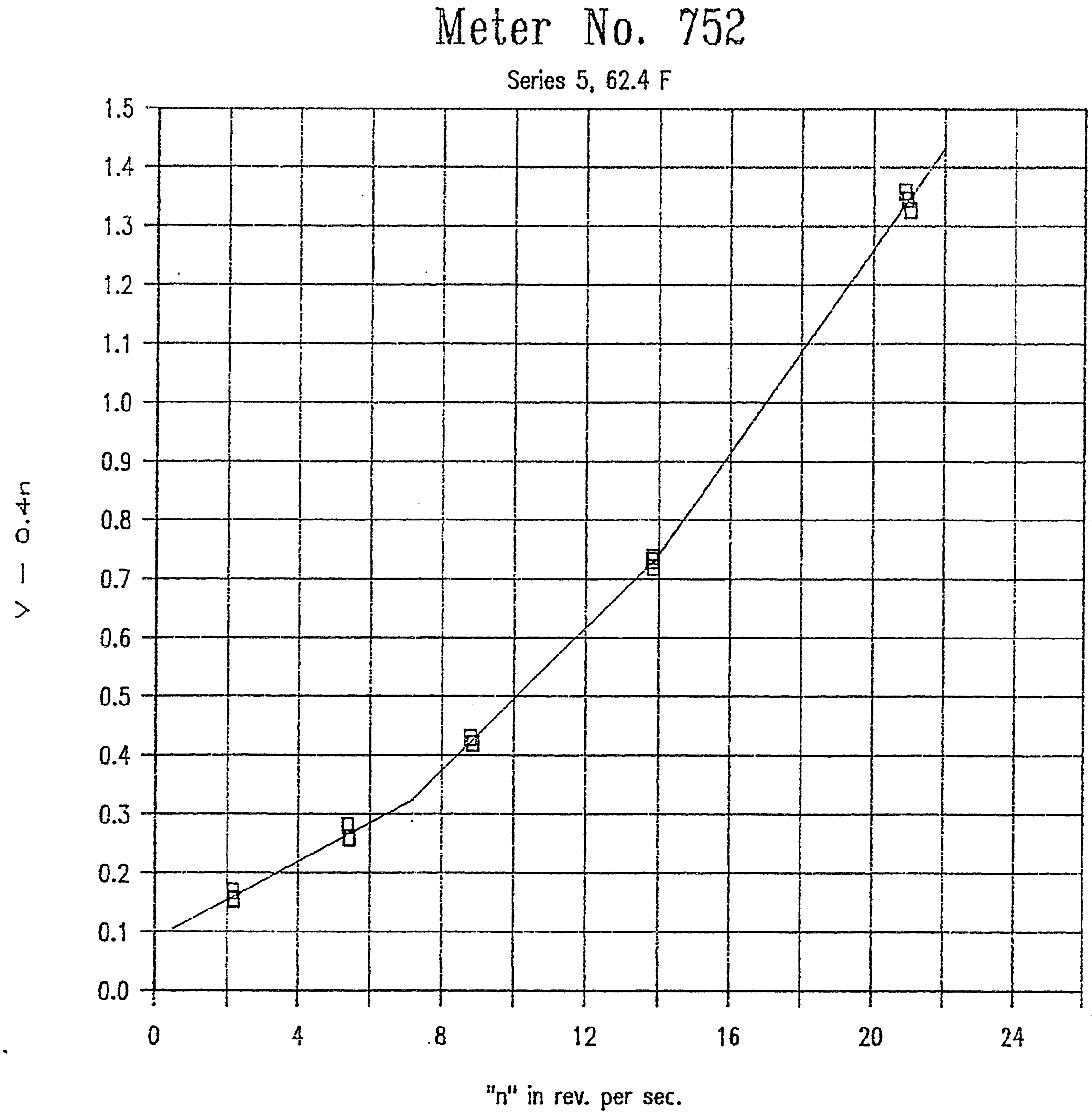
Series 2, 62.2 F



Meter No. 750

Series 1, 63.5 F

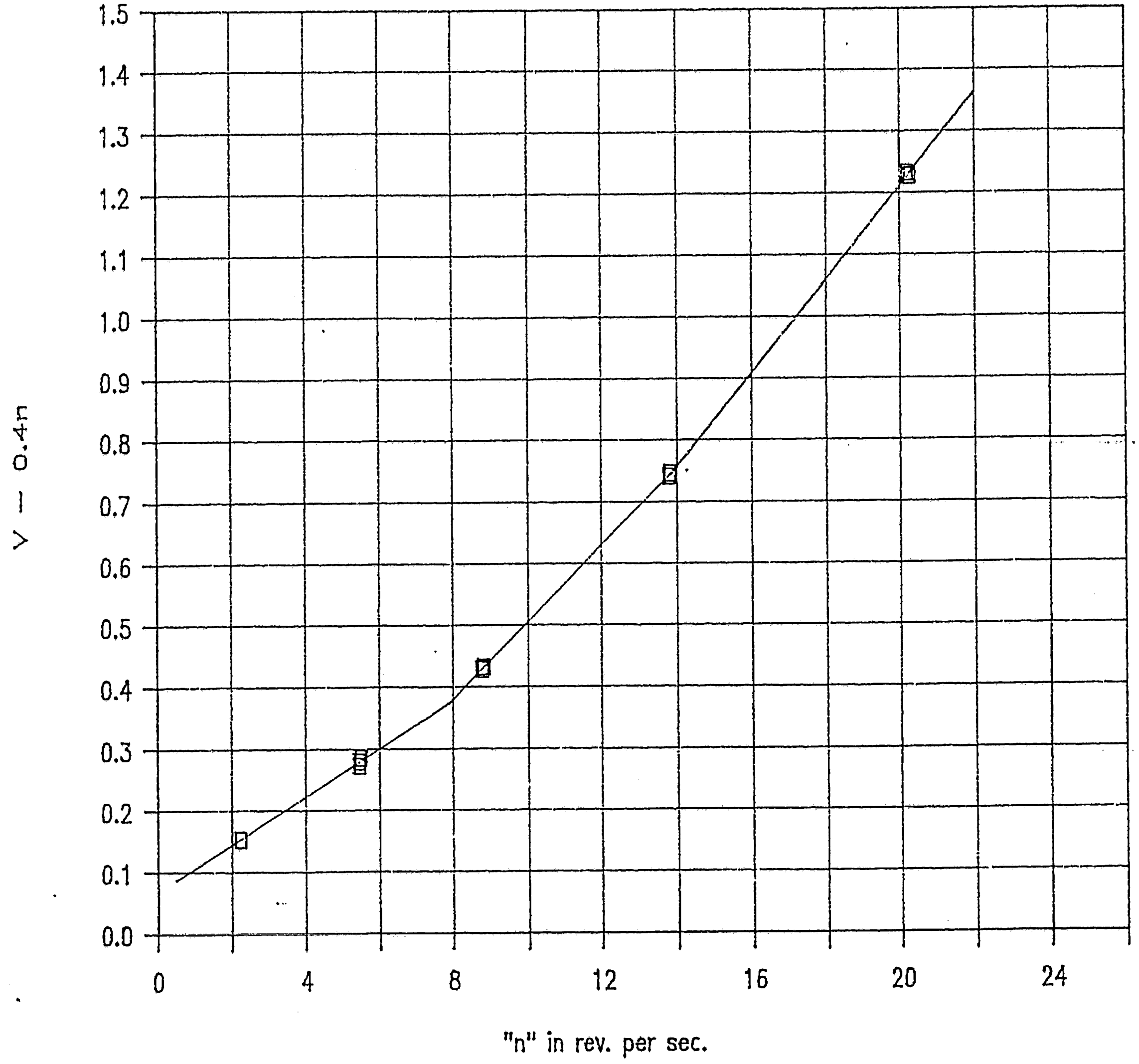




Meter No. 752
Series 5, 62.4 F
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
V – 0.4n
0
4
.8
12
16
20
24
"n" in rev. per sec.

