THE EFFECTS OF CONVERSION ON THE PUMPING PLANT

Danny H. Rogers
Extension Agricultural Engineer
Kansas State University
Manhattan, Kansas

Every farmer needs to make a profit in order to continue farming. Traditionally, farming has not made a large return on investment, so when production costs rise in comparison to crop price and/or yield, profits can quickly turn into deficits. Irrigators are also subject to this economic reality, so they also need to evaluate the cost-effectiveness of production inputs. One component is irrigation fuel. The irrigator should know whether irrigation costs are reasonable and whether irrigation is paying its way.

The irrigation fuel or energy bill is composed of two parts. The first is related to pumping plant performance and the second to crop and irrigation management.

Total fuel bill = Pumping Cost/Volume X Volume Applied

Reducing the total volume applied reduces the fuel bill proportionately. so if the amount of water applied is minimized with good irritation scheduling and high application efficiency, the fuel bill will also be reduced by a similar amount. Good irrigation management practices and high system efficiency would minimize the total volume applied. These topics are the subject of other presentations.

The major factors that influence the pumping cost per volume are: pumping plant efficiency and TDH or total dynamic head, which is the total hydraulic resistance against which the pump must operate. Well efficiency is also a factor, but it is largely determined by design and construction factors that were used during the drilling and development processes. Many wells would produce a greater flow with less drawdown if the screen, gravel pack and development procedure had been better designed, but little can be done to improve the efficiency of a poorly constructed well.

Performance evaluations indicate that many irrigation pumping plants use more fuel than necessary if a properly sized, adjusted and maintained pumping plant were used. In Kansas, the average pumping plant uses about 40% more fuel than necessary. Obviously, some are much worse and others much better. Causes of excessive fuel use include:

1. Poor pump selection. Pumps are designed for a particular discharge, head and speed. If used outside a fairly narrow range in head, discharge and speed, the efficiency is apt to suffer. Some pumps were poor choices for the original condition, but changing conditions such as lower water levels or changes in pressure also cause pumps to operate inefficiently.

2. Pumps out of adjustment. Pumps need adjustment from time to time to compensate for wear.

3. Worn-out pumps. Pumps also wear out with time and must be replaced.

4. Improperly sized engines or motors. Power plants must be matched to the pump for efficient operation. Engine or motor loads and speed are both important to obtain high efficiency.

5. Engines in need of maintenance and/or repair.

6. Improperly notched gear heads. Gear head pump drives must fit the load and speed requirements of the pump and engine.

Pumping plant performance evaluations can be obtained by hiring a consulting firm or contractor to take the measurements, but many farmers are reluctant to spend money to find out if something is wrong. Energy costs, however, can represent a significant portion of the production cost for a crop. The following will help an irrigator analyze irrigation fuel or energy bills to see if they are within reason considering the pumping conditions and price of fuel or energy.

Irrigation pumping energy requirements can be estimated using the Nebraska Performance Criteria shown in Table 1. The Nebraska criteria is a guideline for a performance of a properly designed and maintained pumping plant. Some pumping plants will exceed this criteria, but most will not.

If this estimate indicates low pumping plant efficiency, then hiring a firm to repair or replace the pumping plant may be justified. The irrigator needs to know 1) acres irrigated, 2) discharge rate, 3) total dynamic head, 4) total application depth, 5) total fuel bill, and 6) fuel price/unit in order to make such an estimate.

Step 1: Determine Water Horsepower

Water horsepower (WHP) is the amount of work done on the water and is calculated by

WHP = TDH (GPM)/3960.

where:

GPM = discharge rate in gallons per minute

TDH = total dynamic head (in feet)

TDH is usually estimated by adding total pumping lift and pressure at the pump. Since pressure is usually measured in PSI, convert PSI to feet by multiplying PSI x 2.31 (see conversions in Table 2).

Step 2: Calculate hours of pumping

HR = D (Ac)/(GPM/450)

where:

HR = Hours of pumping

D = Depth of applied irrigation water (inches)

Ac = Acres irrigated

GPM = discharge rate in gallons/minutes

450 = Constant (see conversion in Table 2)

Step 3: Estimate hourly NPC fuel use

FU = WHP/NPC
where:
FU = Hourly fuel use using the Nebraska criteria
WHP = Water Horsepower from Step 1
NPC = Nebraska Performance Criteria (Table 1)

Step 4: Estimate seasonal NPC fuel cost

SFC = FU x H_R x Cost
where:
SFC = Seasonal Fuel Cost if the pumping plant was operating at NPC
H_R = Hours of operation from Step 2
Cost = $/Fuel Unit

Step 5: Determine excess fuel cost

EFC = AFC - SFC
where:
EFC = Excess Fuel Cost (in dollars)
AFC = Actual Fuel Cost (in dollars)
SFC = Estimated Seasonal Fuel Cost using NPC (in dollars)

Step 6: Calculate annualized repair cost

ARP = INVEST X CRF
where:
ARP = Annualized Repair Cost
INVEST = Investment required to repair or upgrade pumping plant
CRF = Capital Recovery Factor (Table 3)

The excess fuel cost may be thought of as the annual payment to cover the cost of a pumping plant upgrade or repair. Repair costs can be annualized by using capital recovery factors (CRF). If the annualized repair cost for the interest rate and return period selected is less than the excess fuel cost, the investment in repair is merited.

