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Discharge Measurement and Energy Efficiency Evaluation of Irrigation Pumping Plants

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DISCHARGE MEASUREMENT AND ENERGY EFFICIENCY EVALUATION OF IRRIGATION PUMPING PLANTS

by

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DISCHARGE MEASUREMENT AND ENERGY EFFICIENCY EVALUATION

OF IRRIGATION PUMPING PLANTS

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

Thesis Advisor Date

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INTRODUCTION

Irrigation has become a firmly established farming practice in South Dakota. Water use permits have been granted for approximately 400,000 hectares (1 million acres) or seven percent of South Dakota cropland. Development of permitted acres is continuing with an estimated 200,000 hectares (500,000 acres) now being irrigated (DeBoer, 1977). Approximately 50 percent of the irrigation water is pumped by electric pumping plants (DNR, 1976).

Efficient electric energy use by irrigation is important both to the individual farmer and to society. Of greatest importance to the farmer is the rising cost of electricity. Kilowatt-hour rates have risen approximately 15-20 percent in 1978 and are expected to go up another 15 percent in 1979 (Mebius, 1978). Demand charges, or standby charges, based on total connected horsepower are also increasing. Further increases in the cost of electricity are expected as energy from the Missouri mainstem dams contributes a smaller portion of the total electric energy in South Dakota and energy from coal-fired generating plants becomes more predominate.

Competition from segments of society other than agriculture may place limits on the amount of electric energy available for irrigation in the future. Maximum system capabilities of individual rural electric cooperatives will also limit irrigation energy use. Large irrigation loads caused some rural electric cooperatives in South Dakota to experience an annual demand peak during the summer of 1977. Many cooperatives will be considering limiting the number of irrigation units in

operation during peak energy use periods in order to reduce demand charges and to keep total system demands balanced between summer and winter.

The use of energy efficient pumping plants enables the irrigator to conserve energy without reducing water use. However, many irrigators are not aware of the importance of pumping plant efficiency. Determination of pumping plant efficiency involves the use of instrumentation not normally available to the individual farmer. This equipment is too expensive to be cost-effective on an individual basis. Also, the irrigator may lack the technical expertise required to make the measurements and to calculate pump efficiency.

No information has been available regarding efficiencies of electric irrigation pumping plants in South Dakota. Pumping plant discharge, a key parameter in the calculation of pumping plant efficiency, is often difficult to measure in the field. A project was initiated at South Dakota State University in 1976 to investigate field pumping plant efficiencies. The following objectives were established for the project.

1. To investigate various methods of measuring irrigation pumping plant discharge.
2. To develop a suitable field procedure for determining electric irrigation pumping plant efficiency.
3. To measure energy efficiency of selected electric irrigation pumping plants in South Dakota.

LITERATURE REVIEW

Flow Measurement

Several methods and devices are available for flow measurement in the field. The methods and devices vary considerably in range of application and accuracy. A literature review was conducted to determine the flow measurement methods most suitable for pump efficiency testing. A good flow meter for pump testing should be accurate under field conditions, easy to transport and install, have a low initial cost, and require little maintenance.

Flow measurement devices can be classified as open channel devices and closed conduit devices. Open channel devices are used when flow takes place in an open ditch or canal. Open channel measurement is useful for pump efficiency testing only when the pump discharges into an open ditch. Open channel discharge is not common for irrigation pumps in South Dakota.

Closed conduit flow measurement devices are more applicable for irrigation pumping plant discharge measurement. Closed conduit devices measure water flow in a pipe under pressure. Several devices are available which can be adapted for pumping plant efficiency testing.

The propeller meter is the most common flow measurement device for closed conduits in irrigation. The propeller meter consists of an impeller or propeller suspended in the flow stream and connected to an external register by mechanical or magnetic drive. The speed of rotation of the propeller is proportional to stream flow velocity. The meter register mechanically integrates the rotational speed of the

propeller for a given pipe size and indicates the total volume of water passing the meter. The mechanical integration is accurate only for a specific pipe diameter so the meter must be properly sized and calibrated for each installation. Some meters also indicate instantaneous flow rates.

Propeller meters can be accurate to within plus or minus two percent when properly sized and installed (McCrometer). Proper installation requires sufficient straight pipe upstream from the meter to quiet excessive turbulence. One manufacturer recommends five to ten pipe diameters of straight pipe upstream and cautions against installing meters downstream from valves which may be partially closed (McCrometer). A partially closed valve can cause a jetting action which adversely affects meter performance. Flow straightening vanes installed upstream from the propeller meter will quiet turbulence in a shorter distance than open pipe.

Several flow meters use a constriction in the pipe diameter to increase fluid velocity in a local area. The increased velocity through the reduced flow area creates a pressure differential between points immediately upstream and downstream from the constriction (Figure 1). The magnitude of the pressure differential is a measure of fluid velocity. The orifice, venturi, and flow nozzle are examples of the constriction type of flow meter.

Normally, existing piping arrangements must be modified to allow for the installation of a constriction meter. A pipe flange in a straight section of pipe is usually sufficient for the installation of an orifice plate. The flow nozzle and the venturi tube are constriction meters

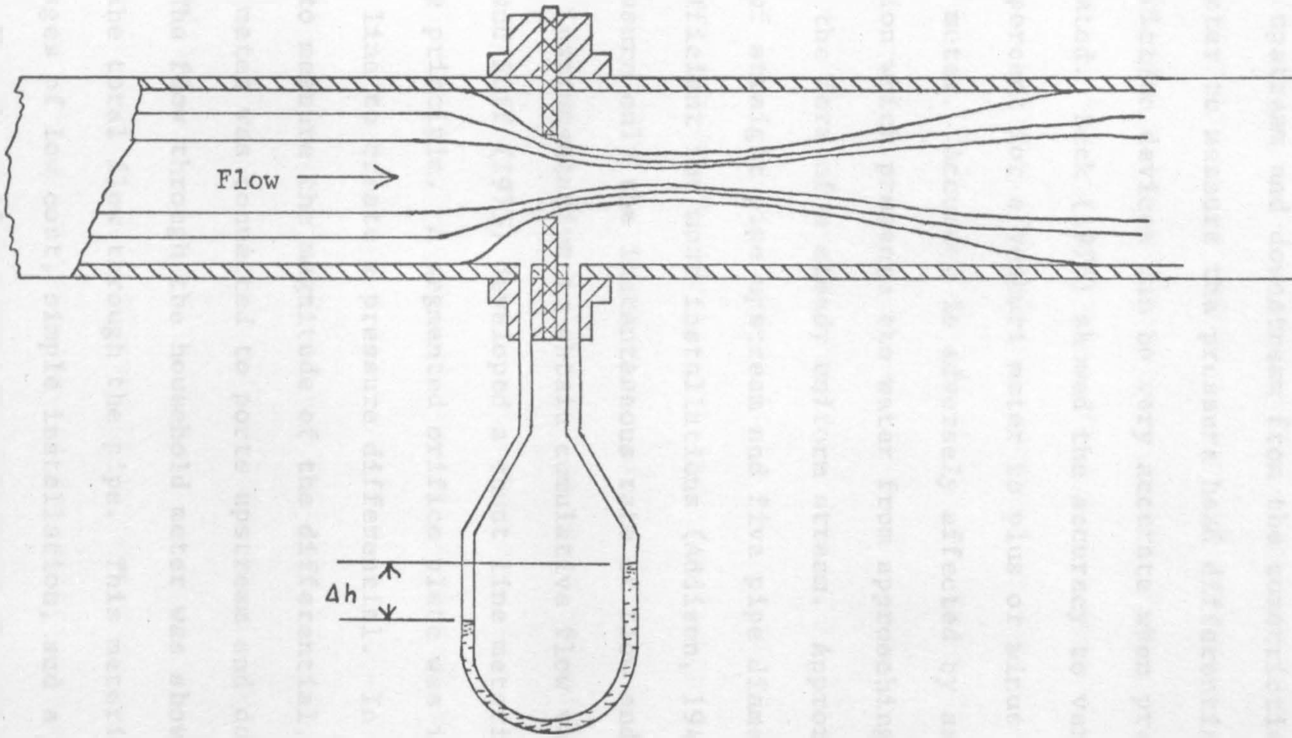

Figure 1. Constriction Flow Meter.

manufactured in short sections of pipe which replace a section of similar length to be removed from the existing system. Pressure taps are placed upstream and downstream from the constriction and connected to a manometer to measure the pressure head differential.

Constriction devices can be very accurate when properly installed and calibrated. Beck (1976) showed the accuracy to vary from plus or minus 3/4 percent for a venturi meter to plus or minus 1 1/4 percent for an orifice meter. Accuracy is adversely affected by any upstream pipe configuration which prevents the water from approaching the constriction axially in the form of a steady uniform stream. Approximately ten pipe diameters of straight pipe upstream and five pipe diameters downstream will be sufficient for most installations (Addison, 1941). Constriction devices measure only the instantaneous rate of flow and must be coupled with other instrumentation to obtain cumulative flow values.

Hill and Ruff (1975) developed a shunt line metering system using the orifice principle. A segmented orifice plate was installed in the irrigation line to create a pressure differential. In place of a manometer to measure the magnitude of the differential, a common household water meter was connected to ports upstream and downstream from the orifice. The flow through the household meter was shown to be proportional to the total flow through the pipe. This metering system offers the advantages of low cost, simple installation, and a flow totalizer. The shunt line metering system was shown to be accurate to within plus or minus five percent, but it must be calibrated for each installation in the field.

A flow measurement device which measures fluid velocity is the

pitot tube. The pitot tube consists of a hollow tube with an attached nozzle which faces upstream parallel to fluid flow. The action of the flow stream striking the nozzle drives a fluid column connected to the hollow tube upward. The height of rise of the water column equals the velocity head plus the pressure head of the flow. In the most common form the pitot tube is combined with a static pressure orifice. The head differential between the pressure measured by the static pressure orifice and the impact nozzle is measured with a manometer to determine stream velocity.

Because the diameter of the pitot tube is small compared to the diameter of the conduit in which it is used, a pitot tube may be considered to measure velocity at a point. A velocity traverse is generally conducted to determine the velocity of fluid flow at several points across the conduit. The average of the point velocities is used to calculate the flow rate through the conduit.

The pitot tube can be easily installed through a small hole in the pipe wall without disturbing the operating configuration of the system being tested. The pitot tube is not suitable for use with water which contains particles of foreign matter large enough to plug the static or impact orifices.

A common objection to the use of a pitot tube device is the inaccuracy of the device in conditions of non-uniform or excessively turbulent flow. Parallel flow lines are necessary for highly accurate measurements and are most easily assured by using the pitot tube in a location which has a long length of upstream straight pipe. Spink (1967) recommended upstream straight pipe length in excess of 50 pipe diameters

for consistent results in the laboratory. However, Addison (1941) showed differences between discharge measured by the pitot tube velocity traverse and absolute measurement to be less than 0.5 percent when the pitot tube was preceded by a bend and a tee in series eight pipe diameters upstream. The minimum length of upstream straight pipe is dependent upon the geometry of the piping system and the degree of accuracy required.

Miramontes (1949) cited the use of a Hall tube and a transverse tube pitot tube device for pump efficiency testing. The Hall tube uses several impact orifices acting simultaneously on the manometer to obtain the average stream velocity. The impact orifices eliminate the need for a velocity traverse across the conduit. Data from a limited laboratory test of one Hall tube device (Morrelli, 1952) showed errors of discharge measurement to be less than plus or minus four percent. The test was conducted with more than 20 pipe diameters of upstream straight run pipe.

Miramontes (1949) also used a transverse tube pitot tube device for pump testing. This device consists of a small diameter stainless steel tube which is placed through the pipe perpendicular to stream flow. Two orifices are drilled into the transverse tube. One orifice faces upstream and produces a pressure equal to static pressure head plus velocity head. The other orifice faces downstream and produces a pressure equal to static pressure head minus velocity head. The head differential between the two orifices is measured with a manometer. All of the velocity head is not measured by the trailing orifice so an empirically determined constant must be applied to determine true velocity. A velocity traverse must be conducted with the transverse tube to measure average velocity.

Low cost reliable electronic systems have made some new flow measurement devices more adaptable to irrigation use. Acoustic or ultrasonic flow meters measure the travel time of high-frequency sound pulses in the moving fluid to determine flow velocity. The sound wave velocity is the speed of sound in the fluid plus or minus the rate at which the fluid is moving toward or against the sound source. Magnetic flow meters measure flow rate by placing a magnetic field around the flow conduit and measuring the voltage induced when water passes through the magnetic field. The voltage developed is proportional to the fluid velocity and the strength of the field. Both magnetic and sonic flow measurement are still too expensive and fragile to consider for general irrigation use.

Fluorometry is a flow measurement method which may be useful where extensive studies require enough measurements to justify equipment costs. Fluorometry involves measuring the concentration of a fluorescent dye in a solution injected into the flow stream and the concentration in the discharge water. The ratio of the concentration of the dye in the injection solution to the concentration in the discharge water is indicative of the ratio of the flow rate of the dye solution to the flow rate of the discharge. If the injection rate is known the discharge may be calculated. Turner (1974) maintains that fluorometers are highly accurate and rugged enough for field use.

Pumping Plant Testing

Schleusner and Sulek (1959) established criteria for appraising the performance of irrigation pumping plants. The recommended

performance standard for electric irrigation pumping plants was 0.66 water kilowatt-hours (0.885 water horsepower-hours) per kilowatt-hour of electricity consumption. The standard is based on an electric motor efficiency of 88 percent and a turbine pump efficiency of 75 percent. Schleusner and Sulek intended to set a performance goal attainable without the very best performance from each pumping plant component. More recent electric motor literature (U.S. Motors, 1970) indicates an electric motor efficiency of 90 percent or greater at full load to be typical for motors rated at over 30 kilowatts (40 horsepower). Turbine pump efficiency of 75 percent is a reasonable goal when hydraulic column and power shaft losses are considered (Western Land Roller, Berkeley, 1959).

Fischbach, Sulek, and Axthelm (1968) presented a method for computing the efficiency of pumping plants. Test measurements included pump discharge rate, pumping lift, discharge pressure, and power plant fuel consumption. A portable propeller type water meter was recommended for measuring pumping plant discharge. Fischbach, Sulek, and Axthelm also recommended an electric well probe to measure lift from the well and a calibrated bourdon tube pressure gauge to measure discharge pressure. Computations were illustrated to determine pumping plant efficiency relative to the standards established by Schleusner and Sulek (1959). No procedure was recommended for separating pump efficiency from power unit efficiency.

Durland (1968) determined irrigation pump efficiencies for a limited number of pumping plants in South Dakota. Durland used a hydraulic dynamometer to measure power developed by the drive unit. Only irrigation pumps driven by internal combustion engines were tested.

The drive shaft from the power unit to the irrigation pump had to be disconnected to measure power developed by the power unit. A propeller meter mounted in a portable open discharge tube was used to measure pump discharge. Durland commented that the equipment used required excessive installation time and recommended developing a faster procedure before further tests were conducted.

Miramontes (1949) gave a detailed description of the pump testing procedure used by Pacific Gas and Electric Company in California to test several thousand pumping plants each year. The procedure determines the energy efficiency of the electric motor and the pump as a unit, or wire-to-water efficiency (Kittredge, 1976), and does not separate motor efficiency from pump efficiency.

Pacific Gas and Electric crews measure power input to the pump motor with the power company service meter. The speed of rotation of the meter disc is timed and power is computed from the rotation speed and the value of the meter constant, potential transformer ratio, and current transformer ratio. Miramontes (1949) stated that power company rules in California require electric meters to be accurate to within 2 percent. Beck (1976) estimated the limit of accuracy of the electric meter when timed with a stopwatch to be plus or minus 1 1/2 percent. Pacific Gas and Electric crews use a transverse tube or Hall tube pitot tube device for measuring discharge. Water level in the well is measured with an electric well sounder or an air line. Pressure in the discharge line is measured with a calibrated pressure gauge.

Results are available from a few irrigation pump efficiency studies (Table 1). These results show a large number of irrigation pumps

operating below the 75 percent efficiency level recommended by Schleusner and Sulek (1959). Pump efficiency researchers were unable to ascertain the specific cause of low pump efficiency in most cases, but they cite pump wear and improper sizing of pumps due to poor pump selection or a change in operating conditions as major contributing factors (Fischbach, Sulek, Axthelm, 1968).

Table 1. Reported Irrigation Pump Efficiencies

	Range of Pump Efficiency (Percent)				
Location	Greater than 70	60-70	50-60	40-50	Less than 40
New Mexico[1]	7	18	22	15	5
Nebraska (electric)[2]	16	31	18	4	4
South Dakota[3]	3	2	4	1	5

[1]Abernathy and Cook (1977).

[2]After Schleusner and Sulek (1959) assuming electric motor efficiency of 88 percent.

[3]Durland (1968)

EXPERIMENTAL PROCEDURE

Flow Measurement Tests

A portable propeller meter and two pitot tube devices were available at South Dakota State University for field measurement of pump discharge. A laboratory test was made to determine the accuracy of the devices. Field installations were simulated by various piping arrangements in the laboratory. All of the meters were compared to a calibrated orifice flow meter permanently installed in the laboratory.

The portable propeller meter was a commercial unit consisting of a propeller meter installed in an open discharge tube (Figure 2). The outlet of the tube was designed so that discharge kept the tube full of water at all times. The inlet of the tube was flared to accept several pipe sizes and was equipped with flow straightening vanes. The indicator was a totalizer dial reading in gallons. A stopwatch was used with the propeller meter to make rate of flow measurements.

One pitot tube device tested was the C. W. Cox Hall Tube Flow Meter (Figure 3). The Cox device consisted of a Hall tube sensing element modified for simple field use, a water column manometer for measuring velocity head, and two rubber connecting hoses. The Hall tube required one 1.91 cm (0.75 in) Iron Pipe Size (IPS) hole drilled and tapped into the pipe wall for installation. The hcle was oriented so that the portion of the Hall tube inside the pipe passed through and perpendicular to the center line of the pipe. A jig supplied by the manufacturer was used to align, drill, and tap the hole.