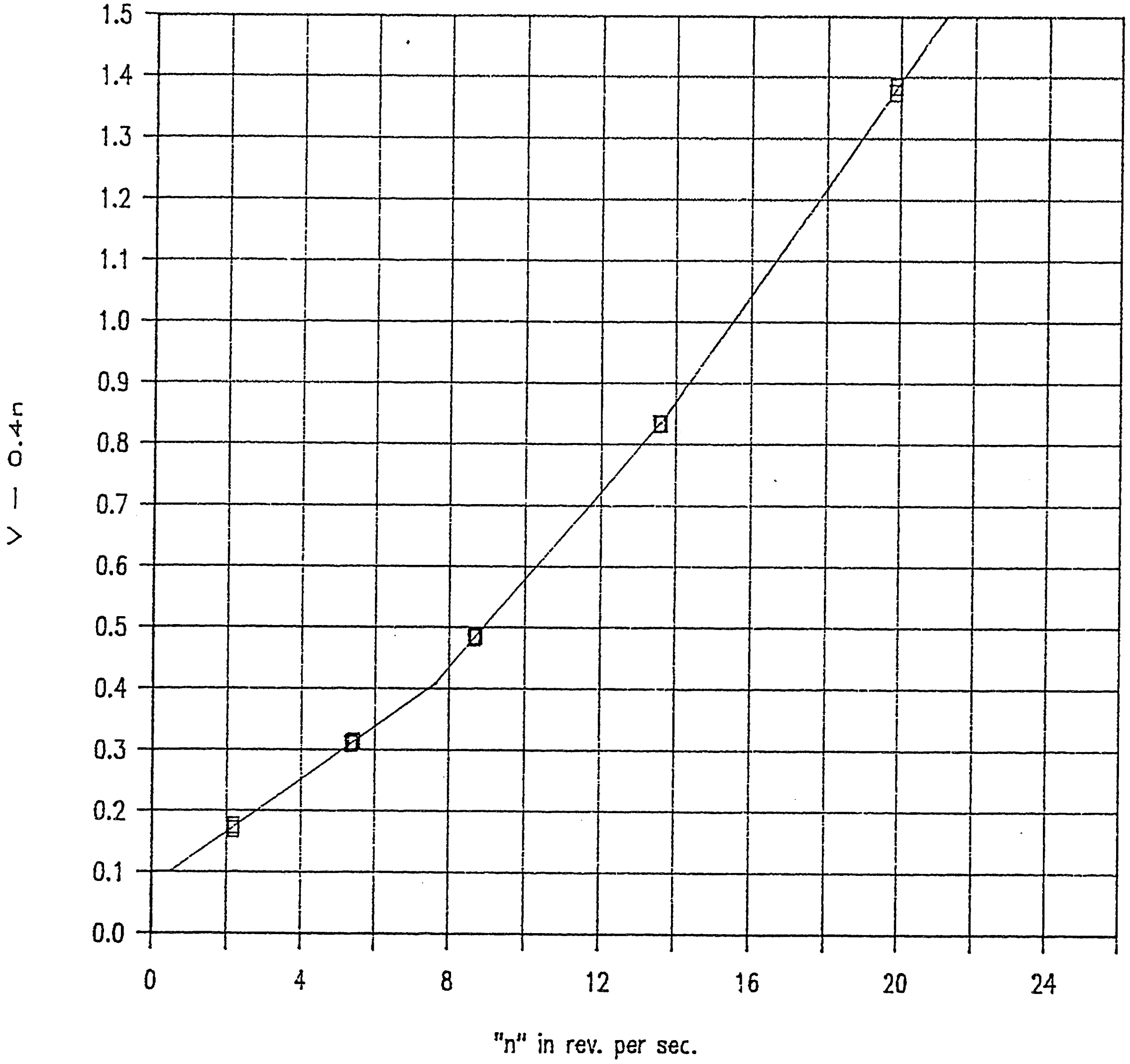
Meter No. 753

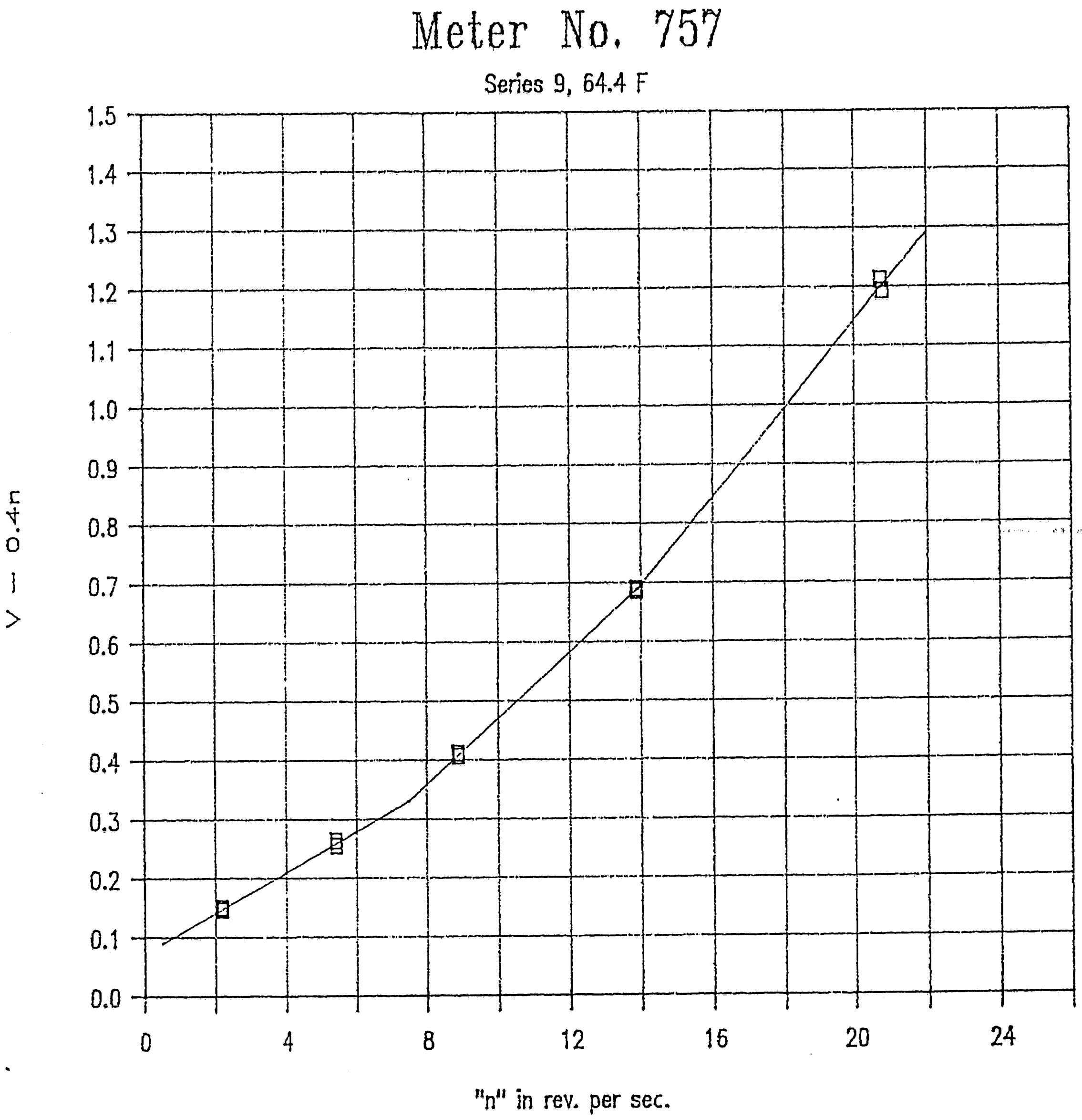
Series 6, 62.4 F

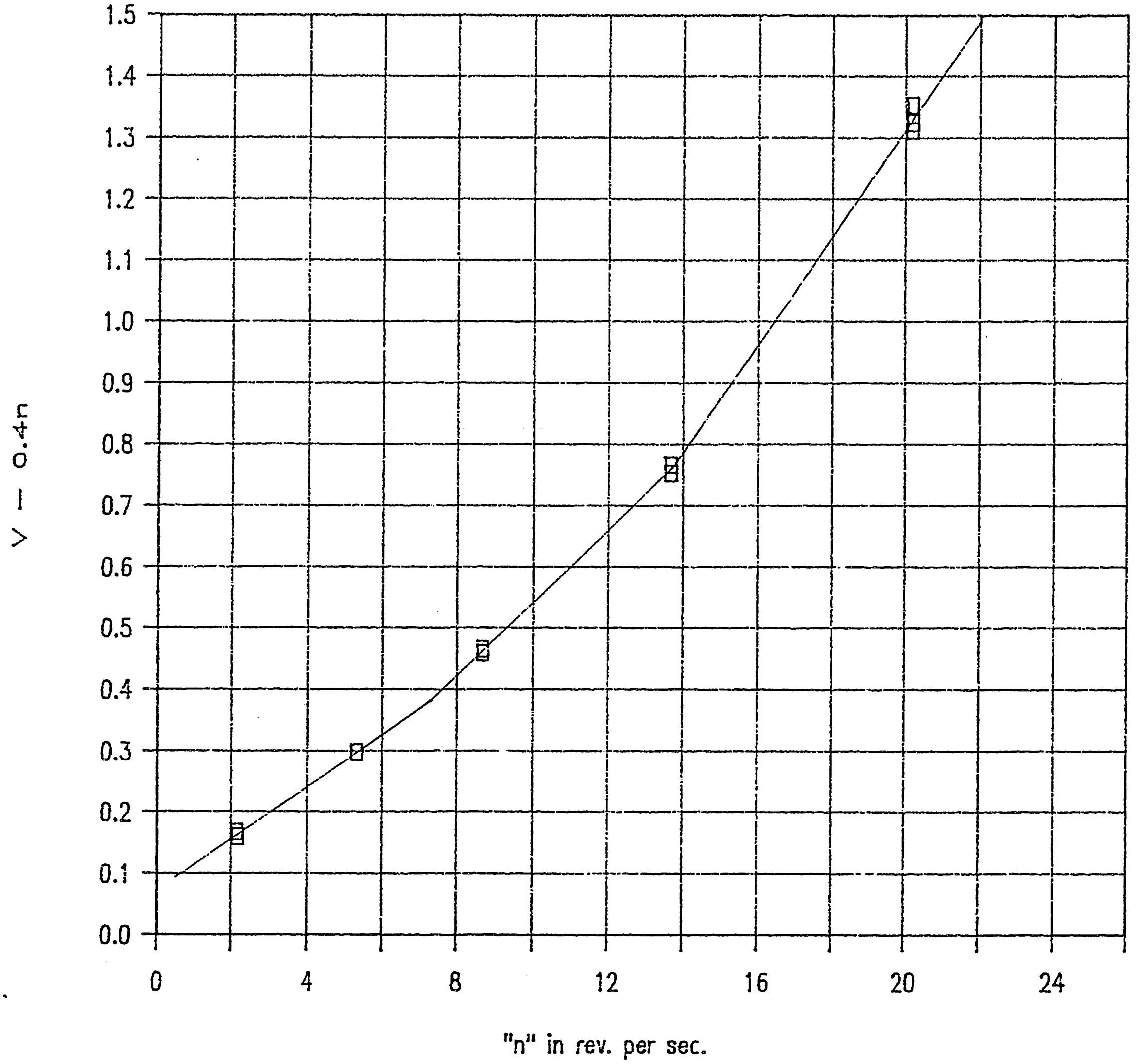


Meter No. 755

Series 6, 62.4 F




Meter No. 757
Series 9, 64.4 F
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
V − 0.4n
0
4
8
12
16
20
24
"n" in rev. per sec.