This procedure is an indicator of your total pumping plant performance. It does not indicate the source of the excessive fuel use, but pumping plant tests in Kansas have generally shown that poor performance is generally the fault of the pump. The low efficiency may be due to excessive pump clearance, worn impellers, or changes in pumping conditions since the pump was installed. However, engines and gear heads can also be problems.

Figure 1 provides an example farm problem and a place for you to fill in information from your farm. The example farm results in an annualized repair cost of $2287. Since $2287 is less than $3385, the investment in repair of the pumping plant would be merited. The excess fuel use could be divided by the CRF (example $3385/.3811 = $8882) to indicate the amount you could afford to spend in upgrading the pumping plant.

The water power equation, shown in Step 1, establishes that the power needed to lift water is proportional to the amount and the total head requirement. Reducing either will reduce water horsepower requirements and therefore reduce fuel use. However, each pumping plant, if properly observed, will operate most efficiently as a given head-discharge relationship. Once installed, changes in head on discharge requirements could result in a loss of pumping efficiency.

PUMP PERFORMANCE CURVE

A typical performance curve for a pump is shown in Figure 2. The curve can be confusing to read since it shows information on different impeller trim sizes. The total dynamic head is read from the left vertical axis. The pump capacity is read from the horizontal axis and pump efficiency is shown within the chart. Brake horsepower requirements are shown below the head-discharge curve. Brake horsepower is the actual amount of work performed on pumping the water at a given head and capacity plus the additional amount of work required due to pump inefficiency.

Head and Capacity Relationship

The most important part of the pump performance graph is the head-capacity curve which shows the relationship between the total dynamic head and the capacity for a given pump. A given pump can produce only a certain flow (capacity) for a given head, and vice versa. The example pump performance curve in Figure 2 shows that this pump with a 9-3/16 inch impeller trim (marked as curve A) can produce a total dynamic head of 60 feet and pump 300 gpm. If a given field needed 400 gpm of capacity, this pump could then generate only 50 feet of total head.

Most pumping plants have head requirements in excess of the capability of a single bowl or stage of a pump. Pressure or head increases are accomplished by combining stages of a given pump in series. Additional stages of the pump are added together until the total dynamic head requirements of the pumping system are met. Total dynamic head includes head requirements due to pumping lift, elevation changes, friction losses, and system operating pressure. So, if 250 feet of total dynamic head is required with a desired pumping rate of 400 gpm, then five stages of this pump would be required. Adding stages increases pressure, it does not increase capacity. If capacity were to be changed significantly, the selection of a different pump would be required.

Pumps are generally selected so that the operating point on the performance curve is to the right of the peak efficiency point. Any declines in groundwater and normal wear processes would then tend to push the pump towards higher efficiency, resulting in better performance over a larger period of time than if the original selection was to the left of maximum efficiency.

Efficiency

The pump performance curve also gives information on pump efficiency. The efficiency curves intersect with the head-capacity curve and are labeled with percentages. Each pump will have its own maximum efficiency point. Figure 2 shows this pump's maximum efficiency is 81 percent for operating conditions of approximately 380 gpm with an impeller trim A. When operating at 300 gpm and 60 feet of head, efficiency is approximately 78 percent. When operating at 50 feet of total head and 400 gpm efficiency is approximately 80.5 percent.

The pump performance curve also features an efficiency adjustment chart to account for changes in efficiency that occur as the number of stages change. Pump efficiency improves with additional stages since the friction losses that occur are shared. If only a single stage pump is used then the efficiency chart indicates the pump efficiency read from the chart should be reduced by 4 percent. When three stages are used, the readings can be taken directly from the chart. When six stages are used, chart readings can be increased by 1 percent. Some manufacturers record efficiency on the chart for single stage pumps and give increases with stages. Others do as shown in this example.

Brake Horsepower

The pump performance curve will give information on the brake horsepower required to operate a pump at a given point on the performance curve. The brake horsepower curves run across the bottom of the pump performance curve. Like the head-capacity curve, there is a brake horsepower curve for each different impeller trim. Continuing with the previous example, a pump with an impeller trim A operating at 50 feet of head and 400 gpm would require approximately 6.2 horsepower. The addition of stages increase horsepower by an equal amount.

Impeller Trims

Pump performance curves generally show performance for various impeller diameters or trims. Manufacturers will put several different trim curves on a pump performance curve to make pump specification easier, although this sometimes makes the pump performance curve more difficult to read.