Two rubber hoses connected the Hall tube sensing element to a water

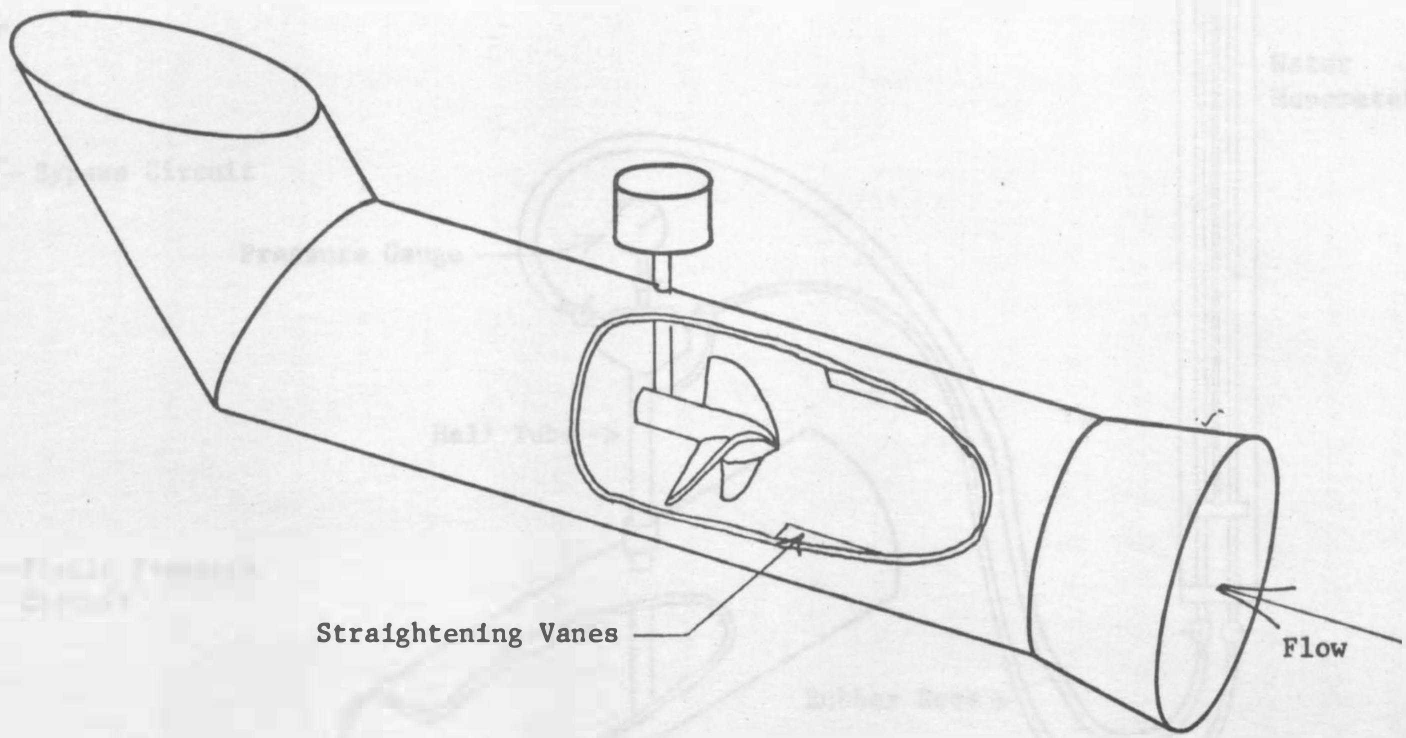

Figure 2. Open Discharge Tube with Propeller Flow Meter

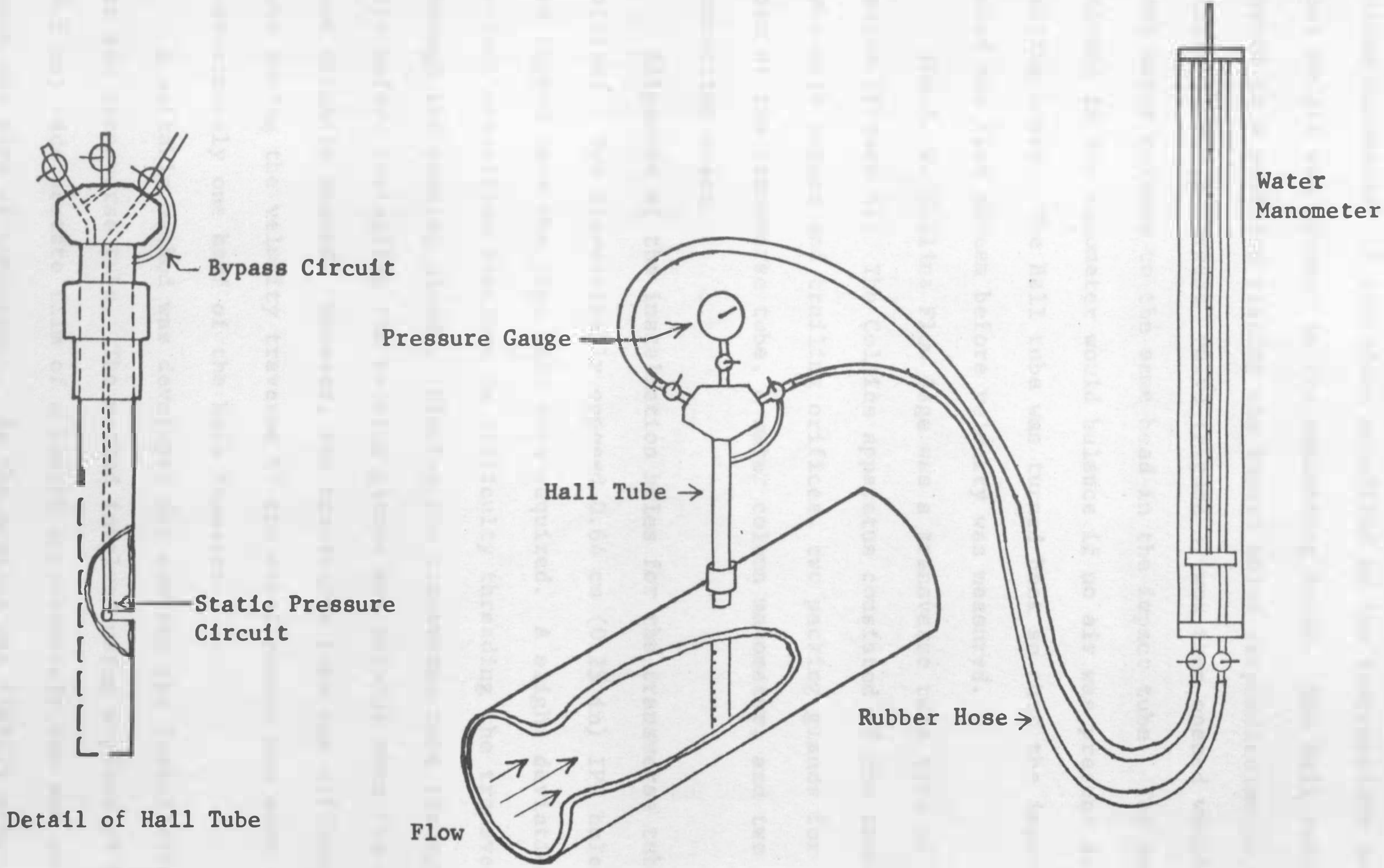

Figure 3. C. W. Cox Hall Tube Flow Meter

column manometer. A procedure specified by the instructions assured that no air was present in the connecting hoses. The Hall tube was turned to a position placing the impact holes perpendicular to the stream flow. A "bypass" valve (Figure 3) was then opened which exposed both water columns to the same head in the impact tube. The two water columns in the manometer would balance if no air was present in the connecting hoses. The Hall tube was turned back so that the impact holes faced the flow stream before velocity was measured.

The R. W. Collins Flow Gage was a transverse tube type of pitot tube device (Figure 4). The Collins apparatus consisted of the transverse tube with impact and trailing orifices, two packing glands for installation of the transverse tube, a water column manometer, and two rubber connecting hoses.

Alignment of the installation holes for the transverse tube was critical. Two diametrically opposed 0.64 cm (0.25 in) IPS holes drilled and tapped into the pipe wall were required. A slight deviation from perfect opposition resulted in difficulty threading the transverse tube through the packing glands. Placing the transverse tube through the pipe before installing the packing glands was helpful when the holes were slightly skewed. However, the transverse tube was difficult to move during the velocity traverse if the misalignment was more than approximately one half of the hole diameter.

A suitable method was developed for marking the installation holes for the transverse tube. The method involved using a piece of 21.6 cm (8.5 in) wide acetate film of a length approximately one and one half times the pipe circumference. As the acetate was tightly wrapped around

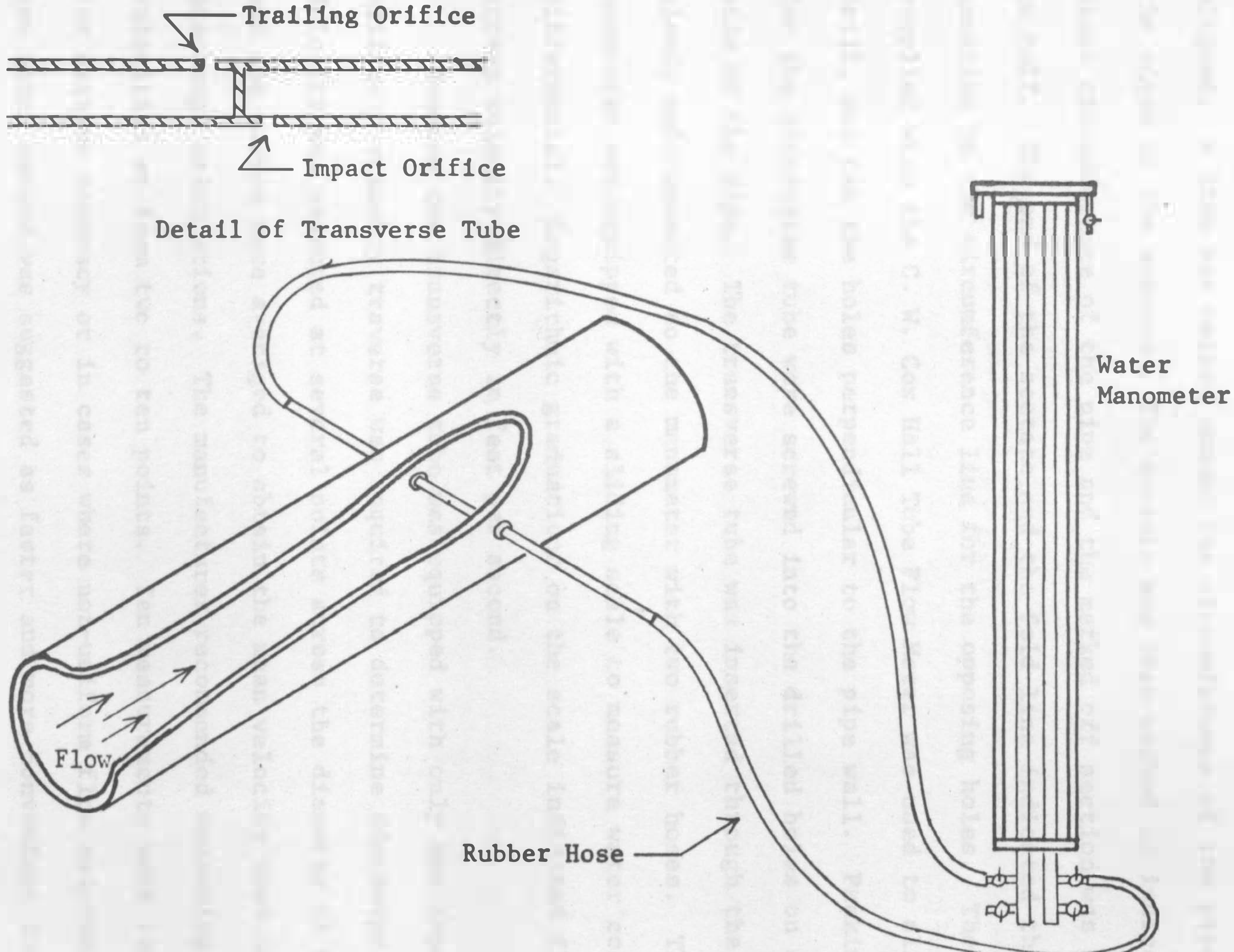

Figure 4. R. W. Collins Transverse Tube Flow Meter

the pipe, the edges of the overlapping section of the acetate were aligned. A line was marked around the circumference of the pipe along the edges of the acetate. The acetate was then marked to indicate the exact circumference of the pipe and the marked off section was folded in half. The end of the acetate and the fold line indicated the proper location on the circumference line for the opposing holes. The jig supplied with the C. W. Cox Hall Tube Flow Meter was used to align, drill, and tap the holes perpendicular to the pipe wall. Packing glands for the transverse tube were screwed into the drilled holes on either side of the pipe. The transverse tube was inserted through the packing glands and connected to the manometer with two rubber hoses. The manometer was equipped with a sliding scale to measure water column differential. Logarithmic graduations on the scale indicated flow stream velocity directly in feet per second.

Because the transverse tube was equipped with only one impact orifice a velocity traverse was required to determine discharge. Velocity was measured at several points across the diameter of the pipe and the values were averaged to obtain the mean velocity used in discharge calculations. The manufacturer recommended measuring point velocities at from two to ten points. Ten measurements were recommended for extreme accuracy or in cases where non-uniform flow existed. The two point method was suggested as faster and more convenient for field use. The two point method was used for the laboratory tests. The pipe cross-section was divided into equal areas by the point velocity measurements. The formula derived to calculate the radius from the pipe center to each point velocity was

$$r_a = \sqrt{\frac{r}{n}(2a-1)} \; ; \; (a = 1,2,\cdots,\frac{n}{2}),(n = 2,4,6 \cdots) \qquad (1)$$

where

r_a = radius to point velocity

r = pipe radius

n = total number of point velocities to be measured

Equation (1) is appropriate only for an even number of point velocity measurements.

Laboratory Flow Measurement Tests

The first laboratory test run included the Hall tube and propeller meters (Figure 5). The Hall tube was installed in a 15.2 cm (6 in) inside diameter PVC pipe. The Hall tube was approximately 210 cm (82 in) or 13 pipe diameters downstream from a 20.3 cm (8.0 in) control valve and a 20.3 cm (8 in) to 15.2 cm (6 in) pipe reducer. The propeller meter was connected to the open end of the 15.2 cm (6 in) PVC pipe. A short length of tractor tire inner tube was used to connect the open discharge tube to the pipe.

Discharge through the system was varied using the 20.3 cm (8 in) valve above the pipe reducer for control. A constant head supply tank in the laboratory supplied recirculated water to the system. Discharge was measured using the laboratory orifice, the Hall tube, and the propeller meter simultaneously.

The transverse tube replaced the Hall tube for the second test (Figure 5). Approximately 12 pipe diameters of straight pipe were upstream from the transverse tube. Discharge was again varied using the 20.3 cm (8 in) valve for control. Discharge was measured with the

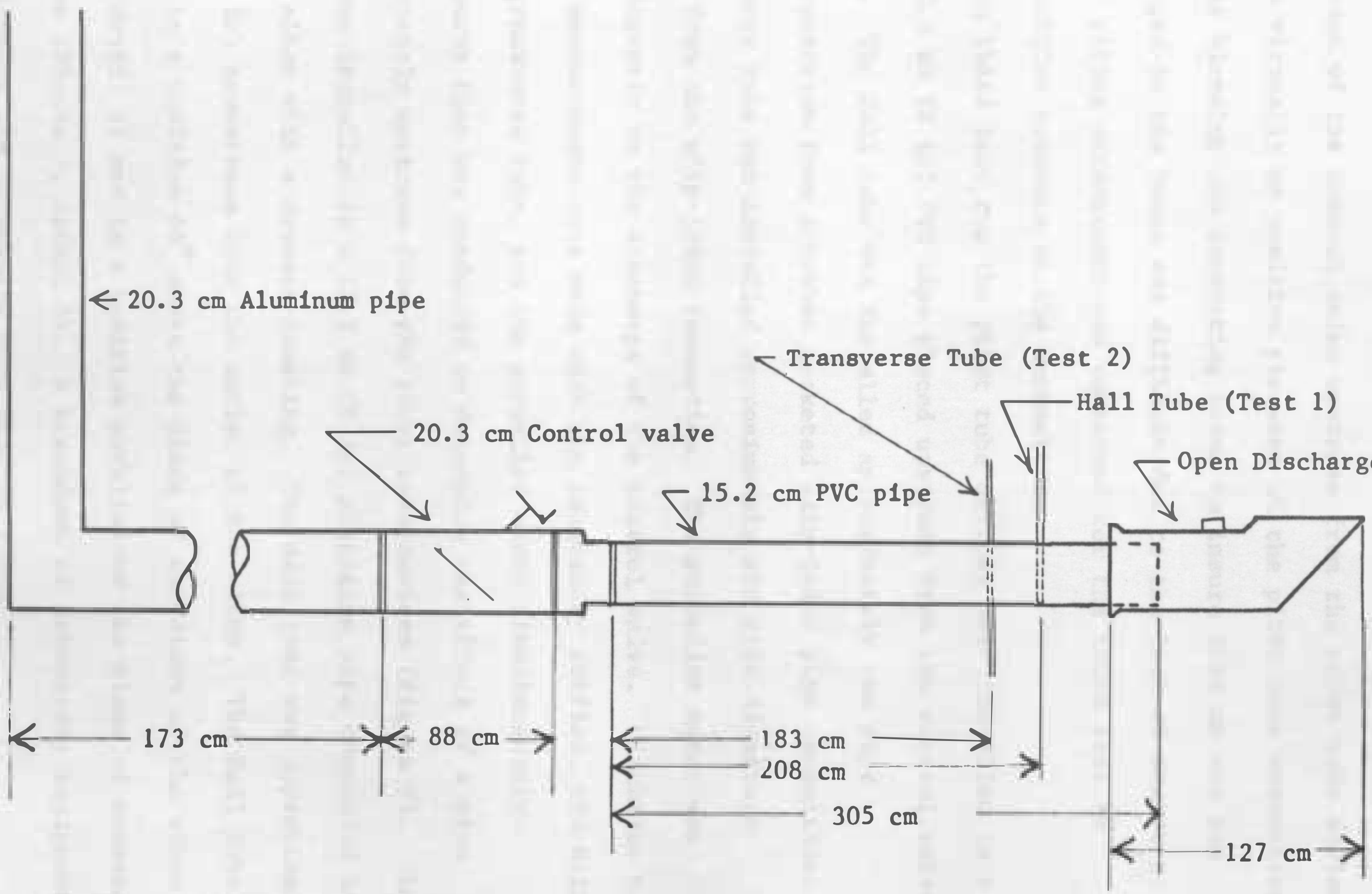

Figure 5. Laboratory Piping Arrangement for Flow Meter Tests One and Two

laboratory orifice, the transverse tube, and the propeller meter simultaneously.

