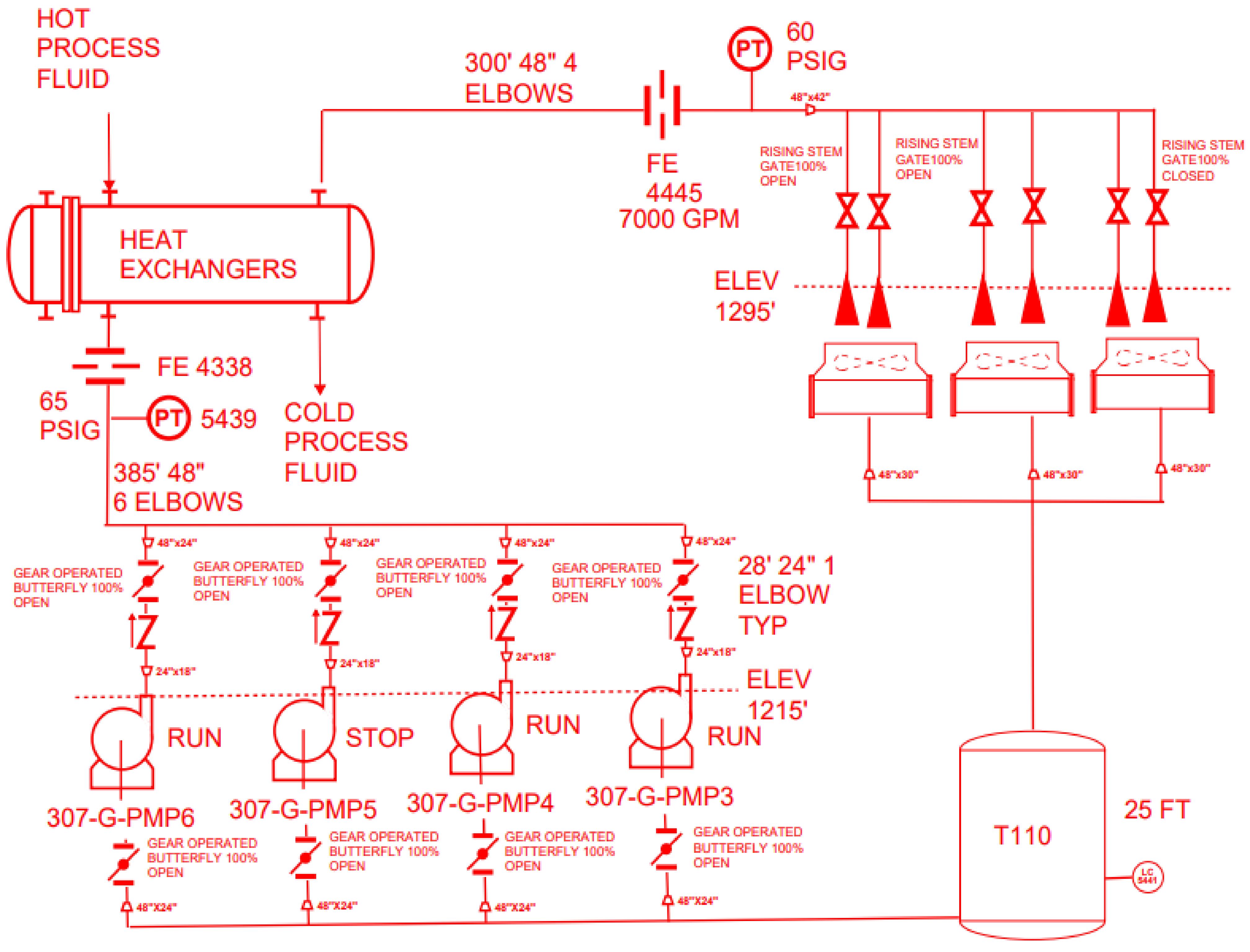
Better Plants®
U.S. DEPARTMENT OF ENERGY

Pumping System Assessment

Week 2: Pump Curves and System Curves

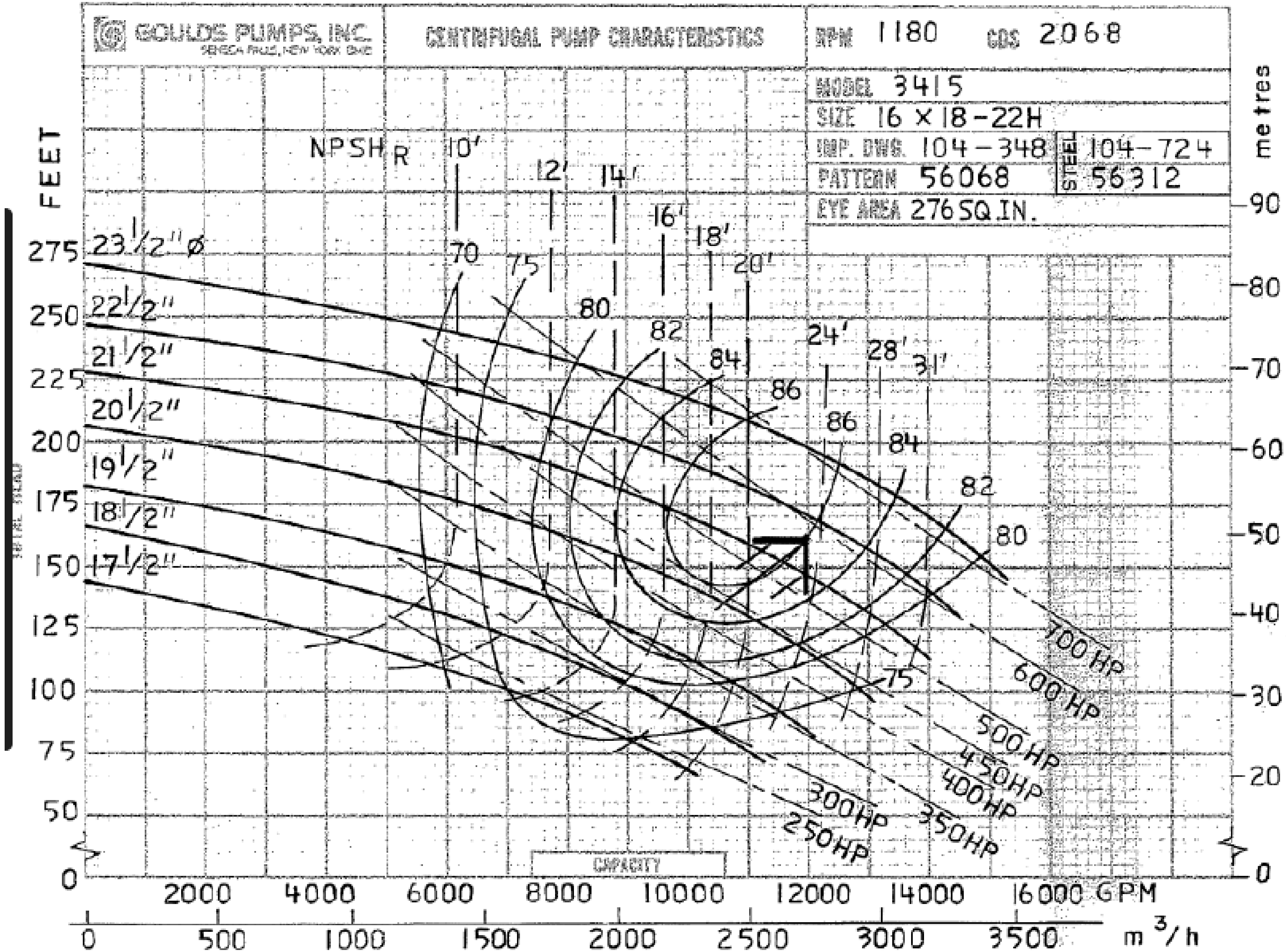
U.S. DEPARTMENT OF ENERGY

Homework 1 review


HOT PROCESS FLUID
300' 48" 4 ELBOWS
PT
60 PSIG
48"x42"
FE 4445 7000 GPM
RISING STEM GATE100% OPEN
RISING STEM GATE100% OPEN
RISING STEM GATE100% CLOSED
HEAT EXCHANGERS
ELEV 1295'
FE 4338
65 PSIG
PT 5439
COLD PROCESS FLUID
385' 48" 6 ELBOWS
48"x30"
48"x30"
48"x30"
48"x24"
GEAR OPERATED BUTTERFLY 100% OPEN
24"x18"
28' 24" 1 ELBOW TYP
ELEV 1215'
RUN
STOP
RUN
RUN
307-G-PMP6
307-G-PMP5
307-G-PMP4
307-G-PMP3
25 FT
T110
LC 5441
48"X24"

DATE 12-9-69

REV. DATE 3/10/77 TRACED, METRIC ADDED P.A.D.



Homework 1 review

1. To save pumping energy we can reduce one or more of the following:
   a. Flow
   b. Head
   c. Operating time

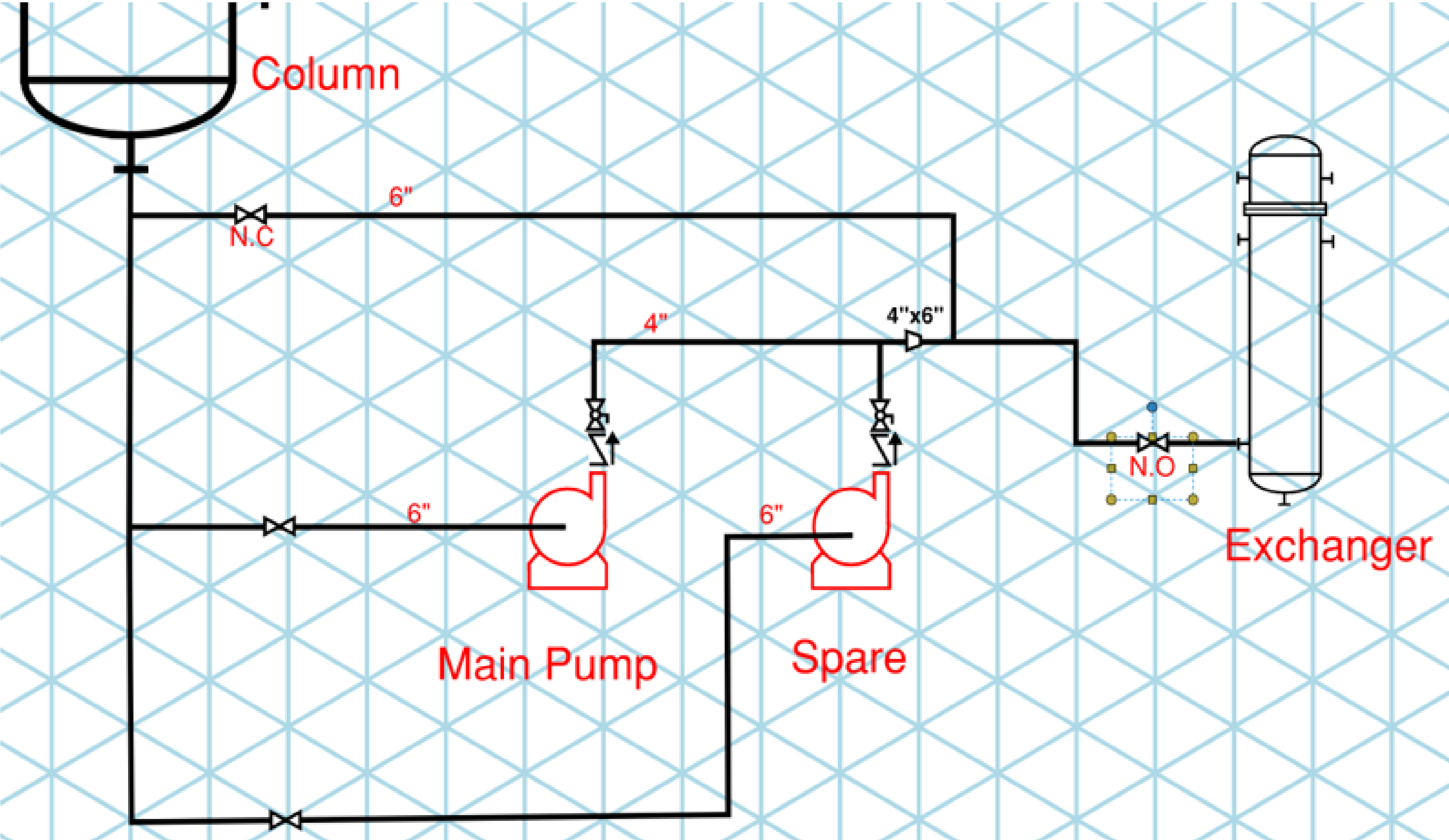
2. Is there flow control on the system? Does the required flow change? Do we sometimes over pressurize the header?

3. What in the motor voltage? Explore magnetic drives for 4160 volt systems.

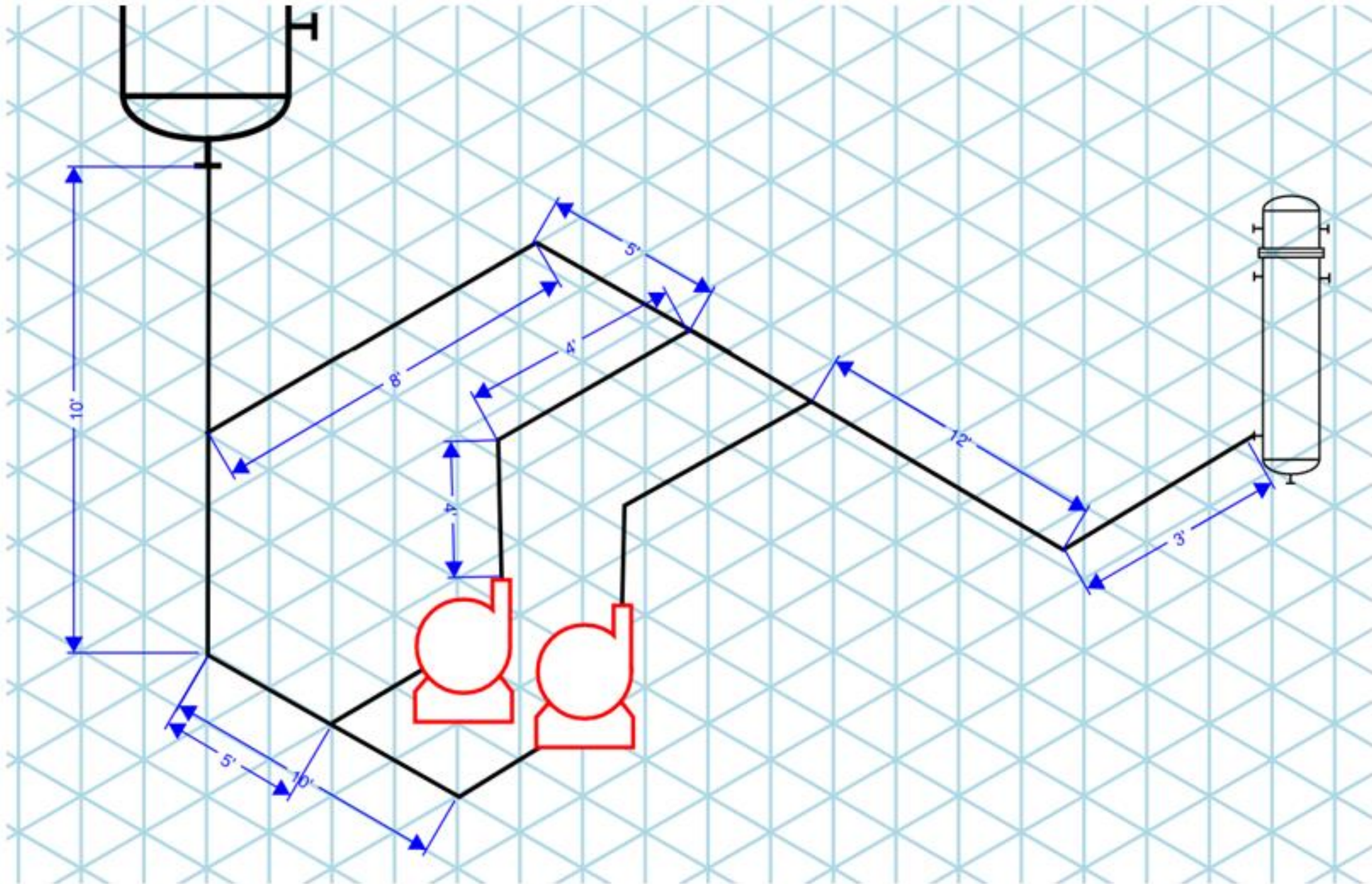
4. Cooling tower fan control?

5. Are you paying sewer charges on cooling tower makeup water?

Homework 1 review

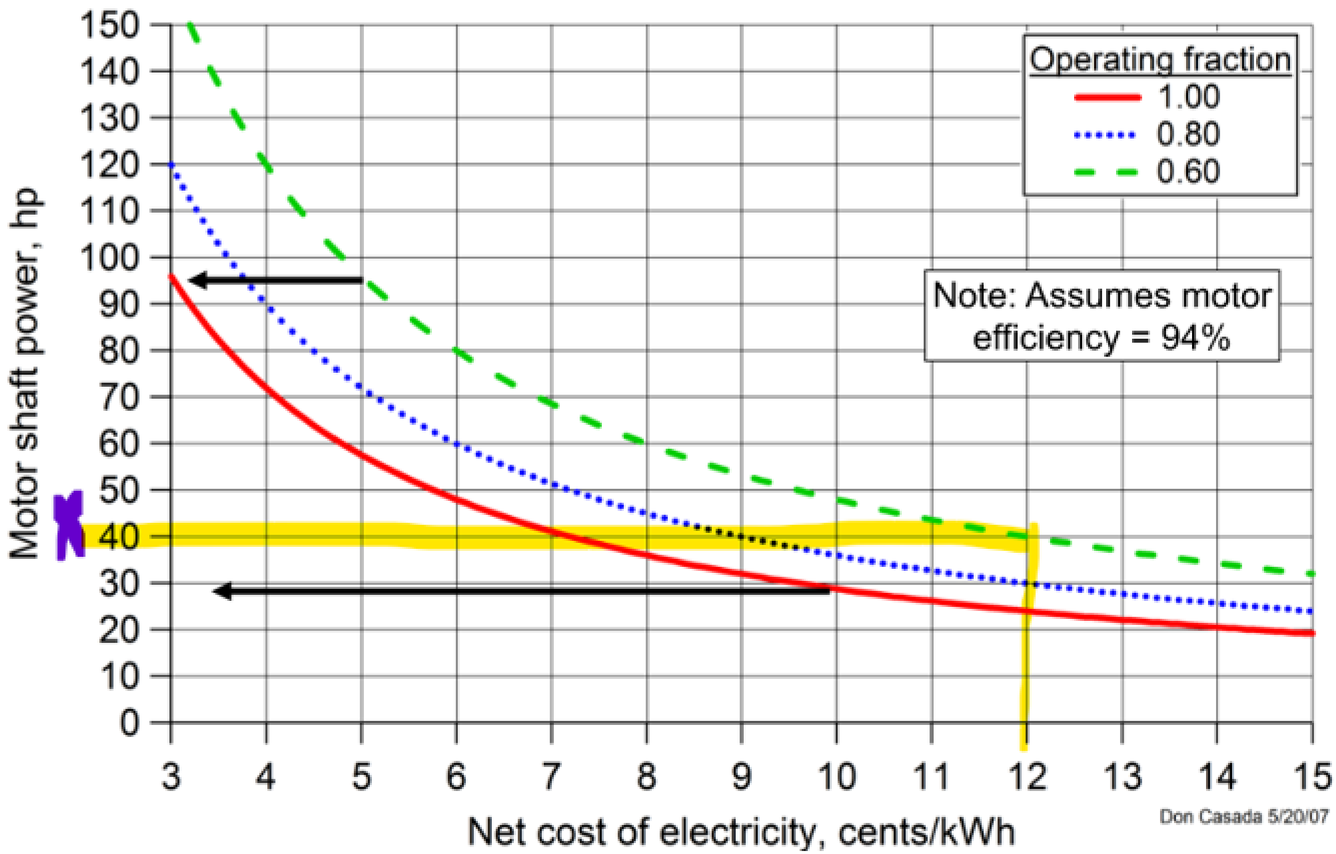


Homework 1 review



Homework 1 review

2. If a plant's net cost of electricity is $0.12/kWh and their pumps typically operate 60% of the time, what is the minimum motor size on a pump that will cost $20,000/year to operate? Hint: see slide 21. Answer: 40 HP



Homework 1 review

3. The flow control valve on a boiler feedwater pump typically operates 50% open with a flow rate of 200 gpm of water going to the boiler at 250 F. Plant engineers measure a pressure drop of 115 psi across the valve. If the pump efficiency is 72% and the motor efficiency is 92%, how many kW in motor input energy is being dropped across the valve?

Answer:

Density of water at 250 F is 58.82 lb_m/ft^3; the density of water at 60 F is 62.36 lb_m/ft^3; so, the specific gravity is 58.82/62.36 = 0.9432.

The head loss across the valve is: HL = (115 psi x 2.31)/0.9432 = 281.65 feet

The kW of pump motor power lost across the valve is:

kW = (200 gpm x 281.65 feet x 0.9432 x 0.746 kW/hp)/(3960 x 0.72 x 0.92) = 15.11 kW

Homework 1 review

4. If the boiler feedwater pump in #3 above operates all the time and the cost of electrical energy is $0.065/kWh and the demand charge is $14.75/kW-mo, how much does the energy loss across the throttled valve cost the plant per year?

Answer:

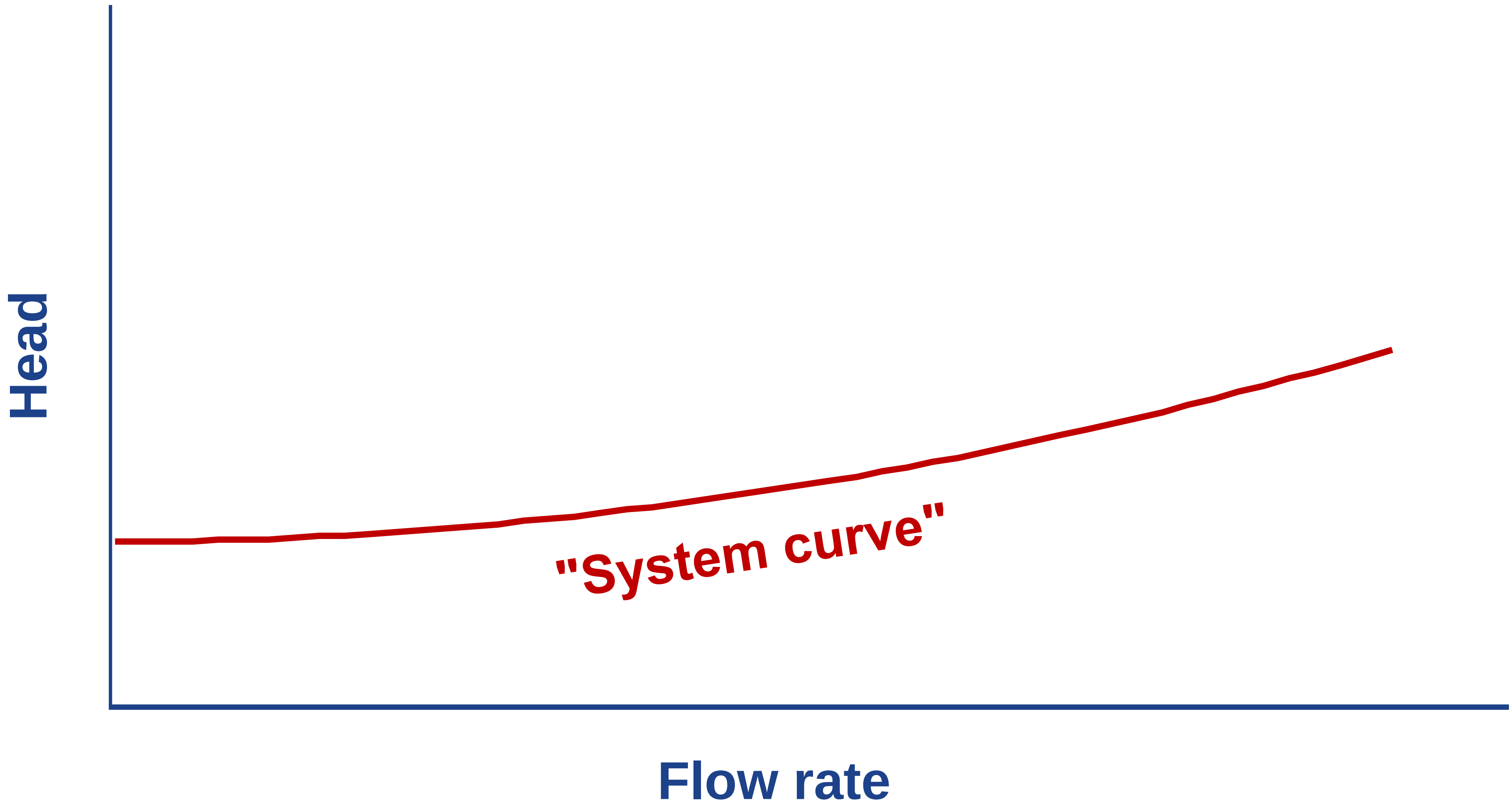
Energy Cost = (15.11 kW x 8760 hy/yr x $0.065/kWh) = $8,604/yr

Demand Cost = (15.11 kW x $14.75/kW x 12 mo/yr) = $2,674/yr

Total Annual Cost = $11,278/yr

Pump Curves & System Curves

Let's start with the system curve



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Energy is required to overcome two types of resistance to flow in systems