Operating Speed

Occasionally manufacturers will provide pump performance curves that will show the effect of changing operating speed or rpm. Figure 3 shows the same 12-inch pump model with trim A operating at 1770, 1470, and 1170 rpm. The curved lines marked A in Figure 2 and 3 are identical. The general effect of reducing speed is a reduction of capacity and head. Pump efficiency can be unaffected with head and capacity changes if the new pumping conditions are proportional to the speed changes. However, most often a specific head or discharge is required which forces the pump to operate at some other point in the curve. This means efficiency will be changed.

The manufacturer cannot be expected to provide a performance curve for every conceivable operating speed and trim. The effect of speed and trim changes can be determined through the use of mathematical relationships, sometimes known as affinity laws. However since the trim of the pump cannot be easily altered after installation, only the affinity laws for speed will be discussed.

The affinity law associated with the rotational speed or rpm of a pump is that discharge is proportional to the ratio of rotational speed; head is proportional to the square of the rotational speed ratio; and brake horsepower is proportional to the cube of the rotational speed ratio. These relationships can be stated mathematically as follows:

$$1)\ \textit{Final Discharge} = \frac{\textit{Final RPM}}{\textit{Initial RPM}}\ x\ \textit{Initial Discharge}$$

$$2)\ \textit{Final Head} = \left(\frac{\textit{Final RPM}}{\textit{Initial RPM}}\right)^2 x\ \textit{Initial Head}$$

$$3)\ \textit{Final BHP} = \left(\frac{\textit{Final RPM}}{\textit{Initial RPM}}\right)^3 X\ \textit{Initial Head}$$

These relationships could be used to develop Figure 3 using information from Figure 2. For example, at rated speed (1770 rpm) and impeller curve A, the pump curve shows 50 feet of head can be developed at a discharge of 400 gpm with a pump efficiency of 80.5 percent. Brake horse power requirements are 6.2 hp. If pump speed is slowed to 1470 rpm, what is the effect on pumping characteristics?

Solution:

Use equations 1, 2 and 3.

$$1)\ \textit{Final Discharge} = \left(\frac{1470}{1770}\right) X\ 400 = 291\ \textit{gpm}$$

$$2)\ \textit{Final Head} = \left(\frac{1470}{1770}\right)^2 X\ 50 = 34.5\ \textit{feet}$$

$$3)\ \textit{Final BHP} = \left(\frac{1470}{1770}\right)^3 X\ 6.2 = 3.4\ \textit{hp}$$

The above results can be compared to values read from Figure 3 to see that the relationships are valid.

Engine Performance Curve

Engine performance curves can also be obtained. Anybody with a new pumping plant installation should request a copy of the performance curves for the pump and engine and be certain the gear head ratio is clearly marked on the unit and recorded with the performance curves. The irrigator is then in a much better position to evaluate the effects of system changes or water declines on pumping plant efficiency.

A typical engine performance curve or map is shown in Figure 4. The horizontal axis shows percent of rated engine speed. The left vertical axis is the percent of rated torque. The intersection of 100 percent rated torque and speed is the maximum rated power for the engine. In this example, 100, 75, 50 and 25 percent of rated power is plotted. On Figure 6, points A and B are plotted along the 50 percent rated power curve. This illustrates that the same power output can be achieved using various combinations of speed and torque. Imposed on the power curves are lines that are lines of equal fuel consumption. For a given engine, the lines would be labeled with values using units such as pounds of fuel per horsepower-hour, or gallons per horsepower - hour, kilograms per kilo watt-hour, or so forth. In this example, these values were replaced by percent of minimum fuel use. The point labeled, 100 percent, is the area of best fuel economy.

Effects of Rotational Speed Changes on Engine Performance

Examination of points A and B from Figure 4 illustrate that the engine at point A is operating at much better fuel economy than at point B. If this situation were a tractor, operator response would be to gear up and throttle down. With a fixed gear head, this would require changing of the gear head at considerable expense.

With pump and engine performance curves, the effect of changing pump speed to accommodate new pumping conditions with the same equipment may be estimated without extensive field testing or discovery of excessive fuel use during or after the irrigation season. Changing speed to accommodate changes in pumping conditions can result in pumping water at very low efficiency. Worst case situations result in decreased water availability and increased pumping costs, although occasionally some changes can improve pumping efficiency. However, since irrigation fuel costs can represent a significant production expense, any changes in operating conditions should be analyzed in order to make certain profitability is not sacrificed.

A series of pump tests were conducted in 1982 by the Northwest Kansas Groundwater Management District #4, Colby, Kansas. In Table 1, the results of two tests conducted on the same pumping plant at different pumping heads. The original pumping conditions were for low head conditions, which are reflected by the higher pump efficiency and overall performance rating. However, the pump efficiency was only 63% and the performance rating was 76% indicating either wear, misadjustment, or changed pumping conditions. Adding a sprinkler system and raising well head pressure from 2 psi to 68 psi drops pump efficiency to 51% and also lowers engine efficiency, making the overall performance rating only 53%. About twice as much fuel was being used as necessary for this pumping condition. Never-the-less the pump supplied adequate pressure and discharge so the pumping plant was not upgraded.