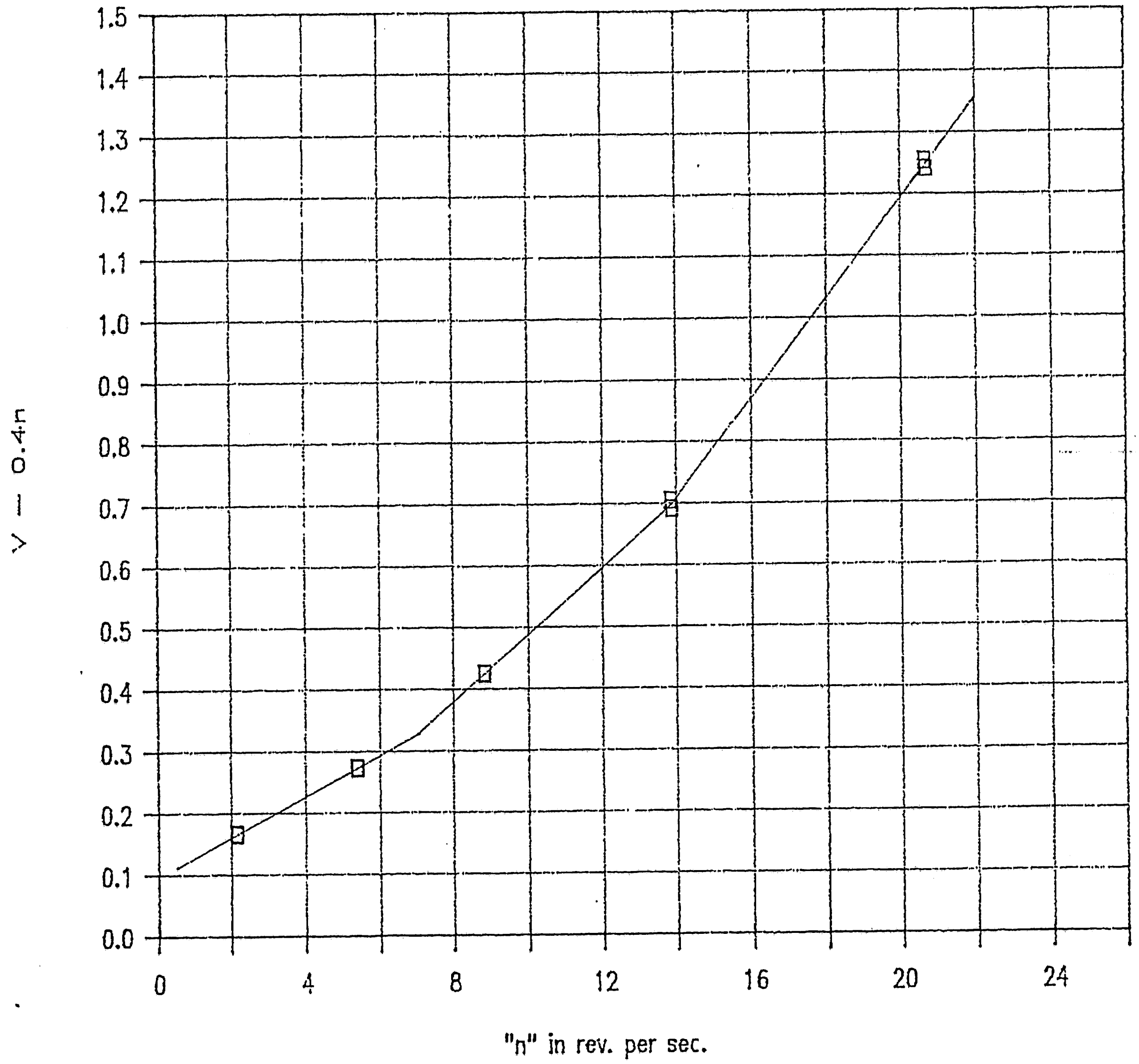


Meter No. 765

Series 7, 63.3 F

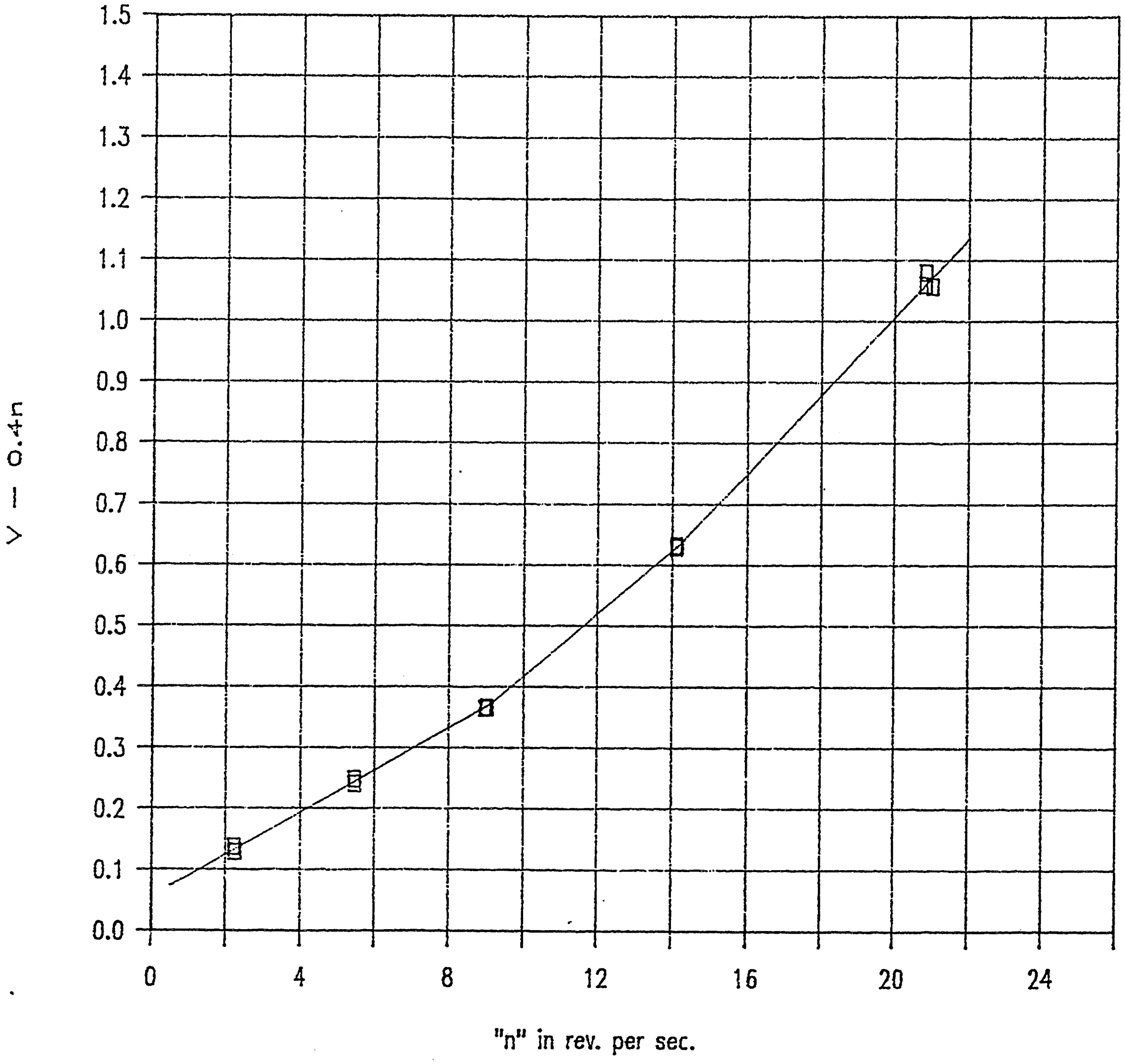
Meter No. 770

Series 9, 64.4 F



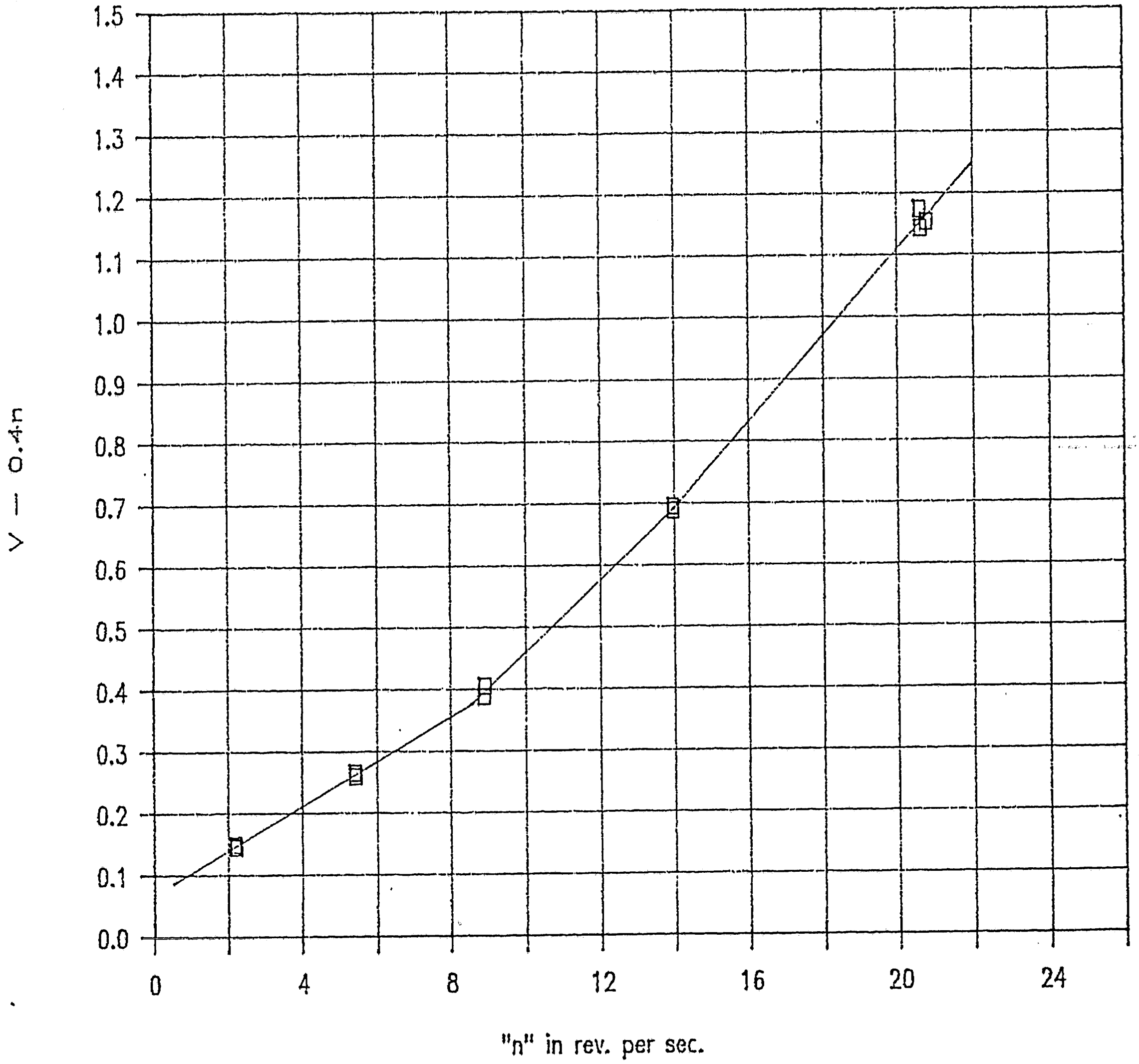
Meter No. 772

Series 8, 64.4 F



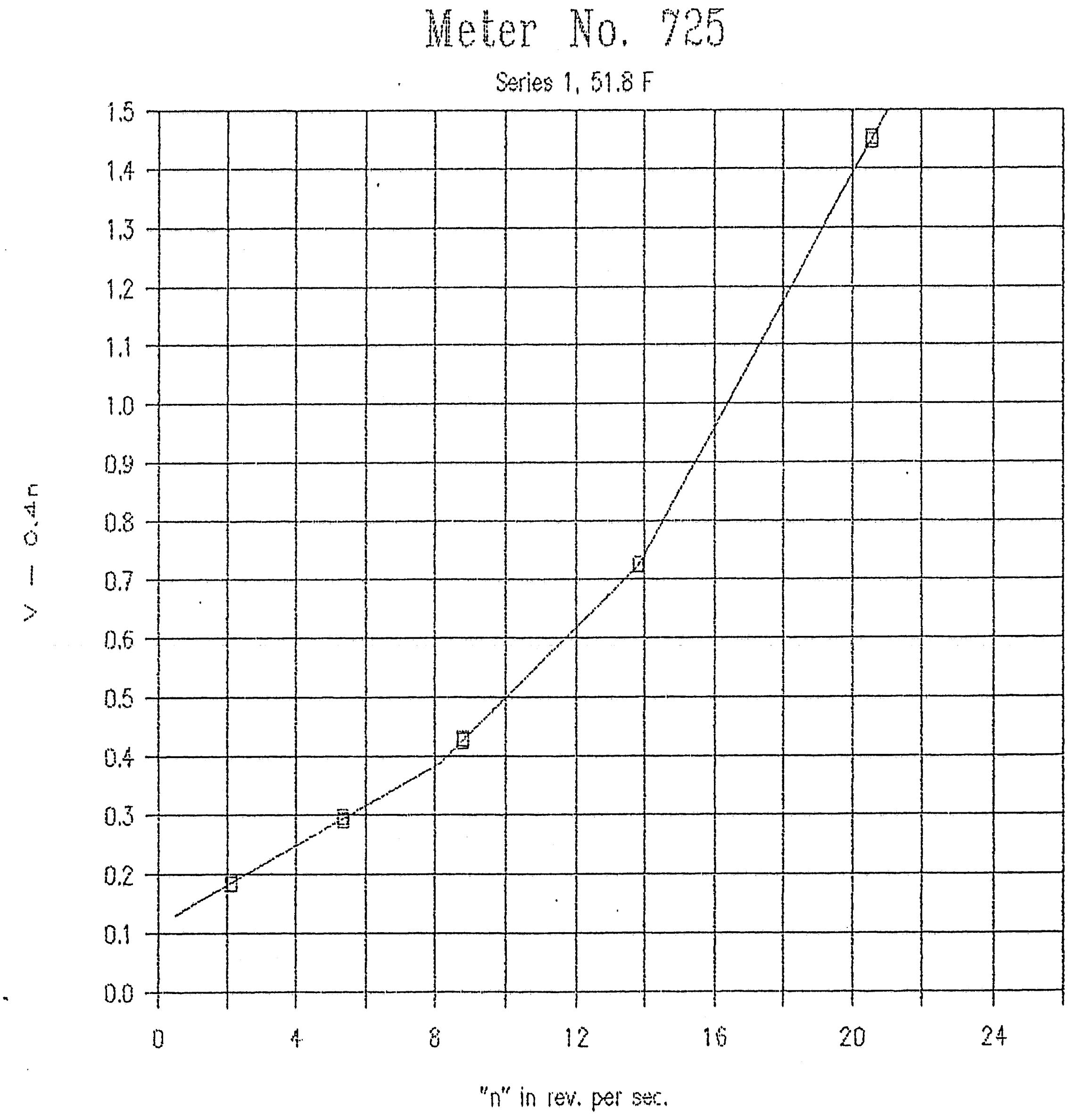
Meter No. 775

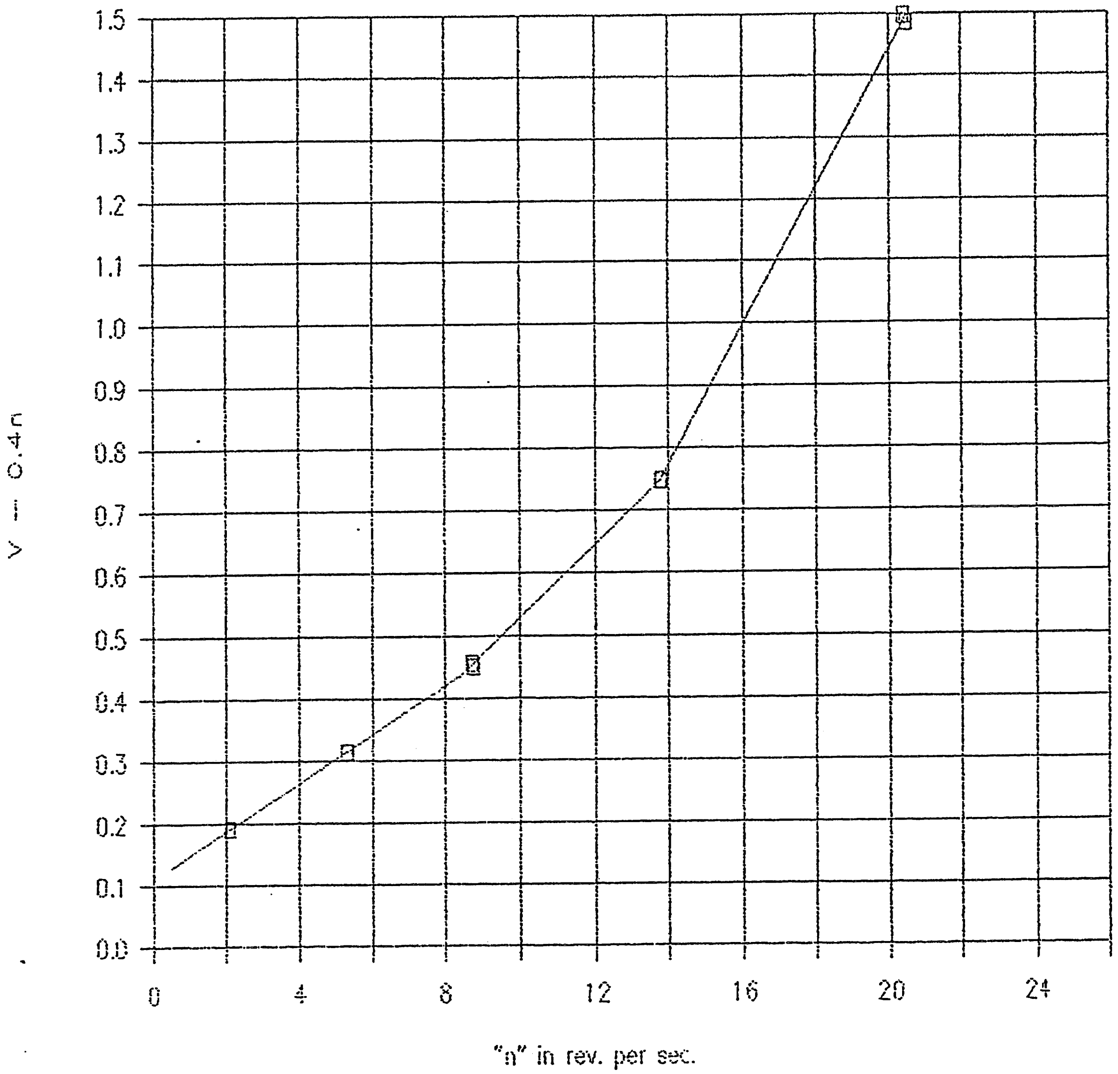
Series 8, 64.4 F



Post-Test Currentmeter Calibration Curves.

October 25 to October 28, 1988

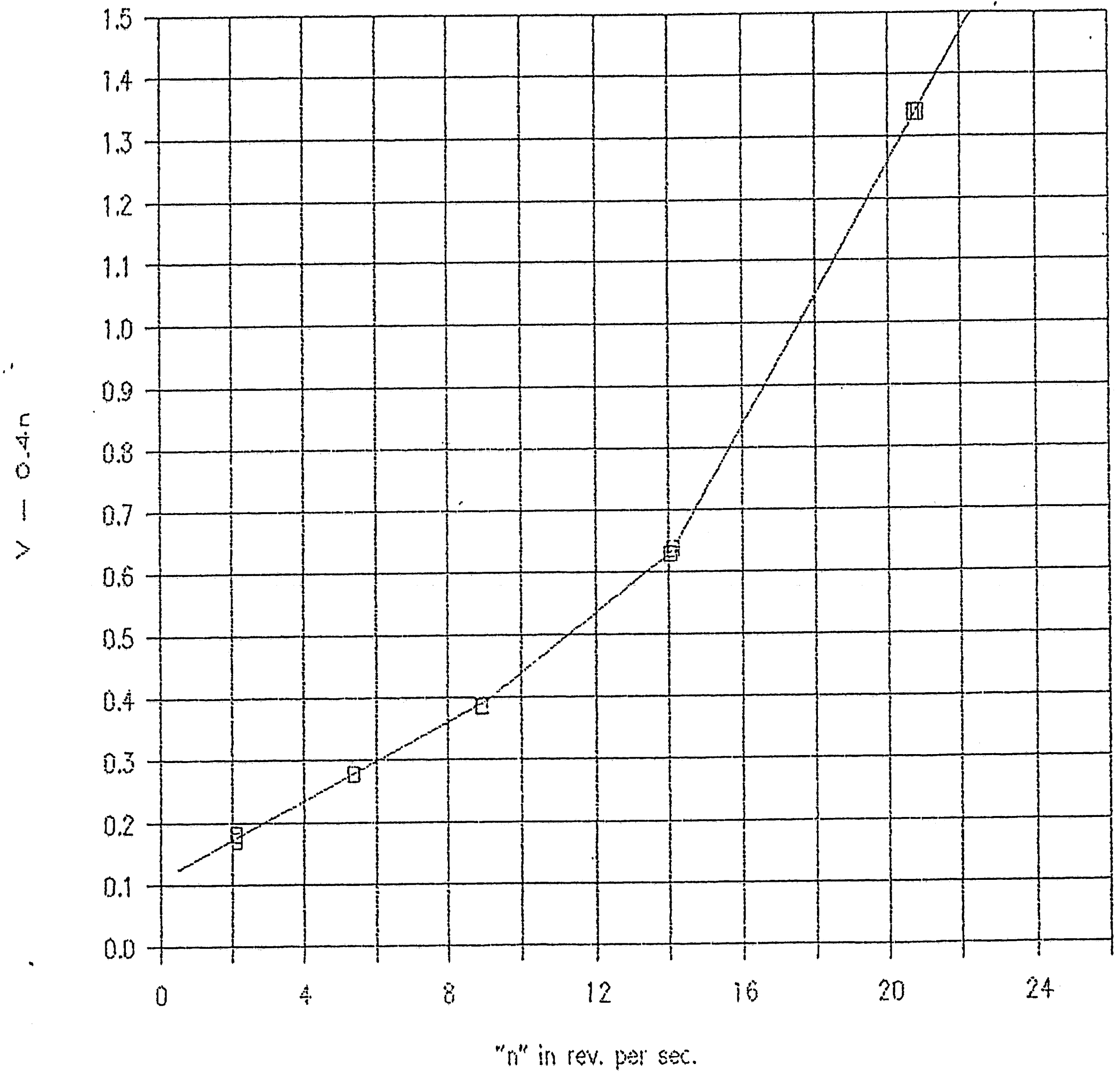

Meter No. 725
Series 1, 51.8 F
V — 0.4n
"n" in rev. per sec.
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
0
4
8
12
16
20
24