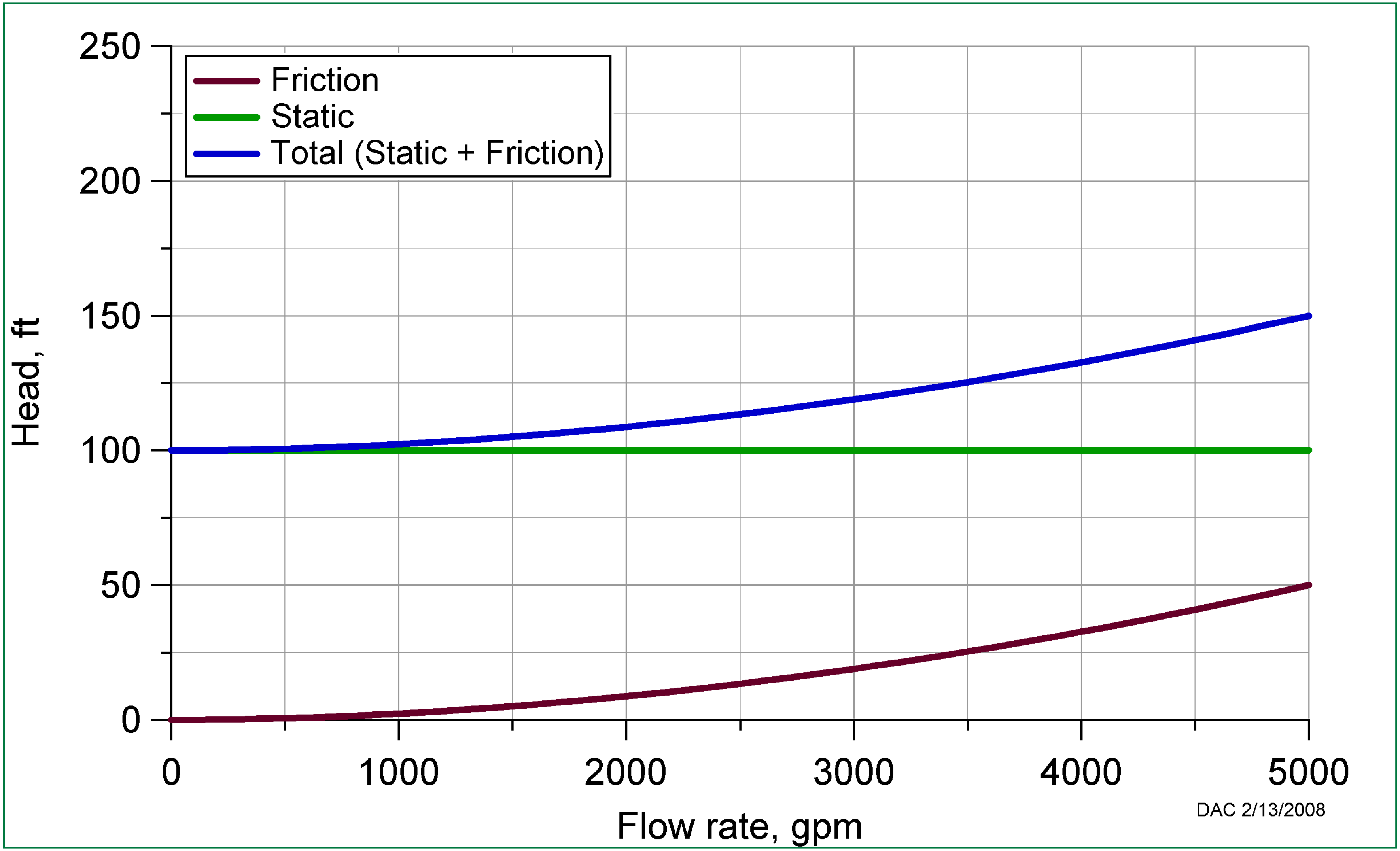
- Static head (independent of flow rate)
- Friction head (dependent on the flow rate)

$$H_{total} = H_{static} + H_{friction}$$

System curves show the two fundamental components - the static head and the frictional head

- Static head refers to the change in elevation from the suction to the discharge
- Tank over-pressures must be included in calculations
- This is basically the change in potential energy of fluid as it moves from the suction tank to the discharge tank
- Closed systems typically do not have static head
- Static heads can be positive, negative or zero

System curves are made up of two fundamental components - static head and frictional head



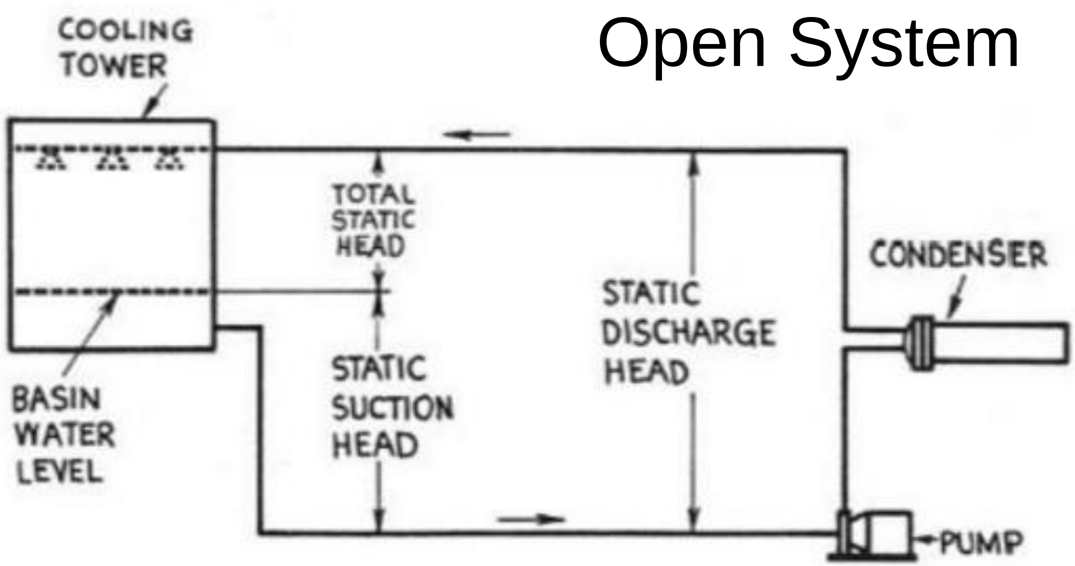
Poll question

- Do closed systems typically have any static head?
  - A. Yes
  - B. No

Open and Closed Piping Systems

- Piping systems for water transmission can be considered in two general categories:
  - Open systems
  - Closed or sealed systems
- Open systems are piping circuits, pumped or gravity circulated, that are open to the atmosphere at some point
- Closed systems are designed and installed as hermetically sealed systems that offer several advantages

Open System



Poll question

- Based on the results of your prescreening efforts, are the pumping systems in your plant:
  - Open
  - Closed
  - Both
  - Don’t know

System Curves

System curves display the total head required to move different amounts of flow through the piping system

System curve equations:

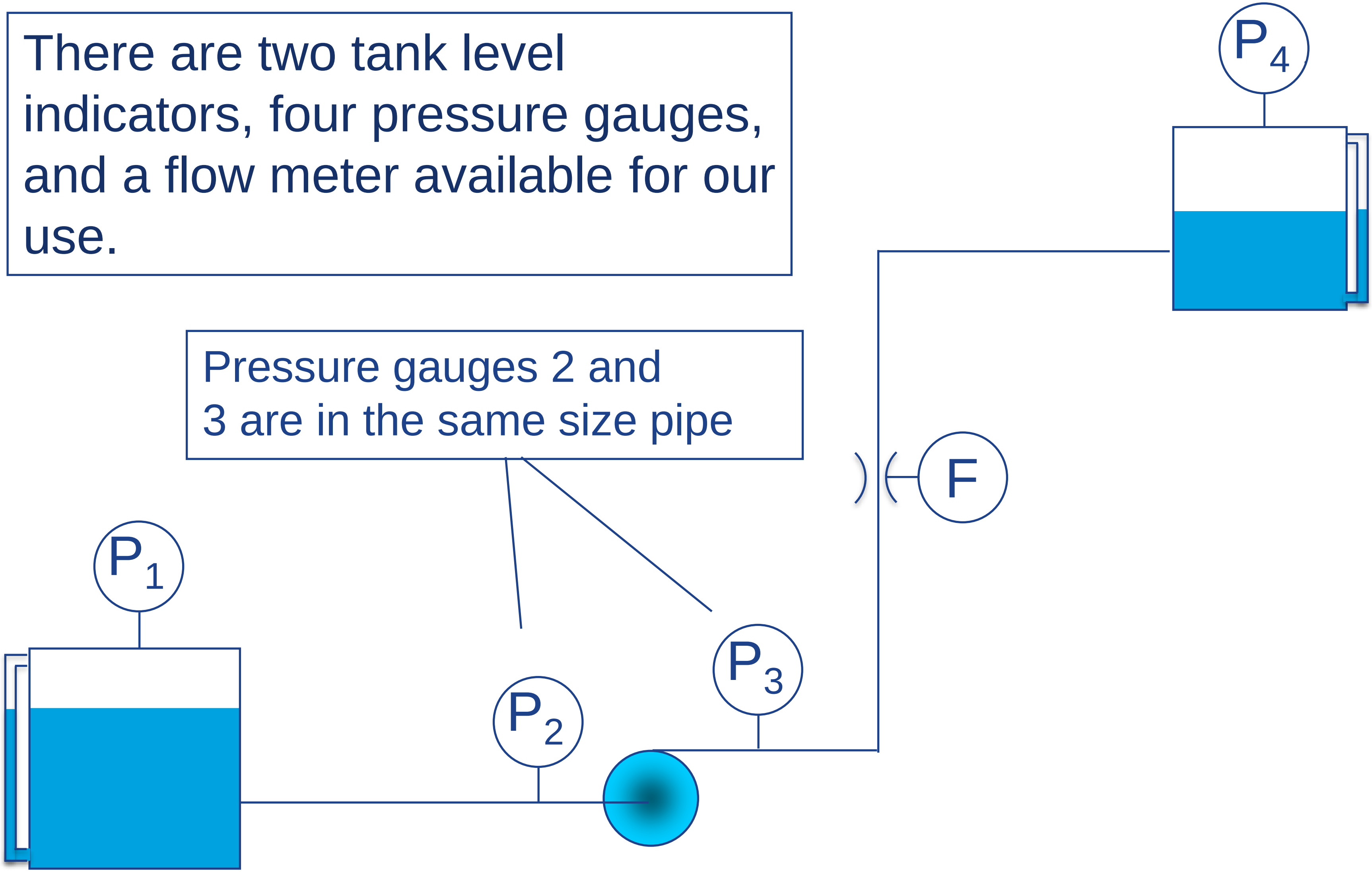
$$H_{total} = H_{static} + k'Q^{1.9}$$

Closed piping systems have zero static head

Open piping systems generally have some static head

We'll use this system as an example: water is pumped from one tank to another

There are two tank level indicators, four pressure gauges, and a flow meter available for our use.



Nobody sells static or frictional head meters

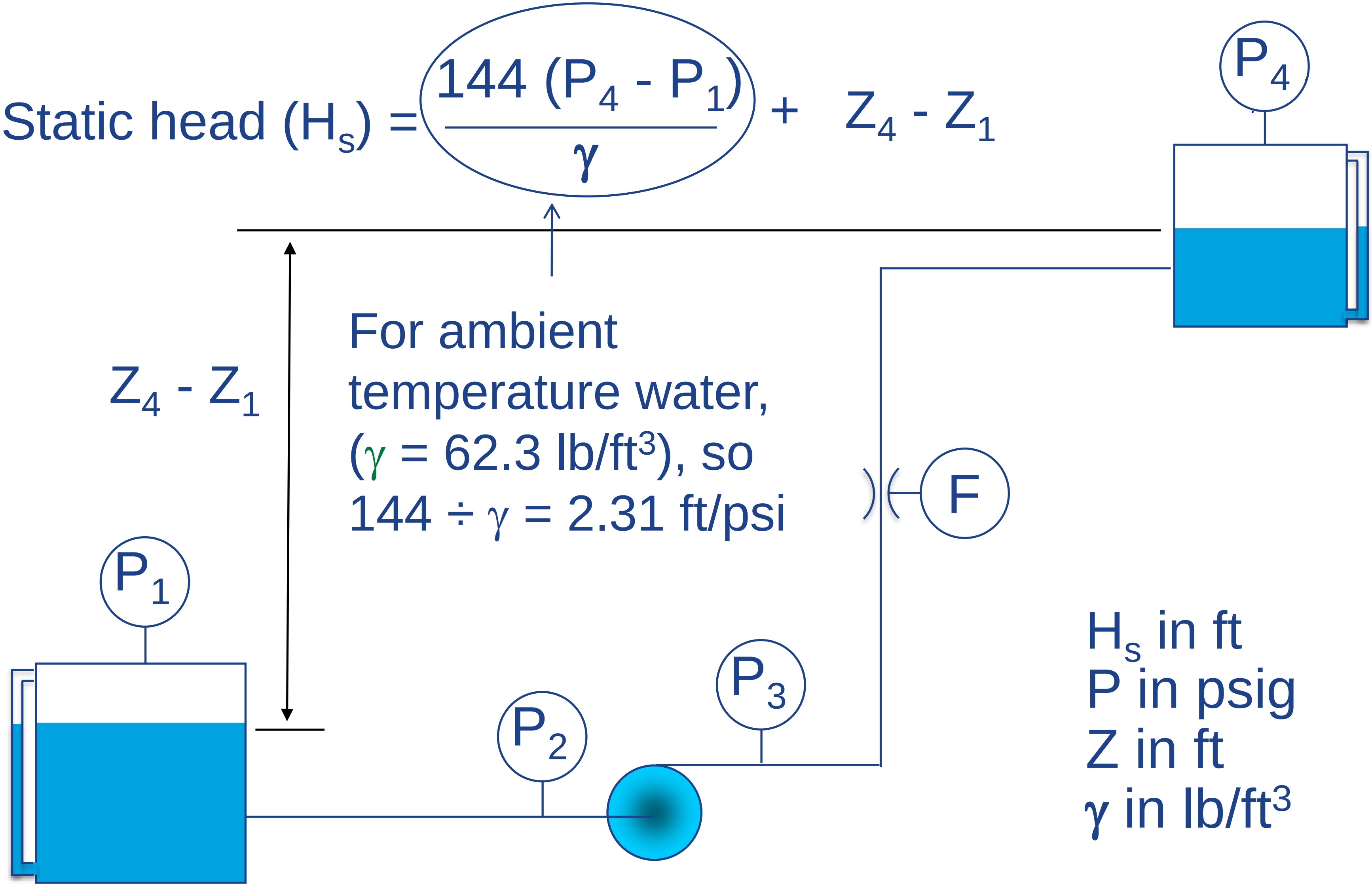
Fortunately, there's a back door, and there are only two pieces of information needed to unlock it:

1) The static head, which we can estimate, and
2) The total head at a single flow rate, which we can measure

The static head is made up of elevation, and sometimes pressure components

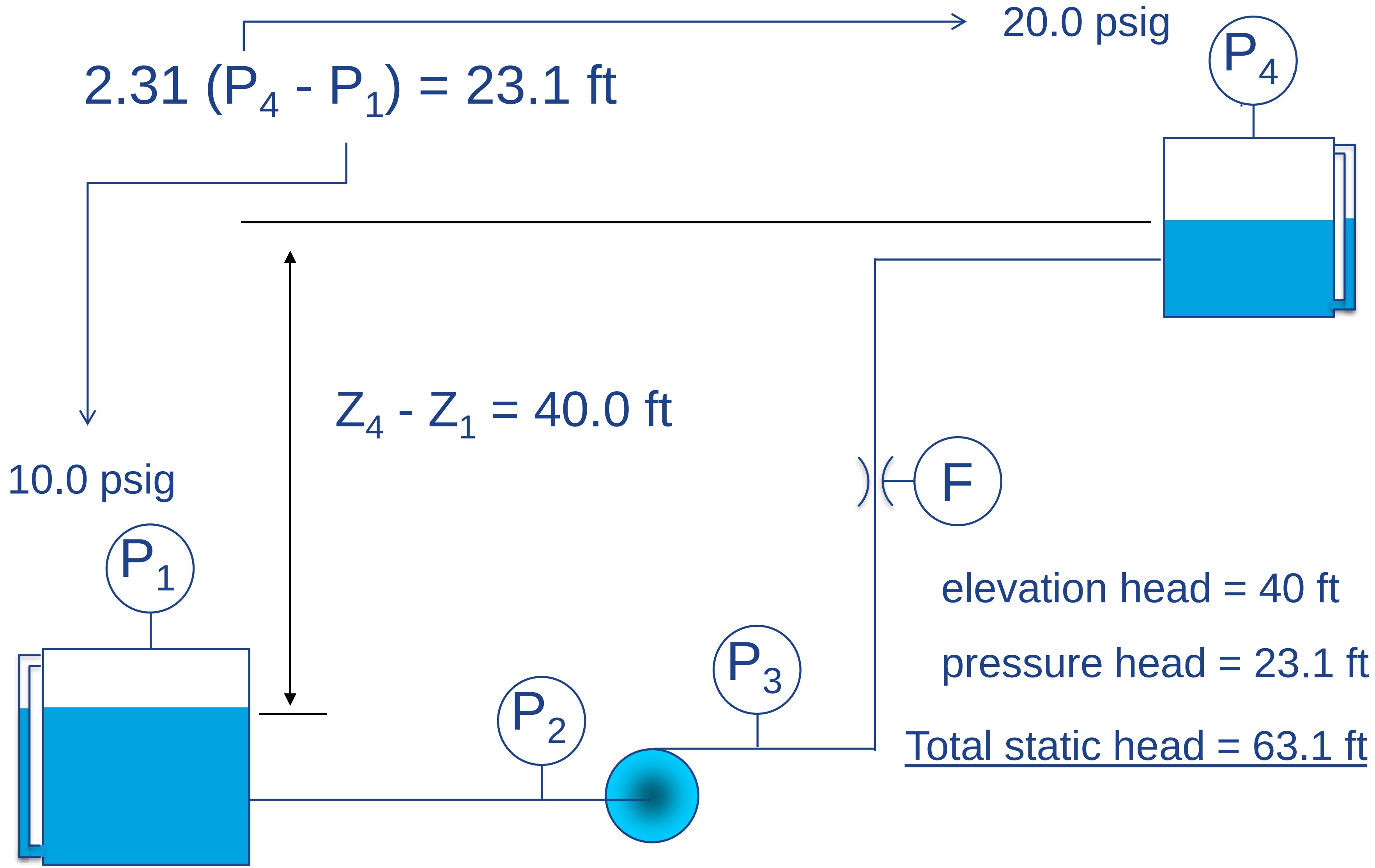
$$\text{Static head } (H_s) = \frac{144\,(P_4 - P_1)}{\gamma} + Z_4 - Z_1$$

For ambient temperature water, (γ = 62.3 lb/ft^3), so $144 \div \gamma$ = 2.31 ft/psi



H_s in ft
P in psig
Z in ft
γ in lb/ft^3

The static head is made up of elevation, and sometimes pressure components



Now that we've got the static head estimated, we can go after the frictional head

Calculating the frictional head at one flow rate

$$H_{tot} = H_s + H_f \qquad \text{or}$$

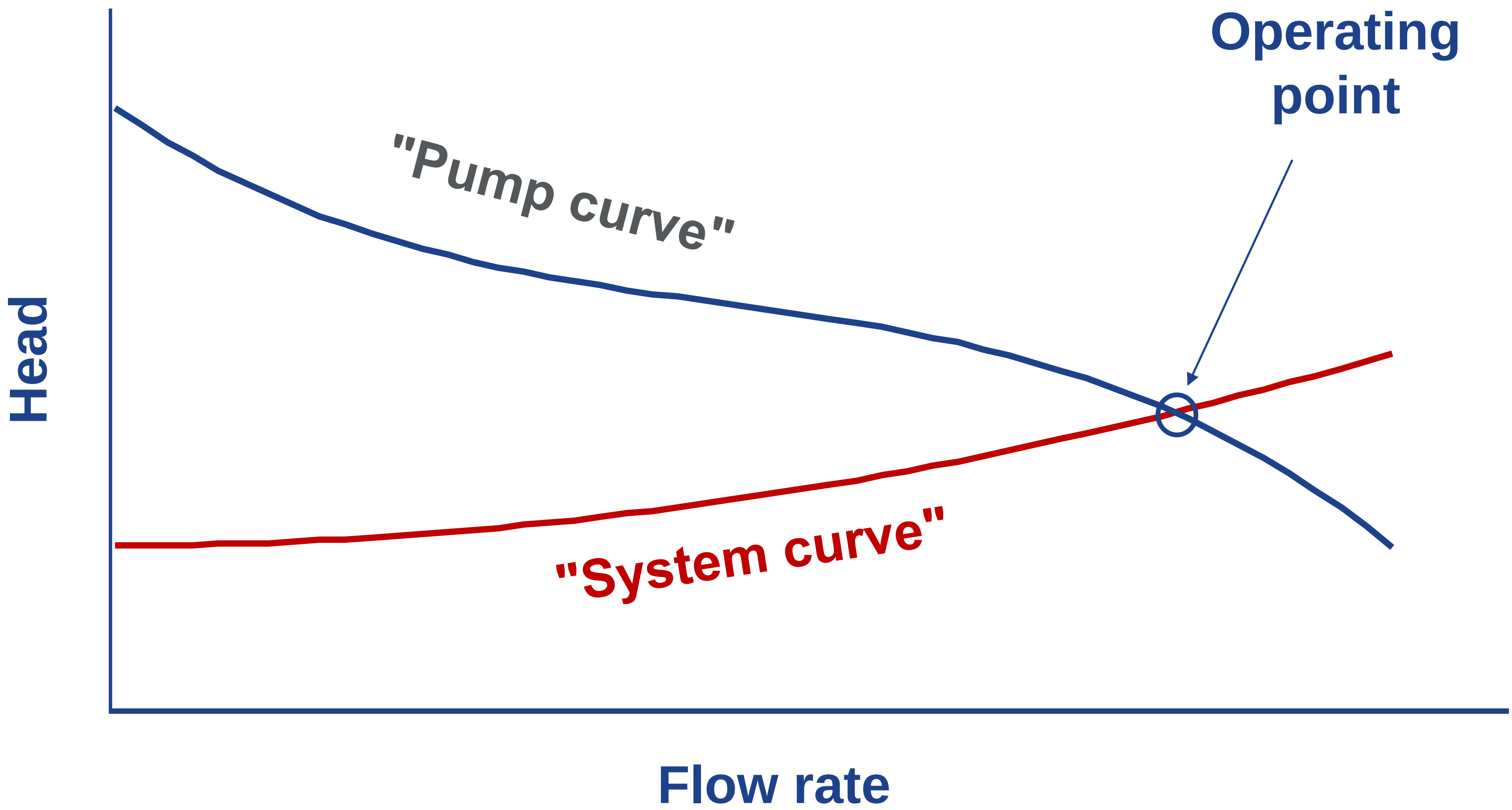
$$H_f = H_{tot} - H_s$$

So, a single point measurement of flow and total head, along with knowledge of the static head, gives us the frictional head at that flow rate

Our example system - how can we get the total head (H_{tot})?