Figures 5 and 6 are actual pump performance curves of two pumps. They will help illustrate why sometimes it is necessary to upgrade the pumping plant with pressure and discharge changes. Assume original pumping conditions were 1100 gpm and 155 feet of TDH. Pump 1 (Fig. 5) can provide 1100 gpm and 31 feet of head per stage. Therefore, 5 stages would provide the desired head at a pump efficiency of 78.5%. Pump 2 on trim 8.19 inches, provides 1100 gpm at 55 feet of head per stage, making a close fit with three stages and a pump efficiency of 82%.

If the producers wanted to switch from an 1100 gpm flood system to a 750 gpm pivot system with 35 psi pressure, would these pumps be able to perform adequately?

Thirty-five psi is about 81 feet of head. Pumping lift would be reduced some because of the reduced discharge, so lets say 70 feet of additional head is needed, making TDH = 155 + 70 = 225 feet.

Pump 1 then needs to provide 225/5 = 45 feet of head per stage. Reading from the pump curve, this pump can provide only 275 gpm. In this case, a new pump would likely be the best course of action. Pump 2, at 750 gpm, can provide 68 feet of head per stage, so three stages can provide 204 feet of TDH. In this case, a slight increase in RPM will mean this pump can provide the new pumping conditions and at a pump efficiency of about 77%.

The formulas provided in the first part of this paper allow an individual to calculate the effect of changing head on fuel cost. Therefore, quick reference Figure 7 shows pumping cost per ac-in for various fuel prices. Figure 8 shows hourly cost of operation for various water horsepower requirements.

SUMMARY

Reducing pressure can be a way of reducing pumping cost. However, pressure reduction on an existing pumping may also decrease efficiency and negate any fuel cost saving potential. Always consider and investigate the effect of changing head or pumping rate on pumping plant efficiency before making any permanent changes.

Acknowledgement: Some material is from the 1982 Irrigation Pumping Plant Performance Handbook, University of Nebraska.

Any mention of trade names does not constitute endorsement or criticism.

Table 1. Nebraska Performance Criteria for Pumping Plants

Energy Source	**WHP-HRS per Unit of Fuel**
Diesel	12.50 per gallon
Propane	6.89 per gallon
Natural Gas	61.7 per MCF
Electricity	0.885 per KWH (kilowatt-hour)

Table 2. Useful Irrigation Conversions

1 psi (pounds per square inch)
= 2.31 feet of head

1 acre-inch/hour
= 450 gallons/minute

Table 3. Selected Capital Recovery Factors (CRF)

Length of Load or Length of Useful Life	Annual Interest Rate (%)				
Years	5	7	10	12	15
2	.5378	.5531	.5712	.5917	.6151
3	.3672	.3811	.4021	.4163	.4380
4	.2820	.2820	.3155	.3292	.3503
5	.2310	.2310	.2638	.2774	.2983
7	.1728	.1728	.2054	.2191	.2404
10	.1295	.1295	.1627	.1770	.1993
15	.0963	.0963	.1315	.14	.1710

Table 4. Selected Pump Test Results from 1982
Pump Test Program (Northwest Kansas GMD #4).

Well Head Pressure PST	WHP	Measured HP °	Pump EFF %	Engine EFF %	Overall EFF %	Performance Rating % NPC*	Excess Fuel Use $^{\text{MCF}}/_{\text{HR}}$
2	35.2	55.8	63.1	21.8	13.8	75.8	0.164
68	38.0	75.0	50.7	19.1	9.7	53.3	0.487

Figure 1: Example Farm Problem and Form For Your Farm

Acreage:	150 acres
Pumping Lift:	300 feet
System Pressure:	22 psi
System Discharge Rate:	1200 gpm
Total Irrigation Application:	24 inches per acre
Fuel Type: Natural Gas	Price: $ 3.50 per MCF
Total Fuel Bill:	$ 11500

Step 1: Determine Water Horsepower

WHP = TDH × (GPM)/3960
= (300 + 22 × 2.31) × (1200)/3960
= 106 WHP

Step 2: Calculate Hours of Pumping

HR = D(Ac)/GPM/450)
= (24) (150)/(1200/450)
= 1348 hrs.

Step 3: Estimate Hourly NPC Fuel Use

FU = WHP/NPC
= 106/61.7
= 1.72 MCF/Hr.