Placement of the control valve upstream from the pitot tube devices resulted in virtually no positive pressure at the pitot tube manometers. Periodically bleeding the connecting hoses to insure that no air had become trapped in the hoses was difficult due to the lack of pressure. A different piping arrangement was connected for the third test to create a positive pressure at the manometers.

For the third test run the pitot tube devices were installed in a piece of 20.3 cm (8 in) PVC pipe placed upstream from the control valve (Figure 6). The Hall tube was installed approximately one pipe diameter downstream from a rubber gasketed slip-joint pipe connection. The transverse tube was installed approximately six pipe diameters downstream from the slip-joint connection. The propeller meter was connected directly to the discharge of the control valve. Discharge was varied and measurements were made with the laboratory orifice, the Hall tube, the transverse tube, and the propeller meter simultaneously.

The fourth test was conducted to determine the effect of a pipe elbow immediately upstream from the pitot tube devices (Figure 9). The Hall tube was installed in a 15.2 cm (6 in) plexiglas pipe connected to a smooth 90° elbow with a dresser coupling. The Hall tube was approximately 5 cm (2 in) downstream from the outlet of the elbow. The Hall tube was tested in a position 45° above the plane of curvature of the elbow (Figure 7, detail A) and in a position parallel to the plane of curvature of the elbow (Figure 7, detail B). A breakdown of laboratory equipment prevented testing the transverse tube near an elbow.

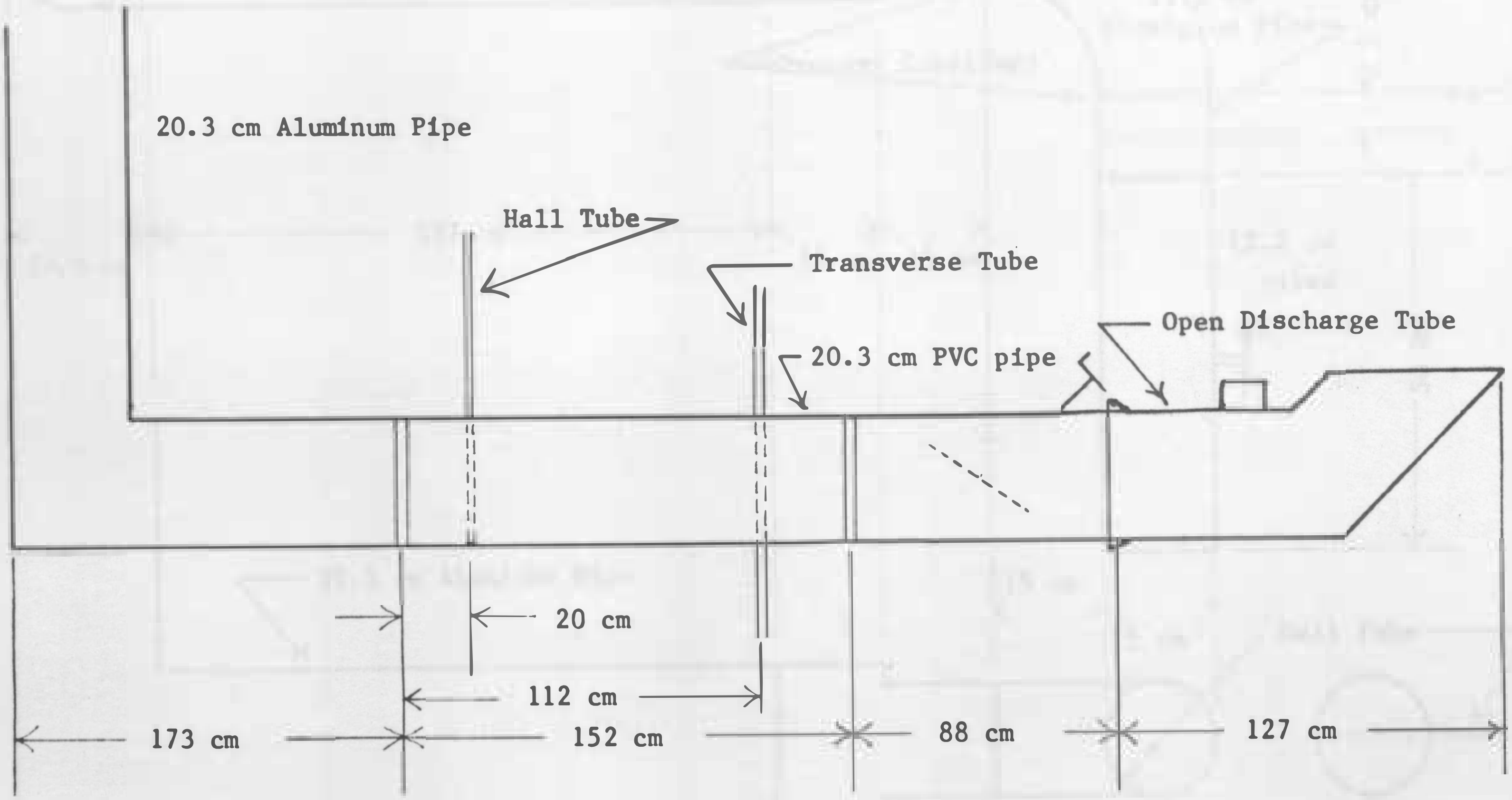

Figure 6. Laboratory Piping Arrangement for Flow Meter Test Three

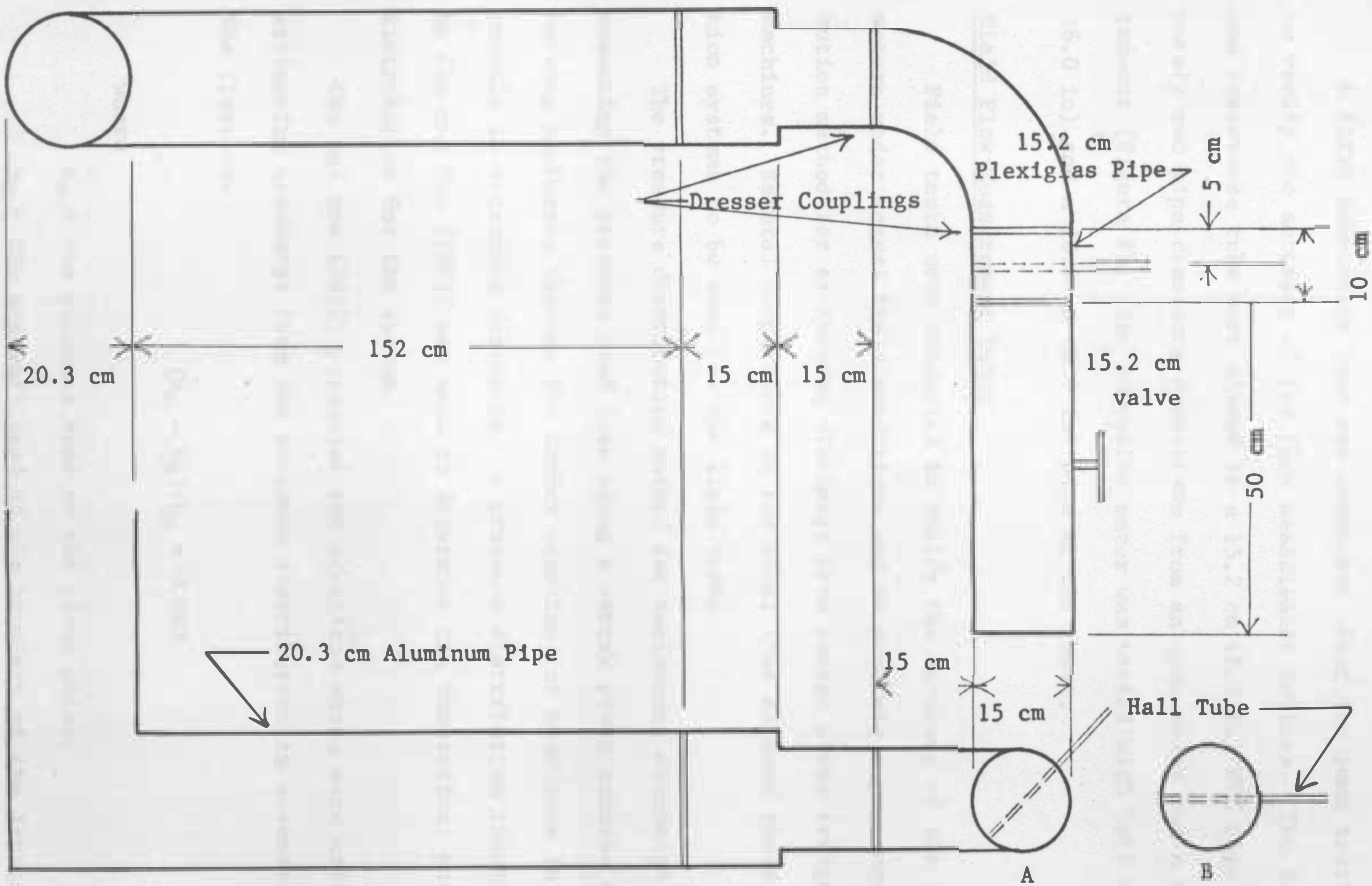

Figure 7. Laboratory Piping Arrangement for Flow Meter Test Four

A fifth laboratory test was conducted after the pump testing season to verify the accuracy of the flow measurement devices. The Hall tube and transverse tube were placed in a 15.2 cm (6.0 in) PVC pipe approximately two pipe diameters downstream from an open valve and a pipe reducer (Figure 8). The propeller meter was tested with both a 15.2 cm (6.0 in) and a 20.3 cm (8.0 in) pipe at the inlet.

Field Flow Measurement Tests

Field tests were conducted to verify the accuracy of the flow meters under actual field conditions and to evaluate a pressure distribution method for estimating discharge from center pivot irrigation machines. Several cooperators in the local area allowed their irrigation systems to be used for the field tests.

The pressure distribution method for estimating discharge involved measuring the pressure head loss along a center pivot machine and working backwards through the Scobey equation for head loss in a closed conduit to determine discharge. A pressure distribution theory developed by Chu and Moe (1972) was used to determine the theoretical pressure distribution for the system.

Chu and Moe (1972) presented two equations which were useful for estimating discharge from the pressure distribution in a center pivot. The first was

$$(h_o - h_R)/h_m = 0.543 \qquad (2)$$

where

h_o = the pressure head at the pivot point

h_R = the pressure head at the boundary of the irrigated area

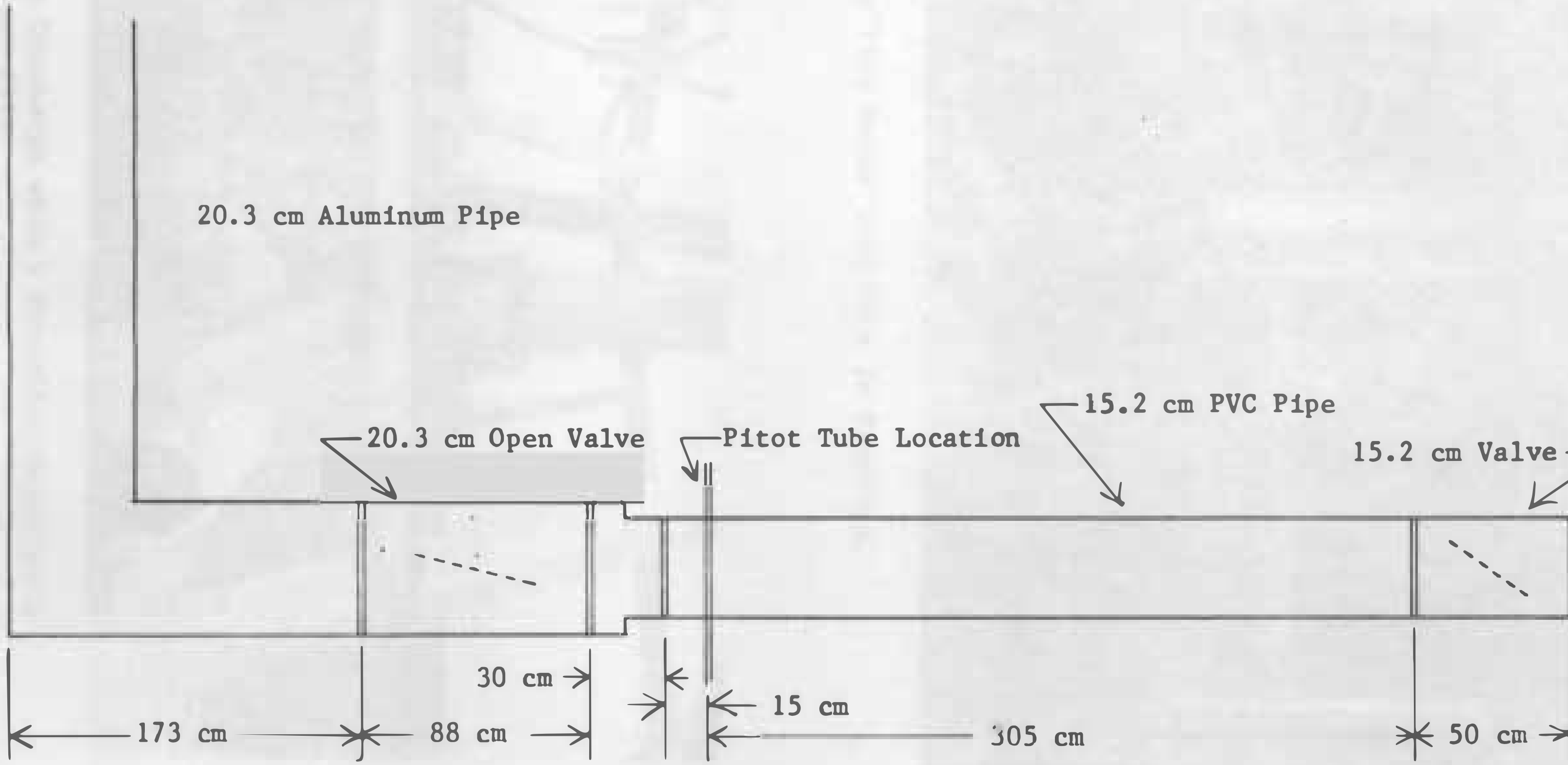

Figure 8. Laboratory Piping Arrangement for Flow Meter Test Five.

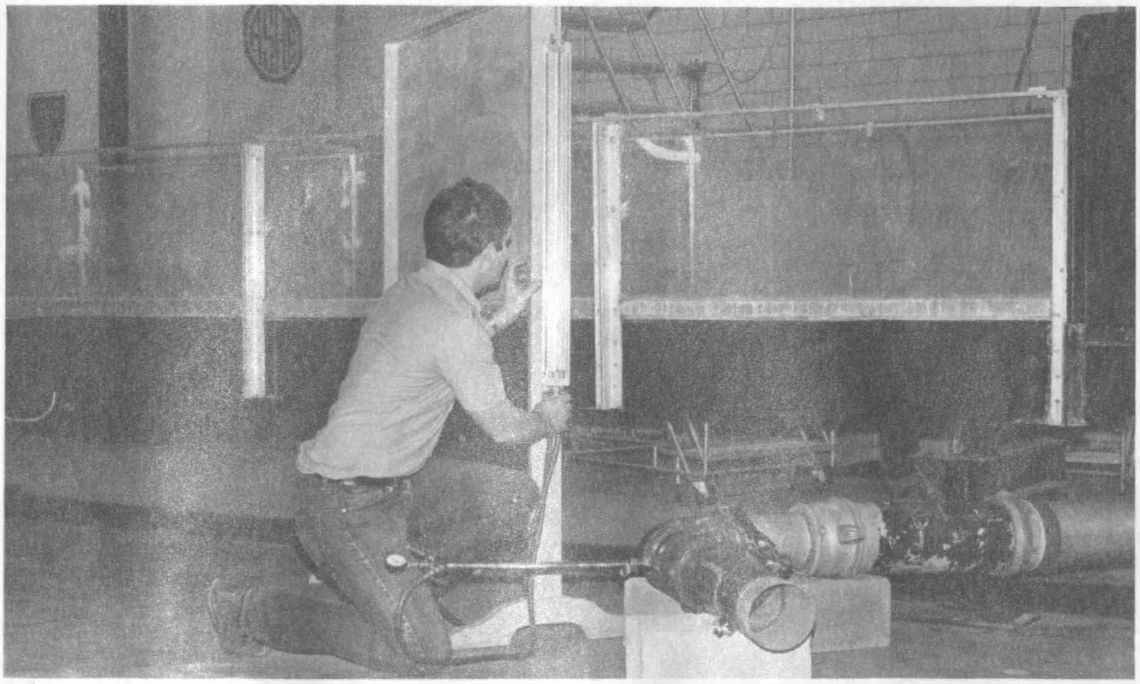

Figure 9. Laboratory Flow Meter Test Four In Progress.