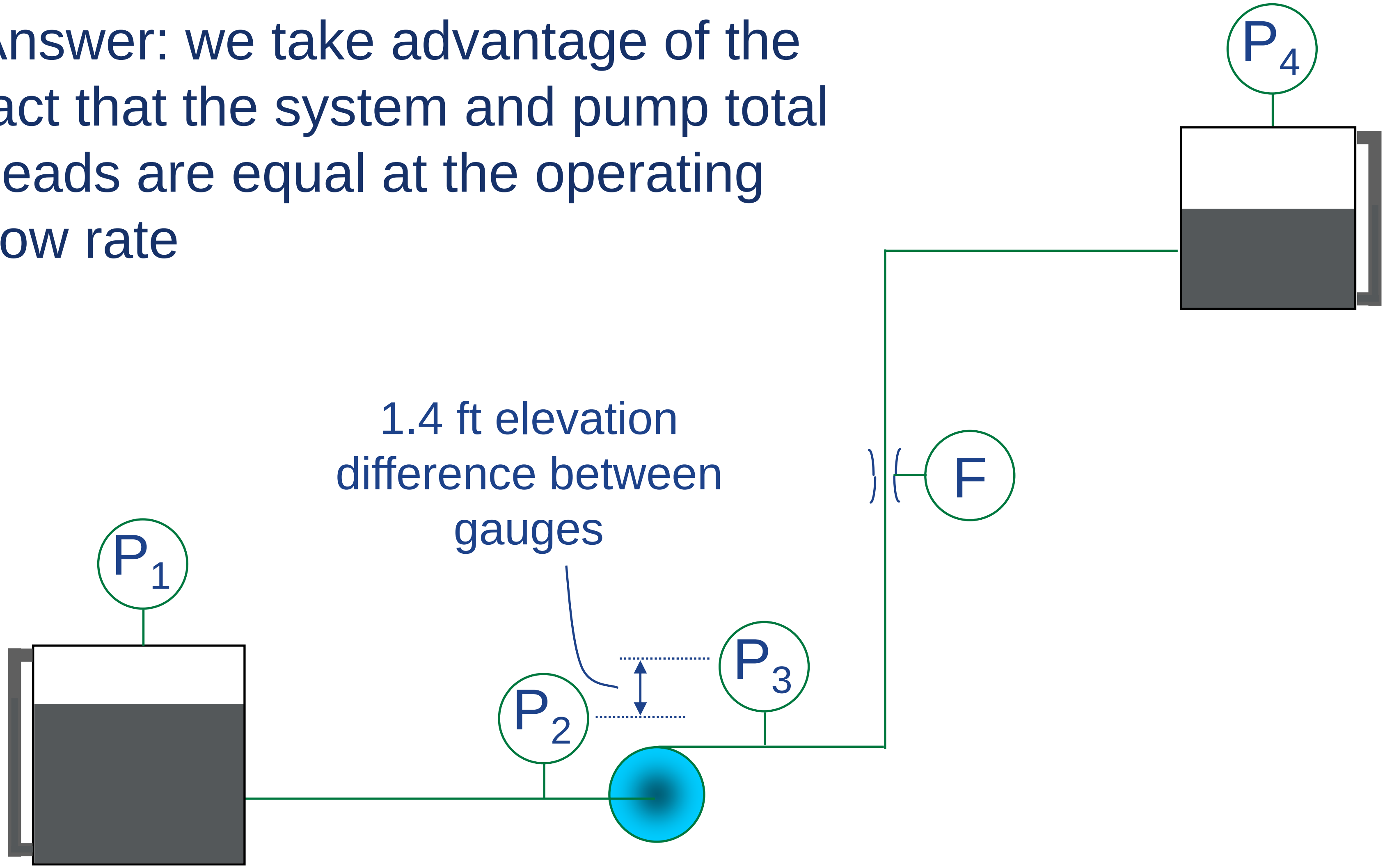
We take advantage of one inviolable fact for centrifugal pumping systems

The system operating point is at the intersection of the pump and system head-capacity curves



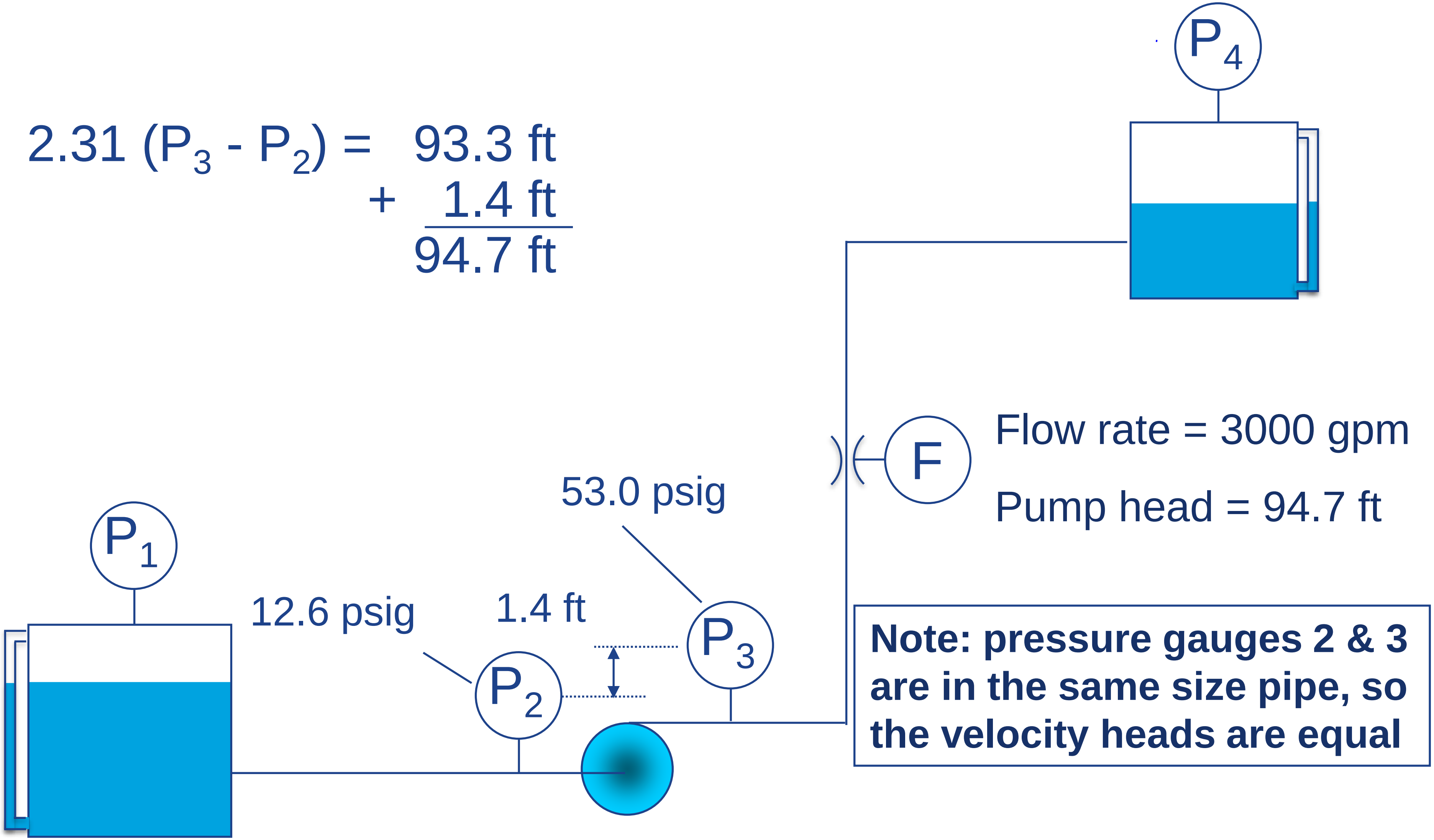
and we can measure the pump head

Answer: we take advantage of the fact that the system and pump total heads are equal at the operating flow rate



The system total head at any flow rate is the same thing as the pump total head - so we measure the pump head

$$2.31\,(P_3 - P_2) = 93.3\text{ ft} + 1.4\text{ ft} = 94.7\text{ ft}$$



Note: pressure gauges 2 & 3 are in the same size pipe, so the velocity heads are equal

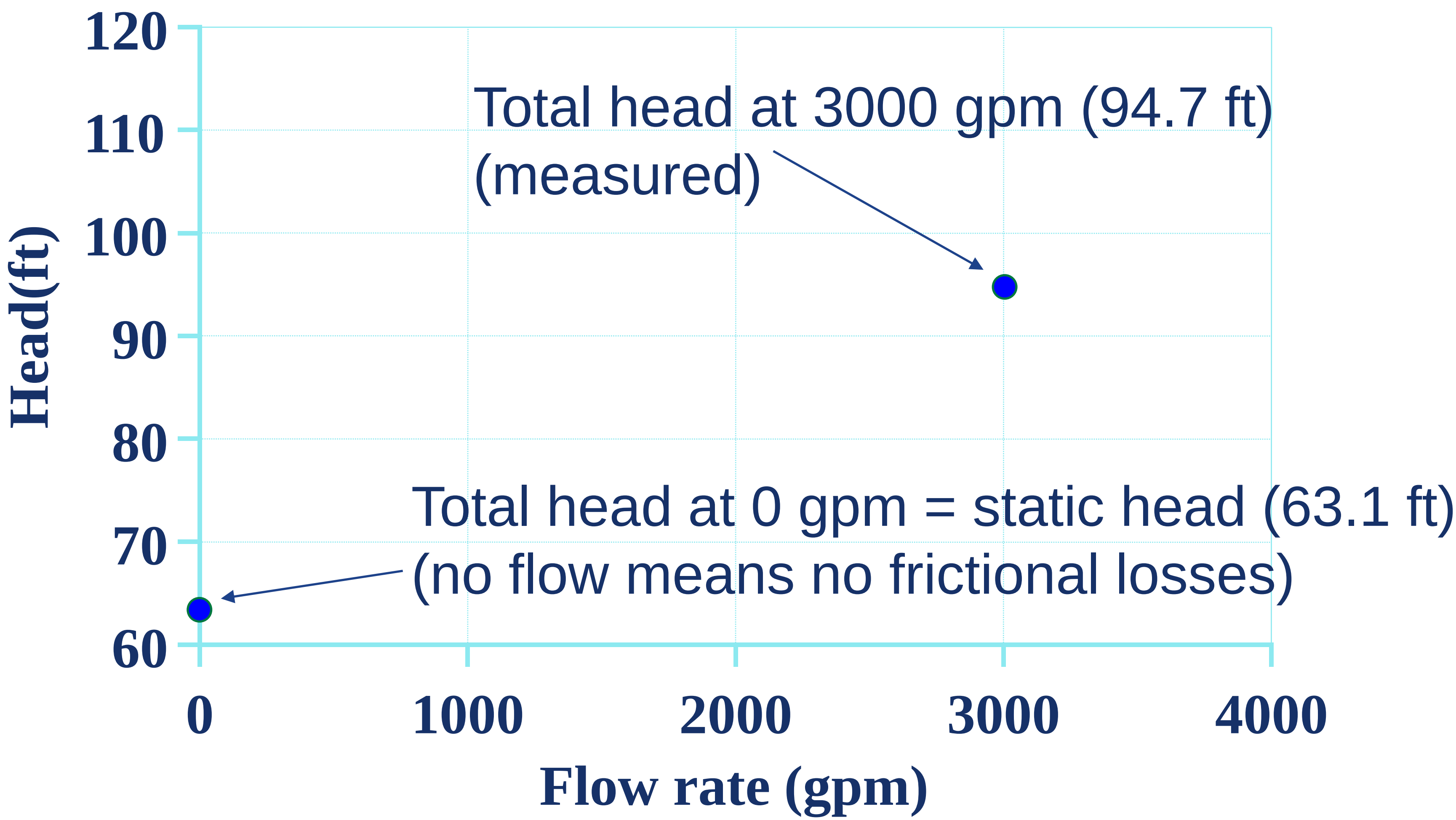
Points to remember……

- For this example, it was assumed that the suction and discharge pipe diameters were identical. In the majority of cases, the pump discharge flange is smaller than the suction flange, typically one standard pipe size down. For example, a pump with a 12-inch suction might have a 10-inch discharge.

- But it is also common to find expanders/reducers in pump suction & discharge lines. The bottom line is that when taking pressure measurements, pay attention to the physical dimensions. Also note whether there are components, such as a discharge check valve, between the pump and the measurement point that create head losses.

- It is particularly important in relatively low head pumps to pay attention to velocity and loss component considerations, since they may represent a significant part of the total pump head.

We have two points on the system curve; now we just have to figure out how to connect them



A little algebra….

$H_2 = H_s + KQ_2^2$

$H_1 = H_s + KQ_1^2$

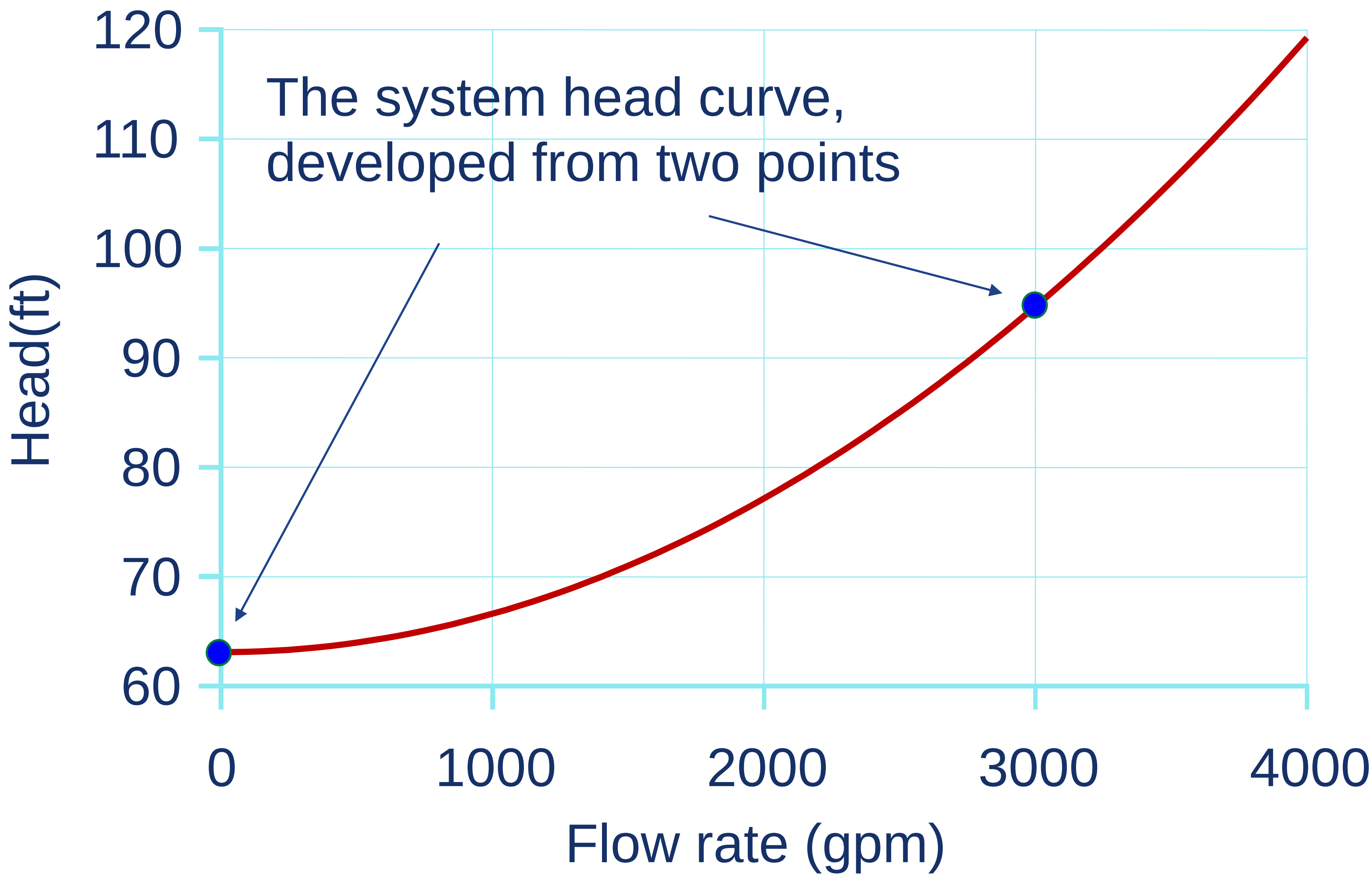
Subtracting yields

$H_2 - H_1 = K(Q_2^2 - Q_1^2)$, so

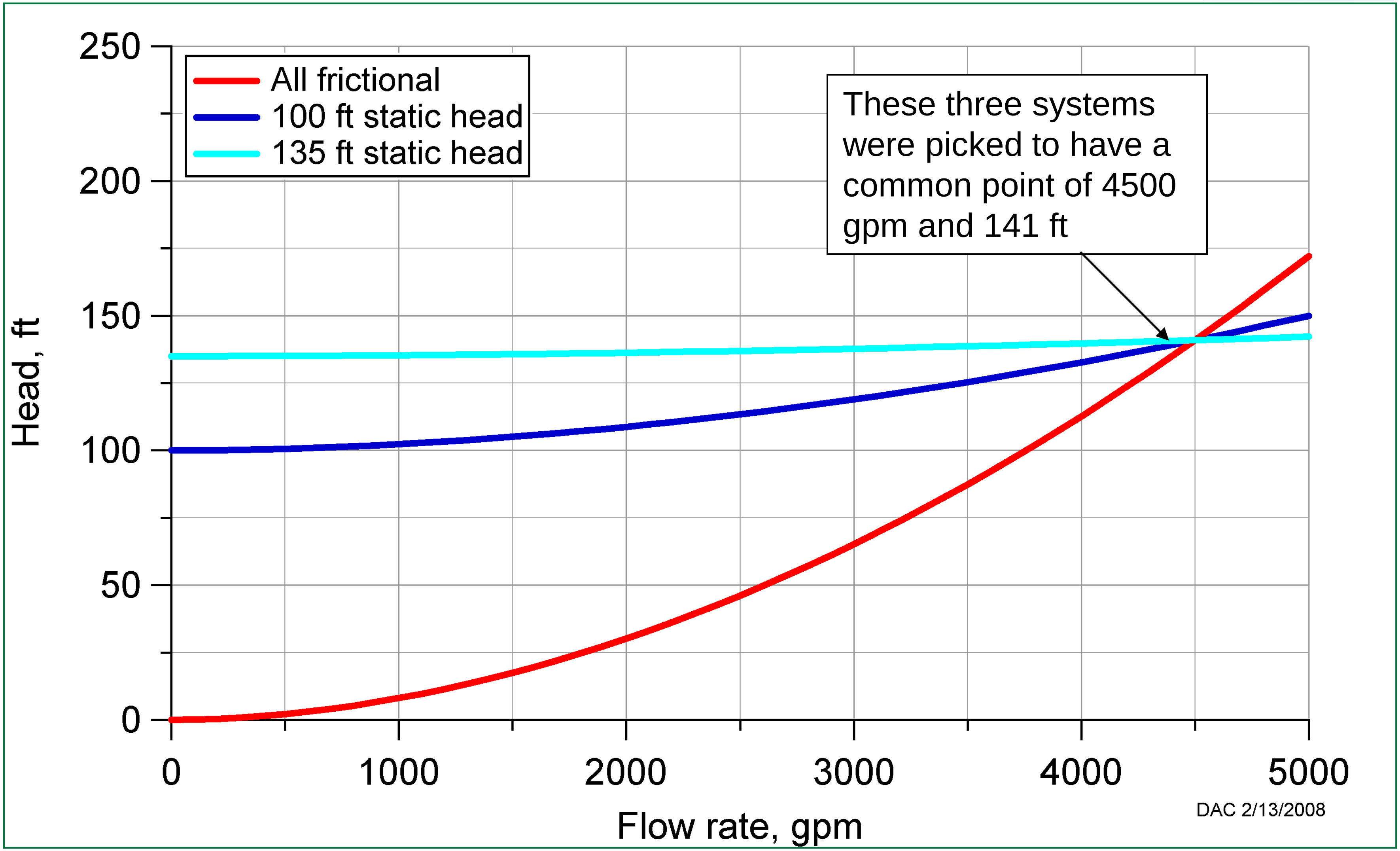
$$K = \frac{(H_2 - H_1)}{(Q_2^2 - Q_1^2)} \quad \text{and } H_s = H_1 - KQ_1^2$$

Although the static head is known in this case, any two flow and head combinations will suffice.

The resultant system curve



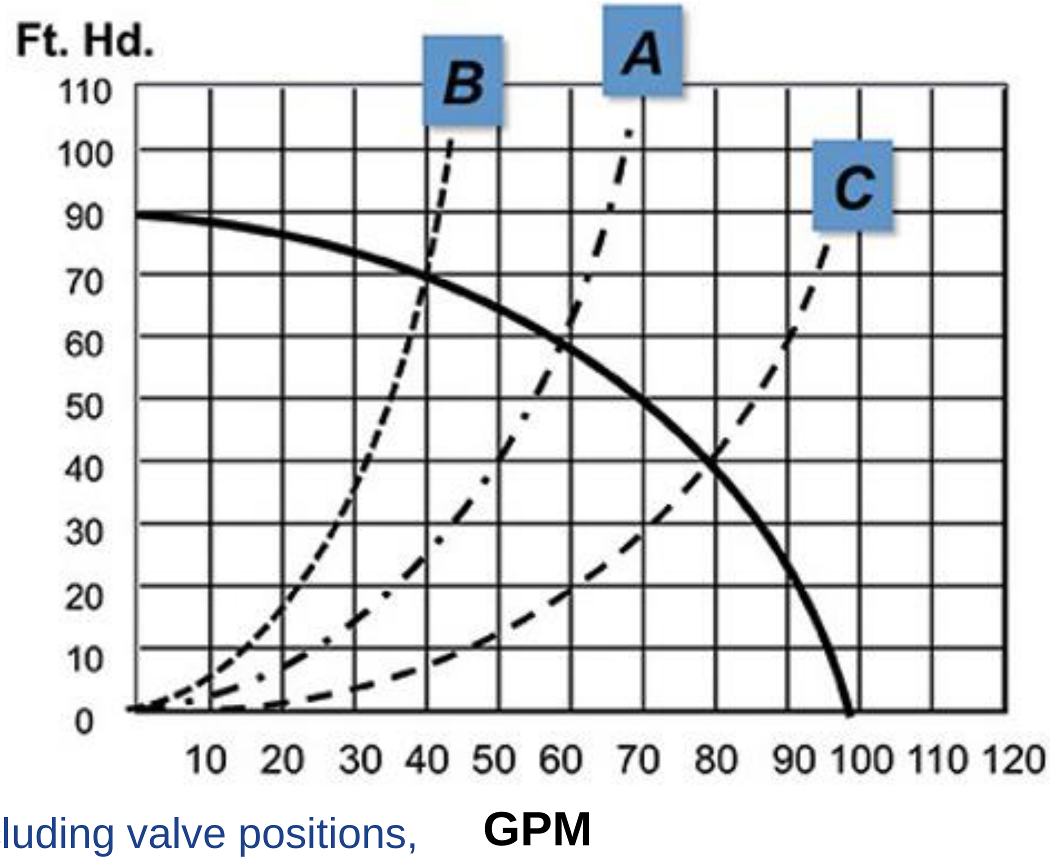
System head curves for three different systems



NOTE: These are three different systems

Where do system curves come from?

- New systems
  - Design calculations and/or hydraulic models
- Existing systems
  - Hydraulic models (lots of time and tolerance are handy assets for this)
  - Field measurements and basic layout information

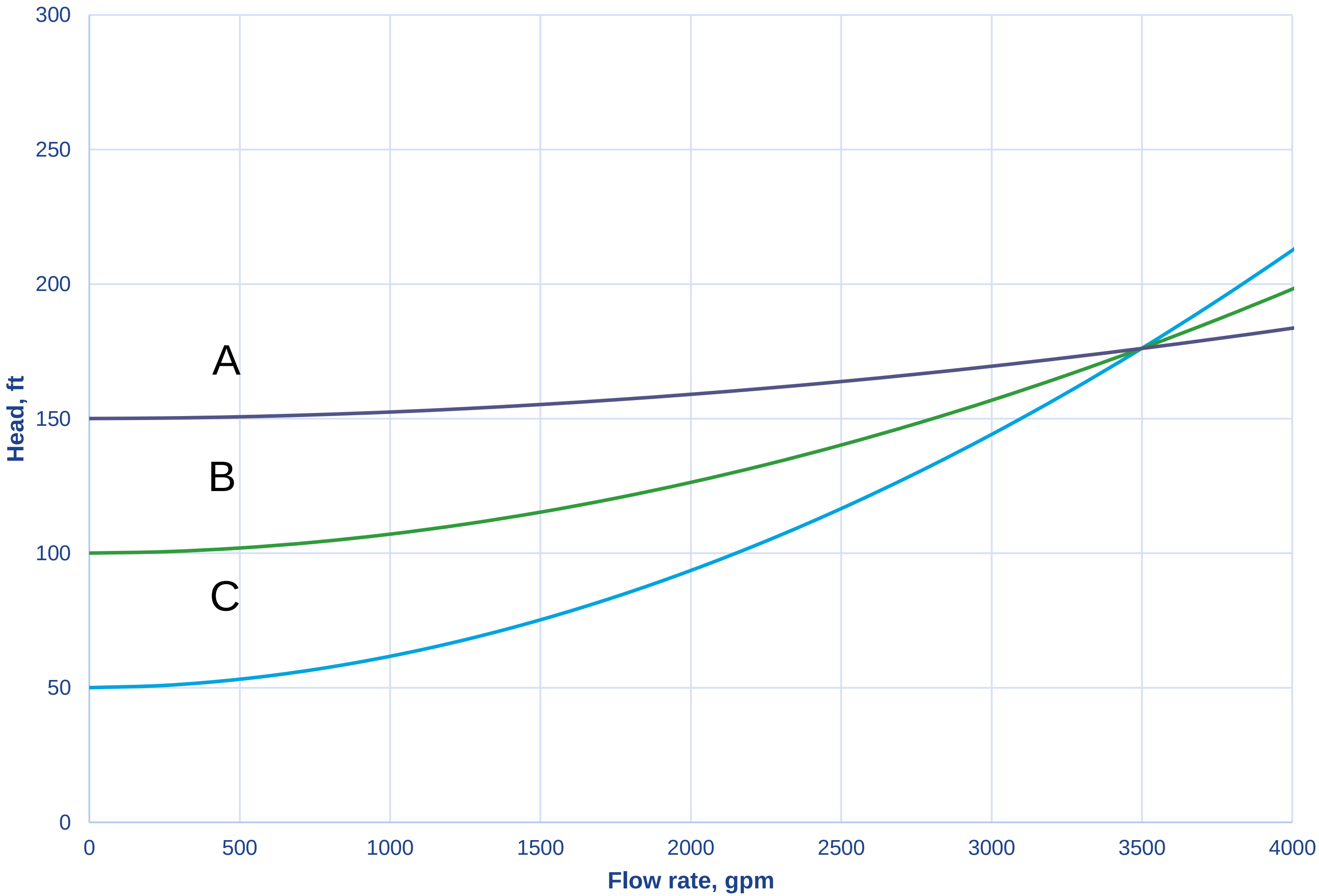


NOTES:

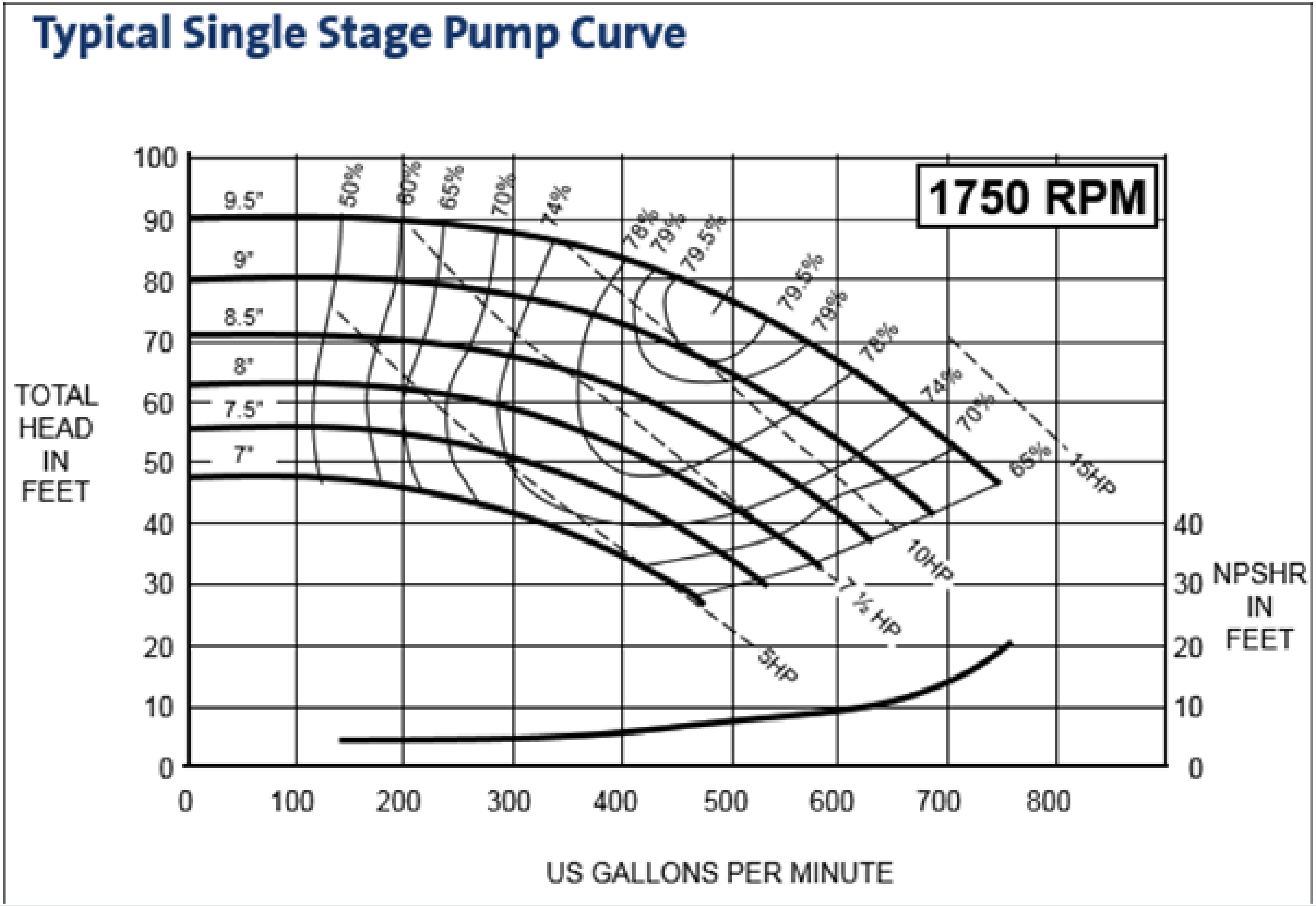
1. If anything in the system changes – including valve positions, flow paths, tank levels, etc., the system curve will change.
2. For systems with multiple suction sources and/or discharge receivers that have different amounts of static head, the system curve will have a more complex characteristic.