Step 4: Estimate Seasonal NPC Fuel Cost

SFC = FU × Hr × Cost
= 1.72 × 1348 × 3.50
= $8115

Step 5: Determine Excess Fuel Cost

EFC = AFC–SFC
= 11500–8115
= $3385

Step 6: Calculate Annualized Repair Cost

Estimate of pump repair: $6000
Desired CRF using 3 years and 7% interest
from Table 3: CRF = 0.3811
ARC = INVEST × CRF
= 6000 (0.3811)
= $2287

Acreage: ______________________ A
Pumping Lift: ______________________ F
System Pressure: ______________________ PS
System Discharge Rate: ______________________ GP
Total Irrigation Application: ______________________ Inche
Fuel Type: Price ______________________
Total Fuel Bill: $ ______________________

Step 1: Determine Water Horsepower

WHP = TDH × GPM/3960
= (_____ ft + _____ PSI × 2.31) × _____ GPM/39
= ____________________ WHP

Step 2: Calculate Hours of Pumping

HR = D (Ac)/(GPM/450)
HR = _____ in × _____ Ac/ (_____ GPM/450)
= _________ Hours

Step 3: Estimate Hourly NPC Fuel Use

FU = WHP/NPC
= _____ / _____
= __________ /Hr.

Step 4: Estimate Seasonal NPC Fuel Cost

SFC = FU × Hr × Cost
= _____ × _____ × _____
= $________________

Step 5: Determine Excess Fuel Cost

EFC = AFC–SFC
= $_____ – $_____
= $________________

Step 6: Calculate Annualized Repair Cost

Repair Estimate $ ____________
ARC = INVEST × CRP
= $_____ × _____
= $________________

Figure 2: Example Performance Curve for a pump with various trims.

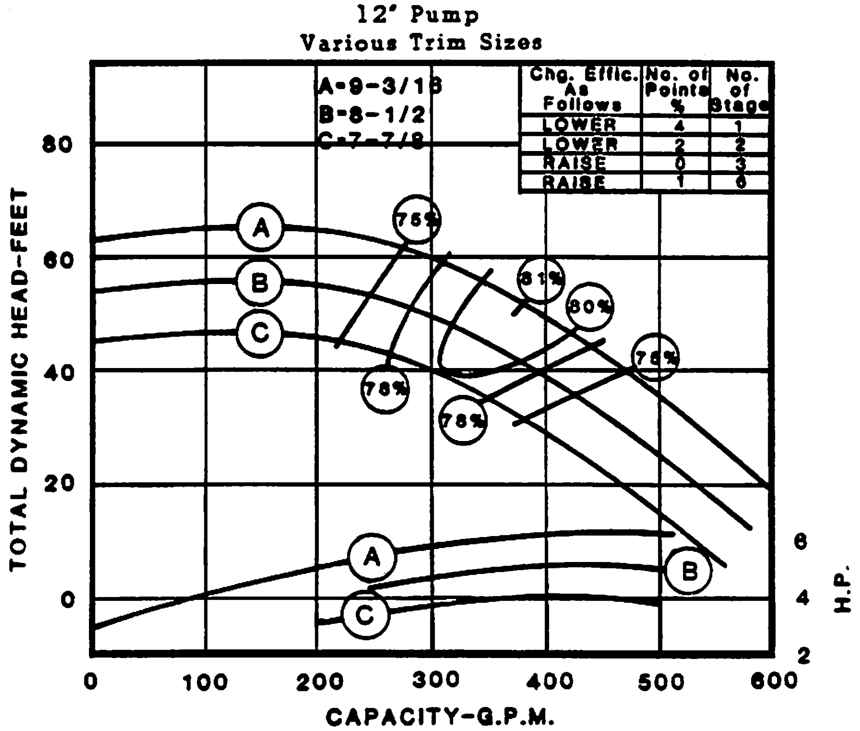


Figure 3: Example Performance Curve for a pump with various speeds.