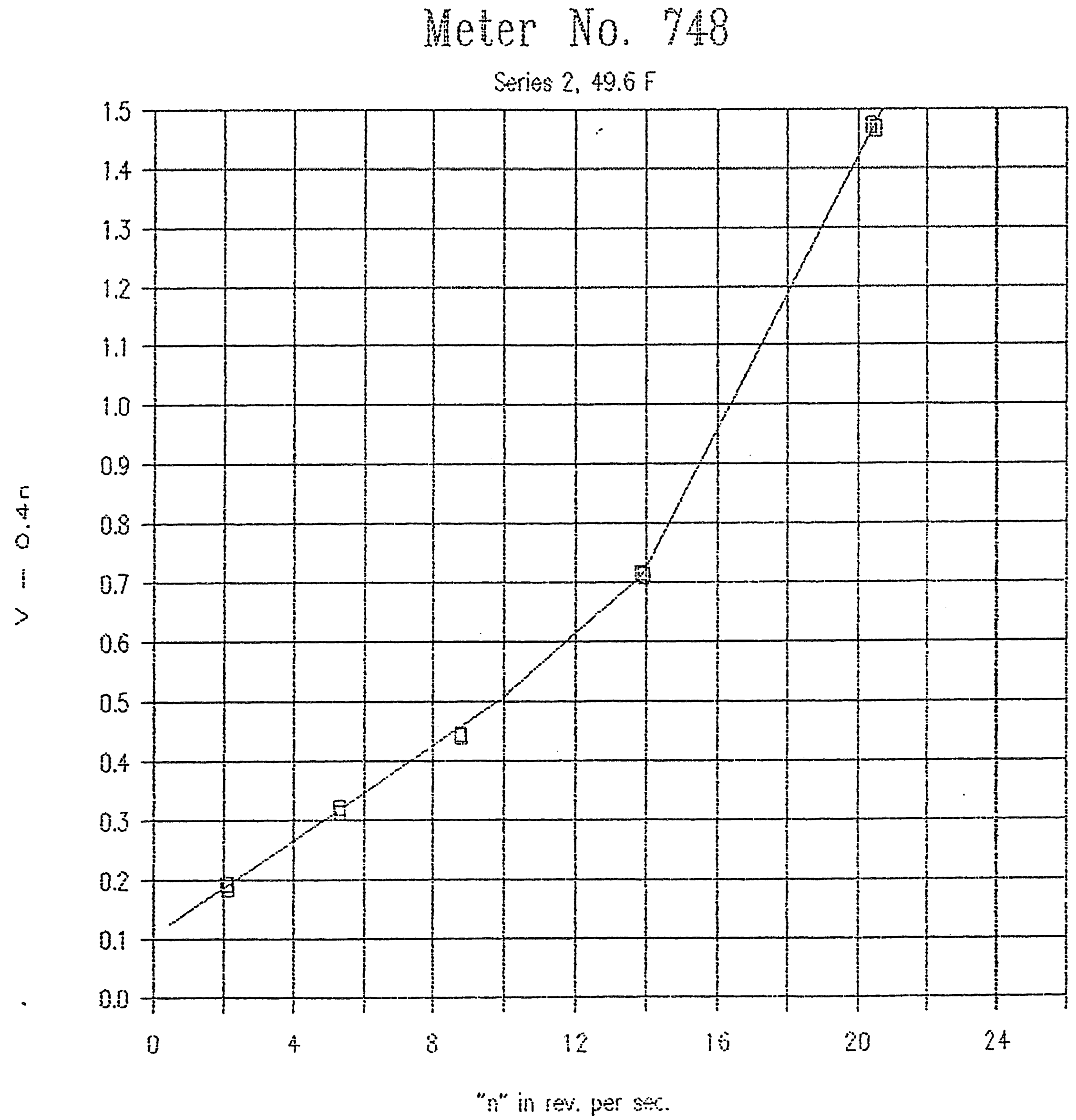


Meter No. 738

Series 1, 51.8 F

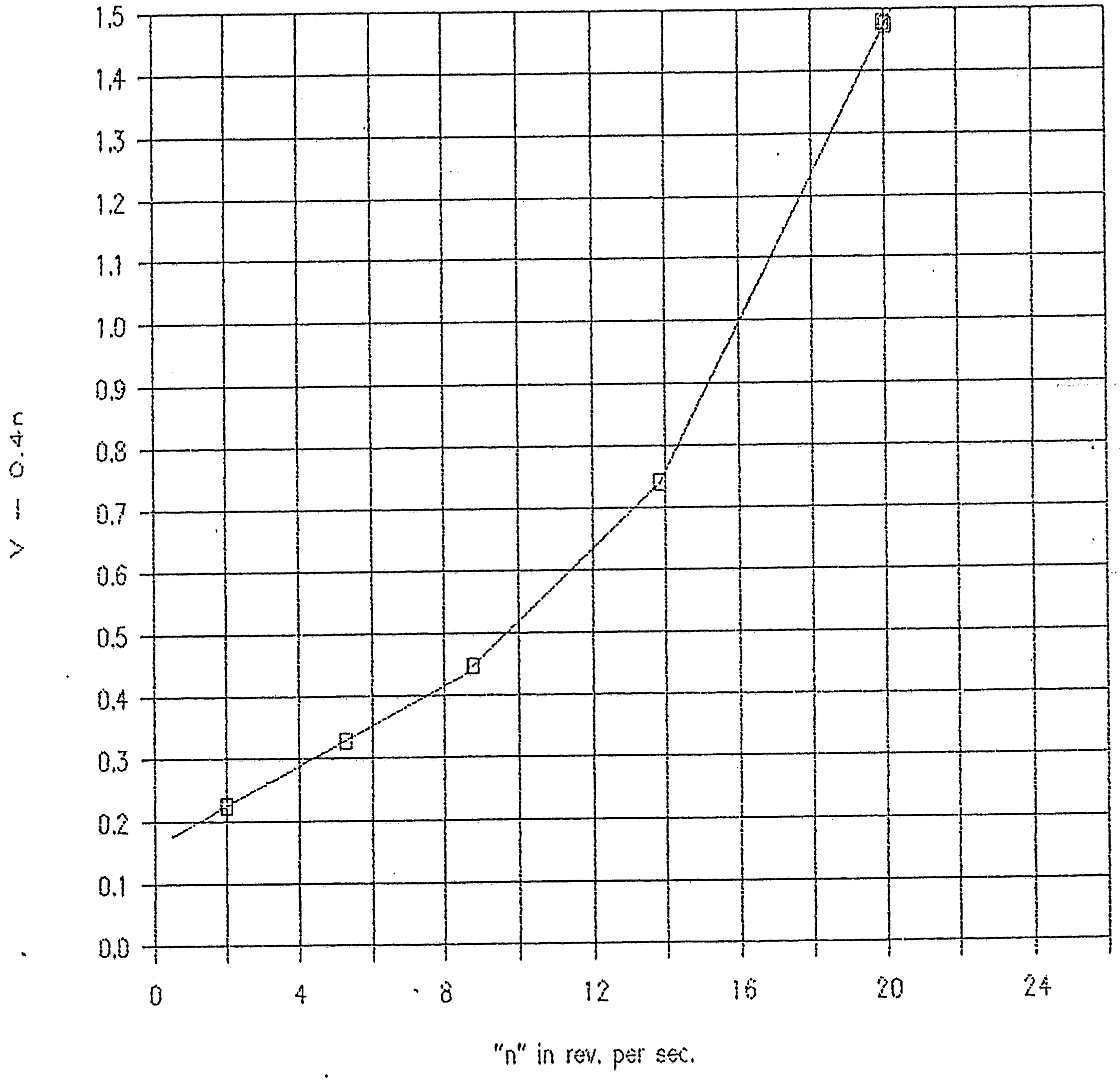
Meter No. 747

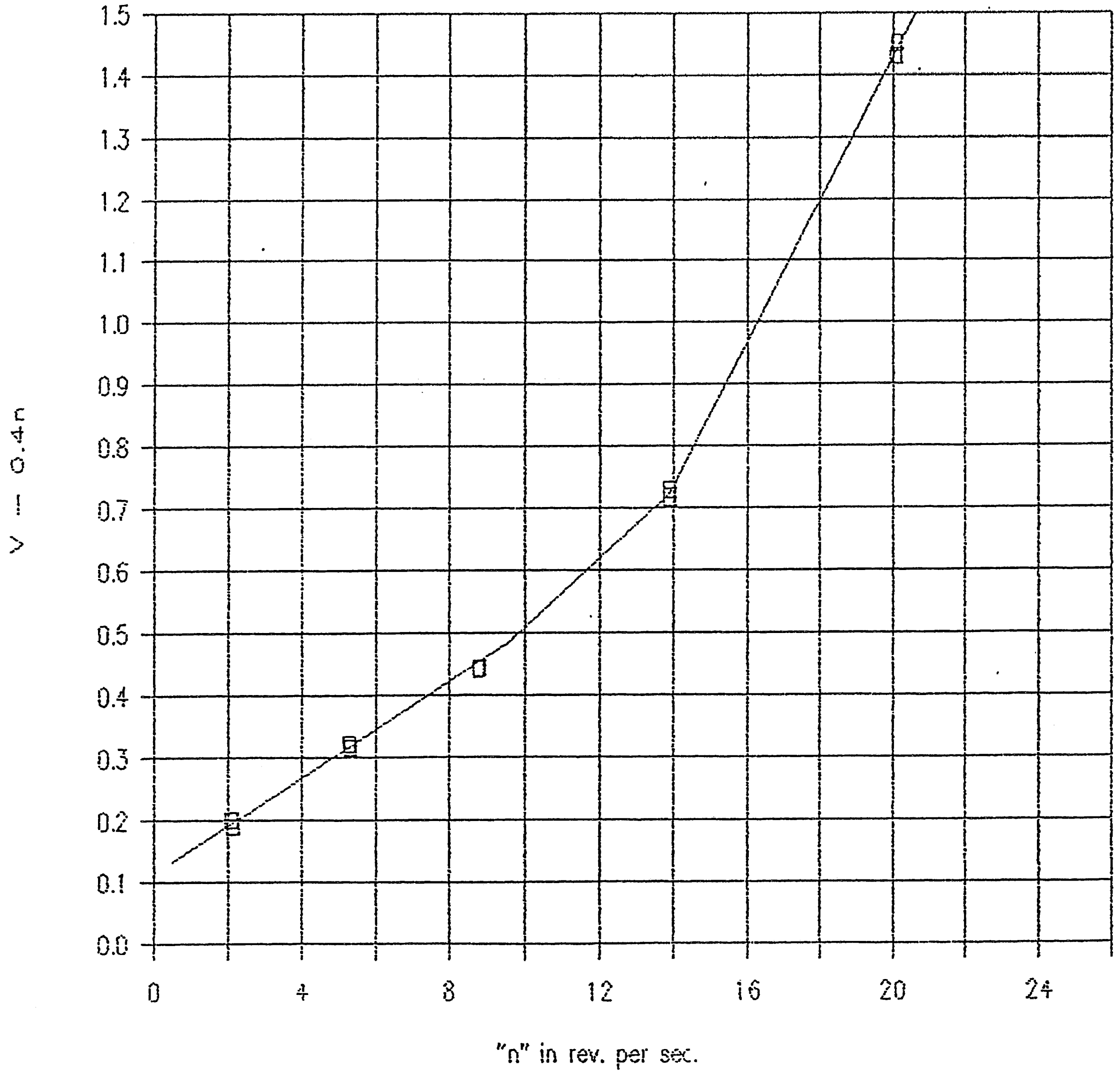

Series 2, 49.6 F
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
V — 0.4n
0
4
8
12
16
20
24
"n" in rev. per sec.


Meter No. 748
Series 2, 49.6 F
V – 0.4n
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
0
4
8
12
16
20
24
"n" in rev. per sec.

Meter No. 750

Series 3, 50.0 F

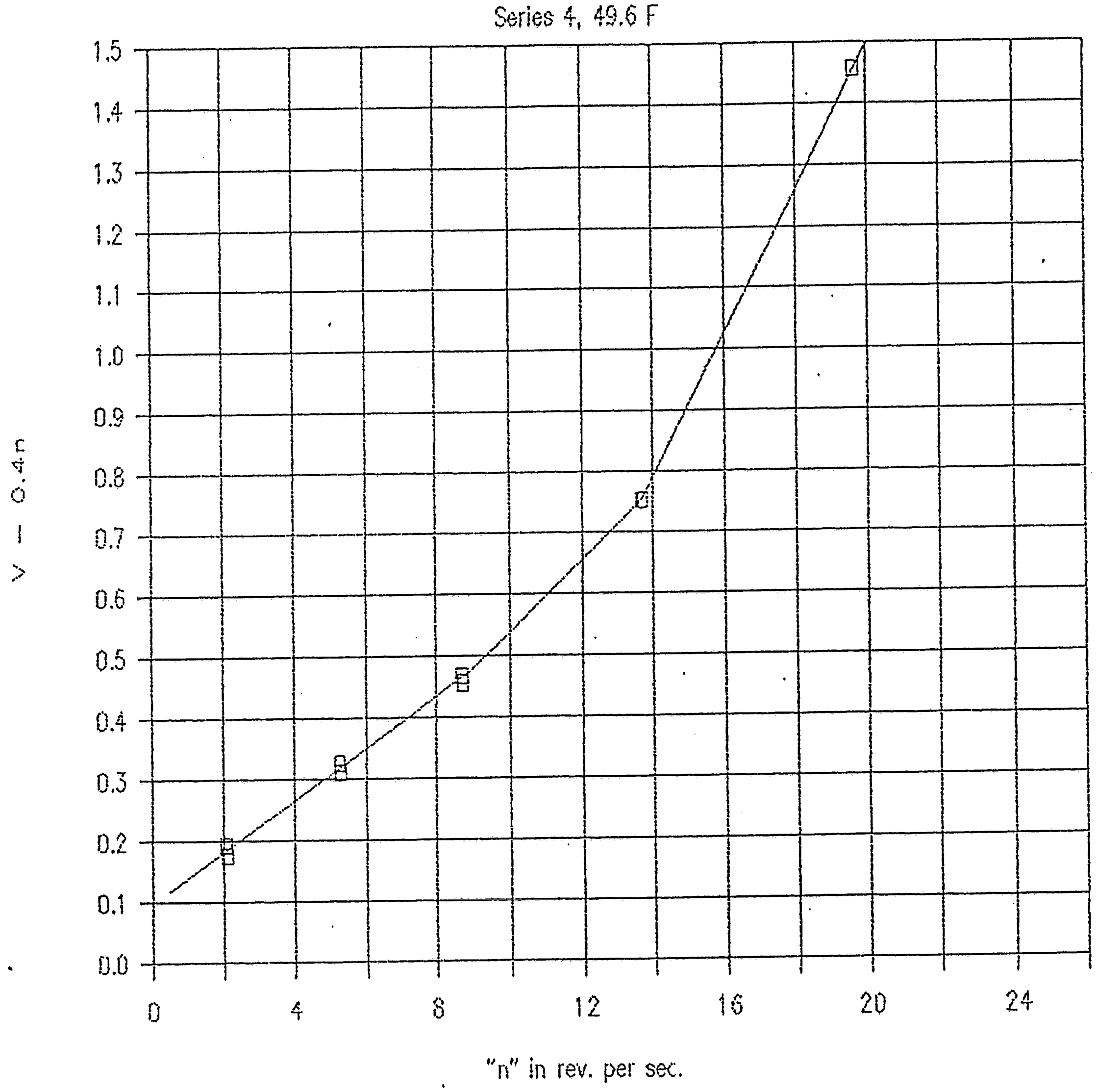




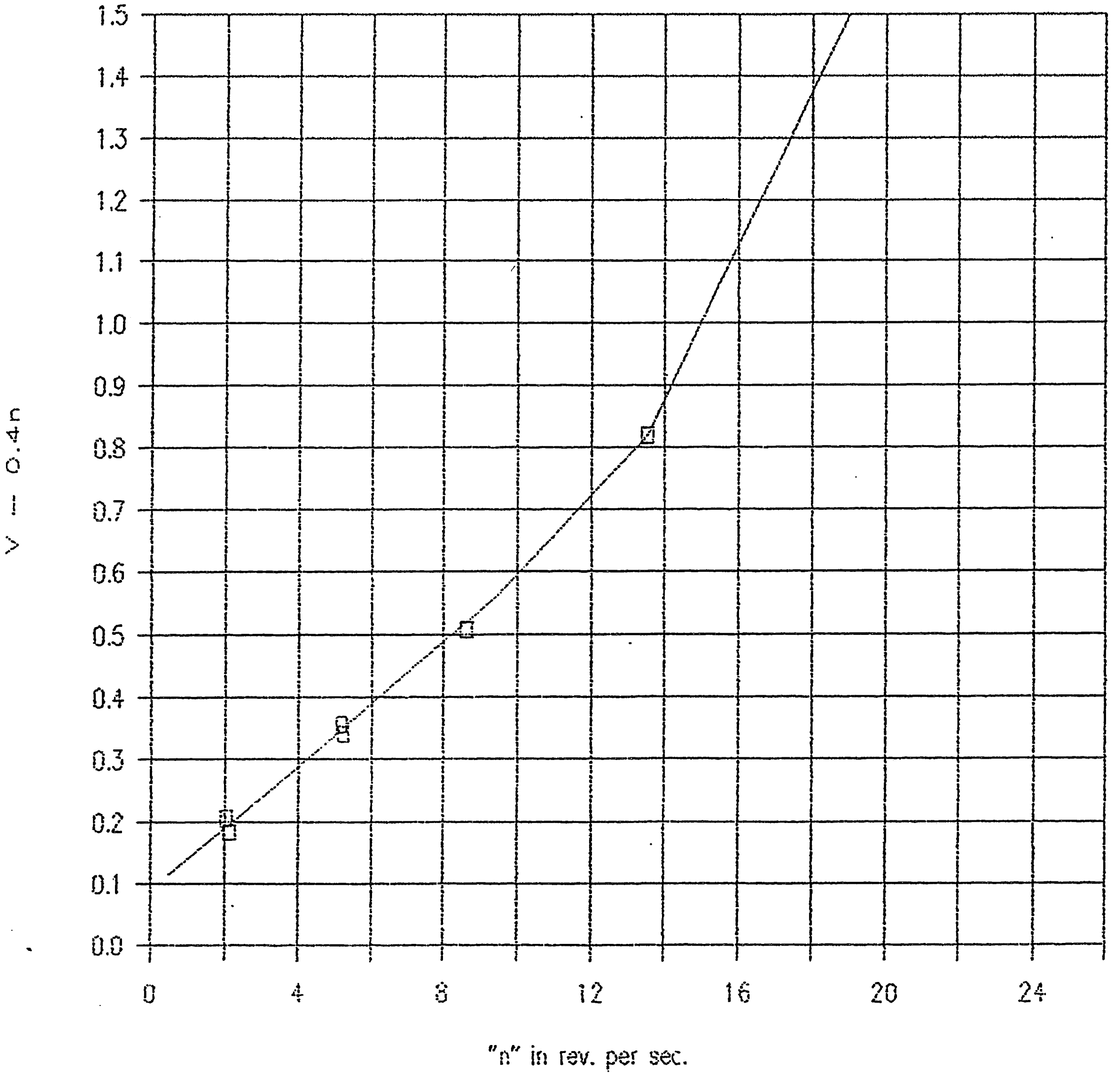
Meter No. 752

Series 3, 50.0 F

Meter No. 753



Series 4, 49.6 F
V − 0.4n
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
4
8
12
16
20
24
"n" in rev. per sec.