Poll question

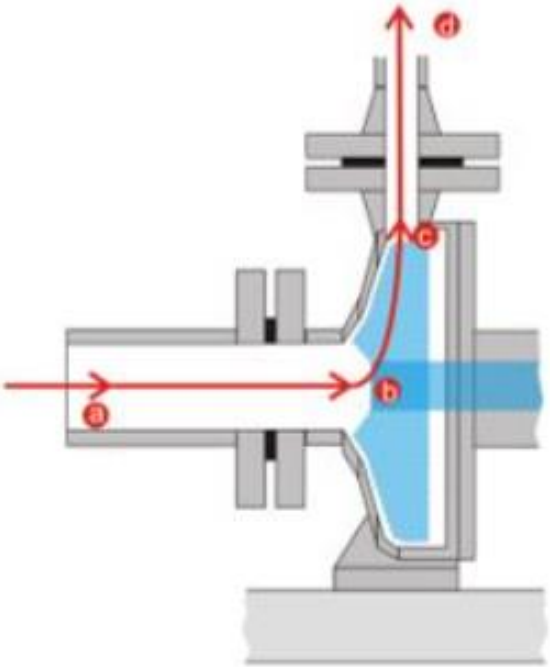
Which system has the most frictional head?

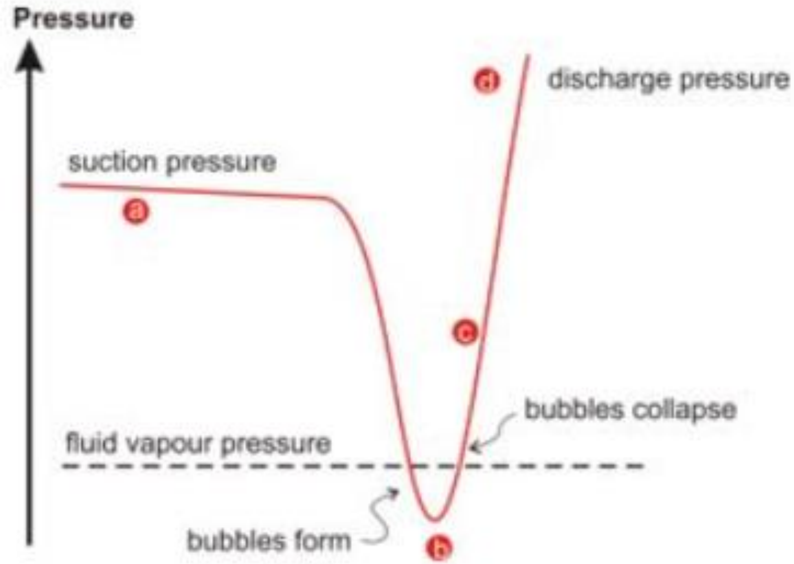


Pump performance characteristics



Pump Cavitation – Boil water within the pump





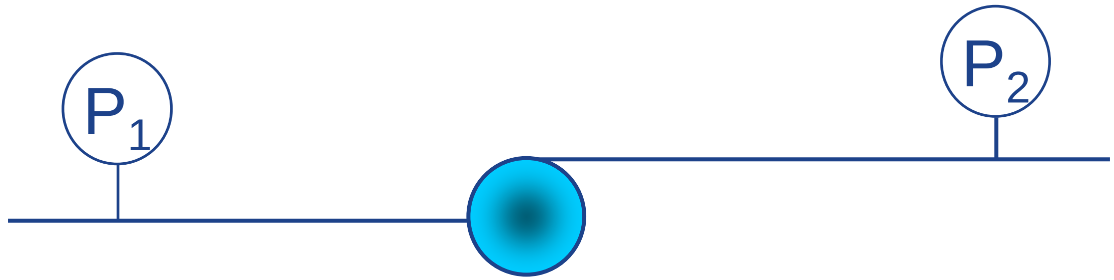
NPSHR and NPSHA

- NPSHA stands for Net Positive Suction AVAILABLE and NPSHR stands for Net Positive Suction Head REQUIRED.
- What is the difference between NPSHA and NPSHR? Well, firstly NPSH is a measure of the pressure experienced by the fluid at the suction of the pump. This is always quoted in feet rather than as a pressure because head is a fluid independent property.
- NPSHA (available) is a property of the system and is calculated by the system designer giving a value of the pressure on the suction side of the pump.
- NPSHR (required) is a property of the pump. This is calculated by the manufacturer as the point where cavitation occurs. (Published curves represent a 3% reduction in pump performance.)

There are four types of performance curves that are used to characterize pumps

- Head
- Shaft power
- Efficiency
- Net positive suction head required (NPSHR)

The Bernoulli relationship is slightly modified to define the pump head



$$\frac{V_1^2}{2g} + \frac{2.31\ P_1}{s.g.} + Z_1 + \mathrm{H_{pump}} = \frac{V_2^2}{2g} + \frac{2.31\ P_2}{s.g.} + Z_2$$

or

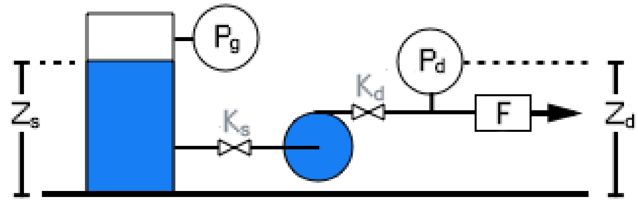
$$\mathrm{H_{pump}} = \left(\frac{V_2^2}{2g} + \frac{2.31\ P_2}{s.g.} + Z_2\right) - \left(\frac{V_1^2}{2g} + \frac{2.31\ P_1}{s.g.} + Z_1\right)$$

$\mathrm{H_{pump}}$ = Pump head at a given flow rate

MEASUR Pump Head Calculator

PUMP HEAD TOOL

Suction tank elevation | Suction gauge elevation



K_s represents all suction losses from the tank to the pump

K_d represents all discharge losses from the pump to the gauge P_d

Fluid Specific Gravity	1.002
Flow Rate	3000 gpm

Suction

Pipe diameter (ID)	12 in
Tank gas overpressure (P_g)	0 psi
Tank fluid surface elevation (Z_s)	10 ft
Line loss coefficients (K_s)	0.5

Discharge

Pipe diameter (ID)	12 in
Gauge pressure (P_d)	124 psi
Gauge elevation (Z_d)	10 ft
Line loss coefficients (K_d)	1

Generate Example | Reset Data

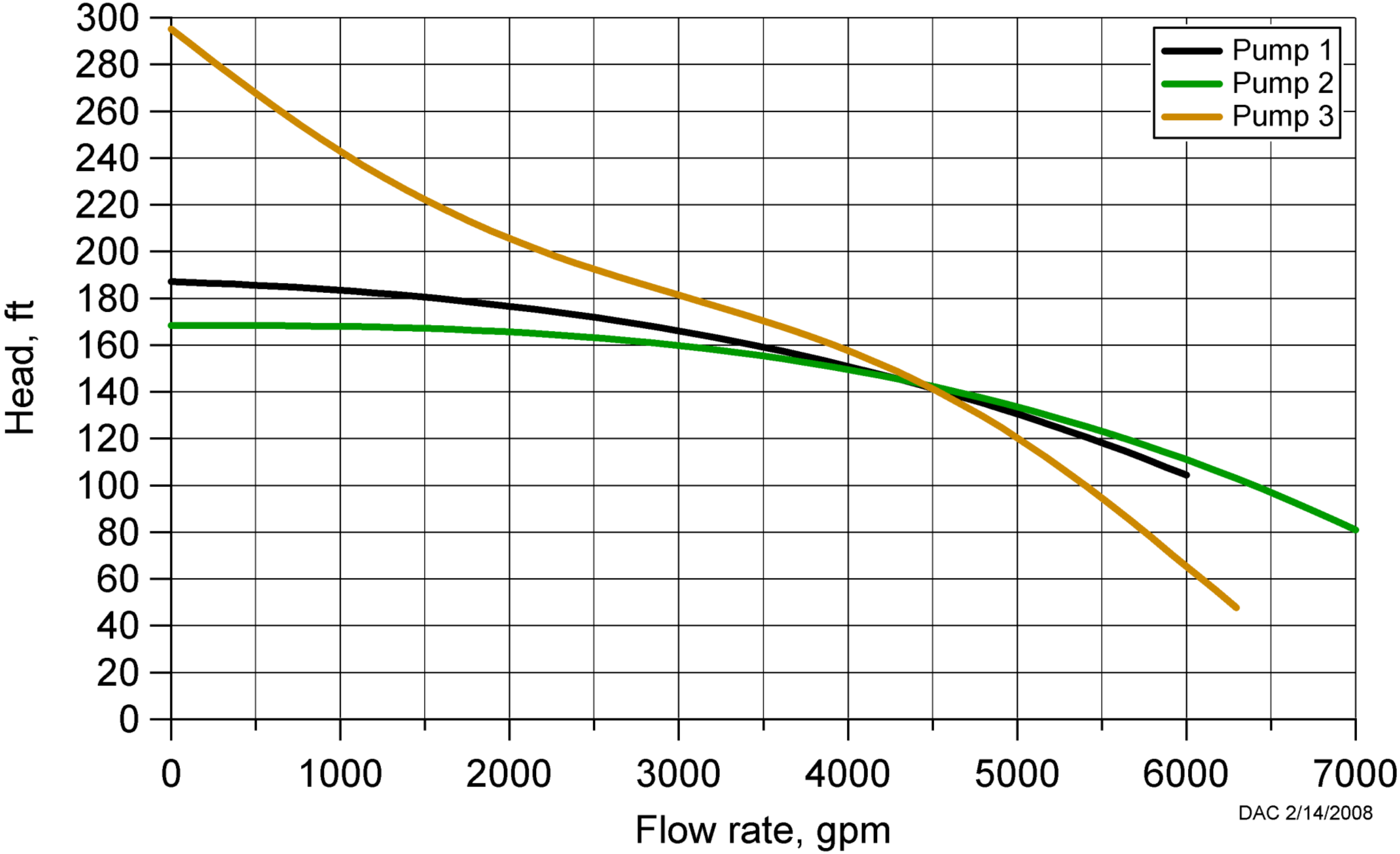
MEASUR Pump Head Calculator Results

RESULTS	HELP

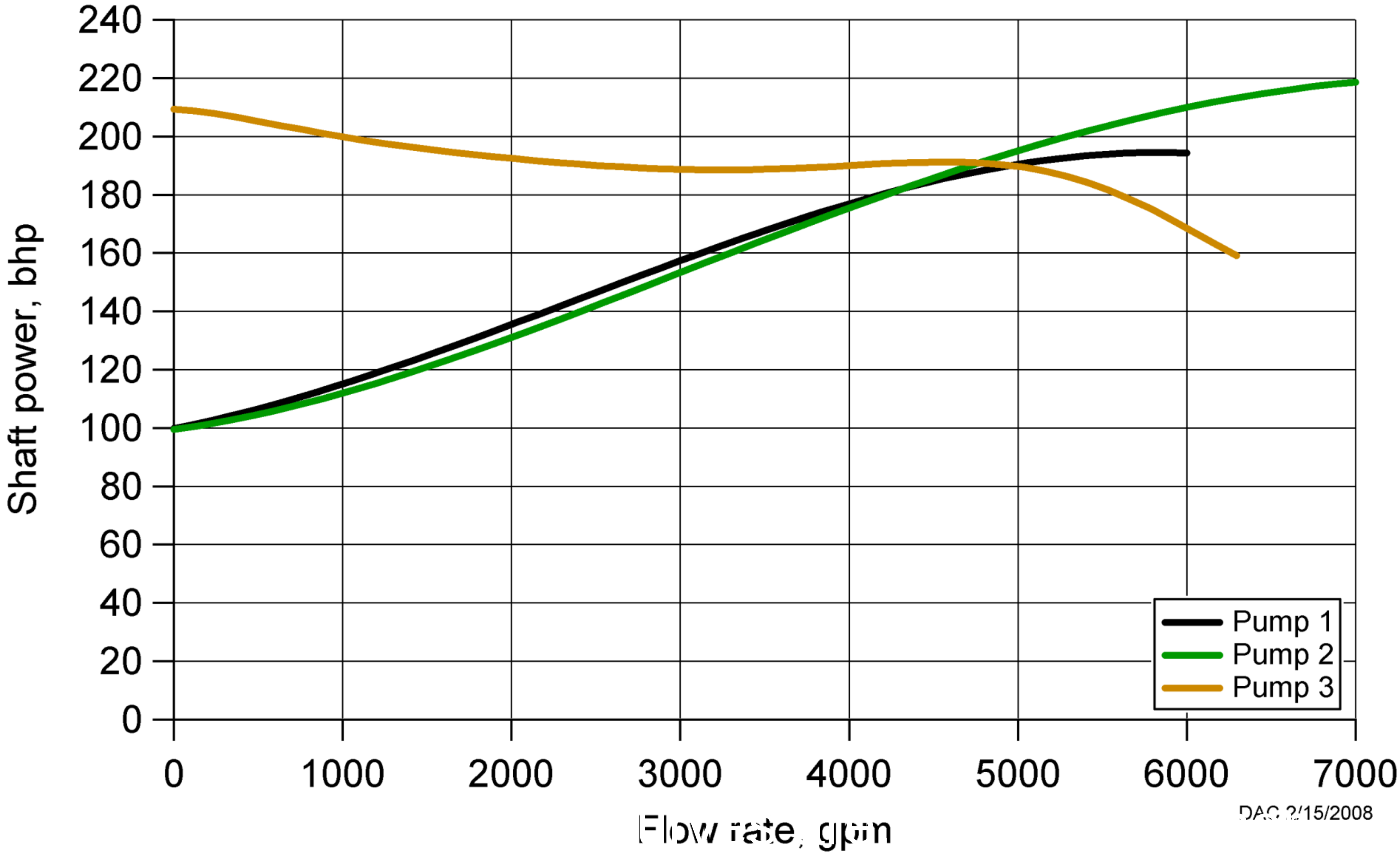
Result Data

Differential Elevation Head	0.0 ft
Differential Pressure Head	285.97 ft
Differential Velocity Head	1.13 ft
Estimated Suction Friction Head	0.56 ft
Discharge Friction Head	1.13 ft
Pump Head	288.78 ft

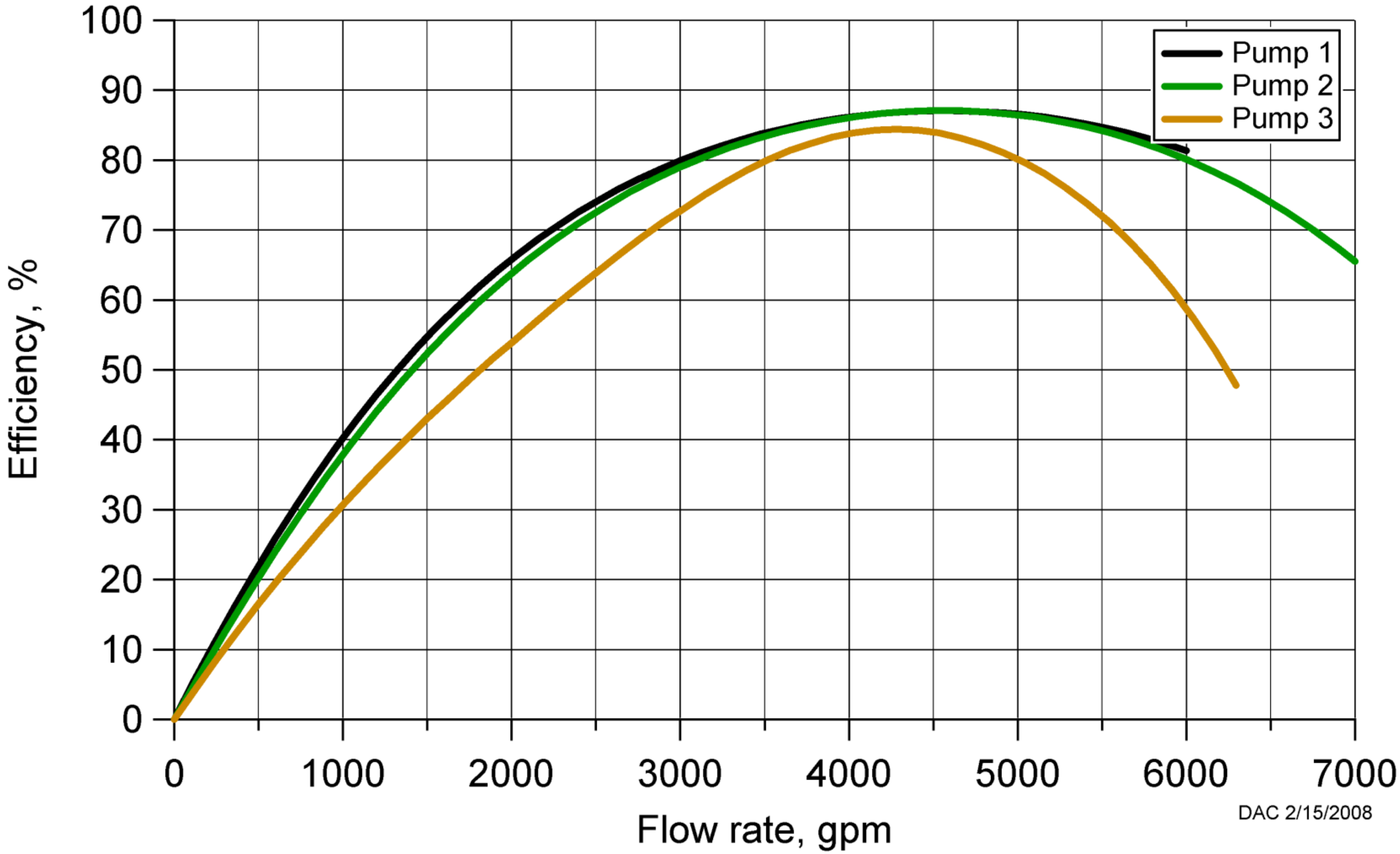
Pump curve shapes vary:
Head curves for three pump designs



Shaft power curves for the three pumps



Efficiency curves for the three pumps



Pump efficiency = fluid power output / shaft power input

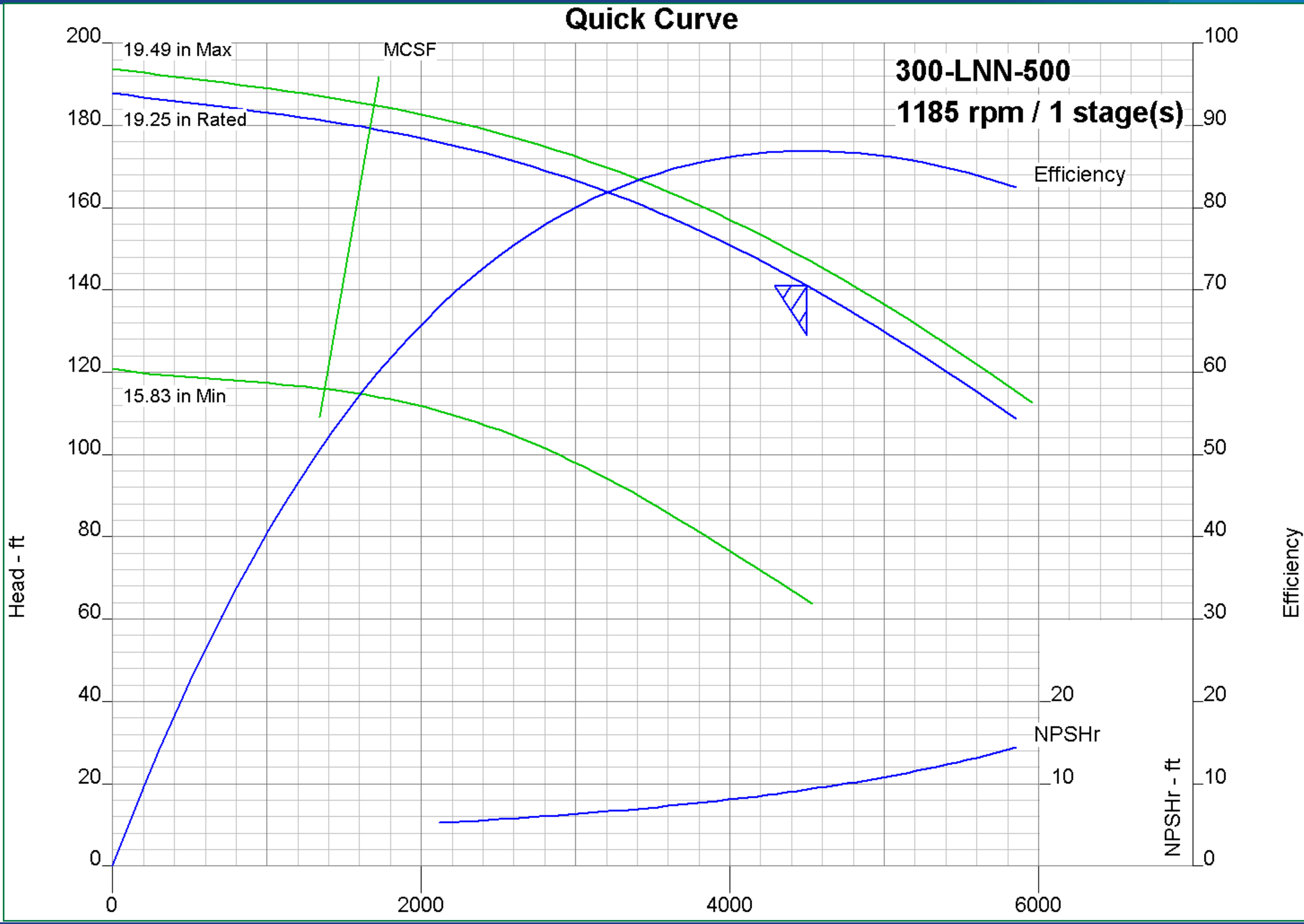
= gpm x ft x s.g. / (39.60 x shaft hp) for efficiency expressed in %

Pump manufacturers provide performance curves in a variety of ways
(Following examples are from pump mfr. performance curve software programs or electronic curves)

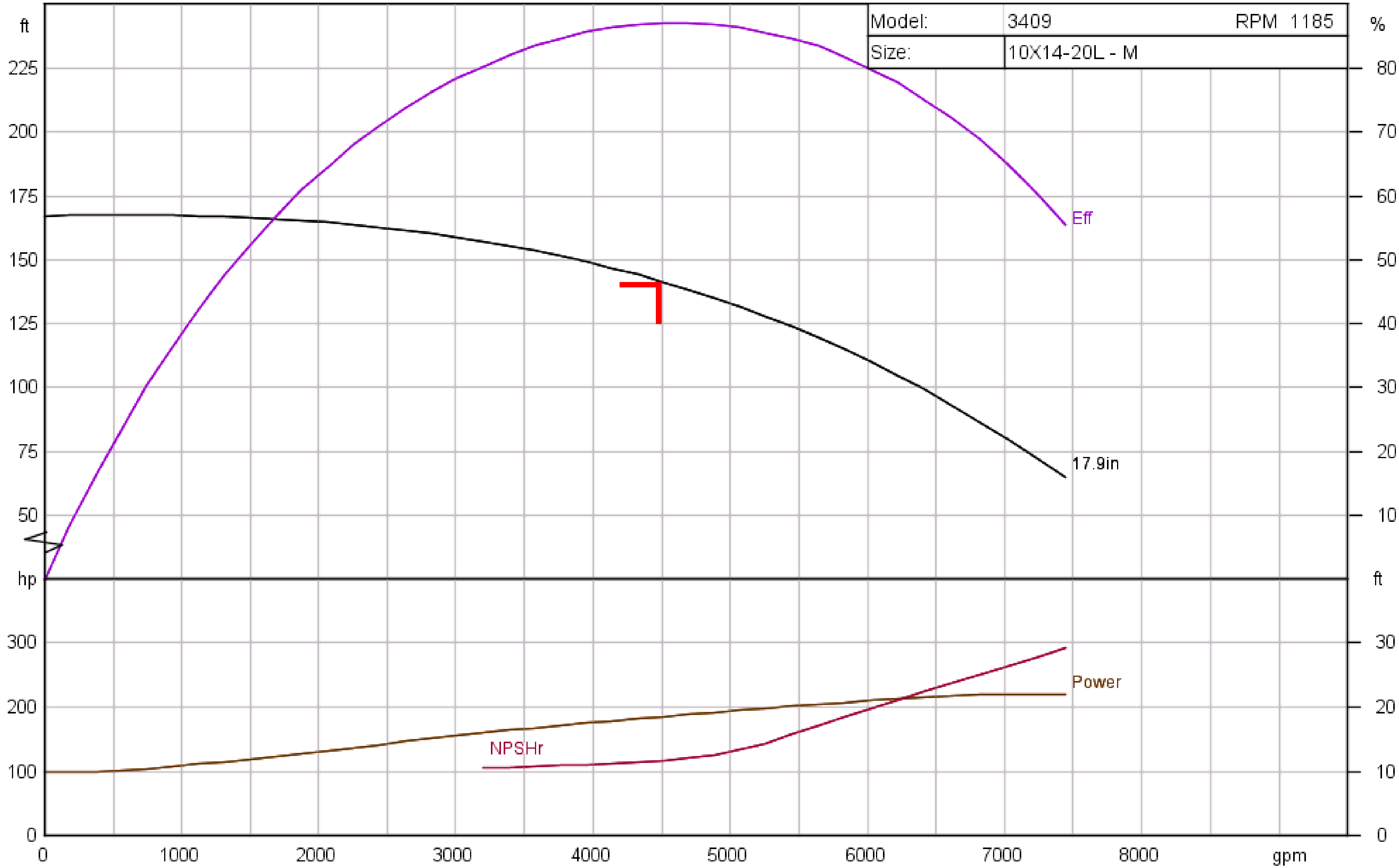
References:

1. Flowserve Pros+ SE, v 3.3.1, www.flowserve.com
2. Goulds Pump Selection System, www.gouldspumps.com/pss.html
3. Grundfos WinCAPS, v. 7.80.16, www.grundfos.com/web/homeus.nsf
4. Floway, www.weirclearliquid.com/
5. Flygt FLYPS, v. 3.1, http://www.flygt.com/

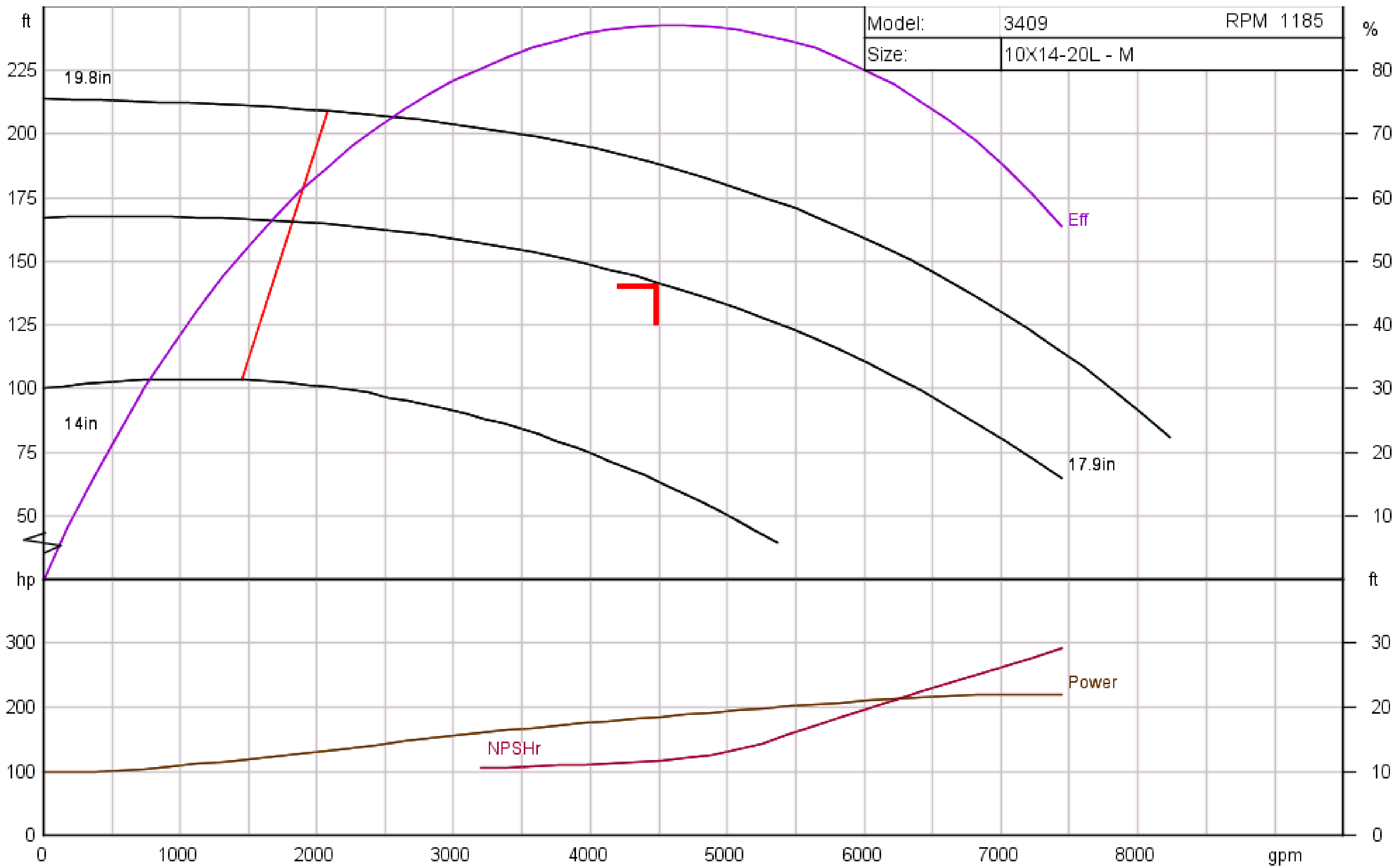
Pump 1 line curves plus min/max impeller size head curves



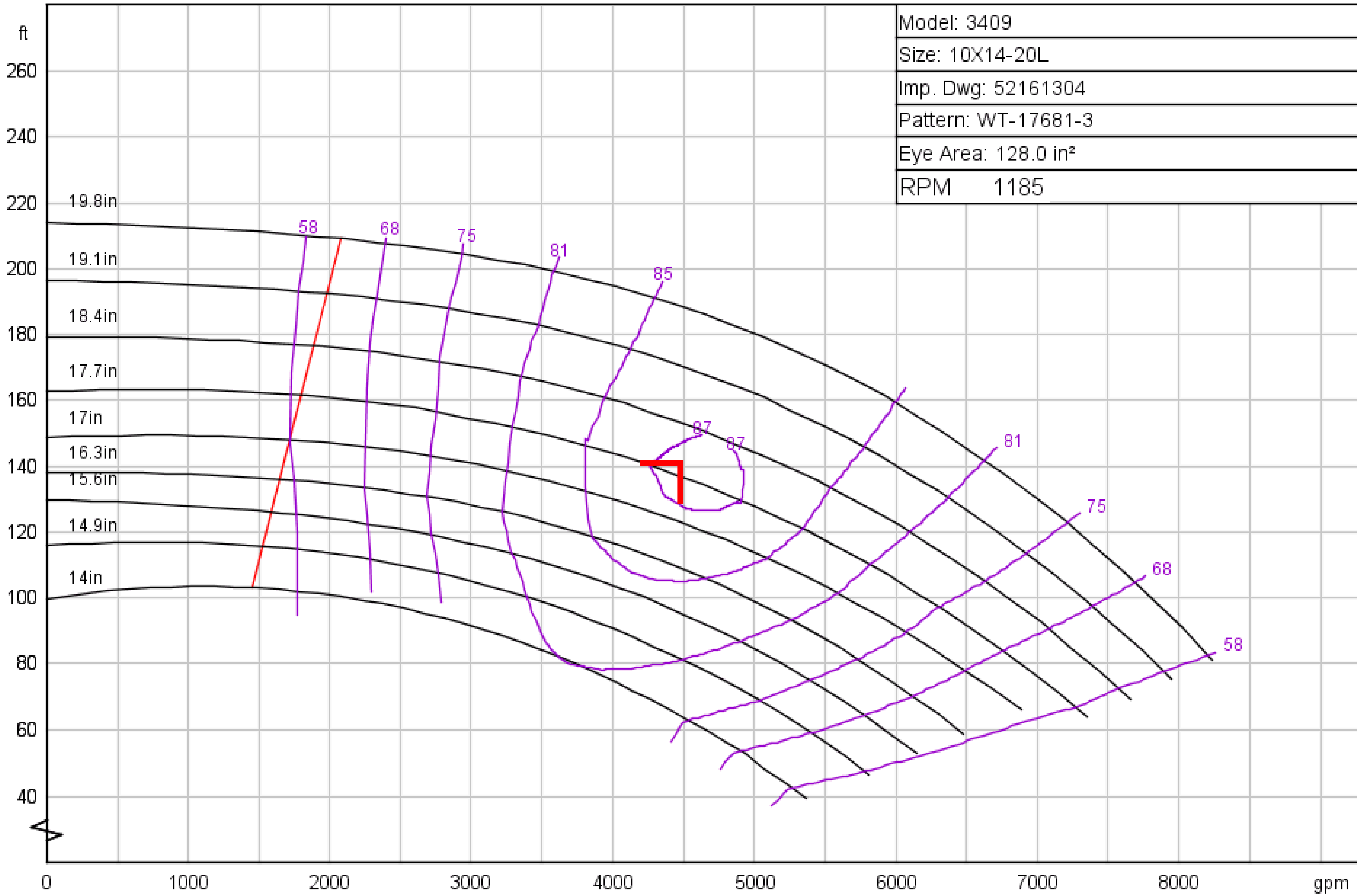
Pump 2 line curves for head, efficiency, shaft power, NPSHR



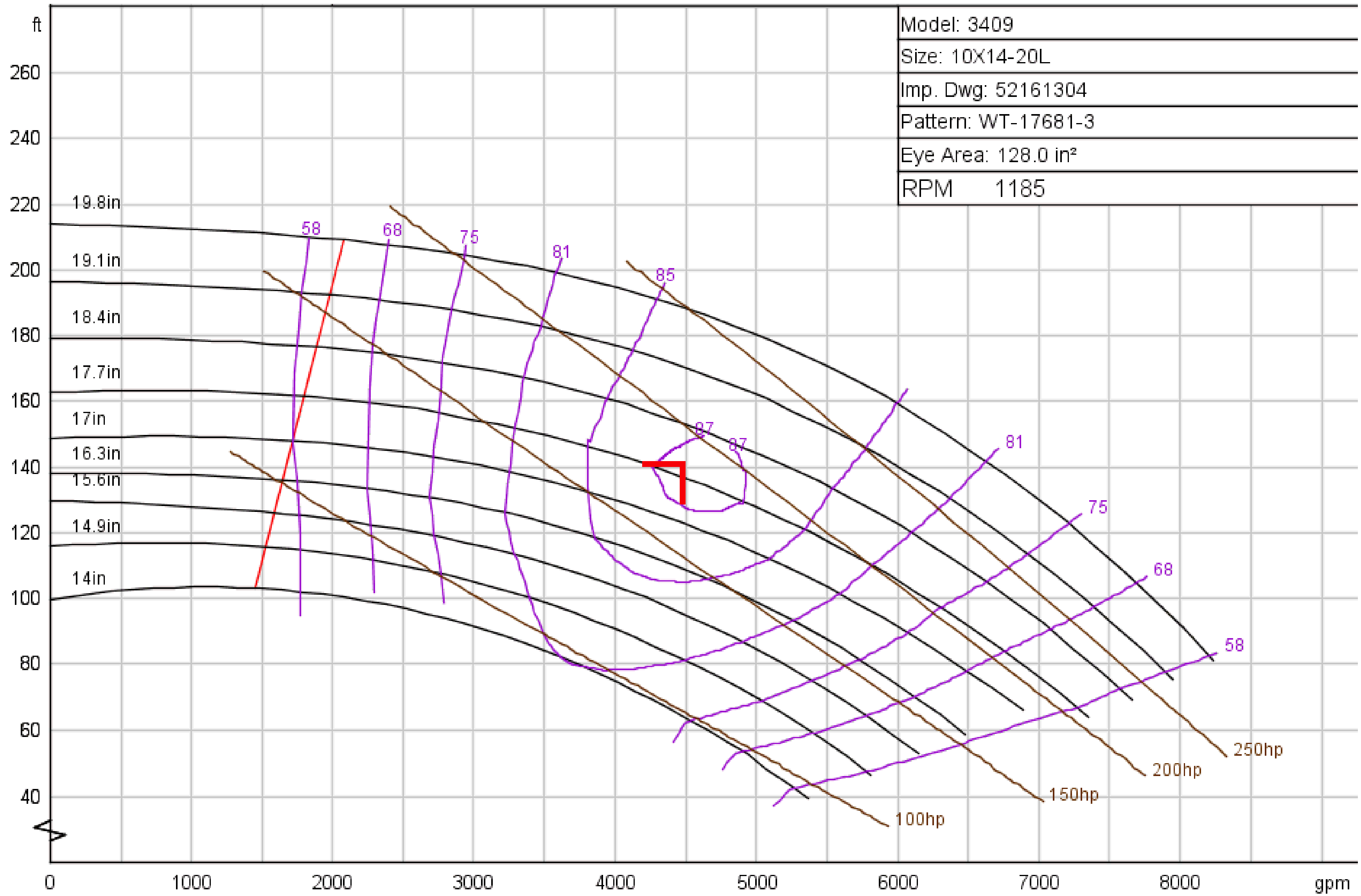
Pump 2 line curves + head curve for max/min impeller diameters



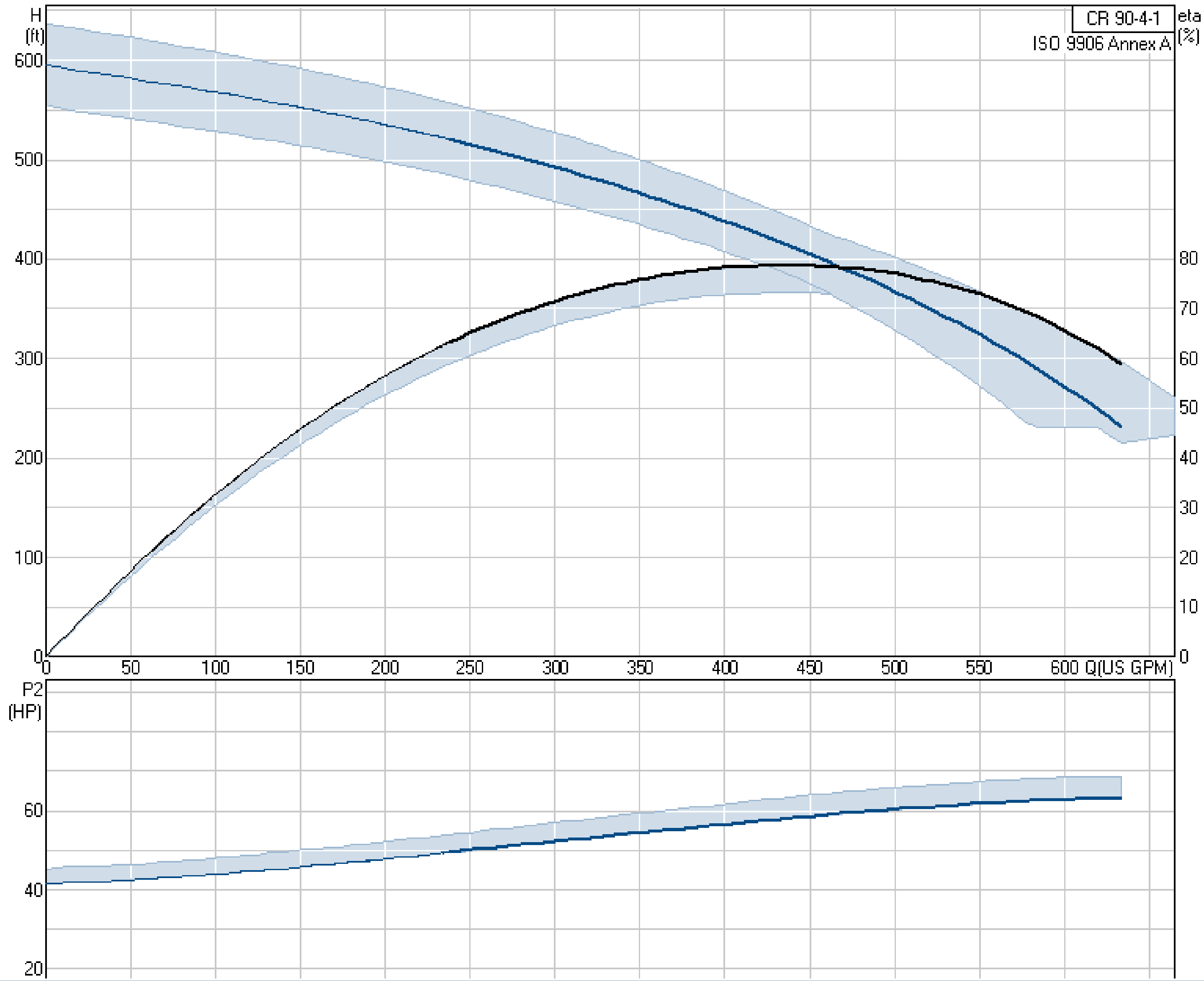
Pump 2 range of impeller sizes, isoefficiency lines



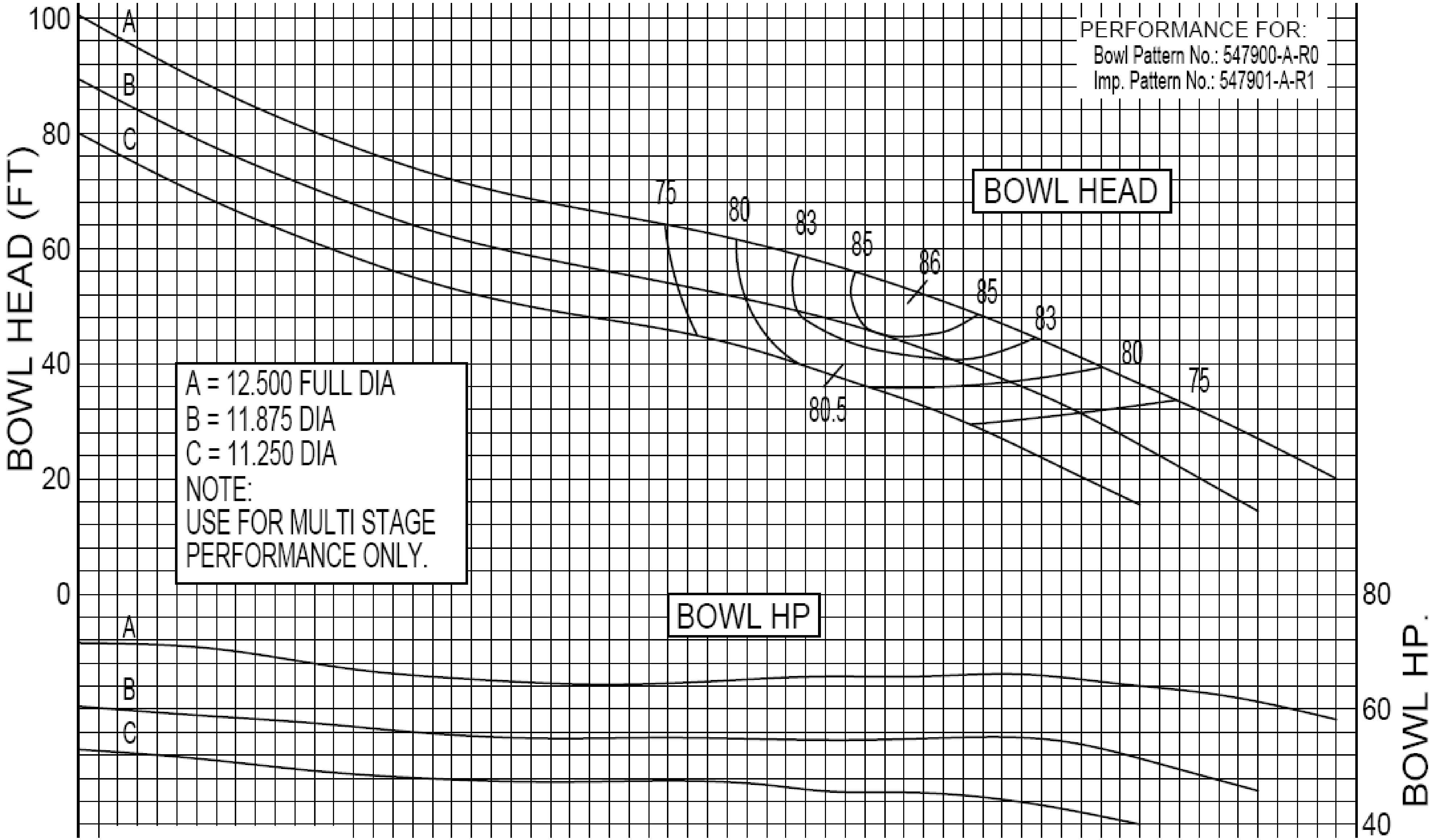
Same as previous slide + shaft power curves



Curves with ISO tolerance bands



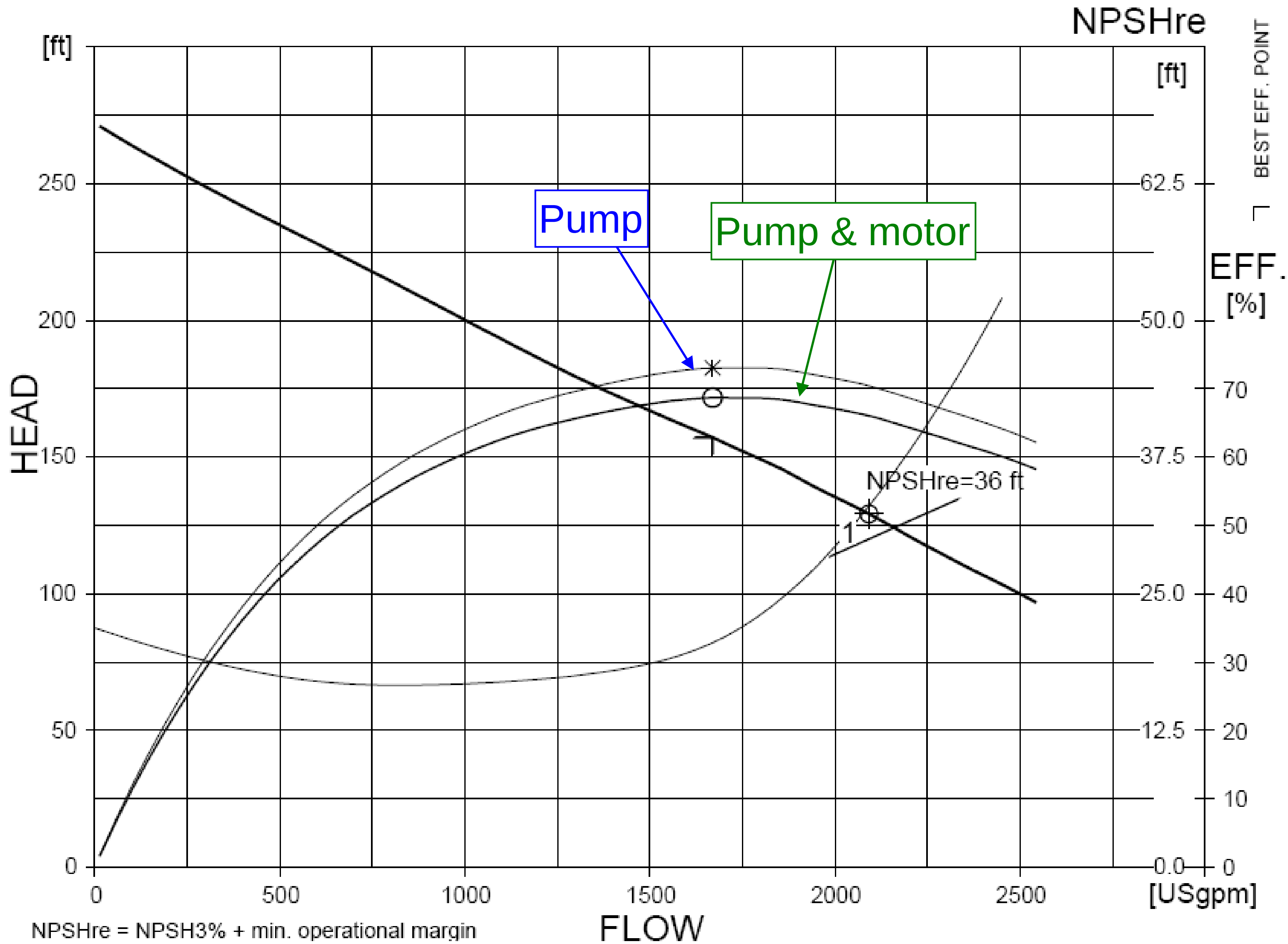
Vertical turbine pump catalog curves are commonly provided in individual stage (bowl) performance format



Vertical Turbine Pump

Vertical turbine pumps are commonly used in all types of applications, from moving process water in industrial plants to providing flow for cooling towers at power plants, from pumping raw water for irrigation, to boosting water pressure in municipal pumping systems, and for many other pumping applications.