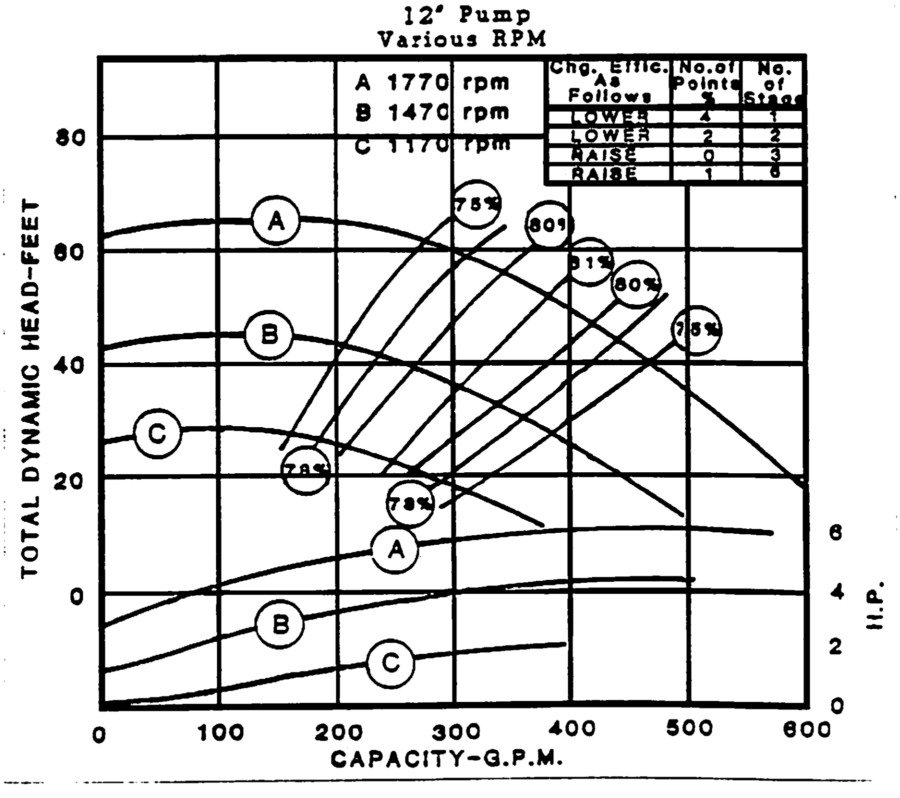


Figure 4: Example of an Engine Performance Curve.

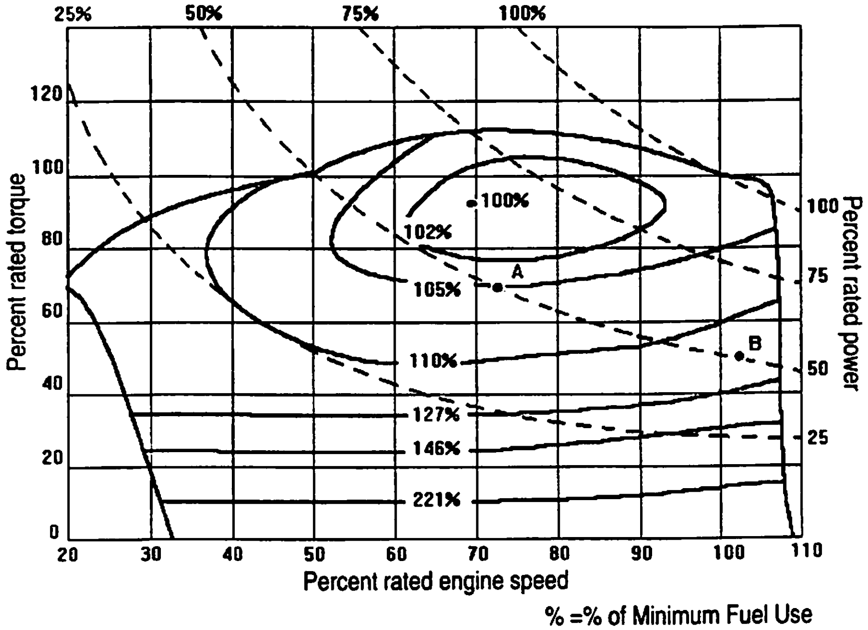
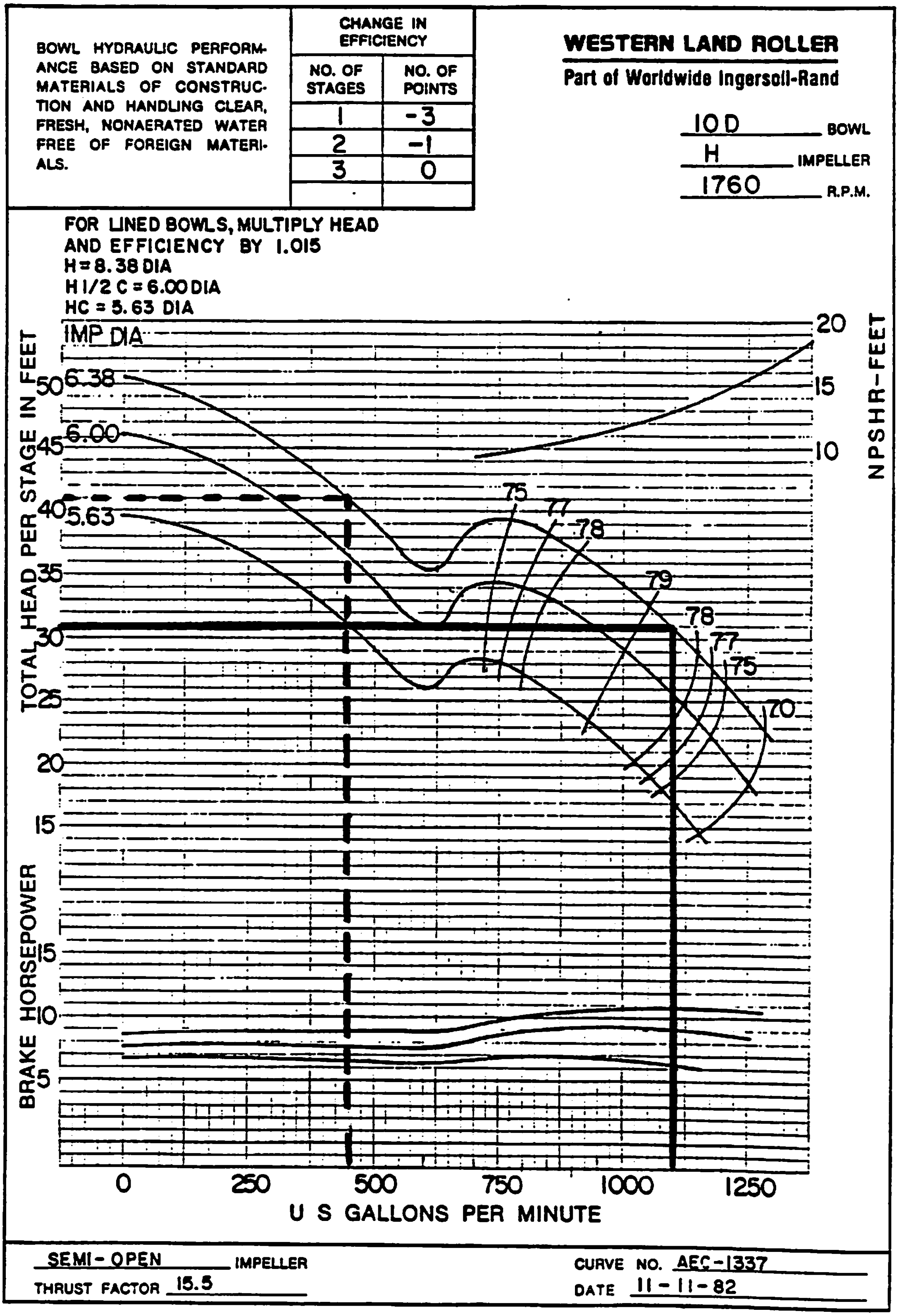