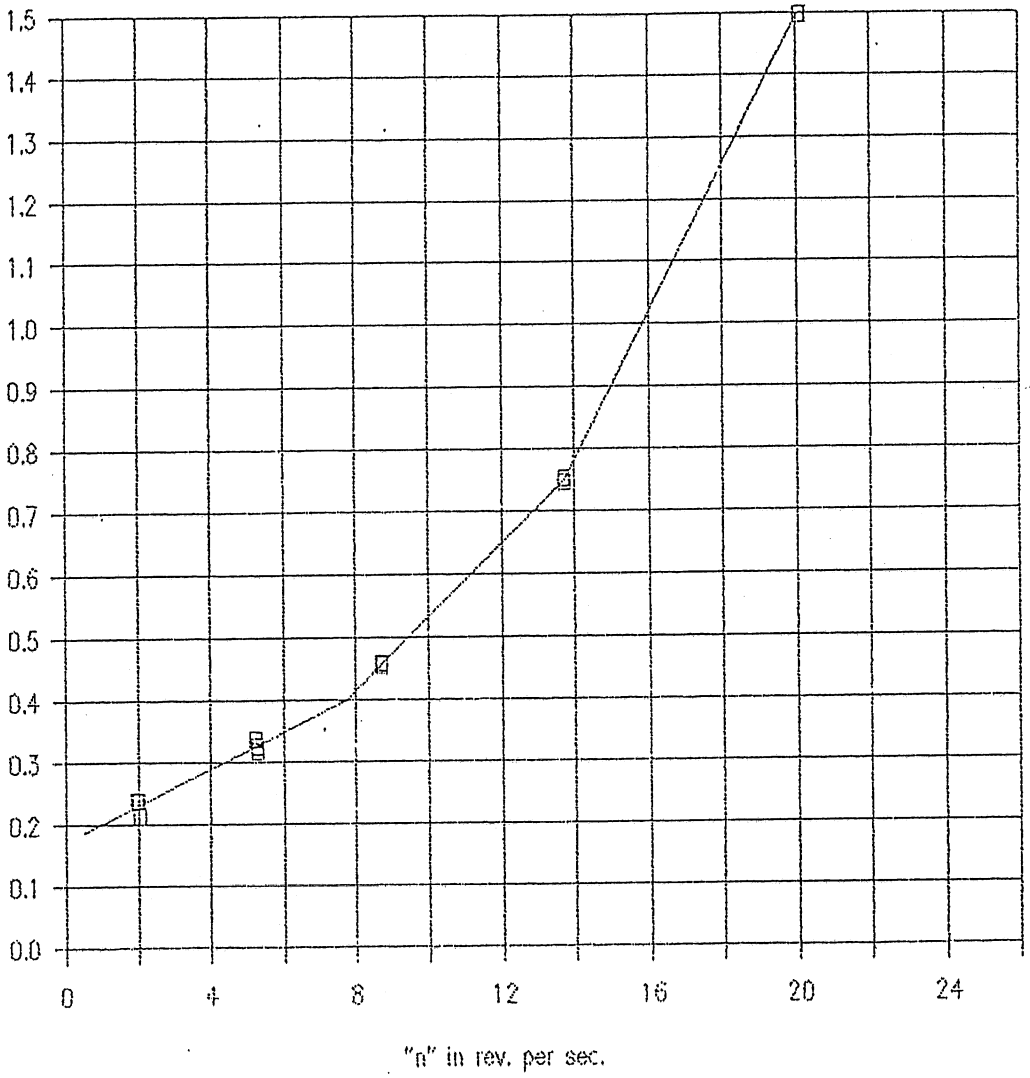


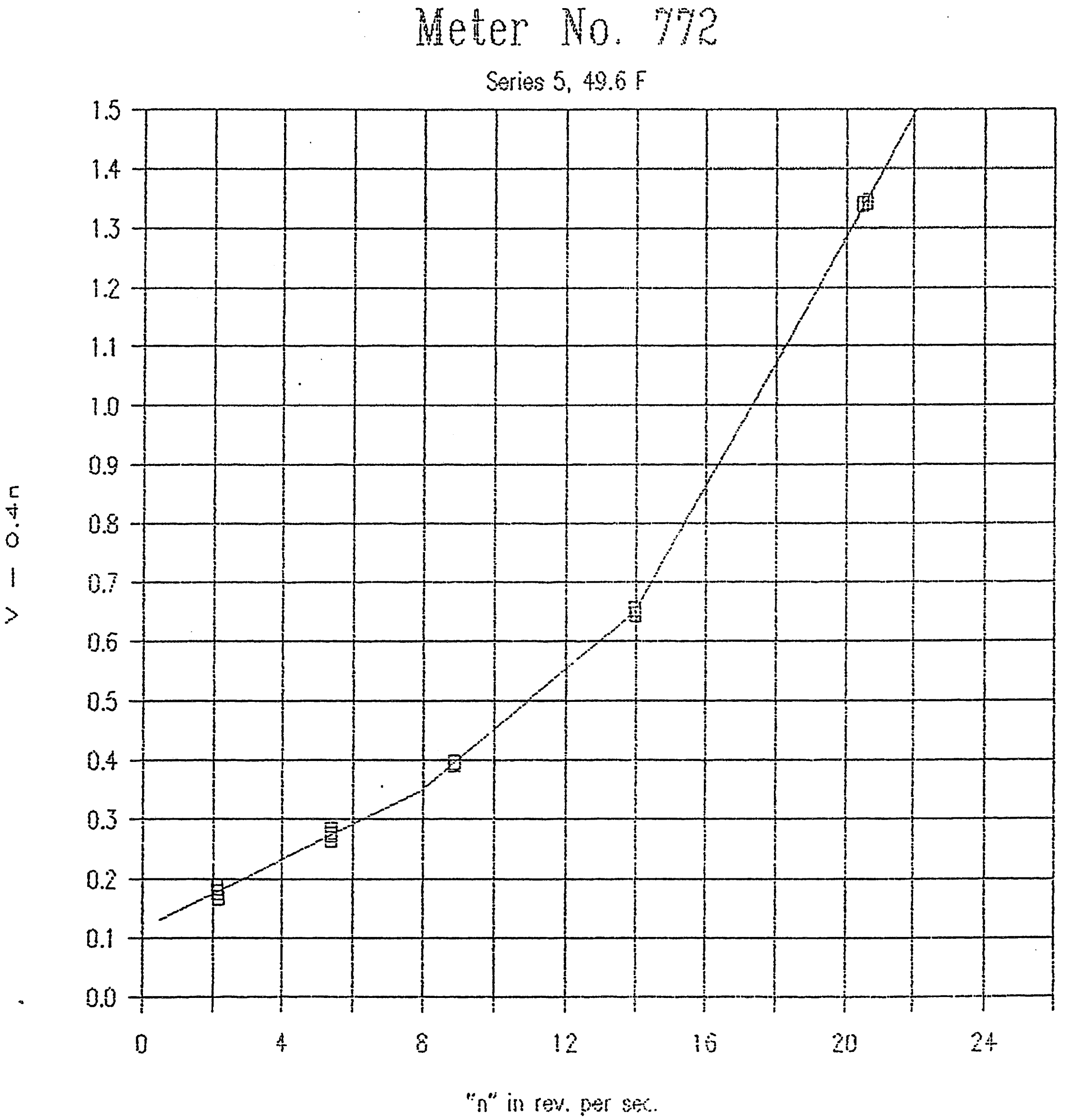
Meter No. 755

Series 4, 49.6 F

Meter No. 770

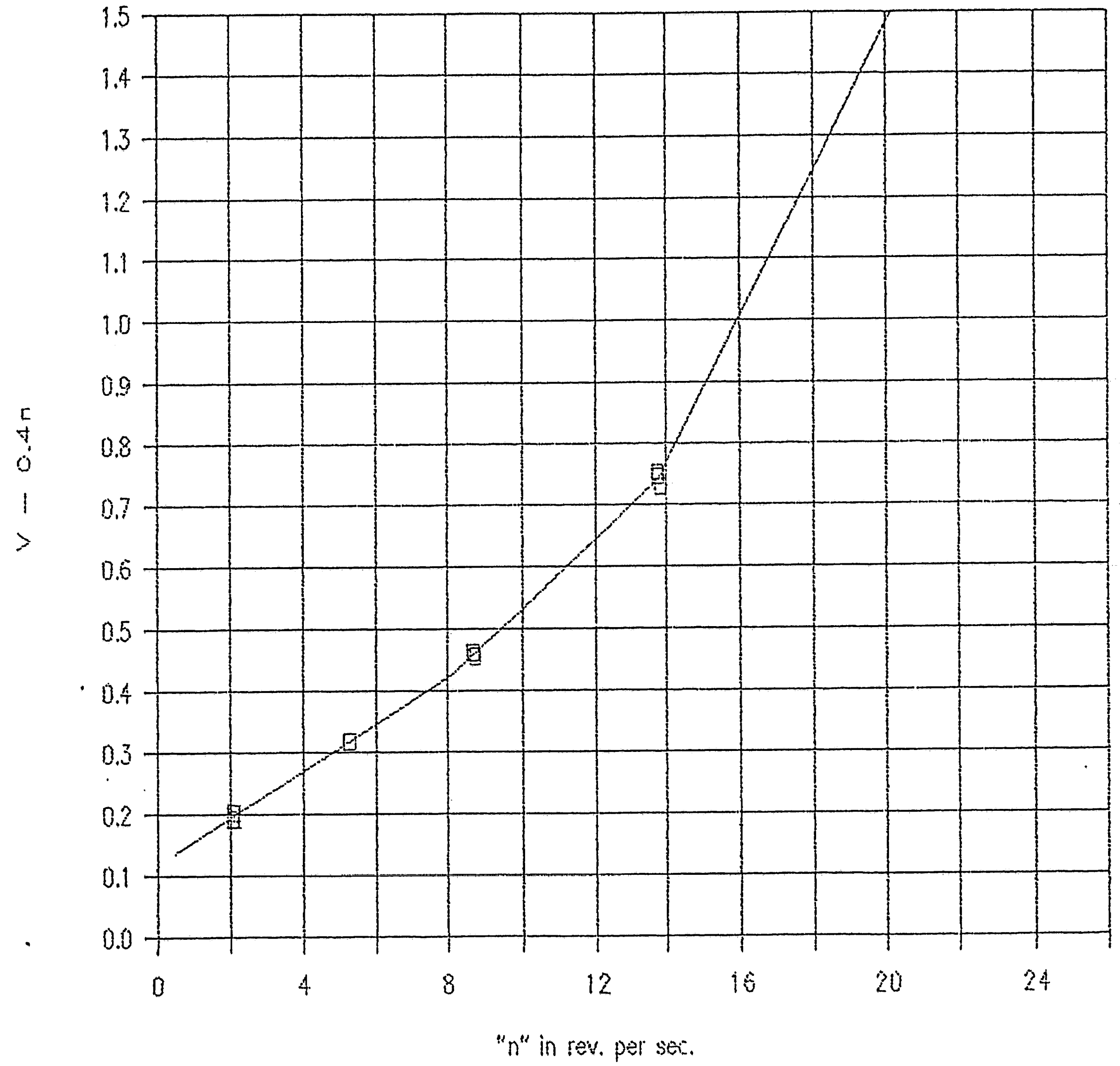
Series 5, 49.6 F



Meter No. 772
Series 5, 49.6 F
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
V − 0.4n
0
4
8
12
16
20
24
"n" in rev. per sec.

Meter No. 775

Series 6, 49.6 F



APPENDIX B

Letter from Gulliver to Spaulding re: Trash Rack Headlosses

John S. Gulliver, Ph.D.
Consulting Engineer
Hydraulics • Water Quality • Hydropower

March 31, 1988

Mr. Douglas Spaulding
Warzyn Engineering, Inc.
715 Florida Avenue South
Suite 306
Minneapolis, Minnesota 55426

Dear Doug:

Enclosed are the computations and analysis you requested for headlosses at the St. Cloud Hydroelectric Facility. Some explanation of the technique is also enclosed.

The headlosses through the intakes of the St. Cloud Hydroelectric Facility were measured in the hydraulic model study, SAFHL Project Report No. 255. This model study did not include the trash racks. Trash rack headlosses were therefore calculated in section VI.G, using the attached information from Idelchick, *Handbook of Hydraulic Resistance*, and the measurements given in Fig. 59 of Project Report No. 255. A sample calculation is also attached. The results are given in Table 2 of Project Report 255 for the loss of head from the upstream water surface elevation to a location behind the trash racks, behind the gate slots, and just upstream of the turbine runner at the tail end of the pit. The measurements have a ±0.1 ft uncertainty, and thus some inconsistancies result. In an effort to make the measured headlosses along columns and rows consistant, I have adjusted some of the measurements within the ±0.1 ft interval, as judgement would dictate. The results are as follows:

Estimated headloss through intakes (ft). Headlosses are cumulative.
The right turbine is that closest to the shoreline.

Discharge (cfs)		Behind Trashracks		Behind Gate Slots		At End of Pit	
	Turbine:	Left	Right	Left	Right	Left	Right
Q_{PL}	Q_{PR}						
3250	3250	.6	.42	.65	.44	.65	.47
3250	——	.5		.6		.65	
——	3250		.42		.44		.47
2120	——	.24		.26		.30	

I recommend using these headloss values in the contractural guarantee between Mortenson Construction and Voith Hydro. Please call if you have any questions or comments.

Sincerely,

John Gulliver
Associate Professor

JG:sp

Enclosures

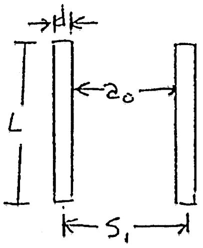
cc: George Barbato

ST. CLOUD HYDROELECTRIC FACILITY

CALCULATED HEAD LOSS ACROSS TRASHRACKS
(Taken from tables in Idelchick)

8 Tie Rods ; 3/4" dia. , ℄ spacing = 2'

Bars ; 4 1/2" × 1/4" , ℄ Spacing = 3 3/4"



$L = 18\,d$

$\frac{a_0}{S_1} = \frac{3.5}{3.75} = 0.93$

$A = 895\ ft^2$

$K = \sigma_1 \sigma_2$

$h_L = 2K\frac{\bar{V}^2}{2g}$ $\qquad \bar{V} = Q/A$

At $Q = 3325$ cfs,

$V = 3.72\ ft/sec$ $\quad \frac{V^2}{2g} = 0.215\ ft$ $\qquad Re \cong \frac{V a_0}{\nu} \cong 8 \times 10^4$

	θ					
	0	5	10	15	20	25
σ_1	1.0	1.05	1.07	1.1	1.1	1.1
σ_2	0.2	0.25	0.3	0.35	0.4	0.5
K	0.20	0.26	0.32	0.38	0.44	0.55

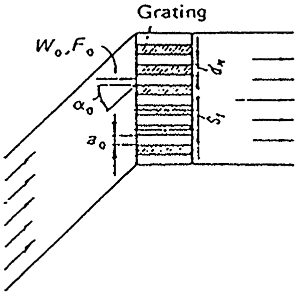
HEAD LOSSES

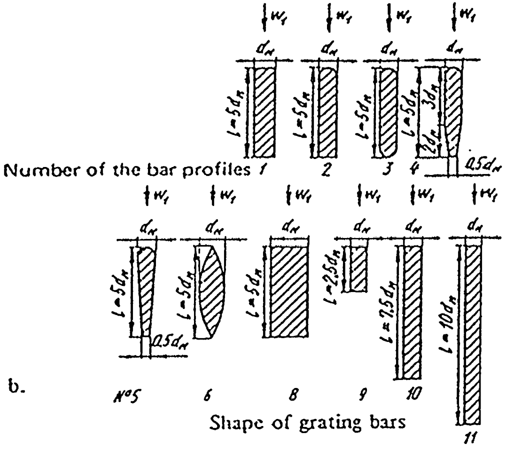
Left Unit			Right Unit		
0.086	.086	.086	.086	.138	.146
.086	.086	.086	.086	.125	.228
.086	.125	.086	.125	.086	.086
.142	.159	.146	.237	.172	.159

$\bar{h}_l = 0.105\ ft$ $\qquad \bar{h}_L = 0.140\ ft.$

Grating made of bars with an angle of attack $\alpha_0 > 0$ at $a_0/S_1 > 0.5$; $\mathrm{Re} = w_0 a_0/\nu > 10^4$ [9, 16, 54, 66]

Diagram 8-10





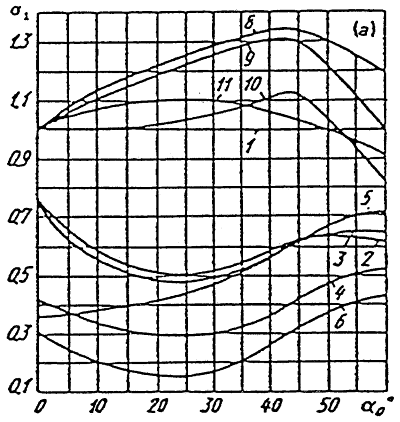
Shape of grating bars

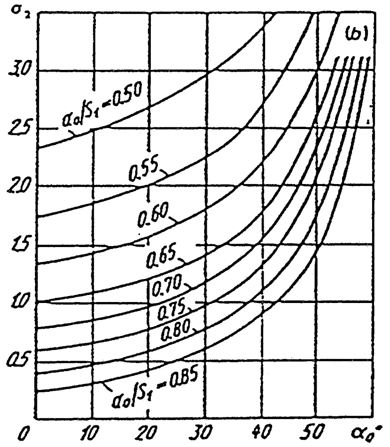
$$\zeta = \frac{\Delta p}{\rho w_1^2/2} = \sigma_1 \sigma_2$$

where for σ_1, see graph a; for σ_2, see graph b.