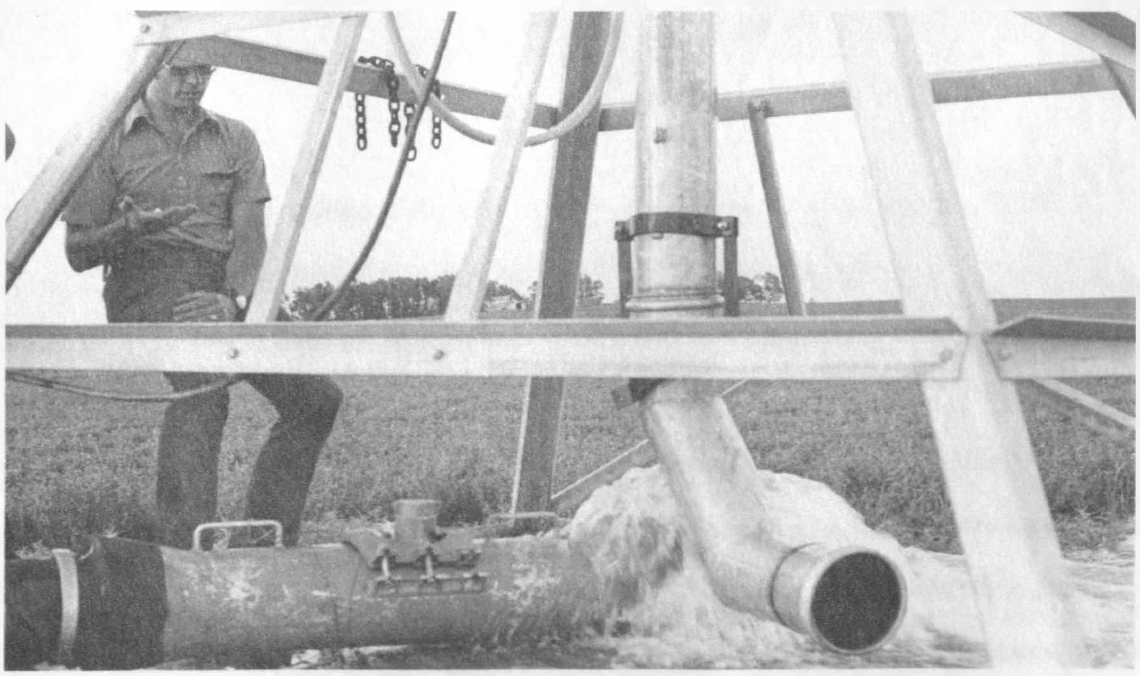

Figure 10. Measuring Discharge with a Propeller Meter at a Center Pivot Site.

h_m = the pressure head loss which would occur in a main line pipe of the same size and length and at the same discharge as the center pivot machine.

Equation (2) related the pressure head loss in the center pivot machine to the pressure head loss in an equivalent closed conduit. Rearranging equation (2) gave

$$h_m = \frac{(h_o - h_R)}{0.543} \quad (3)$$

By measuring the pressure head at two points, the pivot point and the end gun, and dividing the difference by 0.543 as in equation (3), the equivalent head loss in a closed conduit was determined. Using the closed conduit head loss, the measured pipe diameter, and an estimated friction factor the discharge was determined using the Scobey equation for pipe flow (Schwab, et. al., 1966)

$$H_f = \frac{K_s\, Q^{1.9}\, (1.45 \times 10^{-5})}{D^{4.9}} \quad (4)$$

where

H_f = total friction loss in closed conduit, ft/1000 ft

K_s = Scobey's coefficient of retardation

Q = total discharge, GPM

D = inside diameter of pipe, ft.

This two point approach presented some problems in field use. One problem was the error involved in determining the pressure head loss in the center pivot line. A bourdon tube pressure gauge with a small diameter copper tube attached to the inlet was used to measure pressure in the center pivot line. The copper tube was inserted into the

sprinkler nozzle to obtain a pressure reading. Flow through the nozzle was restricted with the pressure gauge and fingertips to reduce the head loss through the sprinkler head. This method produced acceptable pressure measurement results but was not considered accurate enough to estimate discharge on the basis of just two pressure measurements.

The other equation from Chu and Moe (1972) gave the dimensionless distribution function of pressure head loss along a center pivot system.

$$(h_r - h_R)/(h_o - h_R) = 1 - (15/8)(x - 2x^3/3 + x^5/5) \quad (5)$$

where

h_r = the pressure head at a distance r from the pivot

x = r/R, the dimensionless length factor representing distance from the pivot, where r is the distance to a point on the system and R is the wetted radius of the system.

Letting

$$H = (h_r - h_R)/(h_o - h_R)\ , \quad (6)$$

and rearranging

$$h_o - h_R = \frac{h_r - h_R}{H}\ , \quad (7)$$

or

$$h_o - h_R = \frac{h_o - h_r}{1 - H}\ . \quad (8)$$

Equation (8) related the total pressure head loss of the system to the head loss at any point along the system. Several pressure measurements were made and the estimated total pressure head loss was calculated from each measurement. The resulting estimated total head losses were averaged to obtain a best estimate for total pressure head loss. The

denominator of the right hand term of equation (8) may be obtained from Table 2.

Table 2. Solution of Dimensionless Pressure Distribution Equation

$x = r/R$	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$H = \frac{(h_r - h_R)}{(h_o - h_R)}$	1.00	0.82	0.63	0.47	0.32	0.21	0.11	0.05	0.01	0.00	0.00
$1 - H$	0.0	0.18	0.37	0.52	0.68	0.79	0.89	0.95	0.99	1.0	1.0

The field tests included the propeller meter (Figure 10), the Hall tube (Figure 11), the transverse tube (Figure 12), and the pressure distribution method. Where it was possible all the methods were used on the same system and compared. In some cases the particular piping arrangement of the system did not allow for installation of the propeller meter. In other cases the slope on which the center pivot machine was located made any attempt to measure pressure distribution useless due to the effect of varying elevation on the pressure head.

An ideal pitot tube installation has several pipe diameters of straight pipe upstream from the pitot tube. Six to eight pipe diameters of straight pipe were recommended by the instructions provided with the Hall tube and the transverse tube. Straight steel pipe suitable for the installation of a pitot tube device was seldom as long as six pipe diameters on modern turbine pump-center pivot irrigation machine installations. Many installations consisted of the pump head followed by two to five pipe diameters of steel pipe, a control valve, another two to five pipe diameters of steel pipe, and an elbow directing the pipe to an underground connection. On installations with no underground pipe,

Figure 11. Measuring Discharge with the Hall Tube.

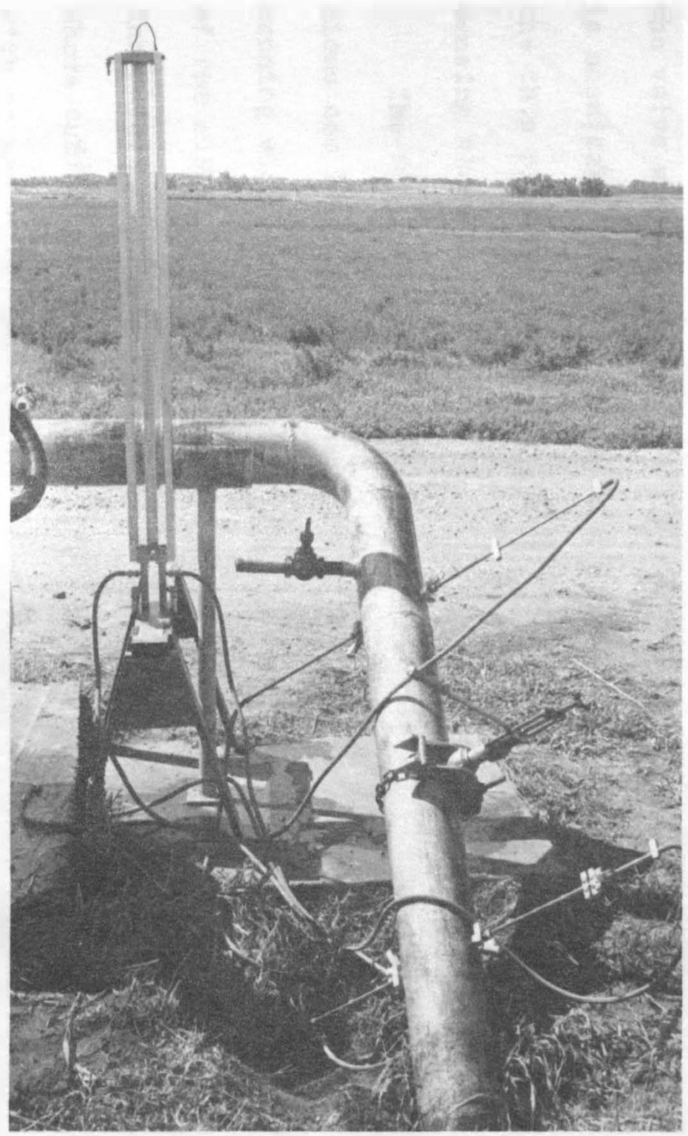

Figure 12. Two Transverse Tubes in a Field Flow Meter Test.

the valve was commonly connected to aluminum pipe. The aluminum pipe is unsuitable for the installation of most pitot tube devices because the thin pipe wall does not allow for drilling and tapping holes for the sensing elements.

The field tests included tests of each pitot tube device at locations one to three pipe diameters from the pump head or an elbow. The sensing elements were placed at a 45° angle to the plane of curvature of the elbows, including the elbow formed by the pump head, because laboratory results indicated that placement to be the most reliable. Where sufficient pipe was available both meters were also installed with an upstream straight pipe of more than six pipe diameters. Installation in the first nozzle hole of the center pivot machine was an option tested for the Hall tube device. A ten-point velocity traverse was made with the transverse tube.

Pumping Plant Efficiency Evaluation

Problem Analysis Machine efficiency is a measure of the useful work provided by a machine from a given energy input. In the case of an electric pumping plant the useful work provided is the kinetic and potential energy transferred to the water. The energy input is the electrical energy supplied to the pump motor. At a given instant the electric pumping plant efficiency is the ratio of water power output divided by electrical power input.

Power of the water leaving the pumping plant may be calculated with the formula

$$E_o = Q \gamma H/1000 \quad (9)$$

Q = pump discharge, m^3/sec

γ = specific weight of water, 9.8067 $Newtons/m^3$

H = total dynamic head, m

E_o = power output of pumping plant, KW.

Electrical power input to the pumping plant was measured in kilowatts using the electric company service meter. Pump efficiency may be calculated from

$$\eta = \frac{output}{input} = \frac{Q \gamma H/1000}{KW_{in}} \quad (10)$$

where

η = efficiency expressed as a decimal

KW_{in} = power input to the pump

In units more common to irrigation, equation (10) becomes

$$\eta = \frac{GPM \times TDH}{5310.4 \times KW_{in}} \quad (11)$$

where

GPM = pump discharge, gallons per minute

TDH = total dynamic head developed by the pump, ft

KW_{in} = electrical power input to the pump motor, kilowatts

From equation (11) it can be seen that the three parameters which must be measured to determine electric pumping plant efficiency are pump discharge, total dynamic head, and electric power input to the motor.

Field Procedure   A field procedure was developed for measuring electric irrigation pumping plant efficiency. The procedure was refined to require as little time from the irrigation farmer as possible. Also, very little "down time" of the irrigation system was necessary. The

very similar to the one used by Pacific Gas and Electric (Miramontes, 1949).

Electrical power input to the pump motor was measured with the electric supply meter. The speed of rotation of the meter disc was timed with a stopwatch. Five, ten or twenty rotations of the meter disc were counted depending on the speed of the disc. Approximately a one-minute interval was timed. Power was calculated with the formula (Pair, et. al., 1975)

$$KW_{in} = (0.060)(K_h)(RPM)(M) \qquad (12)$$

where

KW_{in} = power input to the pump motor, KW

K_h = meter disc constant, representing watt-hours per revolution

RPM = speed of rotation of meter disc, revolutions per minute

M = product of current transformer ratio (CTR) and potential transformer ratio (PTR)

The meter disc constant and the current transformer ratio were stamped on the meter faceplate. In some cases pump efficiency calculations showed the displayed constants to be unreasonable. In these cases the power supplier was contacted to obtain the correct constants. In no case was a potential transformer encountered.

Total dynamic head was calculated with the formula

$$TDH = H_e + \frac{P}{\gamma} + \frac{v^2}{2g} \qquad (13)$$

where

TDH = total dynamic head; m, ft

H_e = elevation head; m, ft

P/γ = pressure head; m, ft

$v^2/2g$ = velocity head; m, ft.

Elevation head was the vertical distance from the free water surface to the pump. For a deep well turbine pump the elevation head was the distance from the water surface in the well while pumping to the pump head. Elevation head in a well was measured with an electric well sounder. This device used a probe which conducted a slight current when immersed in water. The probe was lowered into the well with a two conductor insulated wire. The wire carried the current to a solid state amplifier contained within the wire reel which amplified the current and caused the indicator needle of an electrodynamic meter mounted on the wire reel to deflect when the probe struck water.

A problem was encountered when using the electric probe in a well which had a layer of oil on the water surface. The oil layer was caused by leakage of oil from the pump column and was common to many oil lubricated turbine pumps. An oil film coated the probe so that the needle did not deflect when the probe was lowered through the oil layer and into the water below. The problem could usually be overcome by lowering the probe into the well far enough to assure penetration of the oil layer and jerking the probe up and down to rinse the oil film off the probe. The indicator needle would deflect when the oil film was removed. The probe could then be slowly withdrawn until the oil-water interface was reached, at which point the indicator needle would return to rest. The depth of the oil layer could not be measured and was assumed to be negligible in the energy relations of the pump.

Depth measurements were made from marker tabs attached to the probe wire at 1.5 m (5.0 ft) intervals. Indicator needle deflection could be detected with a precision of approximately 5 cm (2 in) when no oil layer was present. When an oil layer affected the probe, precision was approximately plus or minus 10 cm (4 in). Depth measurements were recorded to the nearest foot.

A calibrated bourdon tube pressure gauge was used to measure pressure head developed by the pump (Appendix B). A four and one-half inch gauge with one pound per square inch (psi) graduations and a 100 psi maximum pressure was used for pressures up to 100 psi. A four and one-half inch gauge with two psi graduations and a 200 psi capacity was used for pressures from 100 to 200 psi. No pressures over 200 psi were encountered.

Velocity head was neglected in this study as is common practice in irrigation design and application. In no cases did the velocity head exceed 0.6 m (2 ft). A velocity head of approximately 0.15 m (6 in) was typical for deep well turbine irrigation pumps.

Discharge was measured with the open discharge propeller tube, the transverse tube, or the Hall tube. The propeller meter was preferred in the few cases where the pipe arrangement of the distribution system facilitated its installation. The Hall tube was used in most cases due to the speed with which it could be installed and operated. Also, most cooperators expressed a desire to have only one hole drilled into their distribution pipe.

Measured data were recorded on a standard data sheet (Appendix E) along with other pertinent information. Included was information on the

place and time of the test and names of the observers and the cooperator. Catalog information including make, model, and serial number for the pump and motor were recorded for reference. Rated speed and horsepower of the motor were also recorded. Age of the pumping plant was established and recorded when the original owner was present.

In cases where the pump was not operating before the efficiency test, a static water level in the well was measured for the information of the operator. The water level while pumping was measured after the pump started. Sufficient time was allowed for the well to reach a near equilibrium indicated by no detectable change in the pumping water level with time. This water level while pumping was very likely not the ultimate drawdown of the well due to the short time period involved. The inaccuracy of the drawdown measurement was carefully explained to the cooperator. Pump efficiency will not change significantly with a few feet of additional drawdown.

RESULTS

Laboratory Flow Meter Tests

The laboratory flow meter tests were conducted under simulated field conditions to determine the accuracy of a propeller meter mounted in an open discharge tube, a Hall tube pitot tube, and a transverse tube pitot tube. A permanent orifice flow gauge mounted in the laboratory was used as a standard for the flow meter tests. The orifice was calibrated with a weigh tank in the laboratory (Appendix A). Data from the laboratory tests are tabulated in Appendix C.

The propeller meter indicated a higher discharge than the orifice at flow rates from 200 to 800 gallons per minute (Figure 13). Greater differences were measured when the open discharge tube was connected to a six-inch pipe. The larger differences can be explained by the geometry of the tube. The open discharge tube was an eight-inch pipe and the propeller meter was calibrated to give accurate results when measuring a fully developed eight-inch flow. The six-inch pipe apparently created a velocity jet when connected to the inlet of the open discharge tube and caused the propeller to indicate higher than true discharge. The consistent difference between the propeller meter and the orifice meter when the propeller meter was connected to an eight-inch pipe (Figure 13) indicated that the propeller meter may have needed recalibration. If the meter had been recalibrated, the error associated with the six-inch pipe could possibly have been reduced to less than five percent.