Figure 5: Example Pump Performance Curve



BOWL HYDRAULIC PERFORMANCE BASED ON STANDARD MATERIALS OF CONSTRUCTION AND HANDLING CLEAR, FRESH, NONAERATED WATER FREE OF FOREIGN MATERIALS.

CHANGE IN EFFICIENCY	
NO. OF STAGES	NO. OF POINTS
1	-3
2	-1
3	0

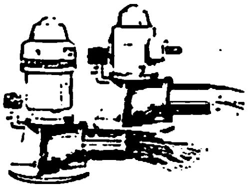
FOR LINED BOWLS, MULTIPLY HEAD AND EFFICIENCY BY 1.015

H = 8.38 DIA

H 1/2 C = 6.00 DIA

HC = 5.63 DIA

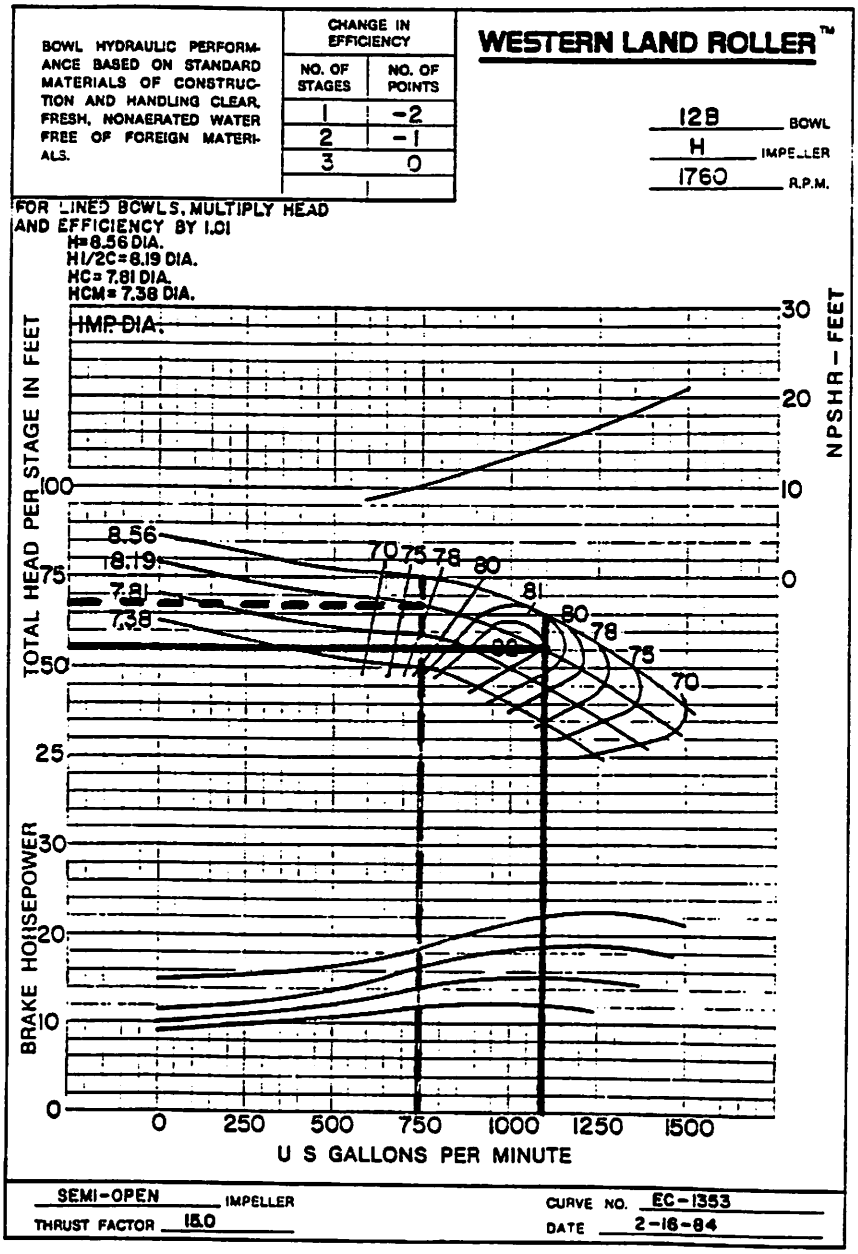
Figure 6: Example Pump Performance Curve