Values of σ_1

	α_0, degrees									
No. of curve	0	5	10	15	20	25	30	40	50	60
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	0.76	0.65	0.58	0.54	0.52	0.51	0.52	0.58	0.63	0.62
3	0.76	0.60	0.55	0.51	0.49	0.48	0.49	0.57	0.64	0.66
4	0.43	0.37	0.34	0.32	0.30	0.29	0.30	0.36	0.47	0.52
5	0.37	0.37	0.38	0.40	0.42	0.44	0.47	0.56	0.67	0.72
6	0.30	0.24	0.20	0.17	0.16	0.15	0.16	0.25	0.37	0.43
8	1.00	1.08	1.13	1.18	1.22	1.25	1.28	1.33	1.31	1.20
9	1.00	1.06	1.10	1.15	1.18	1.22	1.25	1.30	1.22	1.00
10	1.00	1.00	1.00	1.01	1.02	1.03	1.05	1.10	1.04	0.82
11	1.00	1.04	1.07	1.09	1.10	1.11	1.10	1.07	1.00	0.92





Values of σ_2

$\frac{a_0}{S_1}$	α_0, degrees									
	0	5	10	15	20	25	30	40	50	60
0.50	2.34	2.40	2.48	2.57	2.68	2.80	2.95	3.65	4.00	4.70
0.55	1.75	1.80	1.85	1.90	2.00	2.10	2.25	2.68	3.55	4.50
0.60	1.35	1.38	1.42	1.48	1.55	1.65	1.79	2.19	3.00	4.35
0.65	1.00	1.05	1.08	1.12	1.20	1.30	1.40	1.77	2.56	4.25
0.70	0.78	0.80	0.85	0.89	0.95	1.05	1.17	1.52	2.30	4.10
0.75	0.60	0.62	0.65	0.70	0.75	0.85	0.95	1.30	2.05	3.90
0.80	0.37	0.40	0.45	0.50	0.55	0.64	0.75	1.06	1.75	3.70
0.85	0.24	0.25	0.30	0.36	0.42	0.50	0.60	0.88	1.40	3.50

John S. Gulliver, Ph.D.
Consulting Engineer
Hydraulics ● Water Quality ● Hydropower
947 Forest Dale Rd
New Brighton, MN 55112

Mr. Doug Spaulding
Warzyn Engineering

Dear Doug:

This is an invoice for my time in Head loss calculations: St. Cloud Hydroelectric Facility. My time on the project is 3 hours. At our previously agreed rate of $70/hr, the total bill is $210.

Sincerely,
John Gulliver

APPENDIX C

Currentmeter and Performance Data from Confirmed Technical Provisions and Related Data for Generating Equipment, prepared for the City of St. Cloud by Warzyn Engineering, October 1986.

) Turbine Blade Position 100% ≅ 30.5 degrees.
) Min. TWL 963.0 ft.

GUARANTEED SINGLE UNIT EFFICIENCIES AND OUTPUTS AT A NET HEAD OF 16 feet

) TURBINE GATE POSITION	FLOW CFS	TURBINE OUTPUT kW	SPEED INCREASER EFFICIENCY	SPEED INCREASER OUTPUT kW	GENERATOR EFFICIENCY (1)	GENERATOR OUTPUT (kW)	TRANSFORMER EFFICIENCY	OVERALL EFFICIENCY (2)
Blade :FULL ~~GATE~~	3,225	2) 3,945	98.75	3896	97.15	3785	99.25	86.12
BEST GATE EFFICIENCY)F 54 % ~~GATE~~ Blade	1,970	2,460	98.5	2423	96.4	2336	99.11	86.86
Blade 90% ~~GATE~~	2,885	3,575	98.7	3529	97.05	3425	99.22	87.11
Blade 80% ~~GATE~~	2,595	3,240	98.65	3196	96.9	3097	99.2	87.53
Blade 70% ~~GATE~~	2,350	2,950	98.6	2909	96.75	2814	99.17	87.84
Blade 60% ~~GATE~~	2,105	2,655	98.55	2617	96.5	2525	99.14	87.92
Blade 50% ~~GATE~~	1,875	2,360	98.5	2325	96.3	2239	99.1	87.61
Blade 40% ~~GATE~~	1,655	2,075	98.4	2042	96.0	1960	99.05	86.78
Blade 30% ~~GATE~~	1,420	1,760	98.3	1730	95.45	1651	98.96	85.19
Blade 20% ~~GATE~~	1,205	1,470	98.15	1443	94.75	1367	98.83	82.81
Blade 10% ~~GATE~~	1,000	1,185	97.9	1160	93.9	1089	98.5	79.23
IINIMUM ~~GATE~~ Blade R CONTINUOUS BLE OPERATION ;.6 % ~~GATE~~ Blade	920	1,075	97.75	1051	93.6	984	98.45	77.92

(1) GENERATOR EFFICIENCIES GUARANTEED AT 0.8PF, RATED VOLTAGE AND FREQUENCY AND NOT MORE THAN 80°C RISE

(2) AS MEASURED AT THE TRANSFORMER OUTPUT TERMINALS

TABLE I

WARZYN
ENGINEERING INC

Turbine Blade Position 100% $\hat{=}$ 30.5 degrees
Min. TWL 963.3

GUARANTEED SINGLE UNIT EFFICIENCIES AND OUTPUTS AT A NET HEAD OF 17 feet

TURBINE GATE POSITION	FLOW CFS	TURBINE OUTPUT kW	SPEED INCREASER EFFICIENCY	SPEED INCREASER OUTPUT kW	GENERATOR EFFICIENCY (1)	GENERATOR OUTPUT (kW)	TRANSFORMER EFFICIENCY	OVERALL EFFICIENCY (2)
Blade FULL ~~GATE~~	3,230	2) 4,220	98.75	4167	97.2	4050	99.27	86.71
Blade BEST ~~GATE~~ EFFICIENCY F 55 % ~~GATE~~	2,000	2,685	98.55	2646	96.6	2556	99.15	88.30
Blade 90% ~~GATE~~	2,895	3,825	98.75	3777	97.1	3667	99.24	87.55
Blade 80% ~~GATE~~	2,600	3,460	98.7	3415	97.0	3313	99.22	88.06
Blade Blade 70% ~~GATE~~	2,360	3,160	98.65	3117	96.85	3019	99.19	88.32
Blade 60% ~~GATE~~	2,110	2,835	98.6	2795	96.7	2703	99.16	88.45
Blade 50% ~~GATE~~	1,890	2,540	98.55	2503	96.5	2415	99.12	88.18
Blade 40% ~~GATE~~	1,670	2,230	98.45	2195	96.2	2112	99.08	87.32
Blade 30% ~~GATE~~	1,435	1,895	98.35	1864	95.75	1785	99.0	85.82
Blade 20% ~~GATE~~	1,220	1,585	98.25	1557	95.0	1479	98.9	83.45
Blade 10% ~~GATE~~	1,020	1,290	98.0	1264	94.25	1191	98.66	80.19
MINIMUM ~~GATE~~ Blade R CONTINUOUS BLE OPERATION 6.6 % ~~GATE~~ Blade	940	1,170	97.9	1145	93.9	1075	98.5	78.60

(1) GENERATOR EFFICIENCIES GUARANTEED AT 0.8PF, RATED VOLTAGE AND FREQUENCY AND NOT MORE THAN 80°C RISE

(2) AS MEASURED AT THE TRANSFORMER OUTPUT TERMINALS

TABLE 2

WARZYN
ENGINEERING INC

) Turbine Blade Position 100% ≙ 30.5 degrees
) Min. TWL 963.9

GUARANTEED SINGLE UNIT EFFICIENCIES AND OUTPUTS AT A NET HEAD OF 18 feet

) TURBINE GATE POSITION	FLOW CFS	TURBINE OUTPUT kW	SPEED INCREASER EFFICIENCY	SPEED INCREASER OUTPUT kW	GENERATOR EFFICIENCY (1)	GENERATOR OUTPUT (kW)	TRANSFORMER EFFICIENCY	OVERALL EFFICIENCY (2)
Blade FULL ~~GATE~~	3,240	2)4,500	98.75	4444	97.2	4320	99.29	87.06
Blade BEST ~~GATE~~ EFFICIENCY)F 56 % ~~GATE~~	2,040	2,910	98.6	2869	96.75	2776	99.16	88.68
Blade 90% ~~GATE~~	2,910	4,085	98.75	4034	97.15	3919	99.26	87.89
Blade 80% GATE Blade	2,615	3,695	98.7	3647	97.1	3541	99.23	88.39
Blade 70% ~~GATE~~	2,375	3,375	98.65	3329	96.95	3228	99.2	88.66
Blade 60% ~~GATE~~	2,130	3,035	98.6	2993	96.8	2897	99.22	88.78
Blade 50% ~~GATE~~	1,900	2,705	98.55	2666	96.6	2575	99.15	88.44
Blade 40% ~~GATE~~	1,680	2,380	98.5	2344	96.35	2258	99.1	87.66
Blade 30% ~~GATE~~	1,450	2,035	98.4	2002	96.0	1922	99.04	86.31
Blade 20% ~~GATE~~-	1,230	1,695	98.3	1666	95.35	1589	98.93	84.01
Blade 10% ~~GATE~~-	1,025	1,375	98.1	1349	94.5	1275	98.73	80.82
INIMUM ~~GATE~~ Blade R CONTINUOUS BLE OPERATION .6 % ~~GATE~~ Blade	950	1,260	98.0	1235	94.15	1163	98.5	79.34

(1) GENERATOR EFFICIENCIES GUARANTEED AT 0.8PF, RATED VOLTAGE AND FREQUENCY AND NOT MORE THAN 80°C RISE

(2) AS MEASURED AT THE TRANSFORMER OUTPUT TERMINALS

TABLE 3

WARZYN
ENGINEERING INC

) Turbine Blade Position 100% ≙ 30.5 degrees
) Min. TWL 964.8 ft.

GUARANTEED SINGLE UNIT EFFICIENCIES AND OUTPUTS AT A NET HEAD OF 19 feet

TURBINE GATE POSITION	FLOW CFS	TURBINE OUTPUT kW	SPEED INCREASER EFFICIENCY	SPEED INCREASER OUTPUT kW	GENERATOR(1) EFFICIENCY	GENERATOR OUTPUT (kW)	TRANSFORMER EFFICIENCY	OVERALL(2) EFFICIENCY
Blade FULL GATE	3,240	2) 4,765	98.8	4708	97.2	4576	99.3	87.40
Blade BEST ~~GATE~~ EFFICIENCY)F 57% ~~GATE~~ Blade	2,070	3,120	98.65	3078	96.85	2981	99.19	88.94
90% ~~GATE~~ Blade	2,910	4,325	98.75	4271	97.2	4151	99.28	88.19
80% ~~GATE~~ Blade	2,625	3,925	98.75	3876	97.15	3766	99.25	88.69
Blade 70% ~~GATE~~	2,385	3,585	98.7	3538	97.05	3434	99.22	88.96
Blade 60% ~~GATE~~	2,135	3,215	98.65	3172	96.9	3074	99.2	88.99
Blade 50% ~~GATE~~	1,910	2,875	98.6	2835	96.7	2741	99.17	88.69
Blade 40% ~~GATE~~	1,695	2,535	98.5	2497	96.5	2410	99.13	87.87
Blade 30% ~~GATE~~	1,470	2,175	98.45	2141	96.15	2059	99.07	86.51
Blade 20% ~~GATE~~	1,250	1,820	98.35	1790	95.6	1711	98.99	84.37
Blade 10% ~~GATE~~	1,040	1,475	98.2	1448	94.75	1372	98.82	81.37
MINIMUM ~~GATE~~ Blade)R CONTINUOUS BLE OPERATION 6.6 % ~~GATE~~ Blade	970	1,365	98.1	1339	94.5	1265	98.73	80.18

(1) GENERATOR EFFICIENCIES GUARANTEED AT 0.8PF, RATED VOLTAGE AND FREQUENCY AND NOT MORE THAN 80°C RISE

(2) AS MEASURED AT THE TRANSFORMER OUTPUT TERMINALS

TABLE 4

WARZYN
ENGINEERING INC

APPENDIX D

CT and PT
Burden Analysis
and Test Reports

Review of the PT and CT Burdens for the St. Cloud Hydroelectric Facility

The following process was used to determine the burdens on the CTs and PTs located inside the St. Cloud Hydroelectric Facility and directly associated with facility's power production measurements.

1. The first step involved determination of the devices which were burdens to the CTs and PTs. This was done using the schematics #14–DK–3226 and panel layout #14DSB–0916. From these drawings, it was possible to determine which components were burdens on the instrument transformers.
2. The next step involved the ascertation of the actual burdens from their manuals. These manuals were provided to the City of St. Cloud by Ideal Electric. Each manual provided burden specifications for a particular device.
3. Upon completion of step 2, all the burdens had to be summed up. This means summing up burdens for the CTs and summing up burdens for the PTs independently.
4. Once the burdens were known, it was then necessary to proceed to the attached transformer curves to find the correction factor. There is one correction factor for the CTs and one for the PTs. These correction factors are used to find the true power.

The following is the formula used in finding new power:

$$\text{Since power} = E_1 \times I_1 + E_2 \times I_2 + E_3 \times I_3$$
$$\text{New power} = (RCF_V) \times (RCF_I) \times [E_1 \times I_1 + E_2 \times I_2 + E_3 \times I_3]$$

WHERE:

E_n = phase n voltage
I_n = phase n current
RCF_V = Ratio Correction Factor for the Potential Transformer
RCF_I = Ratio Correction Factor for the Current Transformer

BURDENS FOR THE ST. CLOUD HYDROELECTRIC FACILITY

DEVICE	BRAND	MODEL	DESCRIPTION	CT	PT
PF–TD	Scientific Columbus	PF34P	Power Factor Transducer	.1VA	.05VA
32–R	GE	ICW51A	Reverse Power Relay	.425VA	4.73VA
37	GE	ICW51A	Under Power Relay	.425VA	4.73VA
50/51		IFCV51BD	Over Current Relay	10.64VA	19.7VA
VARM	GE	AB–40	VAR Meter	.43VA	.14VA
WM	GE	AB–40	Watt Meter	.43VA	.14VA
PFM	GE	AB–40	Power Factor Meter	.91VA	.68VA
AM	GE	AB–40	Amp Meter	.33VA	NC
40	GE	CEH51A	Loss of Excitation	3.01VA	12.7VA
WHM	Trans Data	EMS7000	Watt–Hour Meter	.3VA	.02VA
46	Westing–house	COQ	Negative Seq. Rly	NC	4.7VA
59	GE	IAV51A	Over Voltage Relay	NC	1.8VA
FM	GE	AB–40	Frequency Meter	NC	1.5VA
ETM			Elapsed Time Meter	NC	3.0VA
VM	GE	AB–40	Volt Meter	NC	.51VA
TRI	Analogic	ITG2600	Trash Rack Indicator	NC	5.0VA
TOTAL				17.00VA	59.40VA
CLASS				B1.0	Y
COEFFICIENT full power				1.0000	1.0014
COEFFICIENT half power				1.0005	1.0014
OVERALL RESULTANT POWER CORRECTION COEFFICIENTS			full power		1.0014
			half power		1.0019

NC – No connection

Hence, the overall revised power output at the St. Cloud Hydroelectric Facility is greater than that computed during the Field Acceptance Tests and Issued in the "Field Acceptance Tests of the Turbine Generator Units at the St. Cloud Hydroelectric Facility" draft report issued March, 1989.