Submersible pump and combined pump & motor (sometimes called wire-to-water) efficiency curves



NPSHre = NPSH3% + min. operational margin
Performance with clear water and ambient temp 40 °C

Break

Pump affinity laws and parallel or series pump operation

Pump affinity laws can be used to predict pump curves for different speeds and impeller diameters

Speed

$$\left(\frac{Q_1}{Q_2}\right) = \left(\frac{N_1}{N_2}\right)^1$$

$$\left(\frac{H_1}{H_2}\right) = \left(\frac{N_1}{N_2}\right)^2$$

$$\left(\frac{P_1}{P_2}\right) = \left(\frac{N_1}{N_2}\right)^3$$

$$\left(\frac{\eta_1}{\eta_2}\right) = \left(\frac{N_1}{N_2}\right)^0$$

Diameter

$$\left(\frac{Q_1}{Q_2}\right) = \left(\frac{D_1}{D_2}\right)^1$$

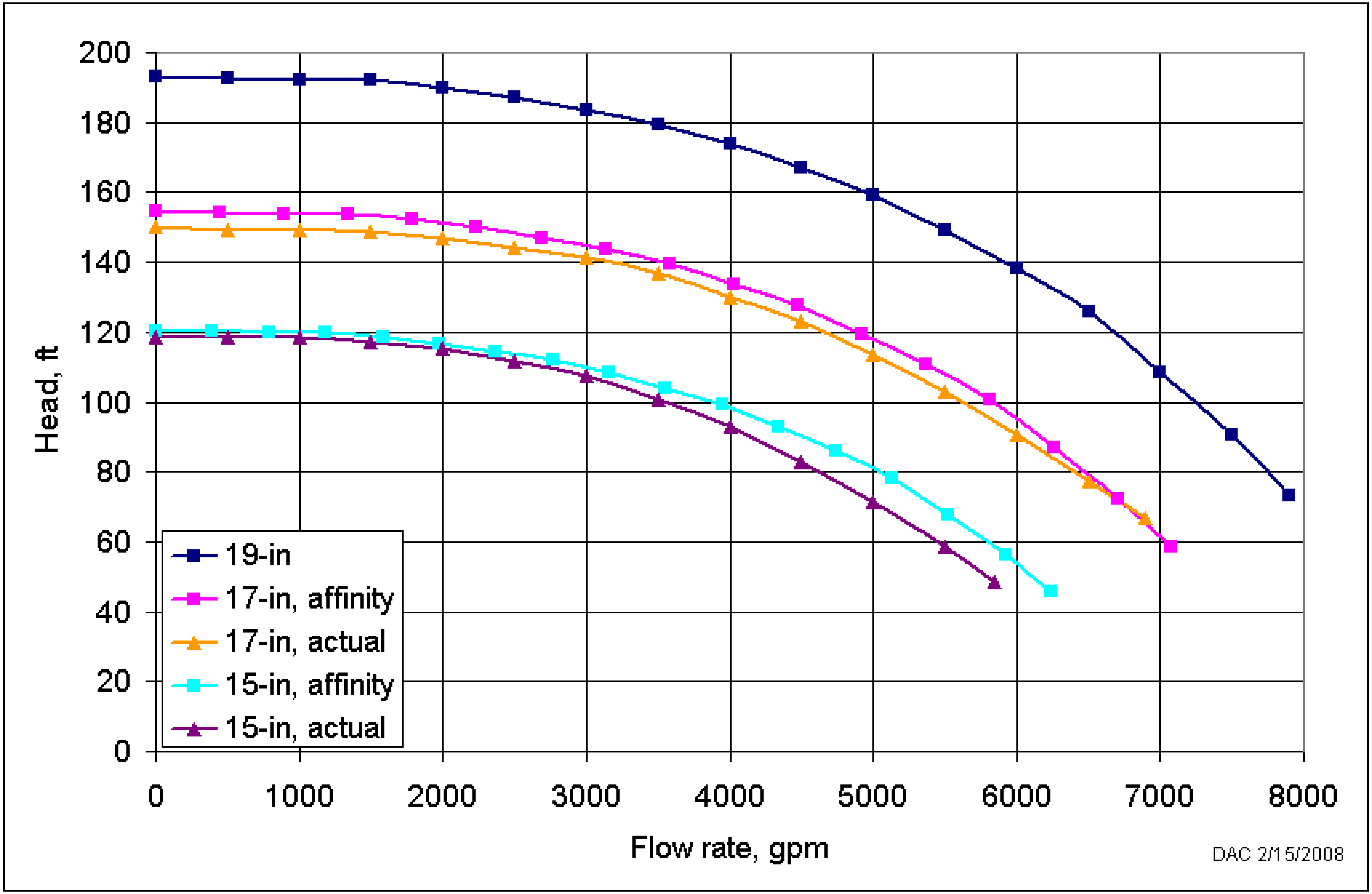
$$\left(\frac{H_1}{H_2}\right) = \left(\frac{D_1}{D_2}\right)^2$$

$$\left(\frac{P_1}{P_2}\right) = \left(\frac{D_1}{D_2}\right)^3$$

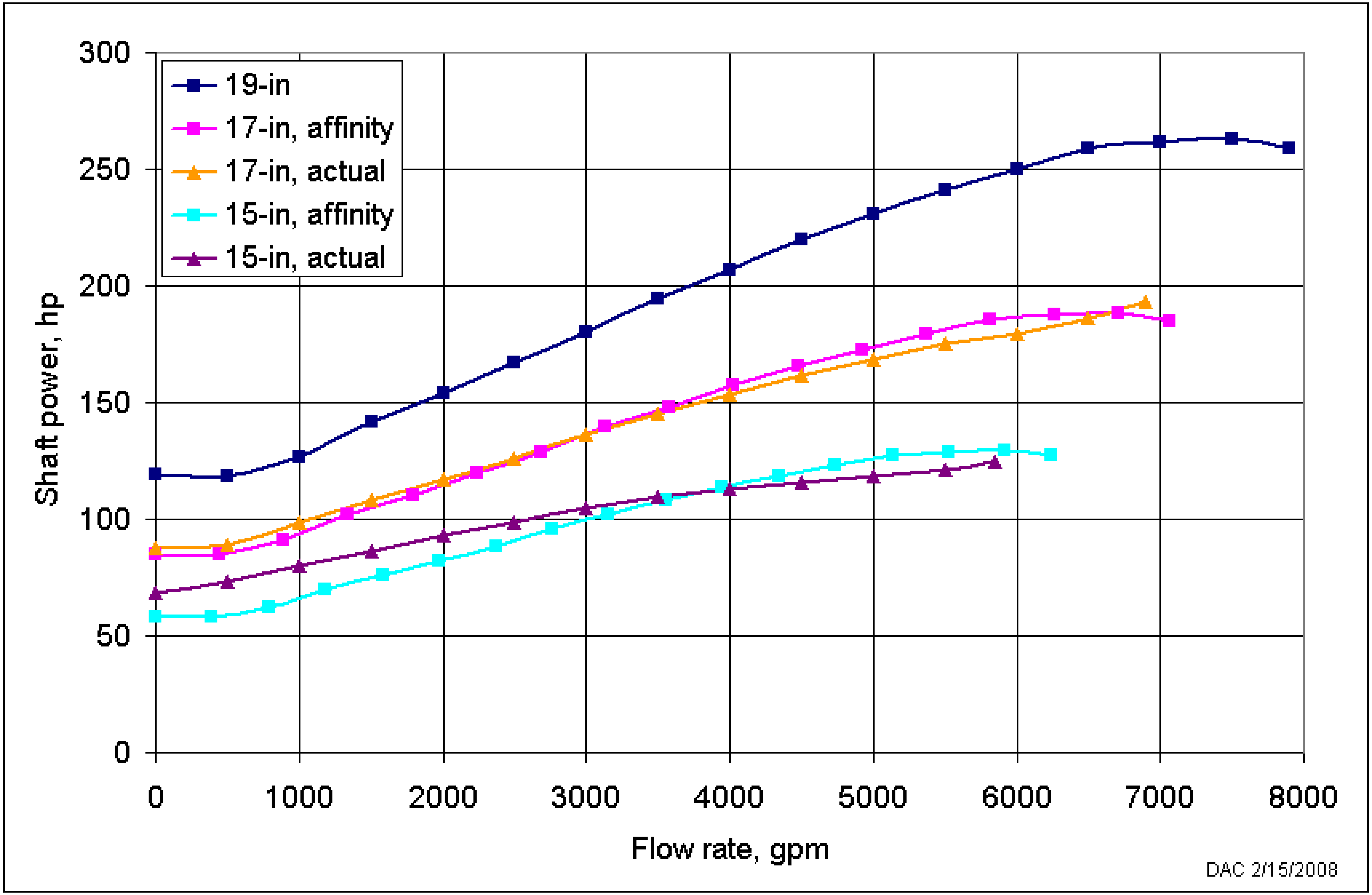
$$\left(\frac{\eta_1}{\eta_2}\right) = \left(\frac{D_1}{D_2}\right)^0$$

Q = flow rate
N = speed
H = head
D = diameter
P = power
η = efficiency

The affinity laws aren't perfect for diameter changes: head curves



The affinity laws aren't perfect for diameter changes: power curves



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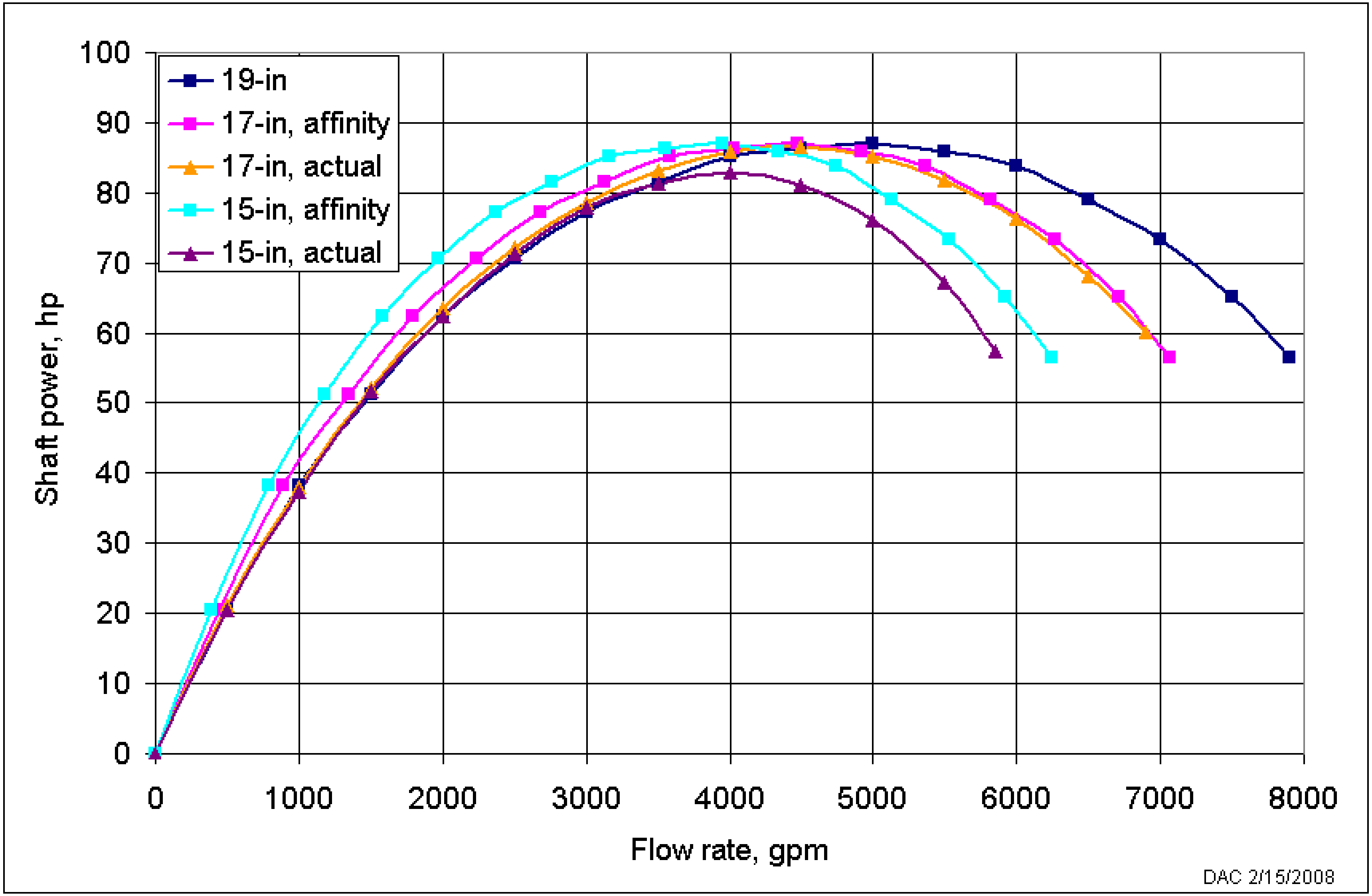
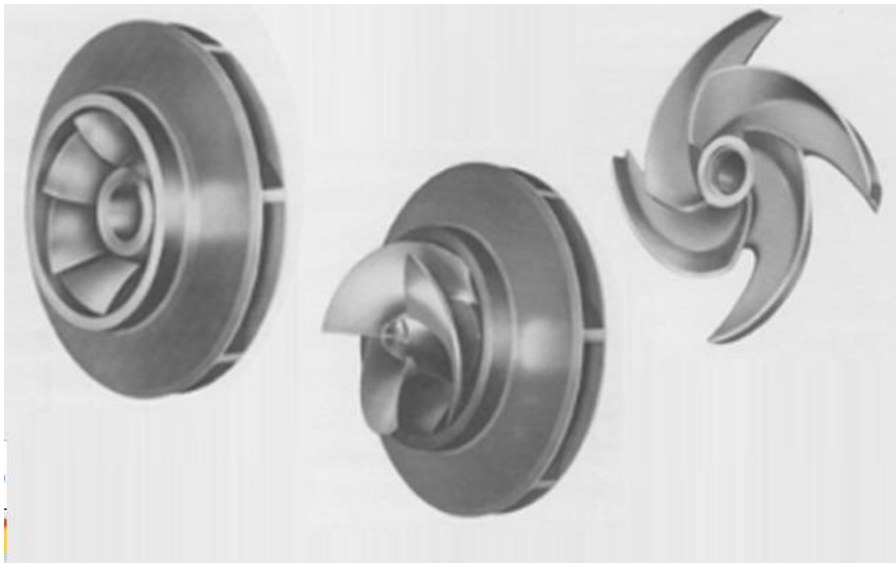
The affinity laws aren't perfect for diameter changes: efficiency curves



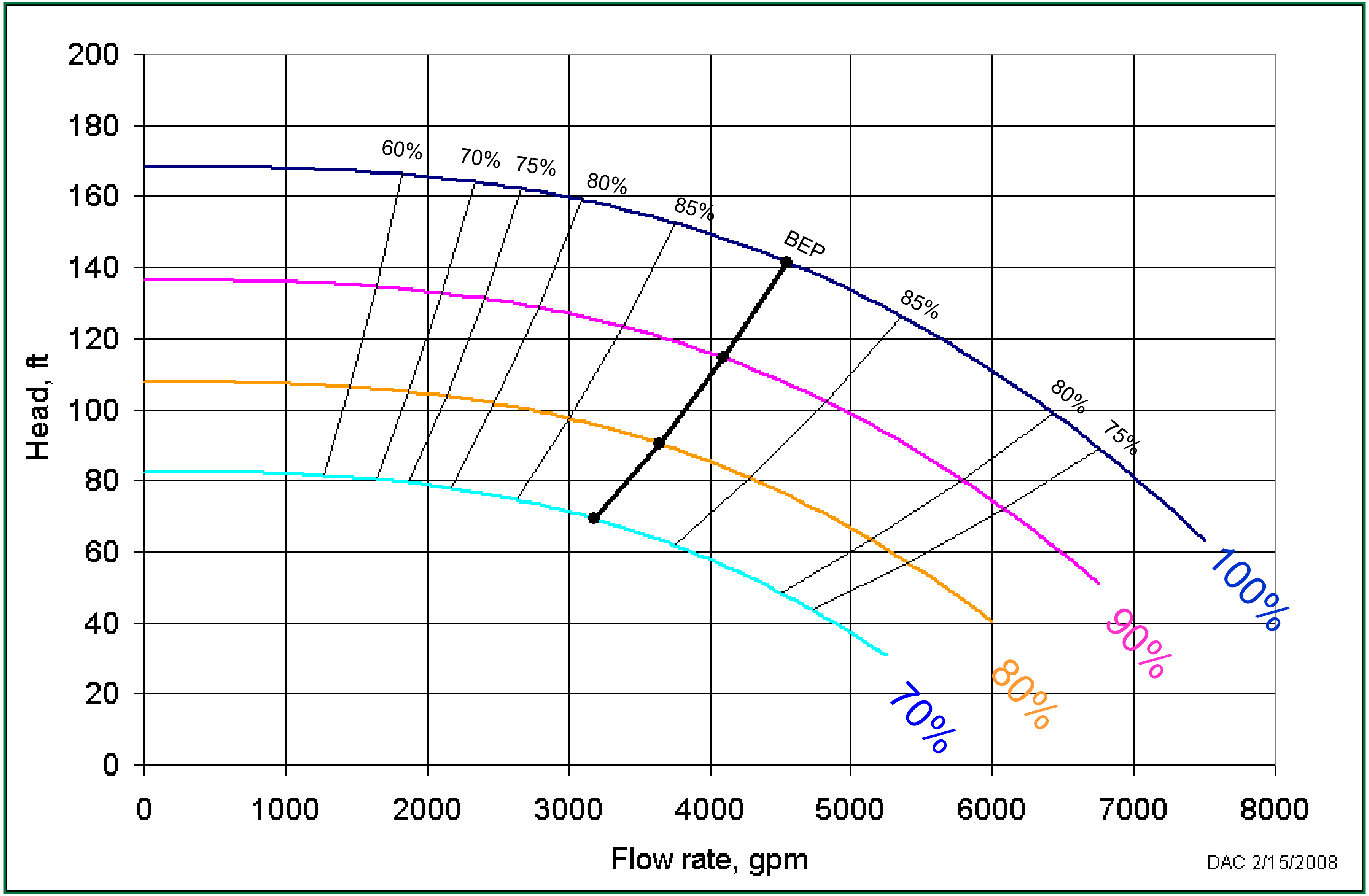
Considering a trim in impeller diameter?

Recommendations:

1. Get actual performance curves from the manufacturer, especially if the trim change being considered is large
2. Do a field performance test of the existing pump

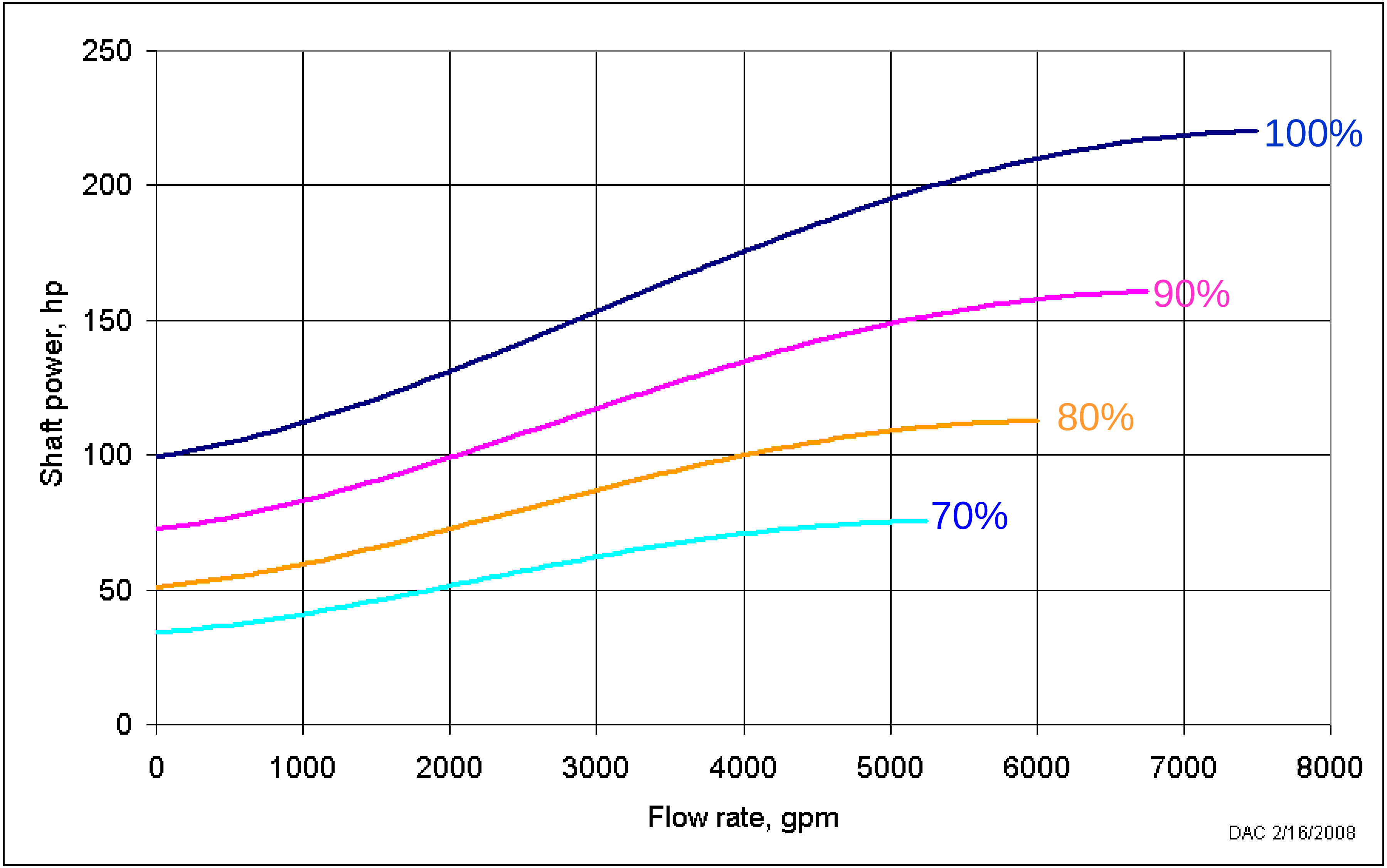


But the affinity laws generally hold up very well with speed changes

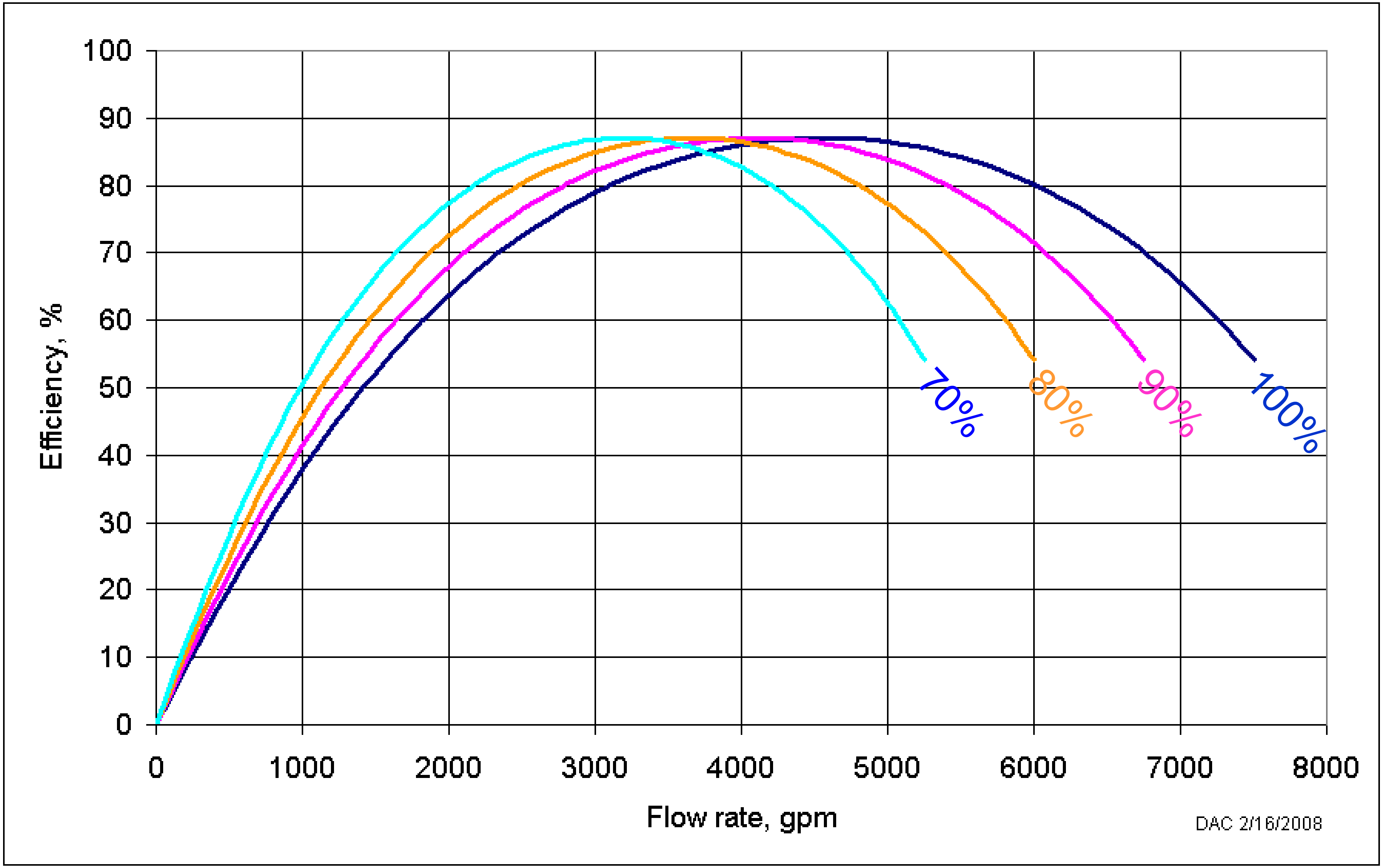


Note: same pump as previous slides, impeller size = 17.9 inches

Shaft power curves at four speeds

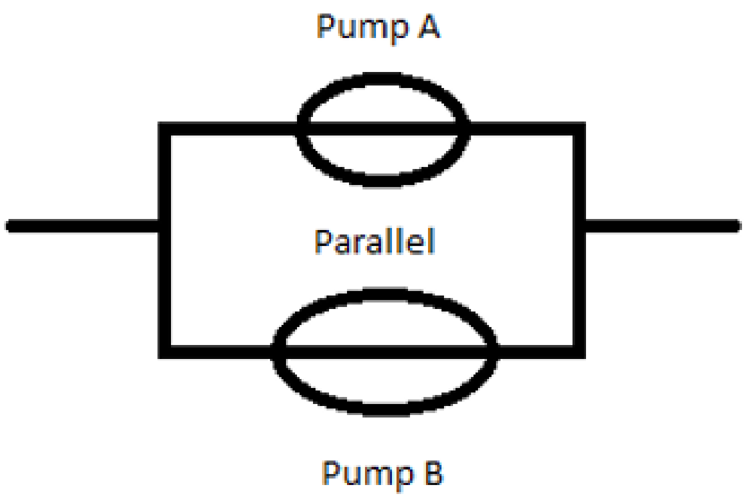


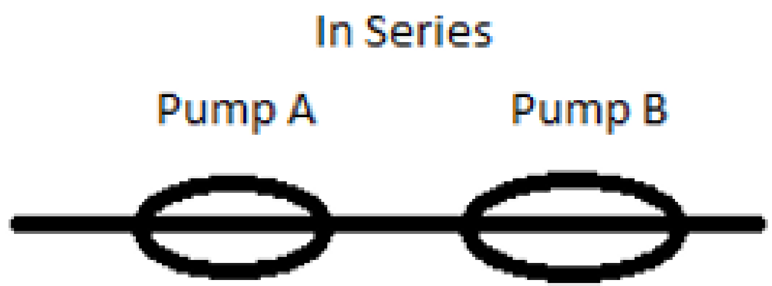
Efficiency curves at four speeds



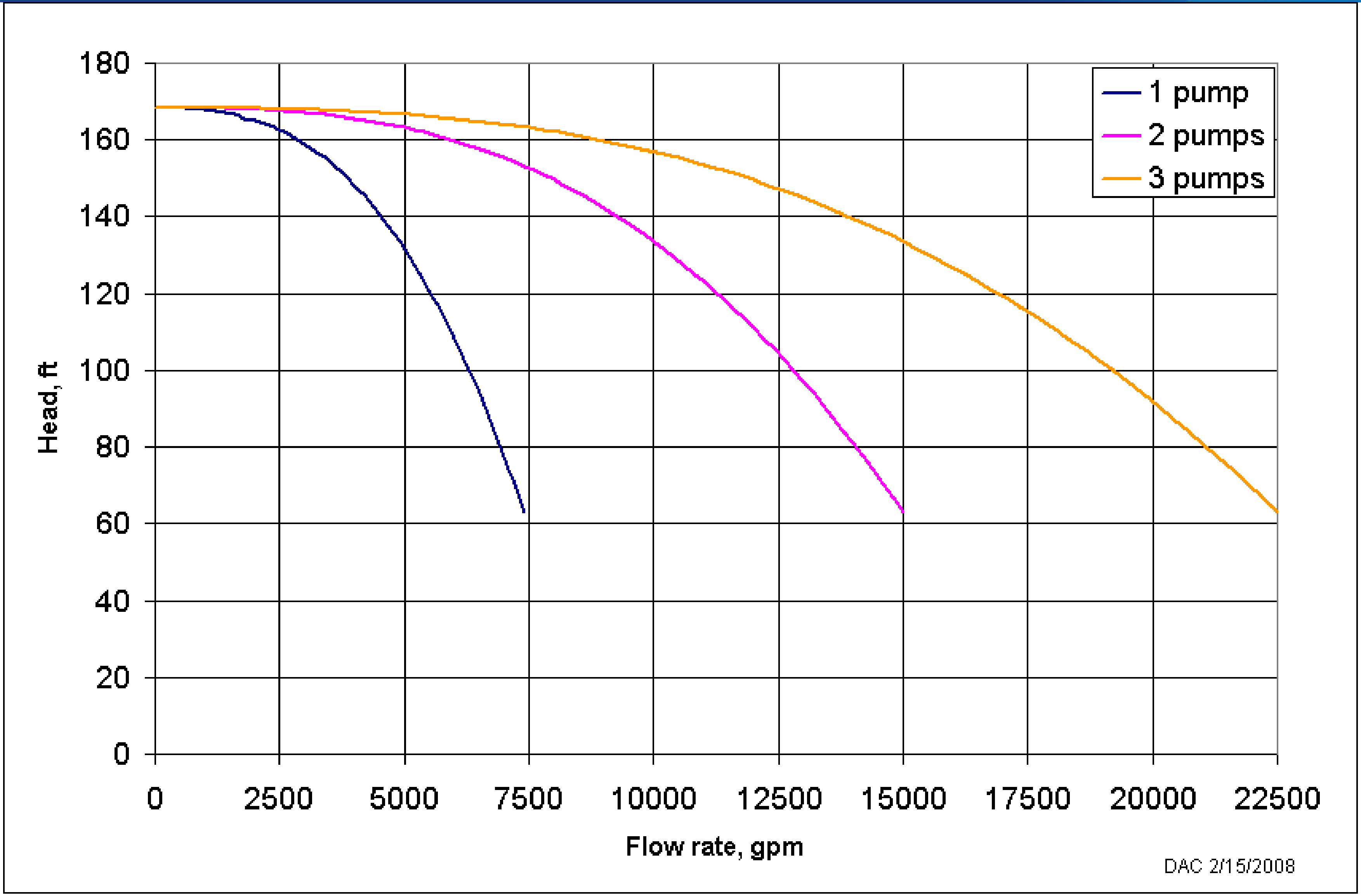
Parallel and series pumping “laws”, like the pump affinity laws apply to the pump curves ***only***