The Hall tube flow meter yielded acceptably accurate results under all flow conditions tested (Figure 14). Differences between the Hall

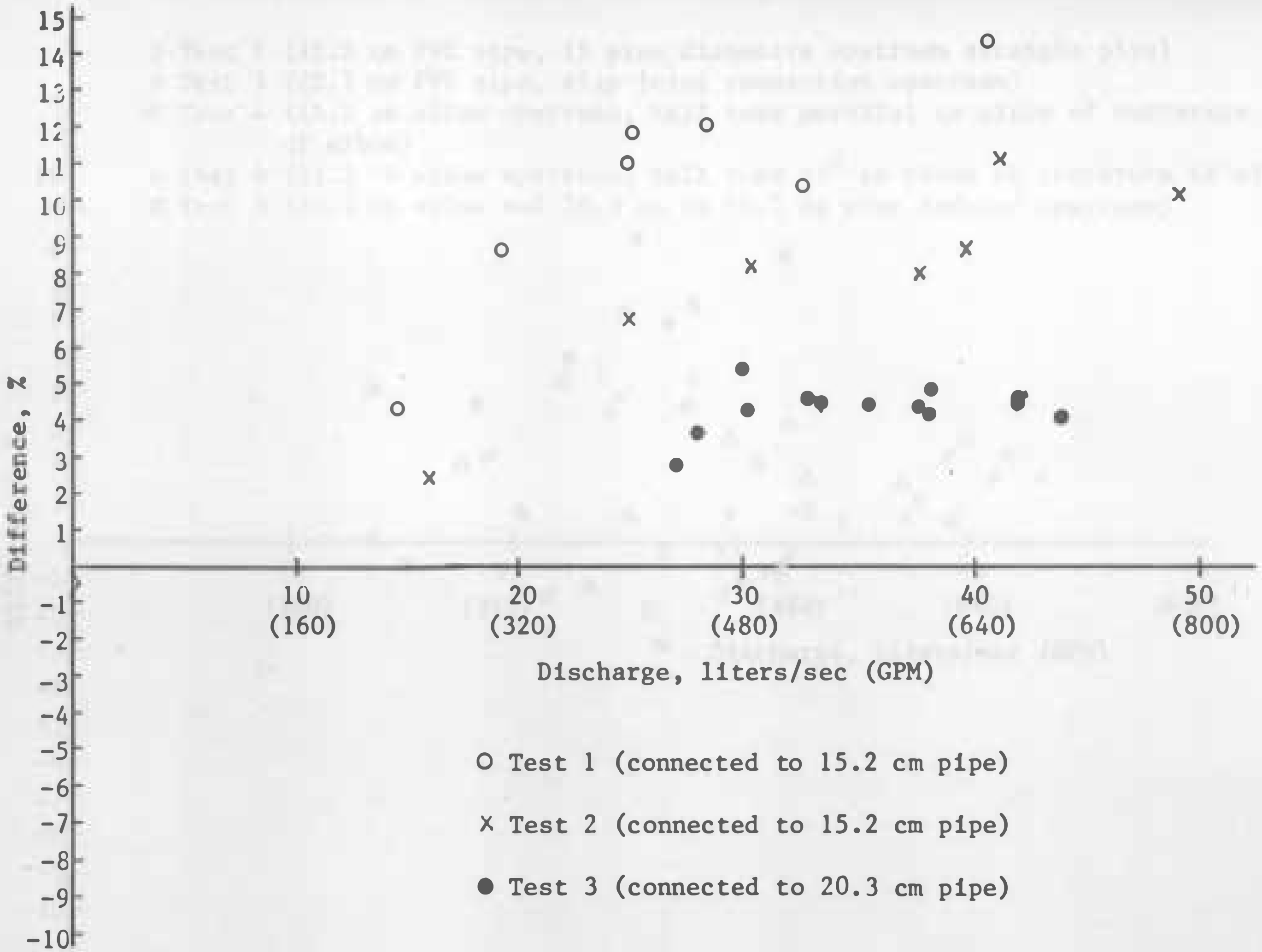

Figure 13. Discharge Measurement Difference Between Propeller Meter and Laboratory Orifice Meter.

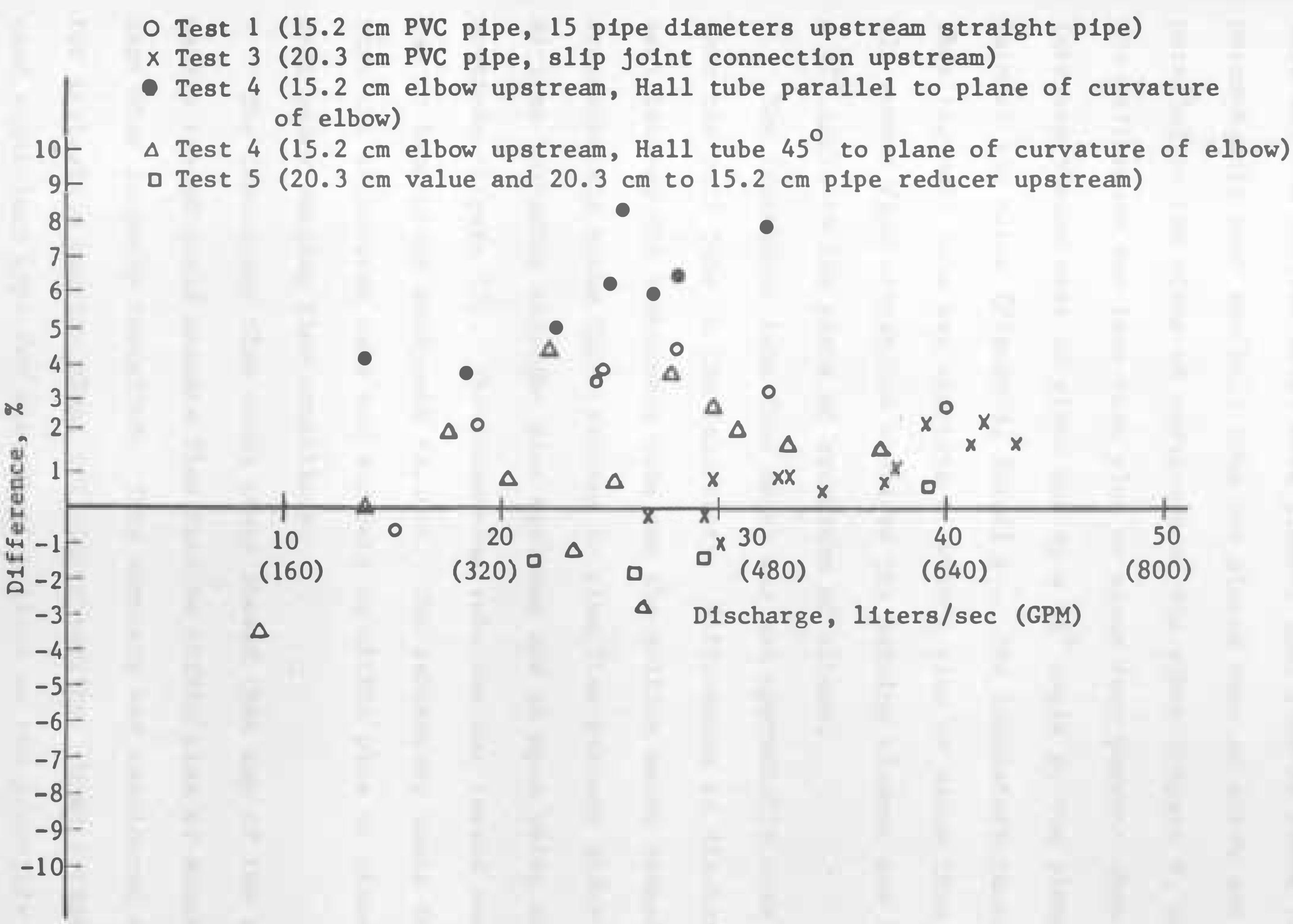

Figure 14. Discharge Measurement Difference Between Hall Tube Flow Meter and Laboratory Orifice Meter.

tube and the orifice meter were greater than plus or minus five percent only when the Hall tube was placed near an elbow and was parallel to the plane of curvature of the elbow (Figure 8, detail B). The difference was less than plus or minus four percent when the Hall tube was placed near an elbow and at a 45° angle to the plane of curvature of the elbow (Figure 8, detail A). The laboratory tests indicated that the Hall tube was accurate to within plus or minus five percent in all common flow situations provided the sensing element was installed at a 45° angle to the plane of curvature of elbows.

The transverse tube flow meter was not appreciably more accurate than the Hall tube in the laboratory. Differences in discharge measurement between the transverse tube and the orifice meter ranged from approximately minus three percent to plus five percent under flow conditions including straight pipe upstream and an open valve and a reducer upstream (Figure 15). The transverse tube was not tested near an elbow due to laboratory equipment failure. The laboratory tests indicated that the transverse tube was accurate to within plus or minus five percent under varying flow conditions.

The laboratory flow meter tests showed that any of the three flow meters tested could measure flow rate to within plus or minus five percent when properly installed. This accuracy was considered acceptable for irrigation pumping plant efficiency testing. Most irrigation systems used eight-inch pipe for distribution lines so the propeller meter was considered adequate for most systems. Equal accuracy could be expected from either pitot tube. The pitot tube devices were shown to be acceptably accurate when used near upstream obstructions to flow.

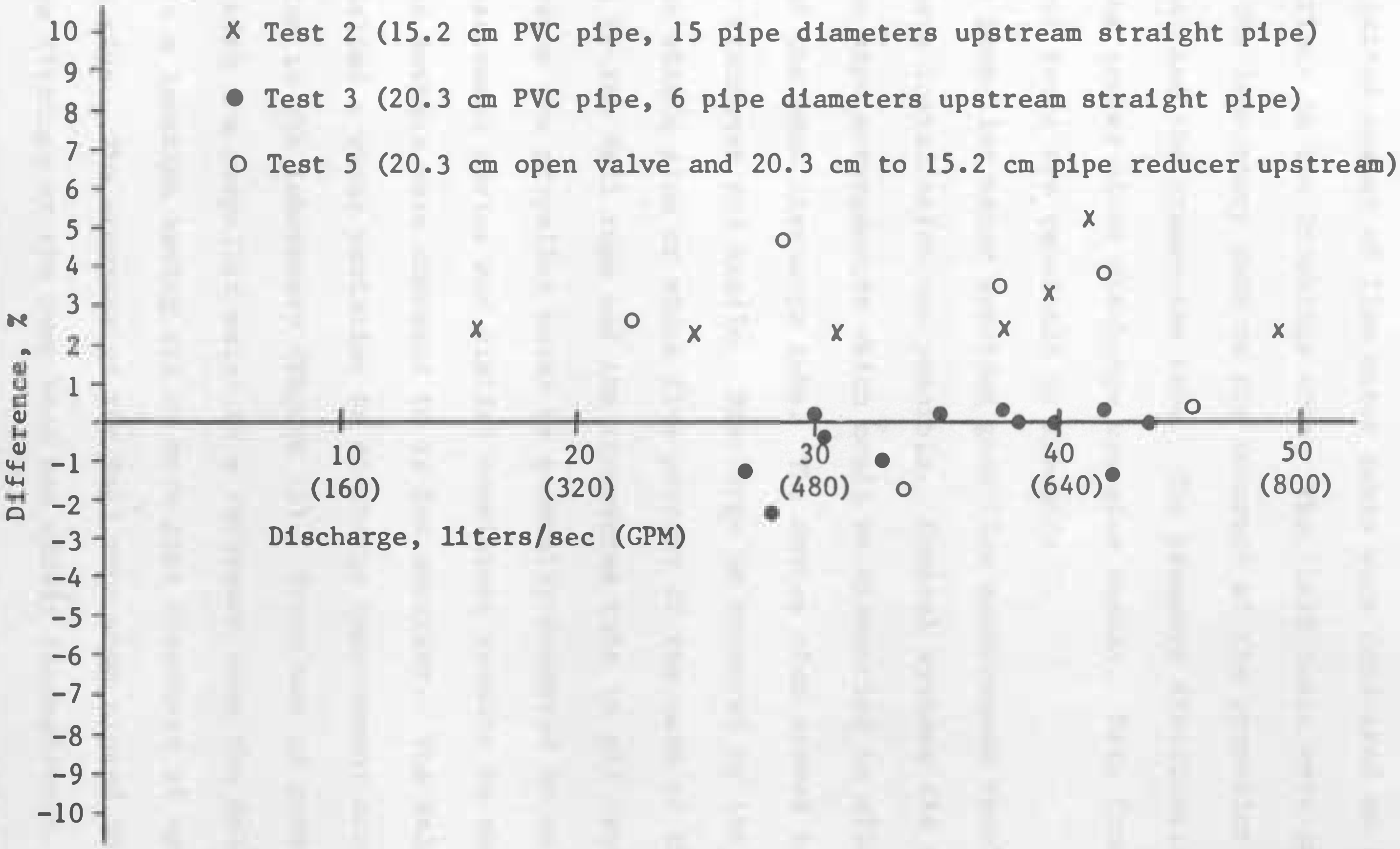

Figure 15. Discharge Measurement Difference Between Transverse Tube Flow Meter and Laboratory Orifice Meter.

Field Flow Meter Tests

A limited number of flow meter tests were conducted on irrigation installations in the Brookings area. The field tests were intended to confirm the laboratory data on the accuracy of the propeller meter, the Hall tube, and the transverse tube. The pressure distribution method for estimating center pivot discharge was also tested. Data from the field flow meter tests are tabulated in Appendix D.

The propeller meter provided good flow measurement results in the field where installation was possible. Several systems did not have distribution pipe arrangements which could be dismantled to allow for installation of the open discharge tube. The device also proved to be somewhat bulky to transport and handle. Discharge as measured by the propeller meter was within plus or minus five percent of the mean of the discharge measured by the Hall tube and the transverse tube in all cases.

Because the propeller meter is generally accepted as an adequate flow measurement device and yielded consistent results in the laboratory the other devices were compared to it for accuracy. The Hall tube flow meter yielded a wider variation in discharge measurement accuracy in the field than in the laboratory (Figure 16). Error was as great as ten percent with the propeller meter as a reference when the Hall tube was placed in a location having six or more pipe diameters of upstream straight pipe. The accuracy of the Hall tube when placed in locations near pipe fittings or the pump head was widely inconsistent. More test data are required to determine specific upstream geometries which are detrimental to the accuracy of the Hall tube.

The transverse tube demonstrated good agreement with the propeller

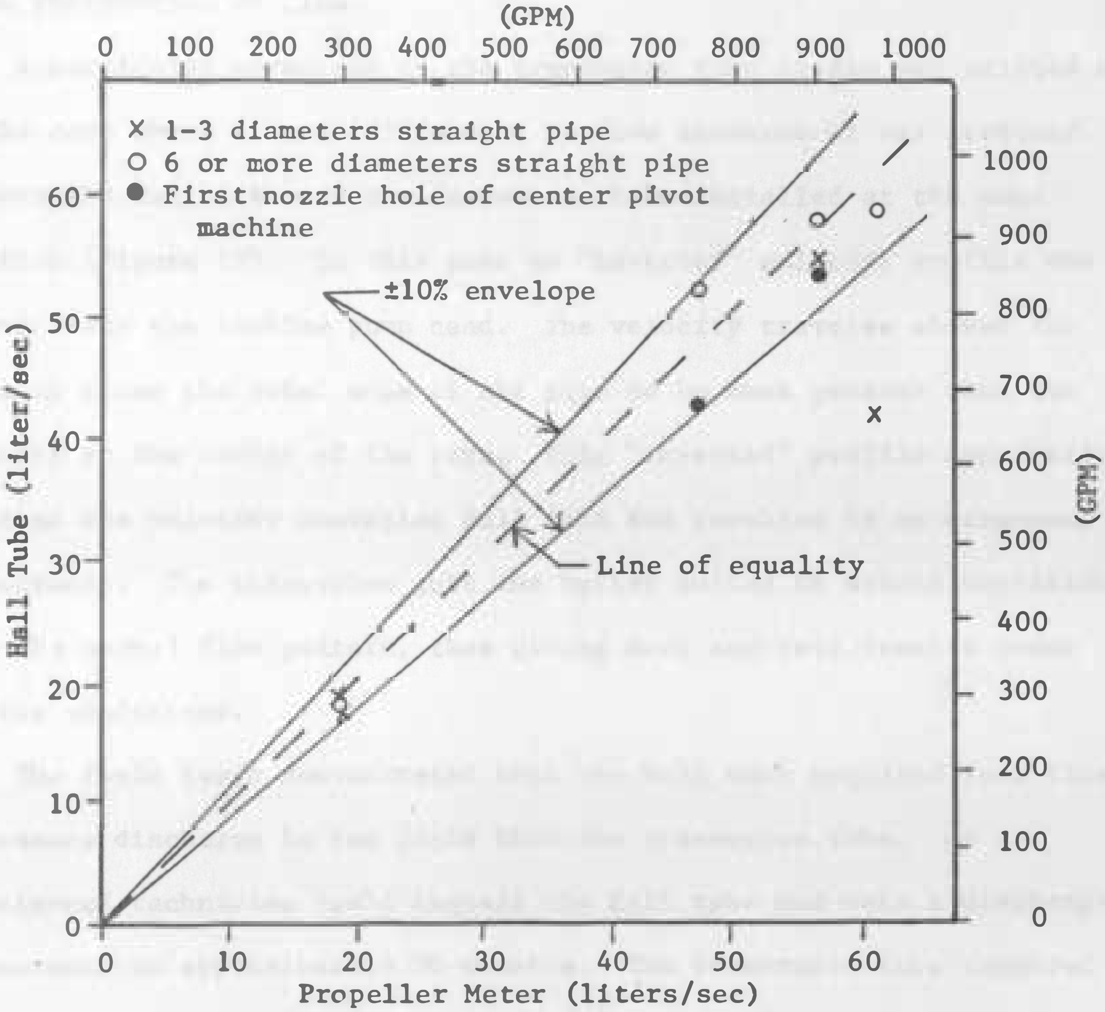

Figure 16. Discharge Measurement by Hall Tube Flow Meter Compared to Propeller Meter in Field Tests

meter in the field tests (Figure 17). Deviations from the open discharge tube measurements were less than plus or minus five percent when the transverse tube was placed more than six pipe diameters downstream from an obstruction. The difference was less than plus or minus ten percent when the transverse tube was placed within three pipe diameters of an obstruction to flow.

A particular advantage of the transverse tube device was pointed out by the case where a large difference in flow measurement was obtained between the Hall tube and the transverse tube installed at the same location (Figure 18). In this case an "inverted" velocity profile was present near the turbine pump head. The velocity traverse showed the velocity along the outer edge of the pipe to be much greater than the velocity at the center of the pipe. This "inverted" profile apparently deceived the velocity averaging Hall tube and resulted in an erroneous measurement. The transverse tube was better suited to detect variations from the normal flow pattern, thus giving more accurate results under adverse conditions.

The field tests demonstrated that the Hall tube required less time to measure discharge in the field than the transverse tube. An experienced technician could install the Hall tube and make a discharge measurement in approximately 30 minutes. The transverse tube required more time for installation due to the difficulty in properly marking the installation holes. Also, the velocity traverse required several manometer readings with a waiting period for each while the manometer columns adjusted. Even with prior experience the transverse tube typically required more than one hour to install and use.