VOITH HYDRO, INC. TELEFAX

DATE: 11-10-88
TO: M. A. Mortenson
ATTN: Don Coulson
RE: St. Cloud
TELEFAX #: 612-520-3430
SENT BY: R. Titemore

NOV 10 2 49 PM '88

FROM: VOITH HYDRO, INC.
East Berlin Road
P. O. Box 712
York, PA 17405

Tel: (717) 792-3511
Tfx: (717) 792-3862 or
(717) 792-2264
Tlx: 4764013 VOITH UI

NO. OF PAGES: 5
(including cover page)

** If you do not receive all the pages, or if trouble occurs during transmission, please call (717)792-3511 and ask for Cheryl @ Ext. 852, as soon as possible.

In response to your 11/10/88 telefax:

1.) Attached are PT test cards Ideal received with the potential transformers. They did not receive any test cards with the current transformers.

2.) Attached is a copy of the factory test report for the main transformer.

I am waiting for a response from Ideal concerning the calibration curves.

Regards
R. Titemore

VY CONTRACT
CORRESPONDENCE

Original-Record Center

COPIES
X Cont. Admin.
X Cont. Mgr.
X Proj. Mgr.
X Prod. Mgr.

NOV 10 '88

TYPE JVM-3

User No.

Ratio 35 :1

Mfr's Serial No. 5239685

Rated Secondary Volts 120

Secondary Burden	Secondary Volts	Ratio Correction Factor	Phase Angle (Minutes)
O VA	120	0.9926	+3
O VA	132	0.9929	+4
Y	120	1.0021	0

Date 9-29-87 Tested by JD

TYPE JVM-3

User No.

Ratio 35 :1

Mfr's Serial No. 5239835

Rated Secondary Volts 120

Secondary Burden	Secondary Volts	Ratio Correction Factor	Phase Angle (Minutes)
O VA	120	0.9975	+2
O VA	132	0.9977	+3
Y	120	1.0020	0

Date 9-29-87 Tested by JD

TYPE JVM-3

User No.

Ratio 35 :1

Mfr's Serial No. 5239213

Rated Secondary Volts 120

Secondary Burden	Secondary Volts	Ratio Correction Factor	Phase Angle (Minutes)
O VA	120	0.9926	+3
O VA	132	0.9979	+4
Y	120	1.0021	0

Date 9-29-87 Tested by JD

TYPE JVM-3

Ratio 35 :1

User No.

Mfr's Serial No. 5240596

Rated Secondary Volts 120

Secondary Burden	Secondary Volts	Ratio Correction Factor	Phase Angle (Minutes)
O VA	120	0.9975	+3
O VA	132	0.9978	+4
Y	120	1.0020	0

Date 9-29-87 Tested by JD

TYPE JVM-3

Ratio 35 :1

User No.

Mfr's Serial No. 5239212

Rated Secondary Volts 120

Secondary Burden	Secondary Volts	Ratio Correction Factor	Phase Angle (Minutes)
O VA	120	0.9976	+3
O VA	132	0.9979	+4
Y	120	1.0021	0

Date 9-29-87 Tested by JD

TYPE JVM-3

Ratio 35 :1

User No.

Mfr's Serial No. 5239662

Rated Secondary Volts 120

Secondary Burden	Secondary Volts	Ratio Correction Factor	Phase Angle (Minutes)
O VA	120	0.9975	+3
O VA	132	0.9978	+3
Y	120	1.0020	0

Date 9-29-87 Tested by JD

TYPE JVM-3

User No.

Ratio 35 :1

Mfr's Serial No. 5239684

Rated Secondary Volts 120

Secondary Burden	Secondary Volts	Ratio Correction Factor	Phase Angle (Minutes)
O VA	120	0.9977	+3
O VA	132	0.9980	+4
Y	120	1.0022	+1

Date 9-29-87 Tested by JD

TYPE JVM-3

User No.

Ratio 35 :1

Mfr's Serial No. 5239663

Rated Secondary Volts 120

Secondary Burden	Secondary Volts	Ratio Correction Factor	Phase Angle (Minutes)
O VA	120	0.9977	+3
O VA	132	0.9980	+3
Y	120	1.0023	-1

Date 9-29-87 Tested by JD

TYPE JVM-3

User No.

Ratio 35 :1

Mfr's Serial No. 5239686

Rated Secondary Volts 120

Secondary Burden	Secondary Volts	Ratio Correction Factor	Phase Angle (Minutes)
O VA	120	0.9976	+3
O VA	132	0.9979	+4
Y	120	1.0021	0

Date 9-29-87 Tested by JD

SOUTH BOSTON, VIRGINIA

CERTIFIED TRANSFORMER TEST REPORT

NERAL ORDER: FH73683 SHOP ORDER: HBT0276
STOMER: VOITH PURCHASER'S ORDER NUMBER: Y-01134-C
PHASE 60 HERTZ COOLANT- OIL SUB/PHASE POLARITY

NDING HIGH VOLTAGE	WINDING LOW VOLTAGE
500 KVA	7500 KVA
500 VOLTS DELTA	4160 VOLTS WYE

FS: 36225 35360 34500 33640 32775 31910 31050

SISTANCES, LOSSES, IMPEDANCE, AND REGULATION CORRECTED TO 075 DEGREE C. SISTANCES, EXCITING CURRENT, LOSSES AND IMPEDANCES ARE BASED ON NORMAL TING, UNLESS OTHERWISE STATED. LOSSES AND REGULATION ARE BASED ON WATTMETER ASUREMENTS. FOR THREE-PHASE TRANSFORMERS, THE RESISTANCES ARE THE SUM OF E THREE PHASES IN SERIES.

SERIAL NUMBER	TEST DATE	RESISTANCES IN OHMS WINDING H.V.	L.V.	AT 100% RATED VOLTAGE %EXCITING CURRENT	NO LOAD LOSS WATT	34500 TO 4160 7500 KVA LOAD LOSS WATTS	%IMP
T02760101	111187	2.5084	.00808	0.2337	9176	28357	6.78
						TOTAL LOSS	
			AVERAGE	.2337	** 9176	37533	6.78
			GUARANTEE	.9700	9150	38300	7.00

REGULATION

POWER FACTOR	100%	80%
AVERAGE	.625	4.511

MPERATURE RISE CALCULATED FROM BASIC DESIGN DATA WHICH HAS BEEN VERIFIED BY ST RESULTS OF SIMILAR TRANSFORMERS.

LOAD	WINDING RISE BY RESISTANCE H.V.	L.V.	GUAR	TOP FLUID RISE	AMBIENT TEMP
100%	49.0	53.0	55	48.3	

INSULATIONS TEST

PLIED POTENTIAL TEST (VOLTAGE IS APPLIED BETWEEN EACH WINDING AND ALL OTHER NDINGS CONNECTED TO CORE AND GROUND)

WINDING	RATED VOLTS	TEST VOLTAGE APPLIED	DURATION OF TEST
H.V.	34500	70 KV	60 SECONDS
L.V.	4160	19 KV	60 SECONDS

IDUCED POTENTIAL TEST: TWO TIMES RATED VOLTAGE ACROSS THE FULL WINDING AT 30 HERTZ FOR 7200 CYCLES.

* HIGH IRON LOSS WAS WAIVERED BY CUSTOMER

HEREBY CERTIFY THAT THIS IS A TRUE REPORT BASED ON FACTORY TESTS MADE IN CORDANCE WITH THE LATEST TRANSFORMER TEST CODE C57 OF THE AMERICAN STANDARDS SOCIATION; AND THAT EACH TRANSFORMER WITHSTOOD THE ABOVE INSULATION TESTS.

DATE 11/25/87 APPROVED BY Lloyd Allen

PAGE 1 OF 1 PAGES

APPENDIX E

1) As built dimensional survey of intake

2) Copy of elevation traverse
performed prior to testing

3) Piezometer traverse

Jan P.

CITY OF
ST. CLOUD
400 2nd STREET SO.
ST. CLOUD, MINNESOTA 56301-3699
ENGINEERING DEPARTMENT

March 31, 1988

To: Gerald Mahon, Project Manager
From: Steve Foss, Project Engineer
Re: Field Measurement of Intake Passages

Based upon comments received during the review of SAFHL acceptance test procedure, field measurements of as-built dimensions of intake passageways were taken.

Two such sets of measurements were made -- one set on March 24, 1988, by Steve Foss and Ron Jordan using a steel tape, and the second on March 29, 1988, by Dan Coulson, Steve Westby and Steve Foss using a level and rod (see attached data sheets).

These measurements have established the height of the intake water passage as 24' 4-1/4" which is 3/4" larger than the 24' 3-1/2" plan dimension.

It is, therefore, my recommendation that the elevations of the top of the intake passage and radius points for curves located at the bottom of the upstream headwall be raised by 3/4".

The recommended changes are shown on Attachment "A." The elevations and dimensions shown on Attachment "A" represent the as-built dimensions and thus would be those utilized in determining the area in the flow calculations.

SDF:jdk

3. FOSS

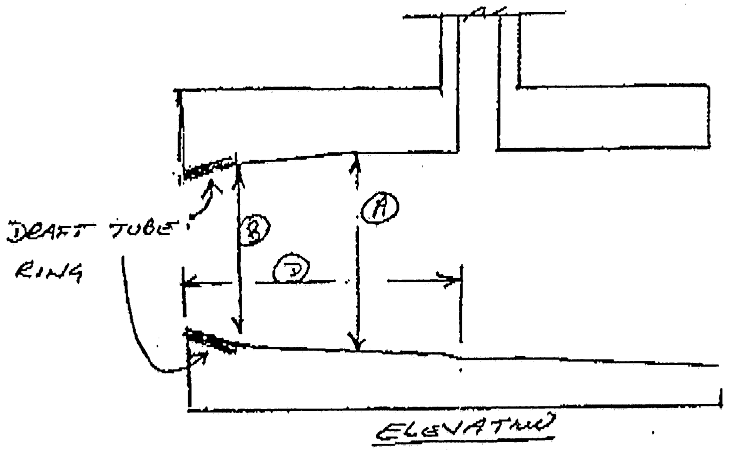
WATER PASSAGE DIMENSION CHECK

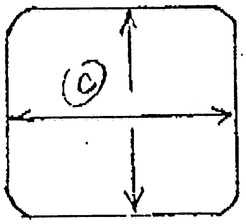
PURPOSE: VERIFICATION OF DESIGN DIMENSION'S OF WATER PASSAGE WAYS BY THE TAKING OF SELECTED SPOT CHECKS IN THE FIELD.

PROCEEDURE: ALL MEASUREMENTS WERE MADE WITH A STEEL TAPE.

FIELD DATA:

DRAFT TUBE

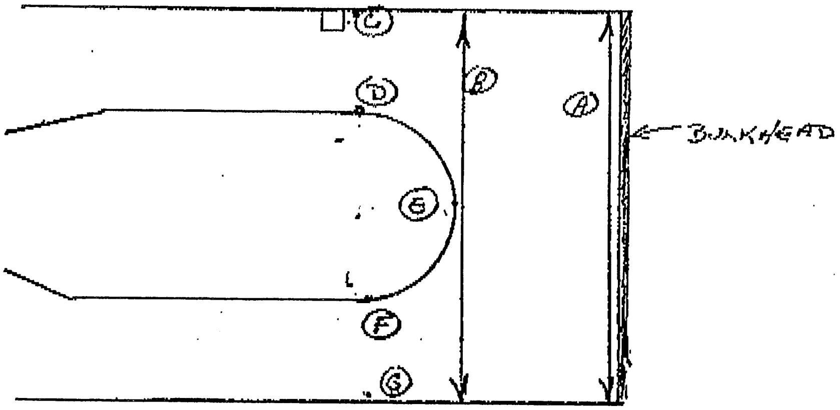




DIMENSION	UNIT I FIELD	UNIT II FIELD	PLAN	Δ UNIT I	Δ UNIT II
A	16-7½ HORIZ	16-7¾ HORIZ	16-7	+ ½"	+ ¾"
	16-8 VERT	16-7½ VERT	16-7	+1"	+ ½"
B	14-4½ HORIZ	14-4⅝ HORIZ	14-4¾	- ¼"	- ⅛"
C	19-3½ HORIZ	19-4 HORIZ	19-3¼	+ ¼"	+ ¾"
	17-9 VERT	17-8½ VERT	17-9⅛	- ⅛"	- ⅝"
D	28-9½	28-9	28-8¾	+ ¾"	+ ¼"

FIELD DATA: CONTINUED

UPSTREAM INTAKE PASSAGE



PLAN VIEW

DIMENSION	UNIT I FIELD		UNIT II FIELD		PLAN	Δ UNIT I	Δ UNIT II
A	29-10 1/2	HORIZ	29-10 3/4	HORIZ	29-10 1/2	—	+ 1/4"
B	29-10 3/4	HORIZ	29-10 3/4	HORIZ	29-10 1/2	+ 1/4"	+ 1/4"
C	24-4 1/2	VERT	24-4 1/4	VERT	24-3 1/2	+ 1"	+ 3/4"
D	24-4 1/4	VERT	24-4 1/4	VERT	24-3 1/2	+ 3/4"	+ 3/4"
E	24-4 1/4	VERT	24-4 1/4	VERT	24-3 1/2	+ 3/4"	+ 3/4"
F	24-4 1/4	VERT	24-4 1/4	VERT	24-3 1/2	+ 3/4"	+ 3/4"
G	24-4 1/2	VERT	24-4 1/4	VERT	24-3 1/2	+1"	+ 3/4"

MAM 3007

M.A. MORTENSON CO.
MPLS., MINN.