- Parallel pumps - sum the flow rates at a given head
- Series pumps - sum the heads at a given flow rate

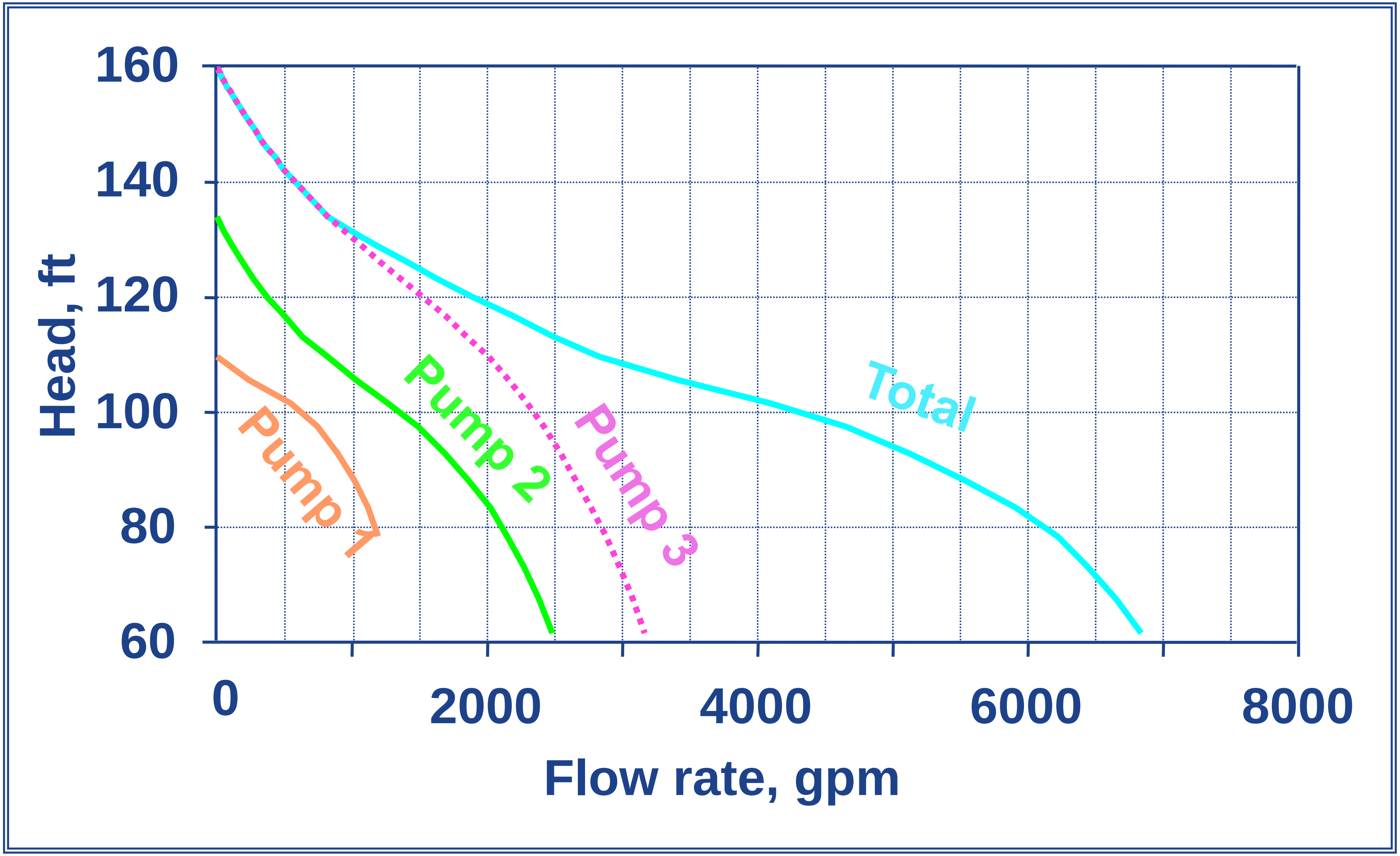




Parallel pumps can help adapt to changing system requirements and provide redundancy



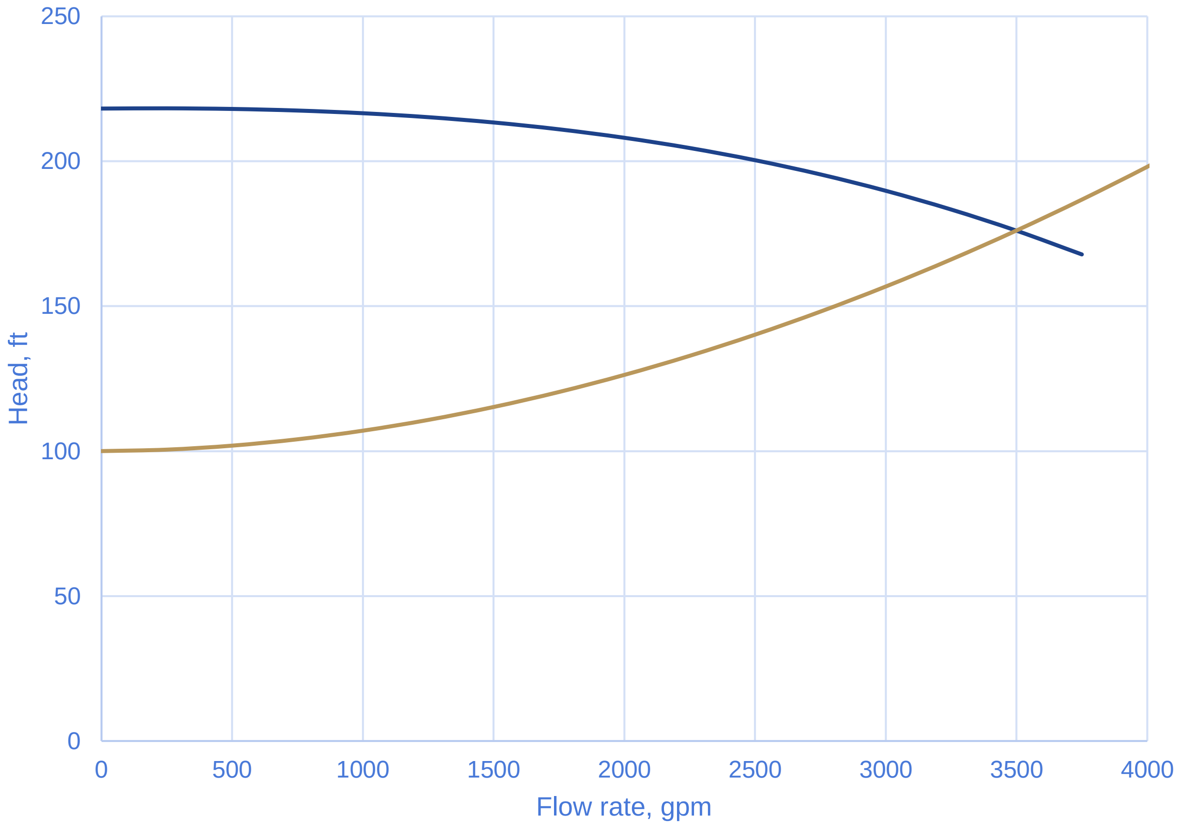
Unlike pumps can also be used in parallel, but with caution



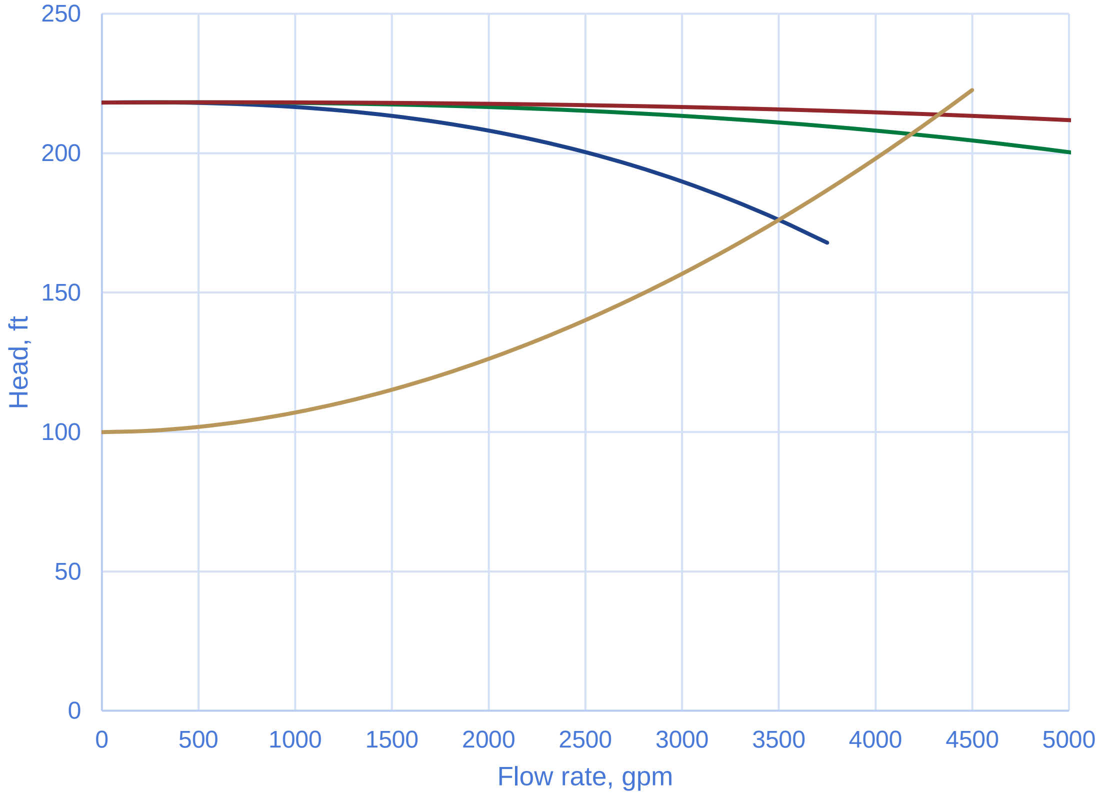
Poll question

What increase in flow would you expect from adding an additional parallel pump?

A. 100%
B. 80%
C. 60%
D. 40%
E. 20%

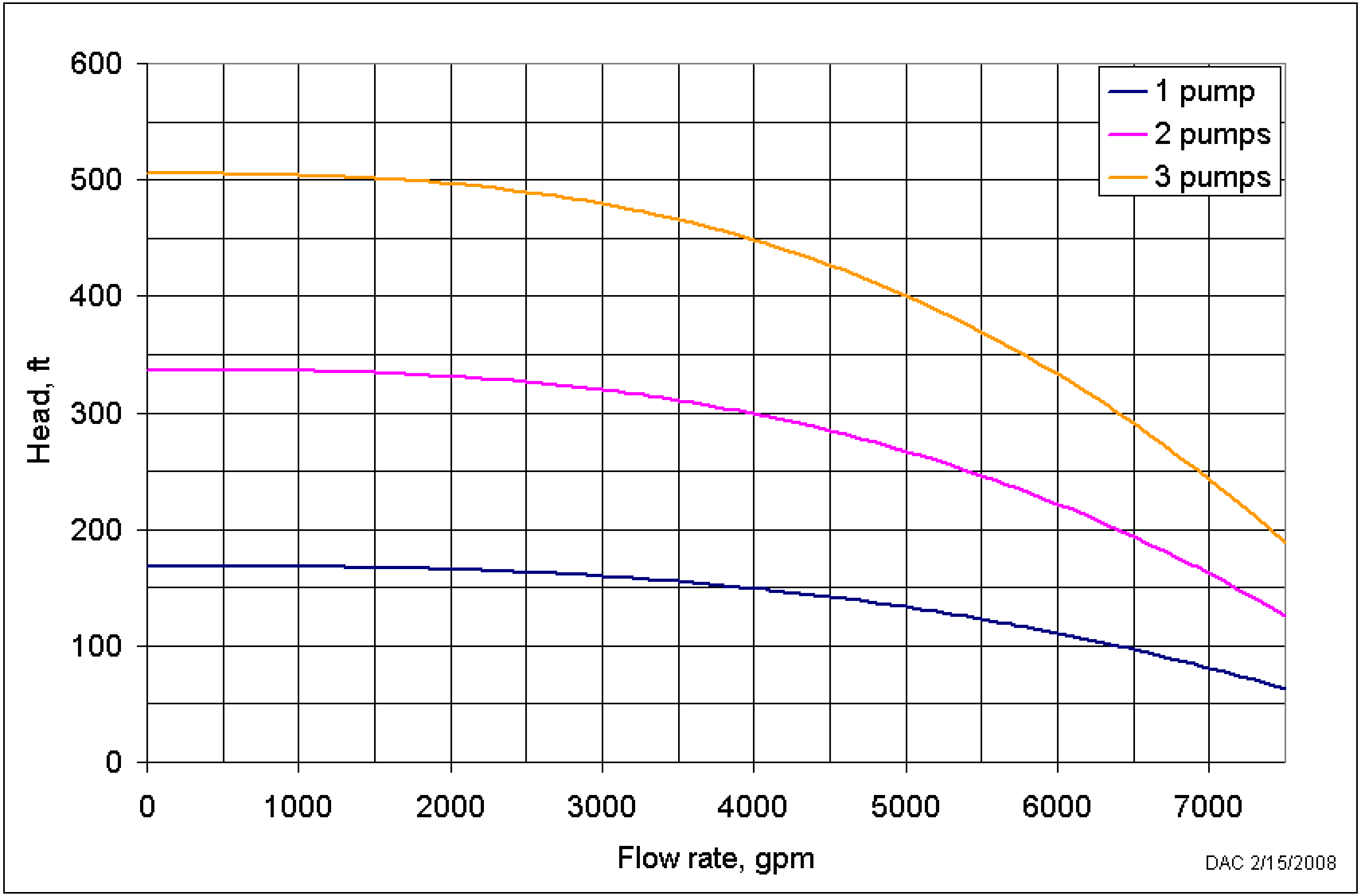


More pumps does not necessarily mean much more flow

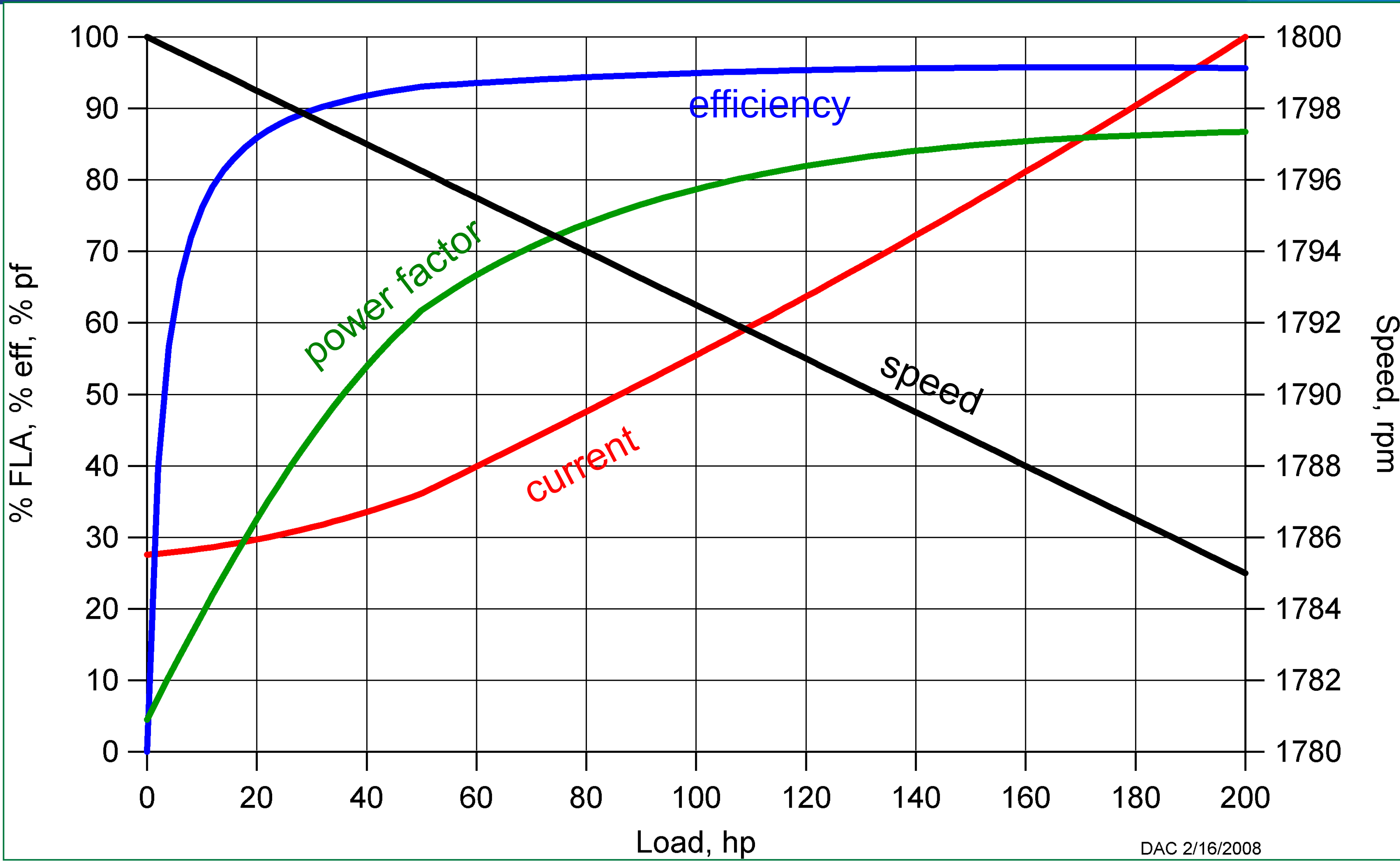


Pumps operating	Flow rate, gpm	Head, ft	% increase in flow
1	3500	176.1	0
2	4185	206.8	19.6%
3	4325	213.8	23.6%

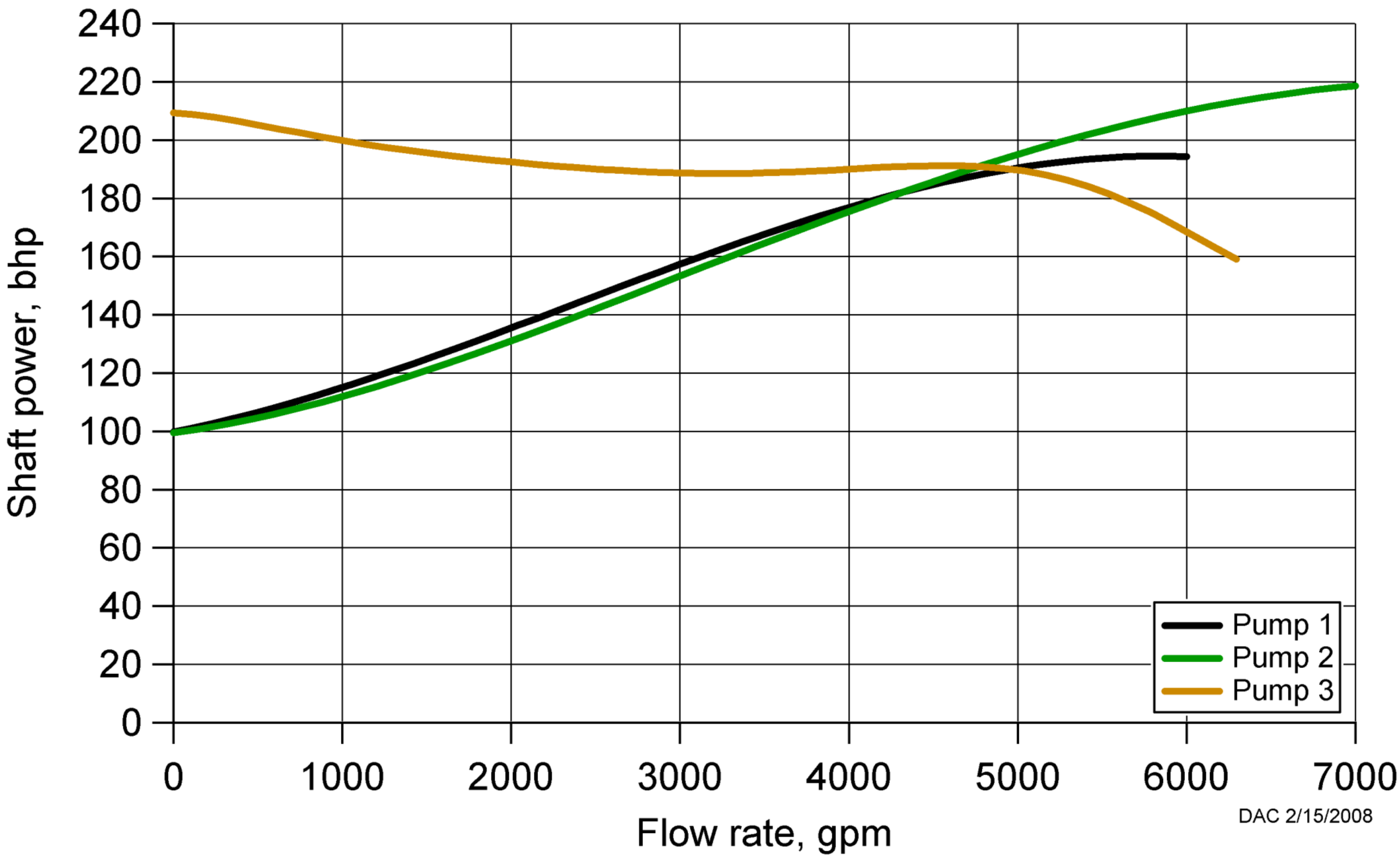
Identical pumps in series; add head at a given flow rate to estimate overall performance