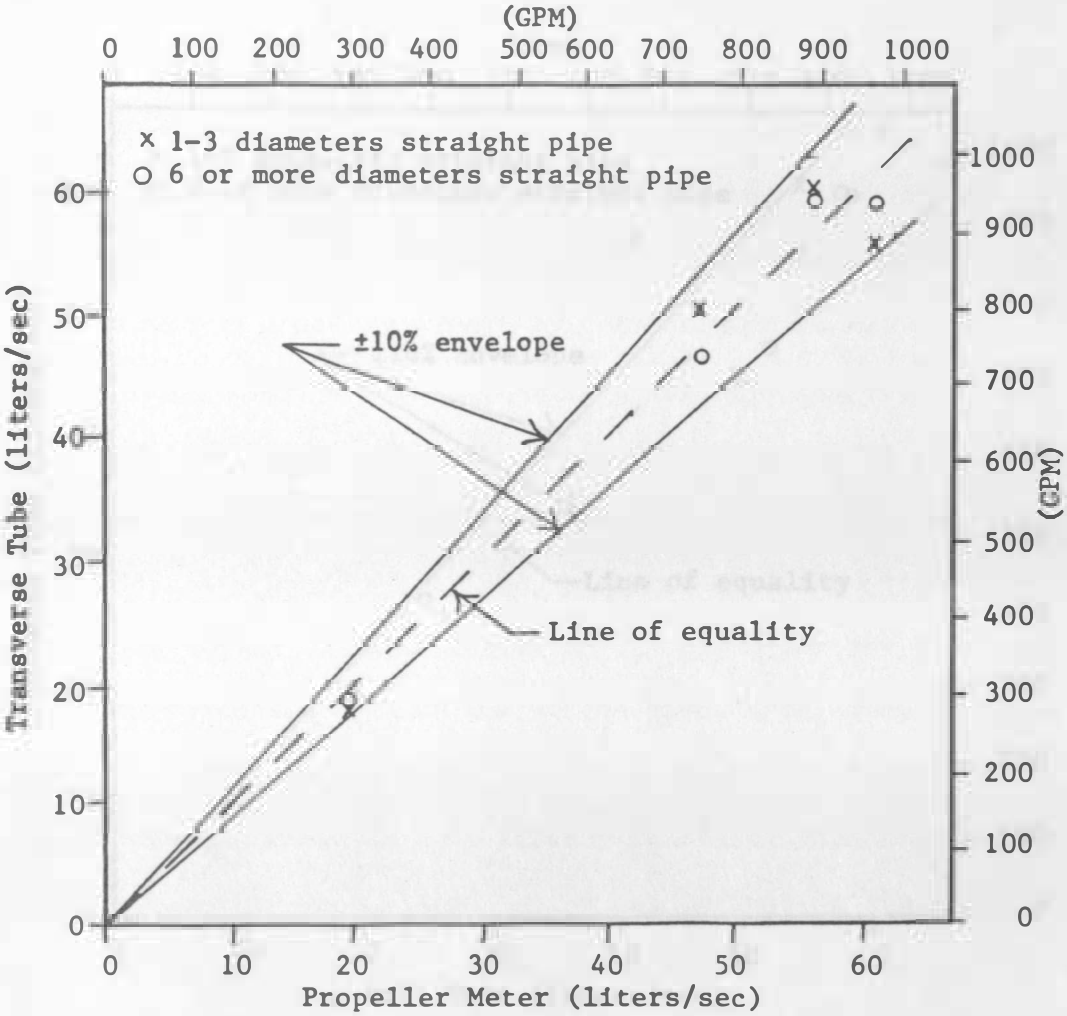

Figure 17. Discharge Measurement by Transverse Tube Flow Meter Compared to Propeller Meter in Field Tests.

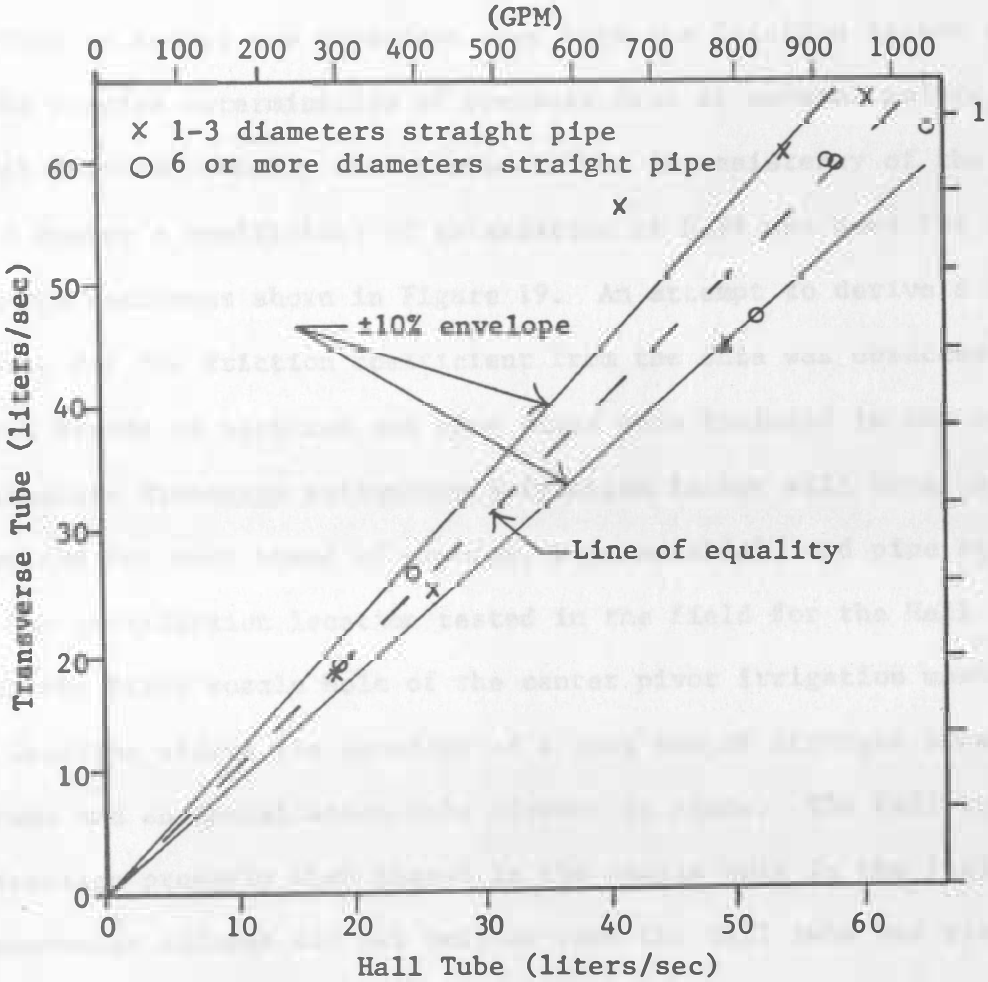

Figure 18. Comparison of Discharge Measurement by Hall Tube and Transverse Tube in Field Tests

Determination of discharge from a center pivot irrigation machine using the pressure distribution curve fitting technique did not yield good results. Figure 19 shows discharge estimated by the pressure distribution method compared to discharge measured by the Hall tube. The Hall tube was used as a reference because more data were available with it than with the propeller meter. The accuracy of the pressure distribution method was dependent upon both the friction factor estimate and the precise determination of pressure drop at several points. Errors in both factors probably contributed to the inconsistency of the method.

A Scobey's coefficient of retardation of 0.34 was used for the discharge estimates shown in Figure 19. An attempt to derive a better estimate for the friction coefficient from the data was unsuccessful. Several brands of machines and pipe sizes were included in the study. For accurate discharge estimation a friction factor will have to be determined for each brand of machine, pipe material, and pipe size.

One installation location tested in the field for the Hall tube was in the first nozzle hole of the center pivot irrigation machine. This location offers the benefits of a long run of straight pipe upstream and an installation hole already in place. The Hall tube did not function properly when placed in the nozzle hole in the field study. The manometer columns did not balance when the Hall tube was placed in the neutral position during the procedure used to check for air in the connecting lines. A subsequent laboratory study resulted in the modification shown in Figure 20. The impact orifices of the Hall tube which were not in the flow stream but were exposed to the line pressure due to the larger fitting used for the sprinkler nozzle were covered with tape

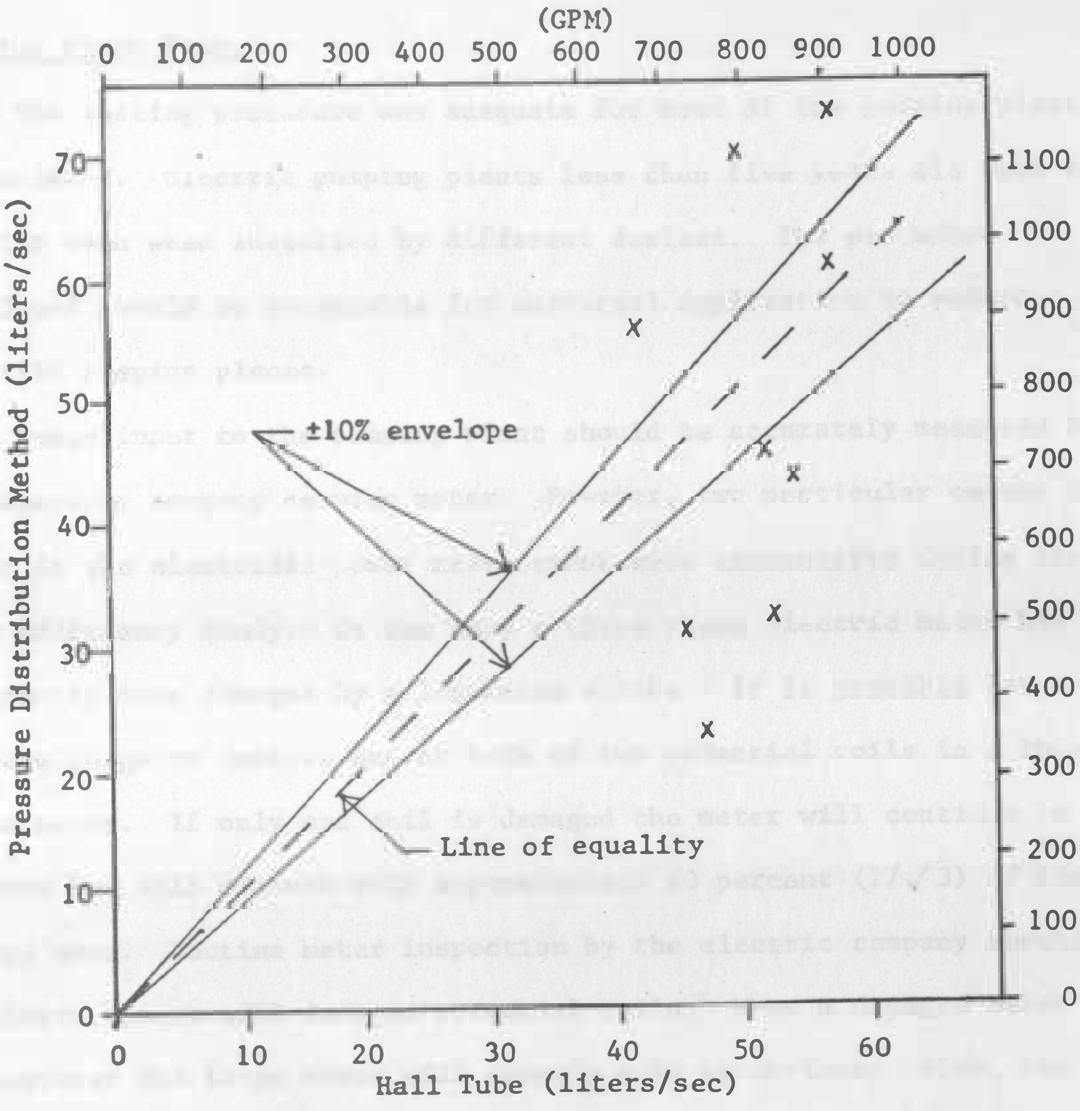

Figure 19. Discharge Estimation by Pressure Distribution Method Compared to Discharge Measured by Hall Tube.

before the Hall tube was installed. The tape prevented water from circulating through the Hall tube and causing the manometer imbalance. The "modified" Hall tube yielded good flow measurement results when used with a one-inch fitting in the laboratory (Figure 21).

Pumping Plant Tests

The testing procedure was adequate for most of the pumping plants encountered. Electric pumping plants less than five years old were very similar even when installed by different dealers. The procedure developed should be acceptable for universal application to modern electric pumping plants.

Power input to the pumping plant should be accurately measured by the electric company service meter. However, two particular causes for error in the electrical power measurement were encountered during the pump efficiency study. In one case a three phase electric meter had apparently been damaged by a lightning strike. It is possible for a voltage surge to destroy one or both of two potential coils in a three phase meter. If only one coil is damaged the meter will continue to operate but will measure only approximately 60 percent ($1/\sqrt{3}$) of the energy used. Routine meter inspection by the electric company should eliminate meters with damaged potential coils. When a damaged meter is encountered the large error will usually make it obvious. Also, the operator will often comment on a reduced power bill after extensive lightning activity.

Another error in the power input measurement was a result of the metering connection of one of the rural electric cooperatives. The

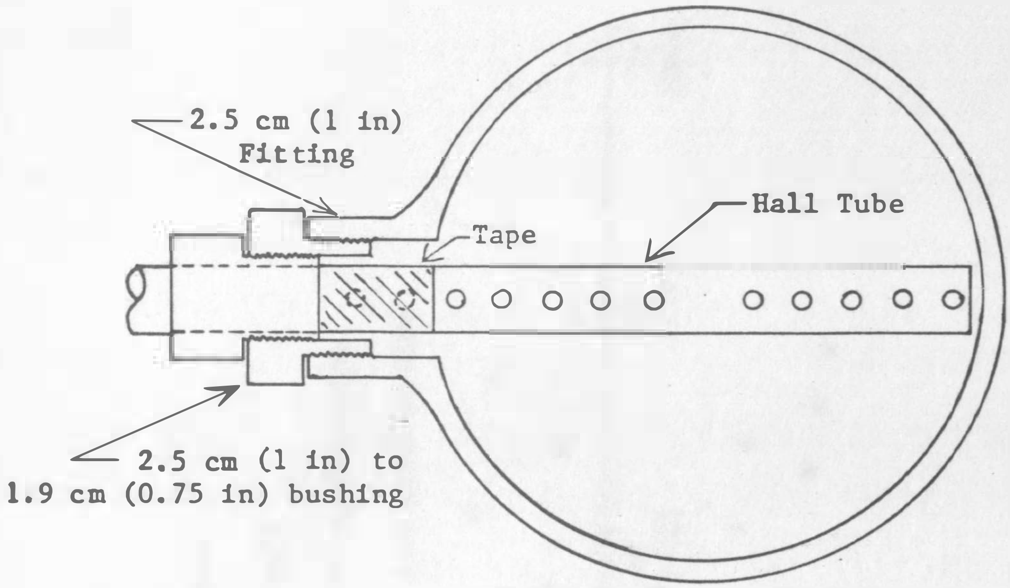

Figure 20. Hall Tube Modification for Use in Center Pivot Nozzle Hole.

cooperative used a single phase meter and measured the power of just one leg of the three phase system. This method of metering results in an appreciable error if the three phases are out of balance. Electric cooperative representatives stated that they were investigating the problem and had documented metering errors as great as seven percent.

Some pumping plants could not be tested because no access hole was provided into the well casing. The electric probe could not be placed into the well to determine the drawdown. The lack of an access hole prevents the operator from monitoring well performance and from performing routine well maintenance. The operator should require the well driller or pump installer to provide a well access hole at least 2.5 cm (1 in) in diameter.

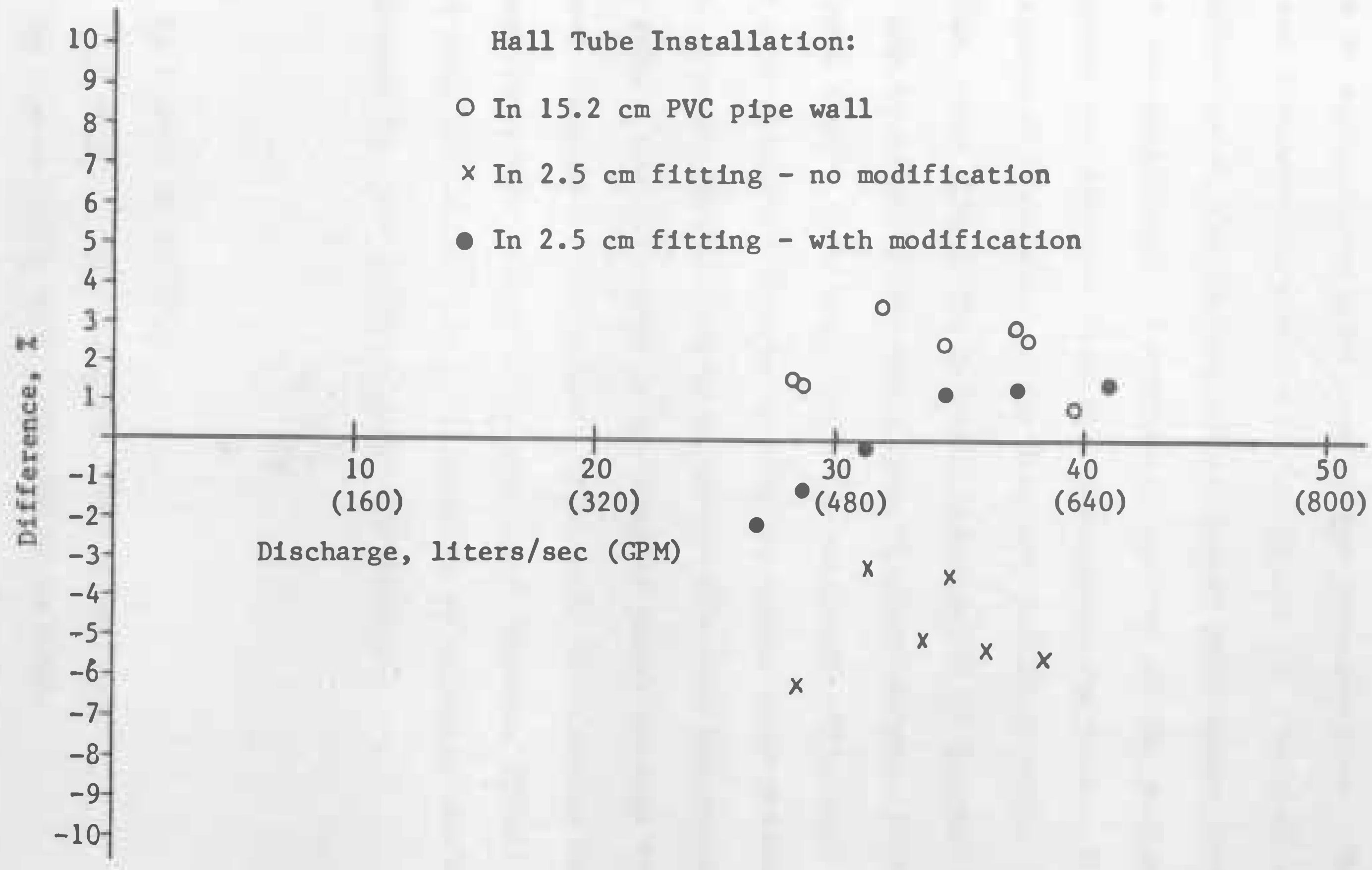

Figure 21. Discharge Measurement Difference Between Modified Hall Tube and Laboratory Orifice Meter.