WESTERN LAND ROLLER™

PERFORMANCE CURVES

Sheet 529
April 1, 1984
Replaces Old Curves



BOWL HYDRAULIC PERFORMANCE BASED ON STANDARD MATERIALS OF CONSTRUCTION AND HANDLING CLEAR, FRESH, NONAERATED WATER FREE OF FOREIGN MATERIALS.

CHANGE IN EFFICIENCY	
NO. OF STAGES	NO. OF POINTS
1	-2
2	-1
3	0

WESTERN LAND ROLLER™

128 BOWL
H IMPELLER
1760 R.P.M.

FOR LINED BOWLS, MULTIPLY HEAD AND EFFICIENCY BY 1.01
H=8.56 DIA.
H1/2C=8.19 DIA.
HC=7.81 DIA.
HCM=7.38 DIA.

SEMI-OPEN IMPELLER
THRUST FACTOR 15.0
CURVE NO. EC-1353
DATE 2-16-84

INGERSOLL-RAND.
PUMPS

Hastings, Nebraska 68901

Figure 7: Pumping Cost For Various Fuel Prices and Head Requirements.

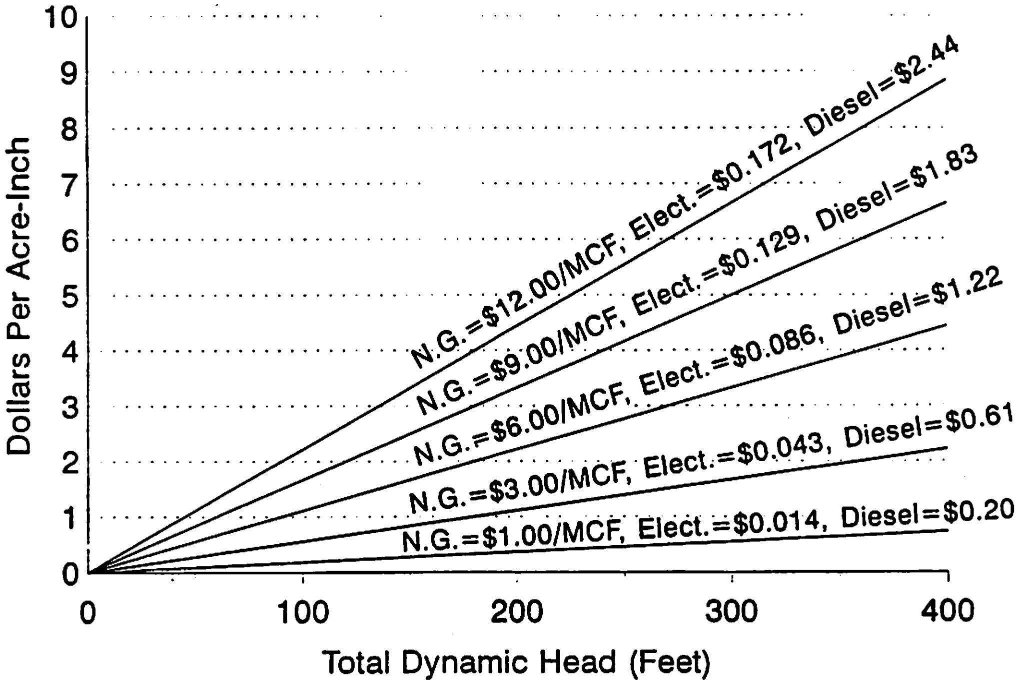


Figure 8: Hourly Irrigation Pumping Cost for Various Fuel Prices and Water Horsepower Requirements.