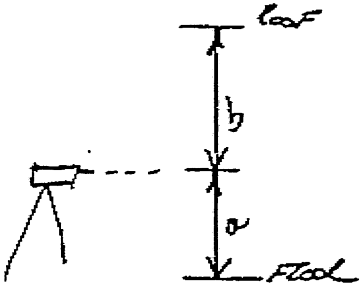
PROJECT:

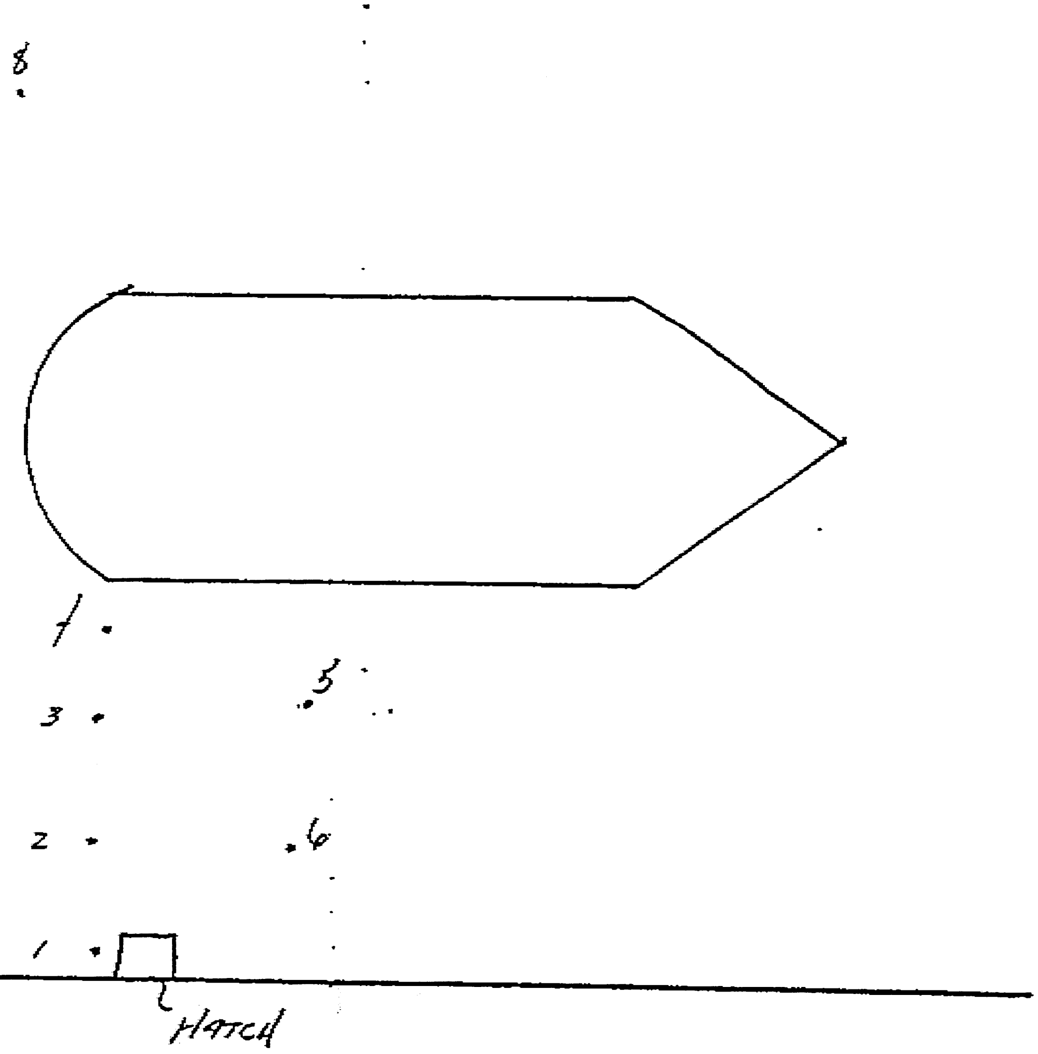
Est. by
Chk. by
Date 5-29-88

By: DAN COULSON
STEVE WESTBY
STEVE FOSS

UNIT I

LOCATION	a	b	TOTAL
1	6.37	18.00	24.37
2	6.37	18.00	24.37
3	6.37	18.00	24.37
4	6.36	18.00	24.36
5	6.37	17.99	24.35
6	6.37	17.99	24.35
8	6.66	17.72	24.38





M.A. MORTENSON CO.
MPLS., MINN.

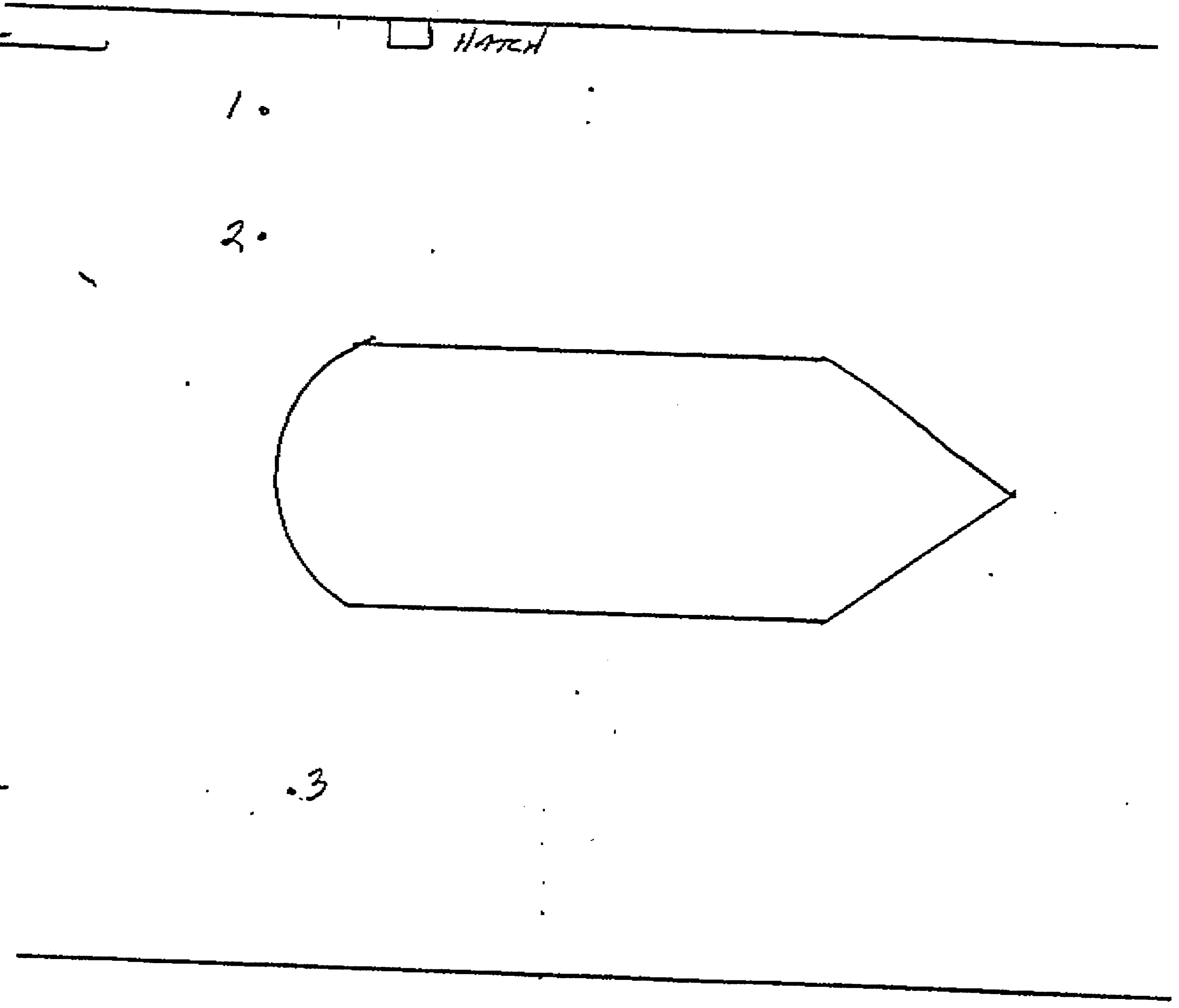
PROJECT:

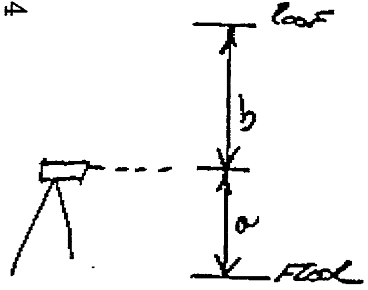
Est. by
Chk. by
Date 3-29-88

By' DAN COULSON
STEVE KOSTAS
STEVE FOSS

UNIT II

LOCATION	a	b	TOTAL
1	5.19	19.16	24.35
2	5.18	19.16	24.34
3	5.20	19.15	24.35



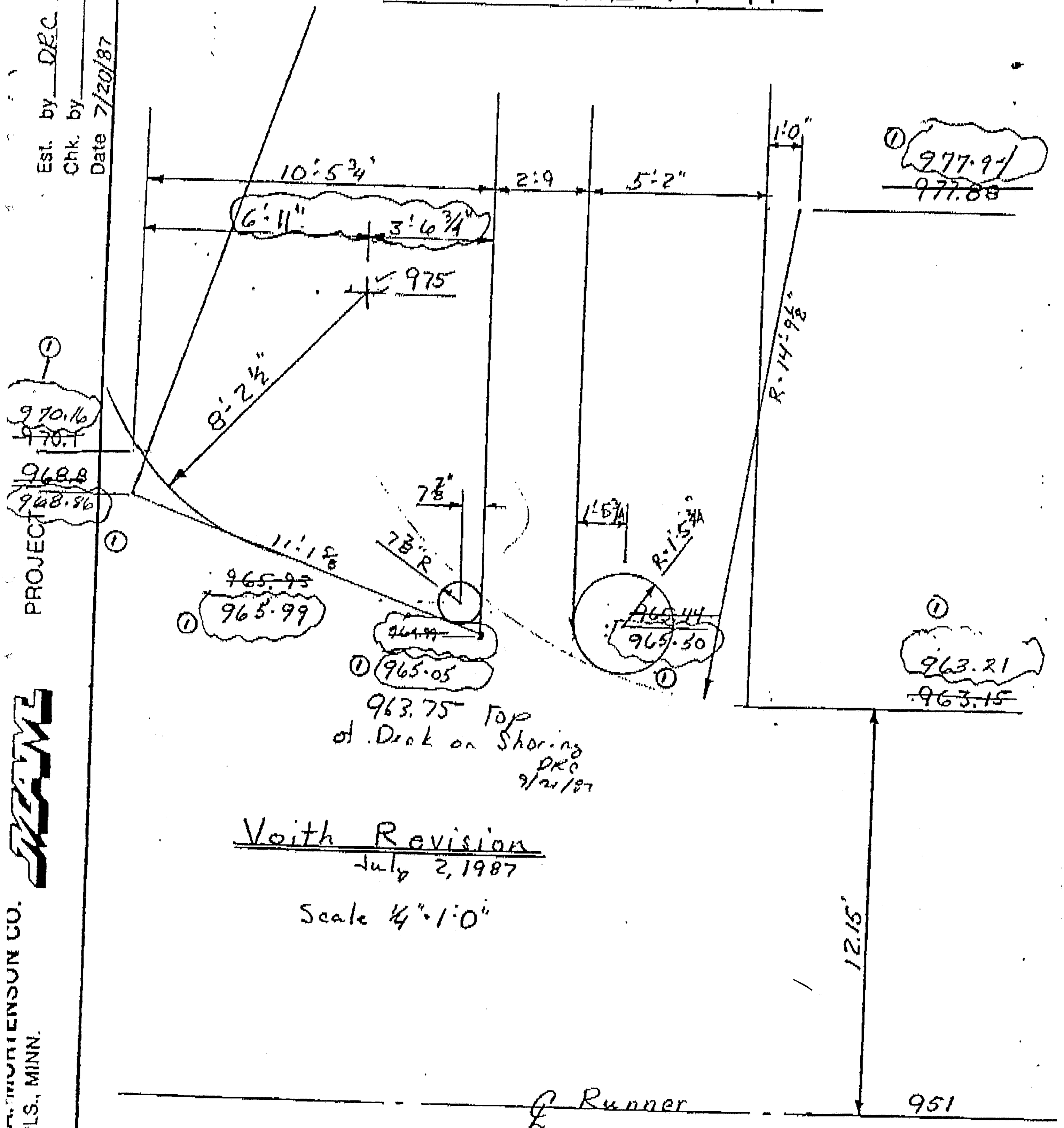


ATTACHMENT "A"

Est. by DRC
Chk. by
Date 7/20/87

PROJECT

M.A. MORTENSON CO.
MPLS., MINN.



Voith Revision
July 2, 1987

Scale 1/4"-1'0"

① REVISION 3/31/88 RAISE INDICATED ELEVATIONS BY 3/4"
SDF

CITY OF
ST. CLOUD
400 2nd STREET SO.
ST. CLOUD, MINNESOTA 56301-3699
ENGINEERING DIVISION - TEL. 612/255-7249

January 4, 1989

Mr. Rick Voigt, Jr.
St. Anthony Falls Hydraulic Laboratory
Department of Civil and Mineral Engineering
Mississippi River at Third Avenue S.E.
Minneapolis, MN 55414-2196

Re: Request for Data Regarding Acceptance Test

Dear Rick:

Enclosed find a copy of the description and specifications sheet on the EMS 7000 metering system. Hopefully, this will include the information you requested under Item No. 2 of your January 4, 1989, telefax.

In regard to Item No. 3 of the same fax, also find a copy of the field notes of installation of bench marks utilized during performance testing. Note that all the benches set were based on two bench marks provided by M. A. Mortenson on site and are not tied into a U.S.G.S. bench. In addition, all exterior temporary bench marks (#1 - #9) were set off one of these bench marks while all interior temporary bench marks (#10 - #13) were set off the other bench. On the bottom right of page #45, the two systems are tied together and the exterior system check is 0.0155 feet higher than the interior system.

If you have any further questions, feel free to give me a call.

Sincerely,

Steve Foss

Steve D. Foss, P.E.
Civil Engineer

SDF:jdk
Enclosures

cc: Gerald Mahon
Jan Petersen
Ken Lever
File

88-6

BENCH TRANSFER / MISC. ELEV.

@ HYDRO PLANT

B.M.- A PT. ON STEEL SHEETING @ TOP OF CONTAINMENT TOWER = 994.99

	4.335			
T.P.	4.30✓	999.29		
	4.265			
			4.427	
B.M.#1			4.402 4.404	994.888
			4.377	
			4.425	
B.M.#2			4.3785 4.377	994.9115
			4.332	

10-18-88

CLDY./COOL

H.FORER 43
T.WAYTASHEK
T.BACKES

			4.449	
B.M#3 (W'LY. PLATE)			4.3405 4.343	994.9495
			4.232	
	3.125			
T.P. @ B.M.#3	3.0855 3.087	998.035		
	3.046			
			3.371	
B.M.#4 (℄ UNIT#2)			3.281 3.283	994.754
			3.191	
			3.386	
B.M.#5 (℄ UNIT#1)			3.3455 3.348	994.6895
			3.305	

88-6

BENCH / ELEV. - HYDRO. PLANT

			12.669	
B.M. #6 BRASS DISC			12.6095 12.606	985.4255
ON ROOF SLAB			12.550	
	4.337			
T.P.	4.3005 4.301	989.726		
(B.M. #6)	4.264			
			4.800	
B.M. #7			4.744 4.743	984.982
(VAULT)			4.688	
	0.760		12.708	
T.P.	0.6305 0.630	985.6125	12.6645 12.664	972.948
(B.M. #7)	0.501		12.621	

10-18-88

	0.935			
T.P.	0.7295 0.730	973.6775		
	0.524			
			10.050	
B.M. #8			9.844✓	963.8335
(SUN DECK)			9.638	
			5.555	
B.M. #9			5.268 5.265	968.4095
(CHANNEL-WALL)			4.981	

BENCH MARK CURCUIT TIE BET.

CURCUIT "1" (OUTSIDE BLDG.) AND

CURCUIT "2" (INSIDE BLDG.)

B.M. #6 BR. DISC	2.96	88.3855			985.4255
T.P.			21.37	67.0155	
CURCUIT "2"				967.0155 KS	967.000

88-6

10-18-88

B.M. ON NOSE 47
OF PIT AS
PROVIDE BY [illegible]

BENCH / ELEV. - HYDRO. PLANT

	~~0.69~~			
~~B.M. #6~~	~~0.67✓~~	~~986.0955~~	~~9.815~~	~~976.2805~~
~~(BRASS DISC)~~	~~0.65~~			
	~~2.94~~			
~~T.P.~~	~~2.8575~~ ~~2.856~~	~~979.138~~		
	~~2.775~~			
~~B.M. ON FLOOR~~			~~12.185~~ ~~12.1035~~ ~~12.104~~	~~967.0345~~
			~~12.022~~	

B.M.	4.45	971.45		967.00
No. 1 #10 TURBINE			5.24	966.21
No. 2 #11 TURBINE			5.24	966.21
No. 1 #12 TURBINE LETTER "I" IN "VOITH"			9.55	961.90
No. 2 #13 TURBINE			6.44	965.01

ADD'NL. MISC. ELEV.

TURBINE "I"
Top FLAT IRON ON DN. STREAM H. RAIL 964.335