Measurements were made on 44 electric irrigation pumping plants in eastern South Dakota (Appendix F). Various problems prevented accurate measurement of all parameters on some of the installations. Thirty-four pumping plant efficiencies were estimated (Table 3). Typical wire-to-water efficiencies of the pumping plants tested were higher than those reported in the literature. Thirty-eight percent of the pumping plants tested exceeded the Nebraska standard (Schleusner and Sulek, 1959) and over half exceeded 95 percent of the Nebraska standard (Table 4). It is apparent that, even though the Nebraska standard of 88 percent motor efficiency may be slightly low for modern electric motors, most of the pumping plants tested were operating at a very high efficiency.

Since only electrically powered pumping plants were included in this study, pump efficiency can be estimated from the wire-to-water efficiency data. Electric motor efficiency is known to stay relatively constant over the life of the motor. Efficiency of electric motors over 40 horsepower is approximately 90 percent (U.S. Motors, 1970). An estimate of pump efficiency can be calculated by dividing the wire-to-water efficiency by the estimated motor efficiency.

$$\eta_p = \frac{\eta}{\eta_m} \qquad (14)$$

where

η_p = pump efficiency

η = wire-to-water pumping plant efficiency

η_m = motor efficiency, assumed to be 0.90.

Estimated pump efficiencies are shown in Table 5. The estimated pump efficiencies are higher than the measured pump efficiencies

Table 3. Wire-to-Water Pumping Plant Efficiencies of Electric Pumping Plants in South Dakota

	Efficiency					
	70% and above	65-69%	60-64%	55-59%	40-54%	Total
Number of Plants	4	11	10	7	2	34
Percent of Total	12	32	29	21	6	100

Table 4. Performance Ratings of Electric Irrigation Pumping Plants in South Dakota by the Nebraska Standard[1]

	Percent of Nebraska Standard					
	Exceeding Standard	95-100%	90-94%	85-89%	Less than 85%	Total
Number of Plants	13	9	3	7	2	34
Percent of Total	38	26	9	21	6	100

[1]After Schleusner and Sulek, 1959

reported by Durland (1968). Several factors contribute to pump efficiency. Most significant of the factors are proper design, pump adjustment, and pump wear. Over 90 percent of the pumps tested in this study had been in service less than four years. Assuming proper well design to eliminate sand pumping, wear should not be a significant factor for most of the pumps. Wire-to-water efficiencies of 54, 58 and 68 percent were estimated for the three pumping plants tested which were over six years old. This represents an efficiency range of 82 to 105 percent of the Nebraska standard for the older pumping plants.

Table 5. Estimated Pump Efficiencies of Electric Irrigation Pumping Plants in South Dakota

	Pump Efficiency						
	Over 80%	75-80%	70-74%	65-69%	60-64%	Less than 60%	Total
Number of Pumps	3	8	7	7	5	4	34
Percent of Total	9	24	20	20	15	12	100

An interesting sidelight can be gleaned from the power input and motor nameplate horsepower ratings. Matching an electric motor to an irrigation pump can be difficult due to the gaps in the horsepower ratings available. Stock electric motors are available in 40, 50, 60, 75, 100 and 125 horsepower models. As an example, an irrigation pump may require 105 horsepower for a given application. The dealer may specify a 100 horsepower motor and offer a lower priced package. The motor will operate at a five percent overload, but it will not be adversely affected if a proper environment is provided.

Estimated load factors were calculated for 41 motors in this study.

If a 90 percent motor efficiency is assumed, the power output of the motor can be calculated by

$$P_o = 0.90\ P_i \tag{15}$$

where

P_o = the power output of the motor

P_i = the electrical power input to the motor

The load factor of the motor is then

$$L.F = \frac{P_o}{P_n} \times 100 \tag{16}$$

where

L.F = load factor, percent

P_n = nameplate power rating.

A load factor of over 100 percent indicates an overloaded motor and a load factor of under 100 percent is an underloaded motor.

Estimated load factors for motors tested in this study ranged from 29 to 116 percent (Table 6). Forty percent of the motors were overloaded with 20 percent operating at greater than a five percent overload. A five percent overload is permissible for motors operating in an ideal environment. Irrigation installations approach an ideal environment only when a well ventilated shading structure is provided. Shading structures were not provided for most of the motors involved in this study. The motor loading data show that many of the irrigation pumping plants tested will suffer from premature motor failure due to overloading.

Table 6. Load Factors of Electric Motors as Power Units for Irrigation Pumping Plants in South Dakota

	Load Factor						
	Above 105%	101-105%	96-100%	91-95%	81-90%	80% or less	Total
Number of Units	8	8	5	7	7	6	41
Percent of Total	20	20	12	17	17	14	100

An important secondary benefit of this study is the education provided to the cooperators. Most of the cooperators involved were present at the test and showed an interest in the measurements that were made and the calculations that showed pumping plant performance. These people will be more aware of the factors affecting pump efficiency and will encourage better energy efficiency for irrigation in the future.

SUMMARY AND CONCLUSIONS

Electric irrigation pumping plants provide water to approximately 100,000 irrigated hectares (250,000 acres) in South Dakota. Irrigation pumping plant efficiency is an important parameter for estimating energy use by irrigation. In order to provide information on electric pumping plant efficiencies, a study was undertaken to develop a pumping plant testing procedure and to measure electric irrigation pumping plant efficiencies in South Dakota.

Irrigation pump discharge must be measured to determine pumping plant efficiency. Because pump discharge is often difficult to measure in the field, several discharge measurement methods were tested under laboratory and field conditions to evaluate the suitability of the methods for pumping plant efficiency tests. A propeller meter, two pitot tube devices, and a pressure distribution method were the flow measurement methods tested.

The propeller meter was mounted in a portable open discharge tube. In laboratory tests the propeller meter measured flow to within five percent of a calibrated orifice meter when the open discharge tube was connected to an eight-inch pipe. Since the propeller meter is generally accepted as an accurate flow measurement device and gave consistent results in the laboratory, the propeller meter was used as a standard for pitot tube field tests.

The Hall tube was a pitot tube device tested which measured average flow velocity in the pipe with several interconnected impact holes spaced evenly across the pipe diameter. The Hall tube measured

flow to within five percent of a calibrated orifice in the laboratory under varying flow conditions. Accuracy of the Hall tube in field tests was not consistent. Differences between the Hall tube and propeller meter were greater than ten percent in some cases. The Hall tube did not operate properly when placed in the first nozzle hole of several center pivot irrigation machines. Subsequent laboratory studies indicated that a modified Hall tube would give accurate flow measurement results when placed in the first center pivot nozzle hole.

A transverse pitot tube device was also tested. The transverse tube measured flow velocity at a point in the pipe. Several velocity measurements were made across the flow stream to determine average pipe velocity. The transverse tube measured flow to within five percent of the calibrated orifice in the laboratory. Field measurements under several conditions were within ten percent of the propeller meter readings.

The pressure distribution method for estimating center pivot machine discharge was not acceptable. Several factors, including inaccurate pressure measurement and poor estimates of roughness coefficients, may have contributed to the error.

The following conclusions were made from laboratory and field tests of the flow measurement devices.

1. A properly functioning propeller meter was the most accurate flow measurement device when a suitable attachment point was available.
2. The transverse tube pitot tube device provided the most accurate discharge measurement when the propeller meter could not

be attached.

3. The Hall tube pitot tube device was suitable for discharge measurement when a long length of straight pipe was available. Installation of a modified Hall tube in the first nozzle hole of a center pivot machine can be an accurate flow measurement method.

4. The pressure distribution method did not produce satisfactory flow measurement results.

Pumping plant efficiencies were determined for 34 electric irrigation pumping plants in eastern South Dakota. Wire-to-water pumping plant efficiencies ranged from 48 percent to 72 percent. Sixty-four percent of the pumping plants tested were operating at more than 95 percent of the Nebraska pumping plant efficiency standard. The following conclusions were made from the pumping plant testing study.

1. A satisfactory electric pumping plant testing method was developed.

2. Based on limited data, electric irrigation pumping plants in eastern South Dakota are presently operating at a high efficiency when compared to those tested in other studies and to the Nebraska pumping plant efficiency standards.

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Appendix A. Laboratory Orifice Flow Meter Calibration

Manometer Differential inches (H_g)	Water Flow (lbs)	Water Flow (ft^3)	Time (sec)	Flow Rate (cfs)
9.83	6000	96.42	67.7	1.424
5.50	4000	64.28	60.5	1.062
2.78	4000	64.28	84.3	0.762
2.61	2000	32.14	45.7	0.703
4.07	2000	32.14	35.7	0.900
5.66	3000	48.21	45.4	1.062
6.62	3000	48.21	42.0	1.148
7.83	3000	48.21	38.6	1.249
9.82	3000	48.21	34.5	1.397
6.62	3000	48.21	41.7	1.156
9.82	3000	48.21	34.5	1.397

Least squares fit line

$$Q = (0.443)h^{0.506}$$

where

Q = flow rate, cfs

h = manometer differential, inches of mercury

or

$$Q = (7.83)h^{0.506}$$

where

Q = flow rate, liters/sec

h = manometer differential, cm mercury

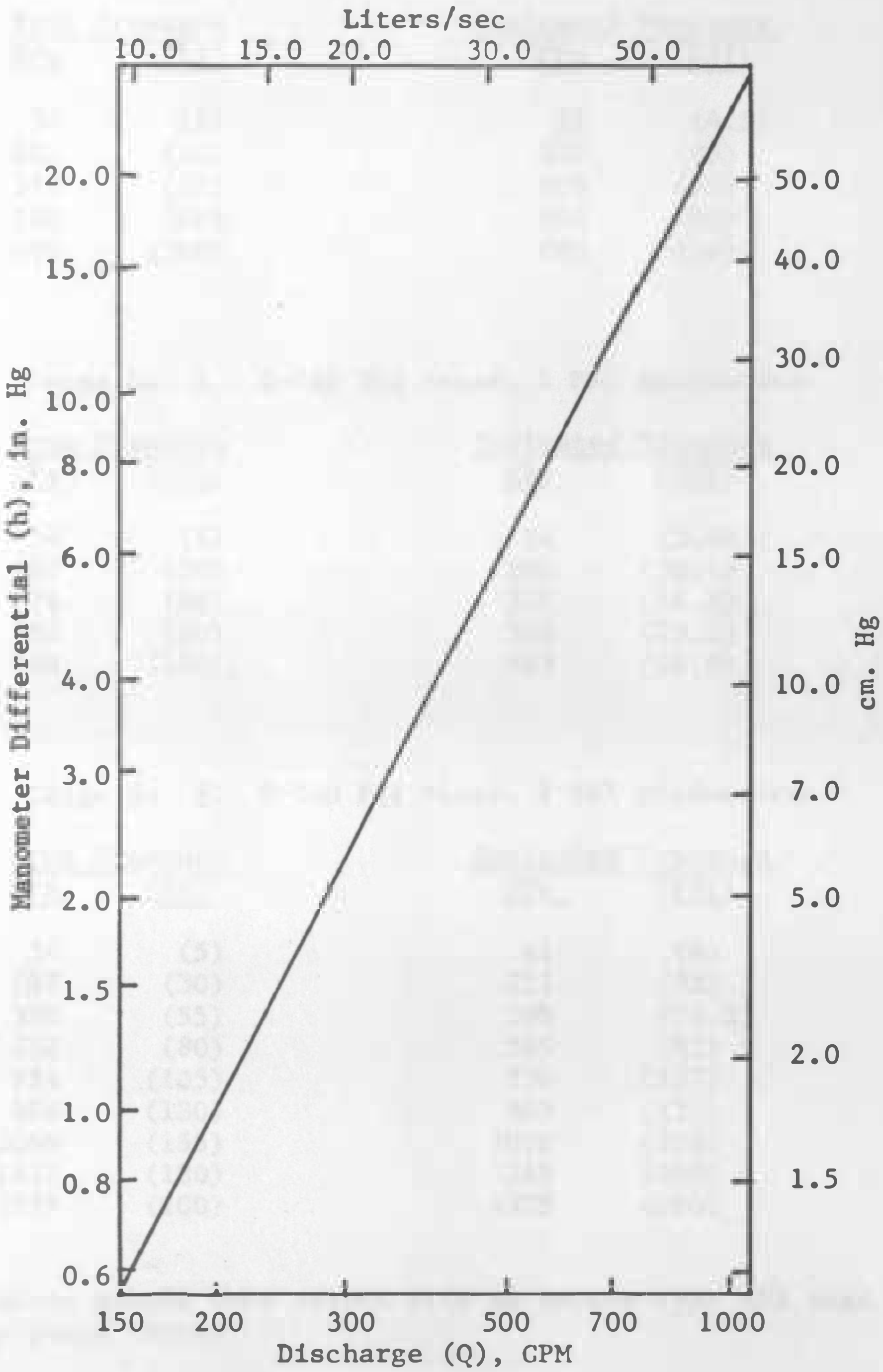

Figure A-1. Laboratory Orifice Flow Meter Calibration Curve

Appendix B. Pressure Gauge Calibration Tests*

Table B1. Gauge No. 1. 0-100 PSI range, 2 PSI graduations.

True Pressure KPa	(PSI)	Indicated Pressure KPa	(PSI)
34	(5)	31	(4.5)
207	(30)	207	(30)
379	(55)	379	(55)
552	(80)	552	(80)
690	(100)	683	(99)

Table B2. Gauge No. 2. 0-100 PSI range, 1 PSI graduation.

True Pressure KPa	(PSI)	Indicated Pressure KPa	(PSI)
34	(5)	34	(5.0)
207	(30)	208	(30.1)
379	(55)	378	(54.8)
552	(80)	548	(79.5)
690	(100)	683	(99.0)

Table B3. Gauge No. 3. 0-200 PSI range, 2 PSI graduations.

True Pressure KPa	(PSI)	Indicated Pressure KPa	(PSI)
34	(5)	41	(6)
207	(30)	221	(32)
379	(55)	390	(56.5)
552	(80)	565	(82)
724	(105)	738	(107)
896	(130)	903	(131)
1069	(155)	1076	(156)
1241	(180)	1241	(180)
1379	(200)	1379	(200)

* All pressure gauges were tested with an Amthor Type 452 dead weight pressure gauge tester.

Appendix C. Laboratory Flow Meter Test Data Set

Table C1. Flow Meter Test 1.

Orifice Meter		Hall Tube			Open Discharge Propeller Meter		
Liters/sec	(GPM)	Liters/sec	(GPM)	% error	Liters/sec	(GPM)	% error
32.6	(517)	33.7	(534)	+3.29	36.0	(571)	+10.4
28.4	(451)	29.7	(471)	+4.43	31.9	(505)	+12.0
24.6	(390)	25.5	(404)	+3.59	27.3	(433)	+11.0
19.2	(304)	19.6	(311)	+2.30	20.8	(330)	+8.6
15.1	(239)	14.9	(237)	-0.84	15.7	(249)	+4.2
24.9	(395)	25.9	(410)	+3.80	27.9	(442)	+11.9
40.7	(645)	41.9	(664)	+2.95	46.6	(738)	+14.4

Table C2. Flow Meter Test 2.

Orifice Meter		Transverse Tube			Open Discharge Propeller Meter		
Liters/sec	(GPM)	Liters/sec	(GPM)	% error	Liters/sec	(GPM)	% error
39.7	(629)	41.0	(650)	+3.3	43.1	(684)	+8.7
49.3	(782)	50.5	(800)	+2.3	54.3	(861)	+10.1
41.5	(658)	43.7	(692)	+5.2	46.1	(731)	+11.1
37.8	(599)	38.7	(613)	+2.3	40.8	(647)	+8.0
30.8	(488)	31.5	(499)	+2.3	33.4	(529)	+8.4
24.6	(390)	25.2	(399)	+2.3	26.3	(417)	+6.9
15.6	(248)	16.0	(254)	+2.4	16.0	(254)	+2.4

Table C3. Flow Meter Test 3.

Orifice Meter		Hall Tube			Transverse Tube			Open Discharge Propeller Meter		
Liters/sec	(GPM)	Liters/sec	(GPM)	% error	Liters/sec	(GPM)	% error	Liters/sec	(GPM)	% error
43.8	(695)	44.7	(708)	+1.9	43.8	(695)	0	45.6	(723)	+4.03
42.1	(667)	42.9	(680)	+1.9	42.3	(670)	+0.4	44.0	(698)	+4.6
39.7	(629)	40.6	(644)	+2.4	39.7	(629)	0	41.6	(660)	+4.9
37.8	(599)	38.0	(603)	+0.7	37.9	(601)	+0.3	39.4	(625)	+4.3
32.9	(521)	33.1	(525)	+0.8	32.5	(516)	-1.0	34.4	(545)	+4.6
30.0	(475)	30.2	(479)	+0.8	30.0	(476)	+0.2	31.5	(500)	+5.3
27.1	(430)	27.1	(429)	-0.2	26.8	(425)	-1.2	27.9	(442)	+2.8
27.7	(439)	27.6	(438)	-0.2	27.1	(429)	-2.3	28.7	(455)	+3.6
30.3	(480)	30.0	(475)	-1.0	30.2	(478)	-0.4	31.5	(500)	+4.2
33.4	(529)	33.7	(534)	+0.9	33.1	(525)	-0.8	34.9	(553)	+4.5
35.5	(563)	35.7	(566)	+0.5	35.6	(564)	+0.2	37.1	(588)	+4.4
38.4	(609)	38.9	(616)	+1.1	38.4	(609)	0	40.0	(634)	+4.1
42.5	(673)	43.5	(690)	+2.5	41.9	(664)	-1.3	44.3	(703)	+4.5

Table C4. Flow Meter Test 4, Hall Tube 45° to Plane of Curvature of Elbow.

Orifice Meter		Hall Tube		
Liters/sec	(GPM)	Liters/sec	(GPM)	% error
20.6	(326)	20.7	(328)	+0.6
23.5	(373)	23.2	(368)	-1.3
26.8	(425)	26.1	(413)	-2.8
30.0	(475)	30.8	(489)	+2.9
33.4	(529)	34.0	(539)	+1.9
37.5	(595)	38.2	(606)	+1.8
31.1	(493)	31.8	(504)	+2.2
27.7	(439)	28.8	(456)	+3.9
25.5	(405)	26.4	(418)	+0.7
22.8	(362)	23.8	(378)	+4.4
18.0	(286)	18.4	(292)	+2.1
13.9	(221)	13.9	(221)	0
9.0	(143)	8.7	(138)	-3.5

Table C5. Flow Meter Test 4, Hall Tube Parallel to Plane of Curvature of Elbow.

Orifice Meter		Hall Tube		
Liters/sec	(GPM)	Liters/sec	(GPM)	% error
25.2	(400)	26.8	(425)	+6.3
25.9	(410)	28.0	(444)	+8.3
28.3	(449)	30.2	(478)	+6.5
32.6	(517)	35.2	(558)	+7.9
27.1	(430)	28.8	(456)	+6.0
22.8	(362)	24.0	(380)	+5.0
18.5	(293)	19.2	(304)	+3.8
13.9	(221)	14.5	(230)	+4.1

Table C6. Flow Meter Test 5.

Orifice Meter		Transverse Tube			Hall Tube		
Liters/sec	(GPM)	Liters/sec	(GPM)	% error	Liters/sec	(GPM)	% error
45.7	(724)	45.9	(727)	+0.4			
41.9	(664)	43.5	(690)	+3.9			
37.5	(595)	38.9	(616)	+3.5			
33.9	(537)	34.5	(547)	+1.9			
28.6	(453)	30.0	(475)	+4.8			
22.1	(351)	22.8	(361)	+2.8			
32.1	(509)				32.1	(509)	0
29.5	(467)				29.1	(461)	-1.3
26.2	(415)				25.7	(407)	-1.9
21.4	(339)				21.1	(334)	-1.5
39.7	(629)				39.9	(633)	+0.6

Table C7. Hall Tube Tests in 2.5 cm (1 in) Fitting.

A. Hall tube in 1.9 cm (0.75 in) hole in pipe sidewall

Orifice Meter		Hall Tube		
Liters/sec	(GPM)	Liters/sec	(GPM)	% error
39.9	(632)	40.3	(639)	+0.8
37.8	(599)	38.9	(616)	+2.5
36.6	(581)	37.8	(600)	+2.7
34.4	(545)	35.3	(560)	+2.4
31.9	(505)	33.0	(523)	+3.4
28.6	(454)	29.0	(460)	+1.3
27.8	(440)	28.2	(447)	+1.4

B. Hall tube in 2.5 cm (1 in) fitting - no modification

Orifice Meter		Hall Tube		
Liters/sec	(GPM)	Liters/sec	(GPM)	% error
38.6	(612)	36.4	(577)	-5.7
36.2	(574)	34.3	(543)	-5.4
34.6	(548)	33.4	(529)	-3.5
33.6	(533)	31.4	(498)	-6.6
31.4	(497)	29.7	(471)	-5.2
28.3	(449)	26.6	(421)	-6.2

C. Hall tube in 2.5 cm (1 in) fitting - with modification

Orifice Meter		Hall Tube		
Liters/sec	(GPM)	Liters/sec	(GPM)	% error
37.3	(592)	37.8	(599)	+1.2
34.6	(548)	34.9	(554)	+1.1
31.4	(497)	31.2	(495)	-0.4
28.9	(458)	28.5	(452)	-1.3
26.8	(425)	26.2	(416)	-2.1
41.5	(658)	42.1	(667)	+1.4

Appendix D. Field Flow Meter Tests

Table D1. Field Flow Meter Tests.

Test No.	Open Discharge Propeller Meter		Hall Tube 1-3D		Hall Tube 6+D		Hall Tube 1st nozzle		Transverse Tube 1-3D		Transverse Tube 6+D		Pressure Distribution Method	
	Liters/sec	(GPM)	Liters/sec	(GPM)	Liters/sec	(GPM)	Liters/sec	(GPM)	Liters/sec	(GPM)	Liters/sec	(GPM)	Liters/sec	(GPM)
1	--	--	48.6	(770)	53.1	(841)	47.4	(751)		--		--	32.2	(510)
2	--	--	62.5	(990)	56.8	(900)	50.5	(800)		--		--		--
3	--	--	49.8	(790)	47.3	(750)		--	44.5	(705)		--	22.7	(360)
4	--	--	61.2	(970)	65.9	(1045)		--	64.5	(1022)	61.8	(980)		
5	47.3	(750)		--	52.4	(830)	42.9	(680)	50.5	(800)	46.7	(740)		--
6		--	26.2	(416)	24.9	(394)	24.4	(386)	24.8	(393)	25.9	(411)		--
7	18.7	(297)	18.7	(297)	18.4	(291)		--	18.0	(285)	18.4	(291)		--
8	56.6	(897)	54.8	(868)	57.9	(917)	53.6	(850)	60.3	(955)	59.2	(939)	43.5	(690)
9	61.3	(971)	41.9	(664)	58.6	(929)		--	55.9	(886)	58.9	(934)		--
10			57.7	(915)		--							60.6	(960)
11			58.0	(920)		--							73.2	(1160)
12			47.4	(752)		--							70.0	(1110)
13			42.5	(674)		--							55.8	(885)
14			52.4	(830)		--							45.1	(715)
15			45.9	(727)		--							30.3	(480)

Appendix E. Pumping Plant Test Data Sheet

OBSERVER ______________________ DATE __________

ASSISTANT ______________________ TIME __________

LOCATION: Owner ______________ Operator __________

Mailing Address ______________ Legal Des. __________

PUMPING PLANT: Motor __________ Model ______________

HP_____ RPM _____ Serial No. ______________

Pump __________ Model ______________

Bowls __________ Serial No. ______________

Seasons of use _____ Dealer ______________

Comments ______________________

ELECTRIC METER: CTR __________ K_h __________ Meter No. __________

DISCHARGE LINE: ID _____ Area _____ Length of straight pipe above pitot _____

WELL: Static level _______ Pumping _______ Drawdown _______

POWER INPUT:

	Disk revolutions	Time (min.)	RPM
Test 1	______	______	______
Test 2	______	______	______
Test 3	______	______	______
		Ave.	______

DISCHARGE MEASUREMENT: Collins _____ Cox _____

Reading -	1	2	3	4	Ave.	GPM	PSI
Test 1	____	____	____	____	____	____	____
Test 2	____	____	____	____	____	____	____
Test 3	____	____	____	____	____	____	____
					Ave.	____	____

CALCULATIONS: _____ ft. lift + 2.31 x _____ PSI = _____ ft. total lift

_____ ft. total lift x _____ GPM / 3960 = _____ water horsepower

_____ K_h x _____ CTR x _____ RPM x 0.08043 = _____ elec. horsepower

_____ WHP / _____ EHP = _____ wire-to-water efficiency

Appendix F. Pumping Plant Tests

Table F1. Pumping Plant Tests

Test No.	Date	Nameplate Power Rating KW	(HP)	Seasons of Use	Electric Meter CTR	K_h	RPM	Water Level Below Surface While Pumping m	(ft)	Discharge liters/sec	(GPM)	Discharge Pressure KPa	(PSI)	Measured Power Input KW	(HP)	Estimated Motor Power Output KW	(HP)	Estimated Motor Load Factor Percent	Water Power Produced KW	(HP)	Wire-to-Water Efficiency Percent	Estimated Pump Efficiency Percent
1	1977 7-18	74.6	(100)	1	16.7	40	1.75	25.6	(84)	57.4	(910)	634	(92)	70	(94.0)	63.1	(84.6)	85	50.8	(68.1)	72.5	80.5
2	8- 3	74.6	(100)	2	3.6	40	7.75	25.6	(84)	52.4	(830)	676	(98)	67.0	(89.8)	60.3	(80.8)	81	48.5	(65.1)	72.5	80.5
3	8-10	56.0	(75)	2	160	1.2	5.68	14.6	(48)	58.0	(920)	614	(89)	65.4	(87.7)	58.9	(79.0)	105	44.0	(58.9)	67.1	74.6
4	8-10	56.0	(75)	3	1	57.6	20.83	18.0	(59)	42.5	(674)	614	(89)	72.0	(96.5)	64.8	(86.9)	116	33.6	(45.0)	46.7	51.9
5	8-11	56.0	(75)	1	1	--	12.20	15.5	(51)	47.5	(753)	738	(107)	—	—	--	—	--	42.3	(56.7)	—	—
6	8-11	56.0	(75)	1	1	57.6	15.15	12.2	(40)	39.6	(627)	645	(93.5)	52.4	(70.2)	47.1	(63.2)	84	30.2	(40.5)	57.7	64.2
7	8-18	44.8	(60)	2	160	1.2	4.27	13.4	(44)	47.4	(752)	524	(76)	49.2	(65.9)	44.3	(59.3)	99	31.1	(41.7)	63.2	70.3
8	10-6	56.0	(75)	2	120	0.6	10.20	5.5	(18)	[illegible]	(900)	503	(73)	44.1	(59.1)	39.7	(53.2)	71	31.6	(42.4)	71.8	79.8
9	1978 6-20	74.6	(100)	2	41.67	4.8	5.85	44.8	(147)	56.2	(890)	441	(64)	70.2	(94.1)	63.2	(84.7)	85	49.4	(66.3)	70.4	78.2
10	6-21	56.0	(75)	2	41.67	4.8	5.00	1.5	(5)	44.5	(706)	772	(112)	60.0	(80.4)	54.0	(72.4)	96	35.1	(47.0)	58.5	64.9
11	7- 7	56.0	(75)	1	40	3.6	7.52	1.5	(5)	99.4	(1575)	393	(57)	65.0	(87.1)	58.5	(78.4)	105	40.5	(54.4)	62.4	69.3
12	7- 7	93.3	(125)	1	40	3.6	12.96	2.1	(7)	120.5	(1910)	555	(80.5)	112.0	(150.1)	100.8	(135.1)	108	69.4	(93.1)	62.0	68.9
13	7- 7	93.3	(125)	1	40	3.6	13.14	2.1	(7)	120.2	(1905)	558	(81)	113.5	(152.2)	102.2	(137.0)	110	69.7	(93.4)	61.4	68.2
14	7-10	44.8	(60)	1	40	3.6	5.32	-18.3*	(-60)*	44.7	(708)	758	(110)	46.0	(61.6)	41.4	(55.5)	92	25.9	(34.7)	56.3	62.6
15	7-10	44.8	(60)	1	40	3.6	5.56	-14.6*	(-48)*	51.3	(814)	--	--	48.0	(64.4)	43.2	(58.0)	97	—	—	—	—
16	7-10	29.8	(40)	1	40	3.6	4.09	-51.5*	(-169)*	58.0	(920)	—	—	35.3	(47.4)	31.8	(42.6)	107	—	—	—	—
17	7-10	37.3	(50)	1	40	3.6	4.91	-16.2*	(-53)*	44.9	(712)	689	(100)	42.4	(56.9)	38.2	(51.2)	102	23.9	(32.0)	56.3	62.5
18	7-10	37.3	(50)	1	40	3.6	4.50	-26.8*	(-88)*	44.3	(703)	862	(125)	38.9	(52.1)	35.0	(46.9)	94	26.6	(35.6)	68.4	76.0
19	7-19	11.2	(15)	10	1	24	2.50	—	—	51.9	(822)	48	(7)	3.6	(4.8)	3.2	(4.3)	29	—	—	—	—
20	7-19	56.0	(75)	2	1	57.6	19.31	15.8	(52)	57.1	(905)	641	(93)	66.7	(89.5)	60.1	(80.5)	107	45.5	(61.0)	68.2	75.7

Table F1 continued

Test No.	Date	Nameplate Power Rating KW	Nameplate Power Rating (HP)	Seasons of Use	Electric Meter CTR	Electric Meter K_h	Electric Meter RPM	Water Level Below Surface While Pumping m	Water Level Below Surface While Pumping (ft)	Discharge liters/sec	Discharge (GPM)	Discharge Pressure KPa	Discharge Pressure (PSI)	Measured Power Input KW	Measured Power Input (HP)	Estimated Motor Power Output KW	Estimated Motor Power Output (HP)	Estimated Motor Load Factor Percent	Water Power Produced KW	Water Power Produced (HP)	Wire-to-Water Efficiency Percent	Estimated Pump Efficiency Percent
21	7-19	22.4	(30)	2	1	57.6	6.91	12.2	(40)	22.1	(350)	510	(74)	23.9	(32.0)	21.5	(28.8)	96	13.9	(18.6)	58.2	64.7
22	7-19	29.8	(40)	2	1	57.6	9.03	15.2	(50)	27.3	(433)	572	(83)	31.2	(41.8)	28.1	(37.7)	94	19.7	(26.4)	63.2	70.2
23	7-20	74.6	(100)	1	1	57.6	24.8	15.8	(52)	62.3	(988)	627	(91)	85.7	(114.9)	77.1	(103.4)	103	48.8	(65.4)	56.9	63.3
24	7-20	74.6	(100)	1	1	57.6	24.3	21.3	(70)	67.0	(1062)	641	(93)	84.0	(112.6)	75.6	(101.3)	101	57.0	(76.4)	67.9	75.4
25	7-20	74.6	(100)	1	1	--	9.05	18.3	(60)	57.7	(915)	558	(81)	--	--	--	--	--	42.6	(57.1)	--	--
26	7-25	56.0	(75)	1	160	1.2	3.95	9.4	(31)	53.2	(844)	448	(65)	45.5	(61.0)	41.0	(54.9)	73	28.8	(38.6)	63.3	70.3
27	7-25	56.0	(75)	3	160	1.2	5.60	12.5	(41)	48.9	(775)	758	(110)	64.5	(86.5)	58.1	(77.8)	104	43.1	(57.8)	66.8	74.2
28	7-25	56.0	(75)	3	160	1.2	5.81	14.6	(48)	60.4	(957)	662	(96)	66.9	(89.7)	60.2	(80.8)	108	48.6	(65.2)	72.7	80.7
29	7-25	56.0	(75)	3	160	1.2	6.12	21.0	(69)	59.0	(935)	586	(85)	70.5	(94.5)	63.5	(85.1)	113	46.7	(62.1)	66.3	73.7
30	7-26	44.8	(60)	3	160	1.2	3.17	11.3	(37)	37.8	(599)	483	(70)	36.5	(49.0)	32.9	(44.1)	73	22.4	(30.1)	61.4	68.2
31	7-26	56.0	(75)	1	160	1.2	5.11	8.8	(29)	54.9	(870)	579	(84)	58.9	(78.9)	53.0	(71.0)	95	36.6	(49.0)	62.1	69.0
32	7-26	56.0	(75)	1	1	57.6	16.22	39.6	(130)	44.2	(700)	472	(62)	56.1	(75.1)	50.5	(67.6)	90	36.0	(48.3)	64.3	71.4
33	7-26	56.0	(75)	2	160	1.2	5.66	17.4	(57)	47.9	(759)	772	(112)	65.2	(87.4)	58.7	(78.7)	105	45.1	(60.5)	69.2	76.9
34	7-31	37.3	(50)	9	1	48	15.41	7.6	(25)	42.1	(667)	538	(78)	44.4	(59.5)	39.9	(53.5)	107	25.8	(34.6)	58.1	64.5
35	7-31	74.6	(100)	2	120	0.6	17.15	7.3	(24)	63.5	(1007)	696	(101)	74.1	(99.3)	66.7	(89.4)	89	48.8	(65.4)	65.9	73.2
36	7-31	56.0	(75)	4	--	--	11.76	10.1	(33)	58.8	(932)	600	(87)	--	--	--	--	--	41.1	(55.1)	--	--
37	8- 2	37.3	(50)	4	40	3.6	4.85	--	--	60.1	(953)	579	(84)	41.9	(56.2)	37.7	(50.6)	101	--	--	--	--
38	8- 2	56.0	(75)	3	40	3.6	6.02	-1.5*	(-5)*	45.1	(715)	703	(102)	52.0	(69.7)	46.8	(62.8)	84	31.1	(41.6)	59.7	66.4
39	8- 3	37.3	(50)	4	160	1.2	3.30	--	--	50.0	(793)	572	(83)	38.0	(51.0)	34.2	(45.9)	92	--	--	--	--
40	8- 8	44.8	(60)	2	120	0.6	10.95	--	--	50.5	(800)	545	(79)	47.3	(63.4)	42.6	(57.1)	95	--	--	--	--
41	8-16	74.6	(100)	12	80	1.2	13.5	13.1	(43)	63.1	(1000)	531	(77)	77.8	(104.2)	70.0	(93.8)	94	41.6	(55.8)	53.5	59.5
42	8-16	56.0	(75)	1	--	--	10.60	14.6	(48)	46.4	(735)	758	(110)	--	--	--	--	--	41.8	(56.1)	--	--
43	8-28	74.6	(100)	3	120	0.6	14.86	--	--	56.8	(900)	--	--	64.2	(86.1)	57.8	(77.4)	77	--	--	--	--
44	9-20	74.6	(100)	7	1	43.2	30.77	26.8	(88)	56.8	(900)	689	(100)	79.8	(106.9)	71.8	(96.2)	96	54.1	(72.5)	67.8	75.3

* negative water levels indicate locations where a centrifugal booster pump with a positive head on the inlet was used.