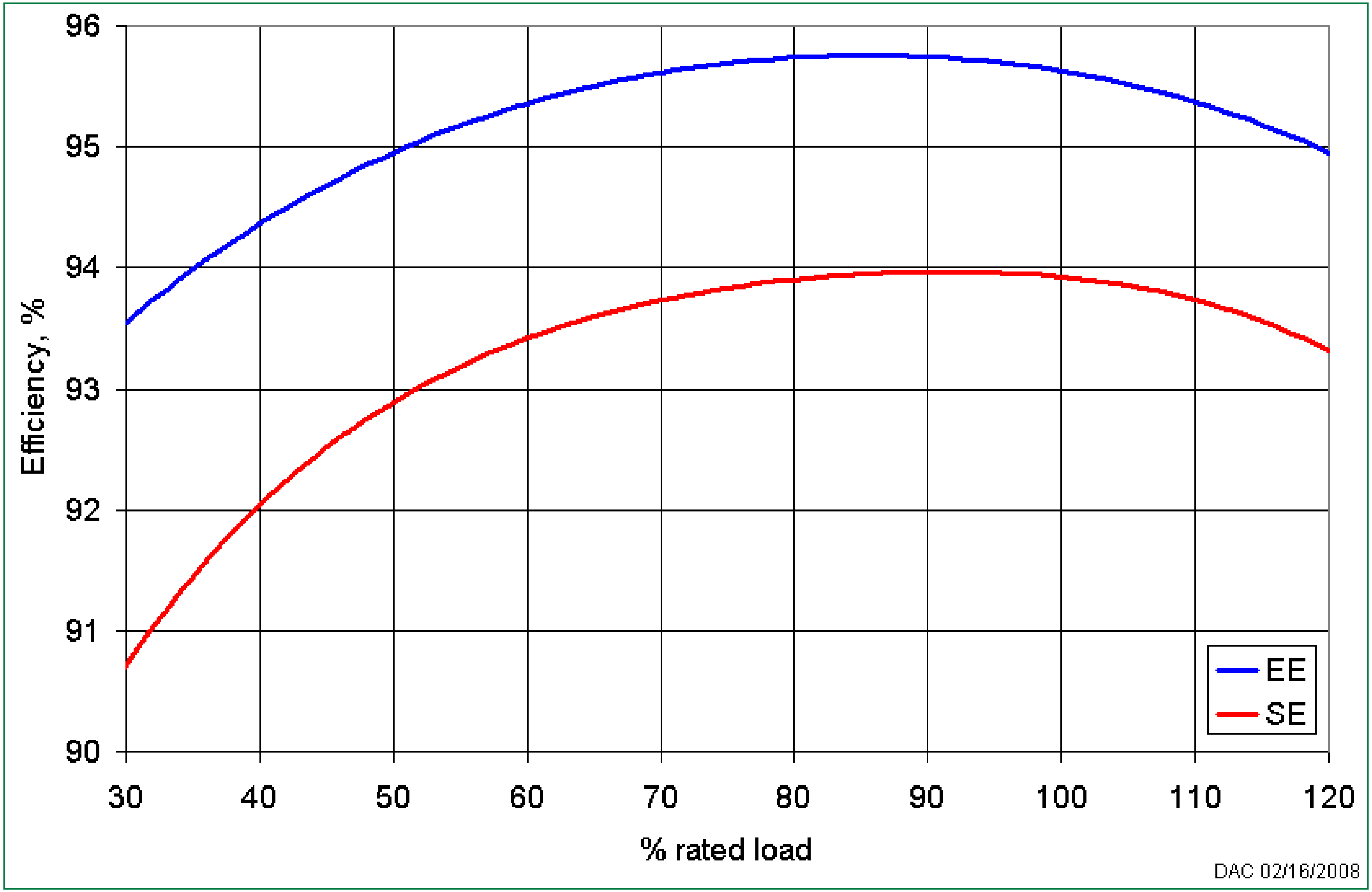
Typical motor performance characteristics (200 hp energy-efficient, 4-pole)



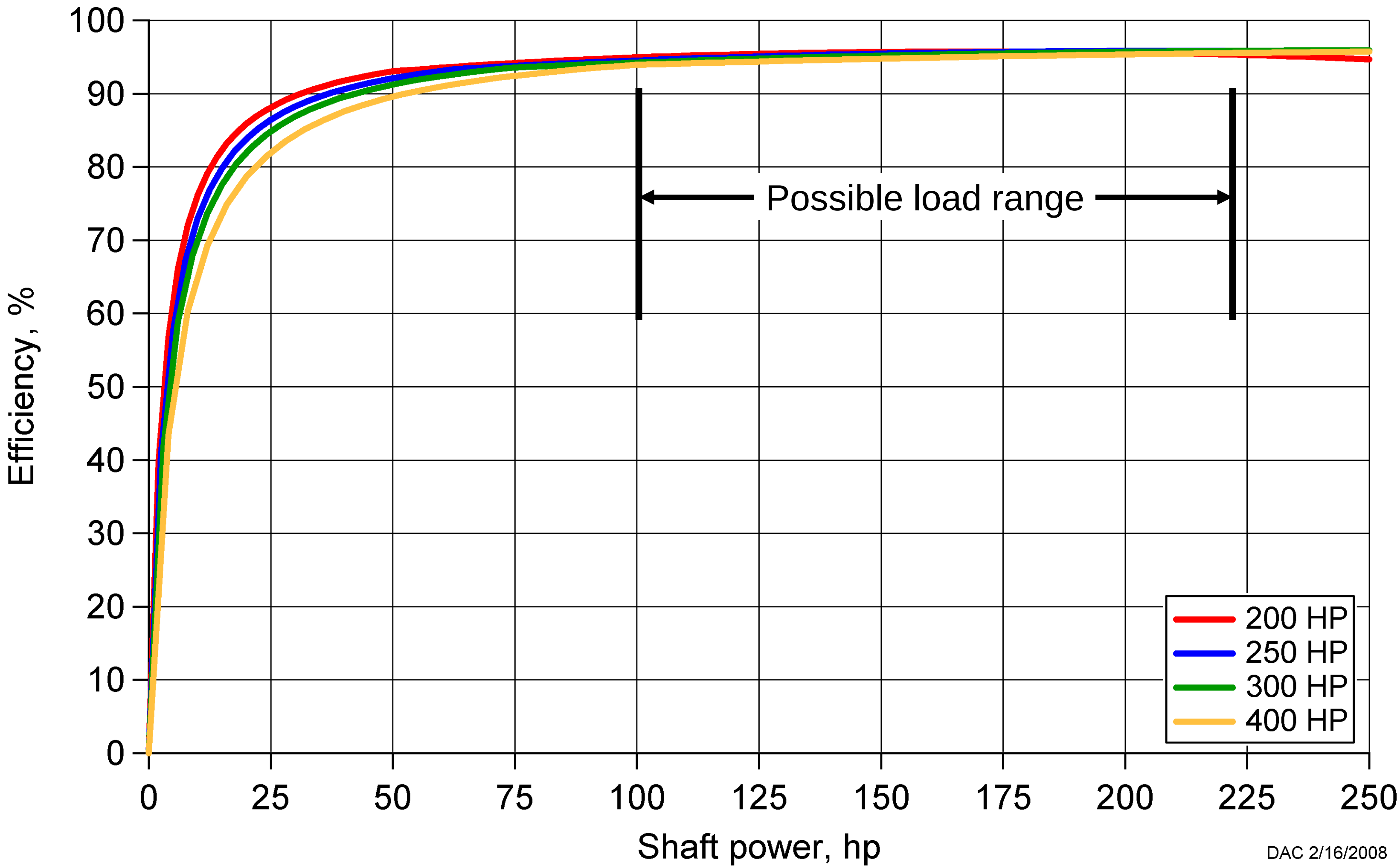
First, let's review what kind of load the pump puts on the motor (at rated speed conditions)



Typical motor efficiencies for 200 hp, 4-pole motors over the normal pump load range

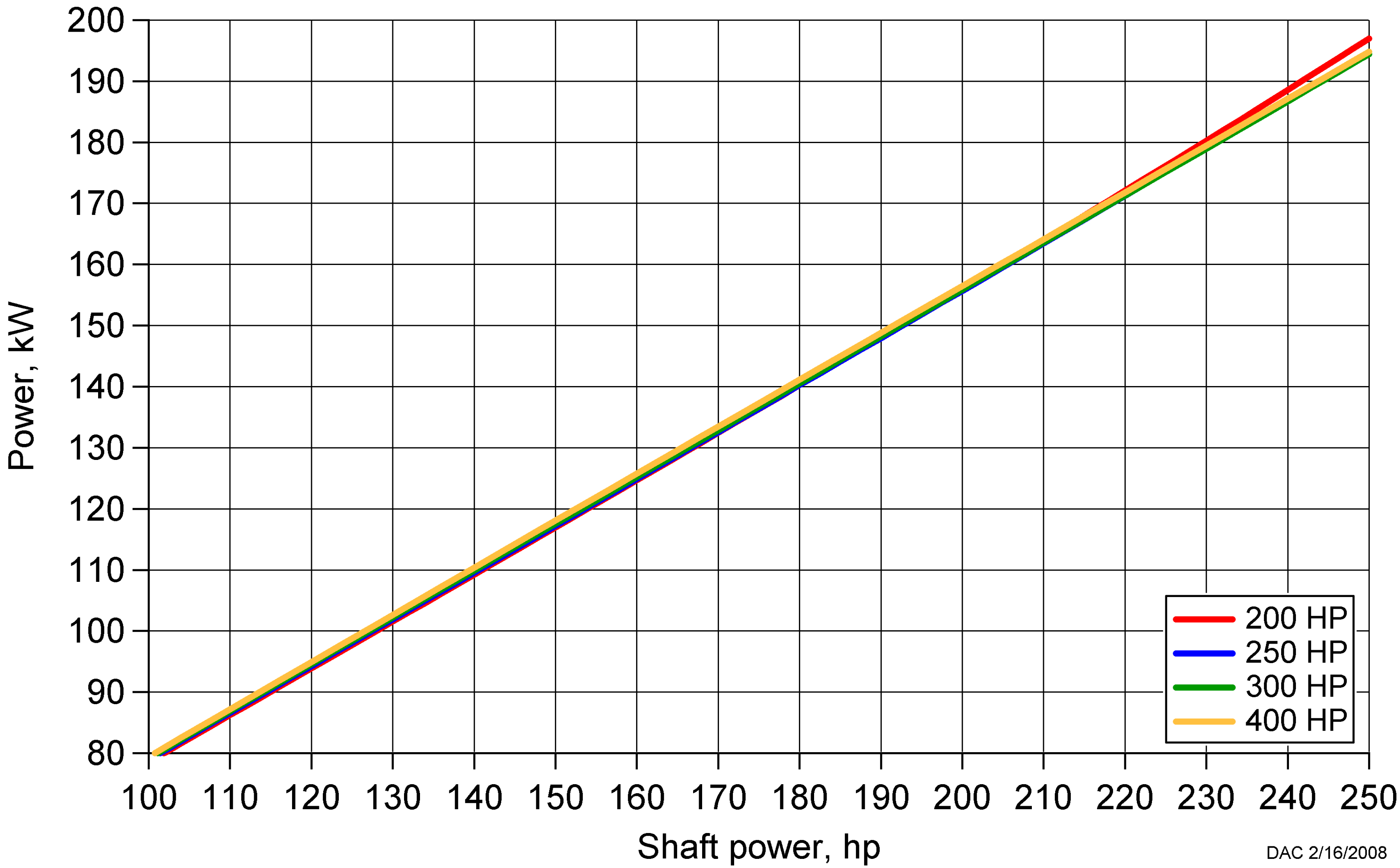


What would be the effect of an oversized motor on motor efficiency?



For this size equipment, the efficiency difference is miniscule – an order of magnitude less than the errors of high quality field measurements

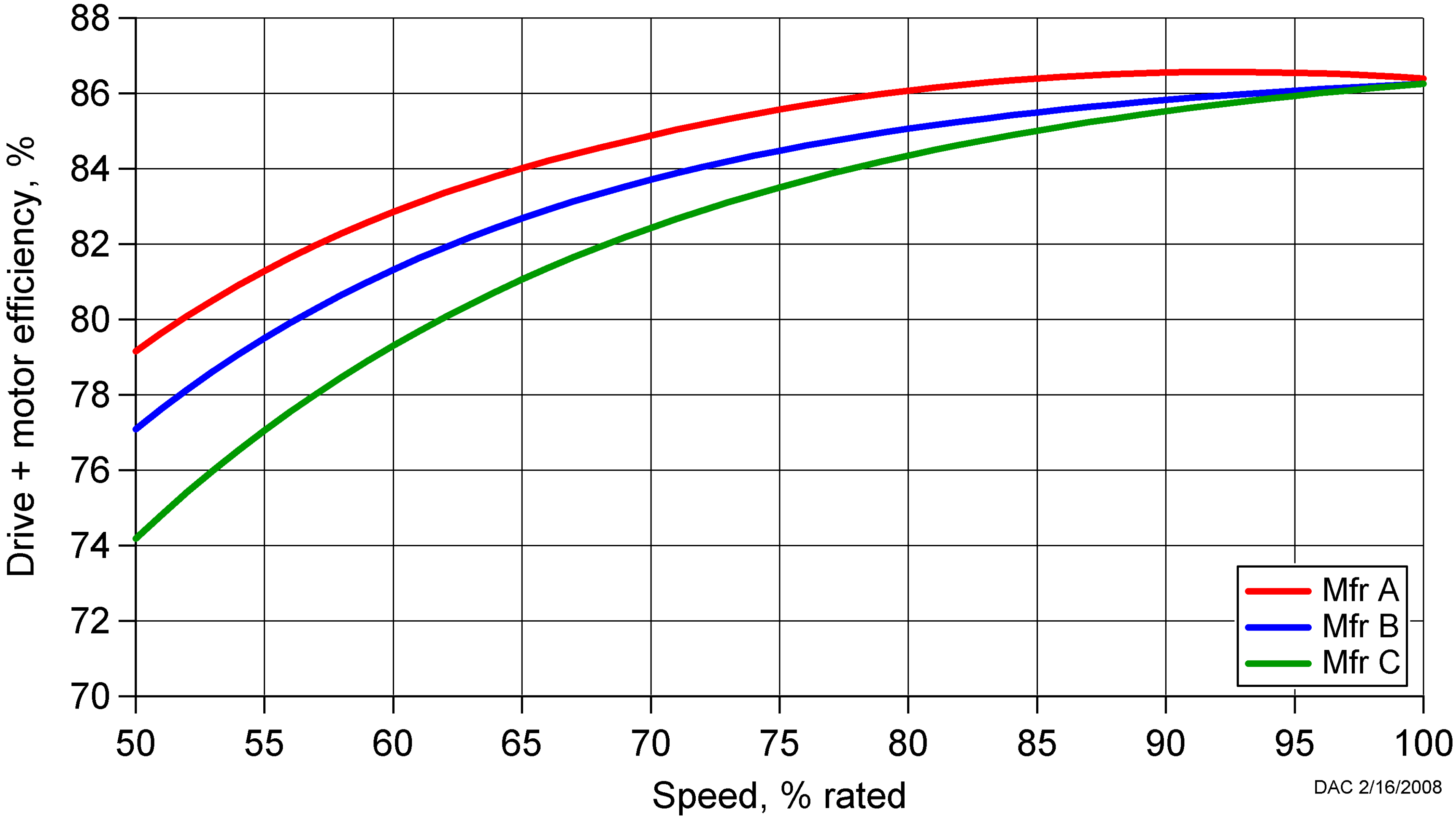
The difference in electric power consumption from oversized motors is trivial



NOTE: The effect of oversizing the pump can be tremendously important, so never attempt to apply this pattern to the other side of the coupling.

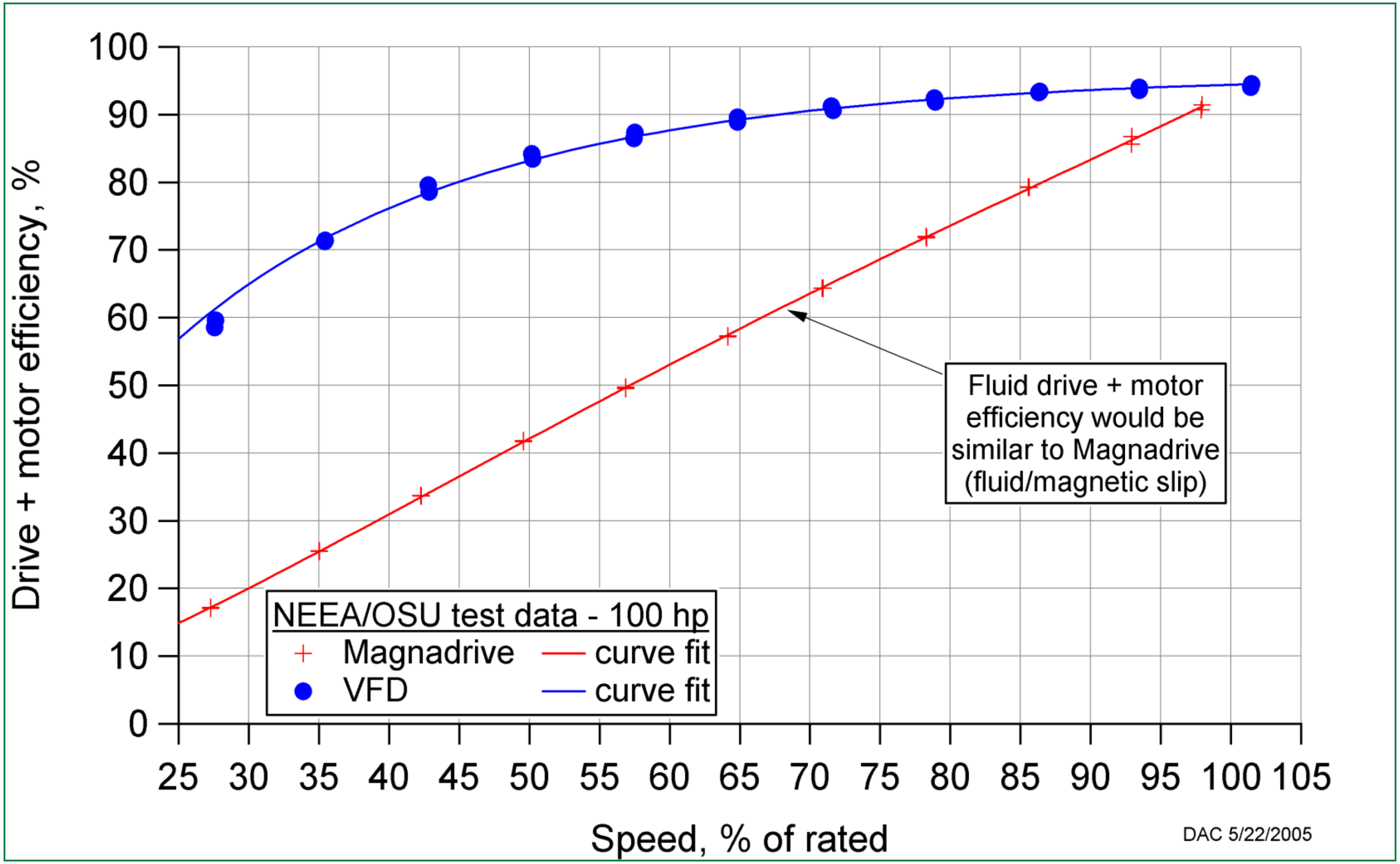
Variable speed drive performance characteristics

Combined motor & adjustable frequency drive results demonstrate high drive efficiencies



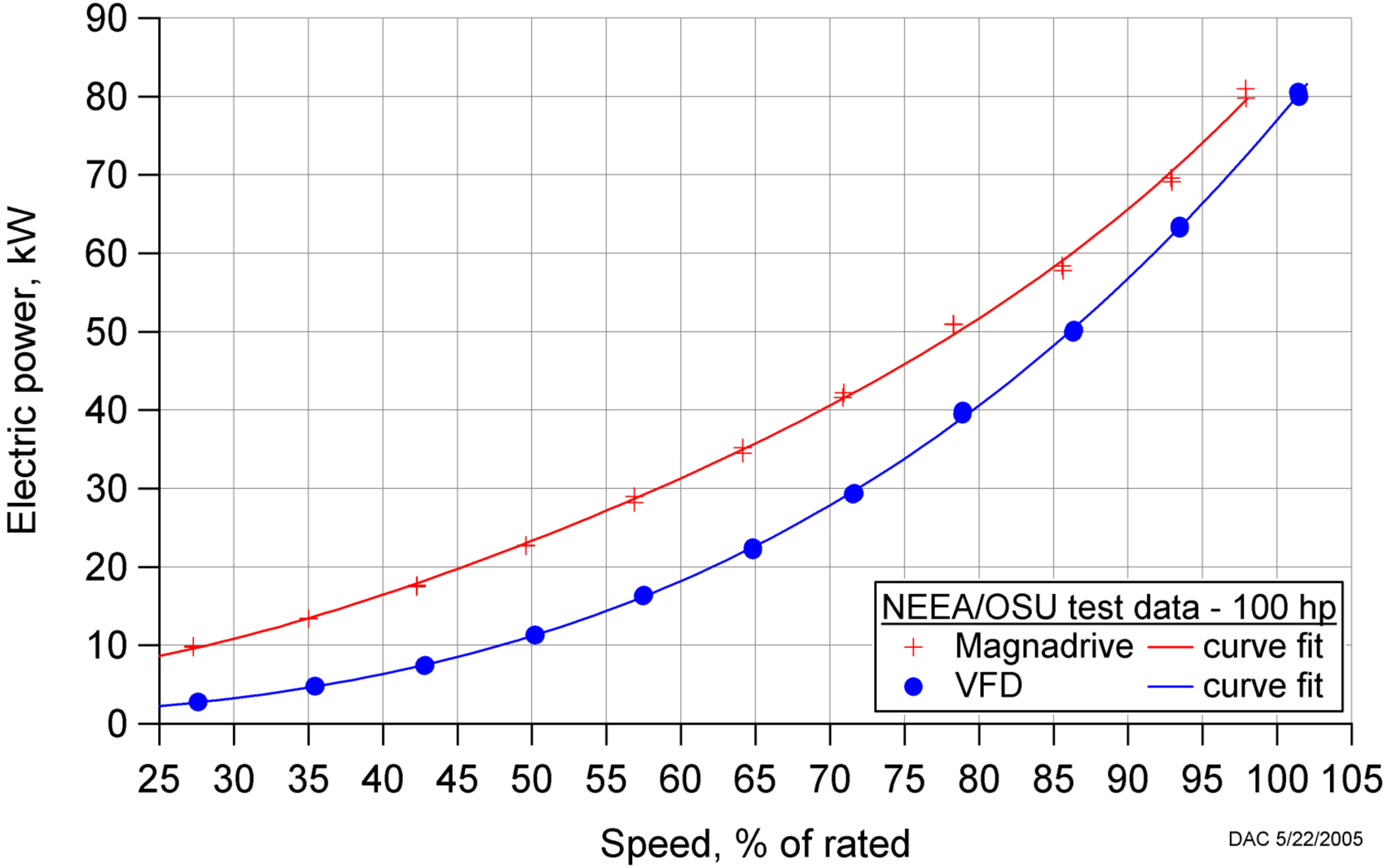
Source: Tests conducted at Y-12 plant motor test facility by Don Casada, Oak Ridge National Laboratory

Comparison of motor + drive efficiencies: AFD and mechanical-side drives



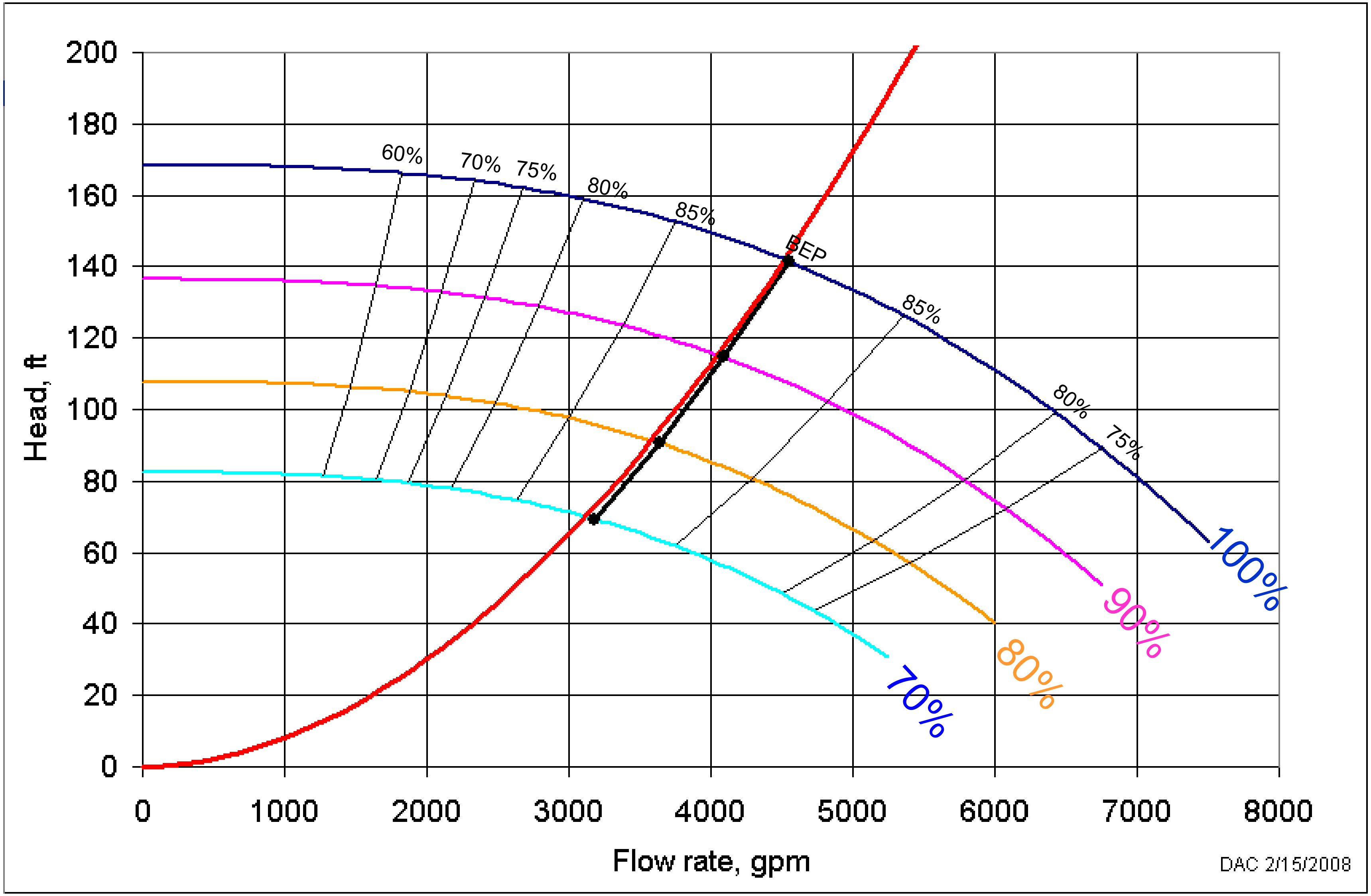
Source:Product Testing: Northwest Energy Efficiency Alliance, Report 00-048, by Oregon State University, March 2000.

But drive efficiency can be misleading - what is more important is the effect on power

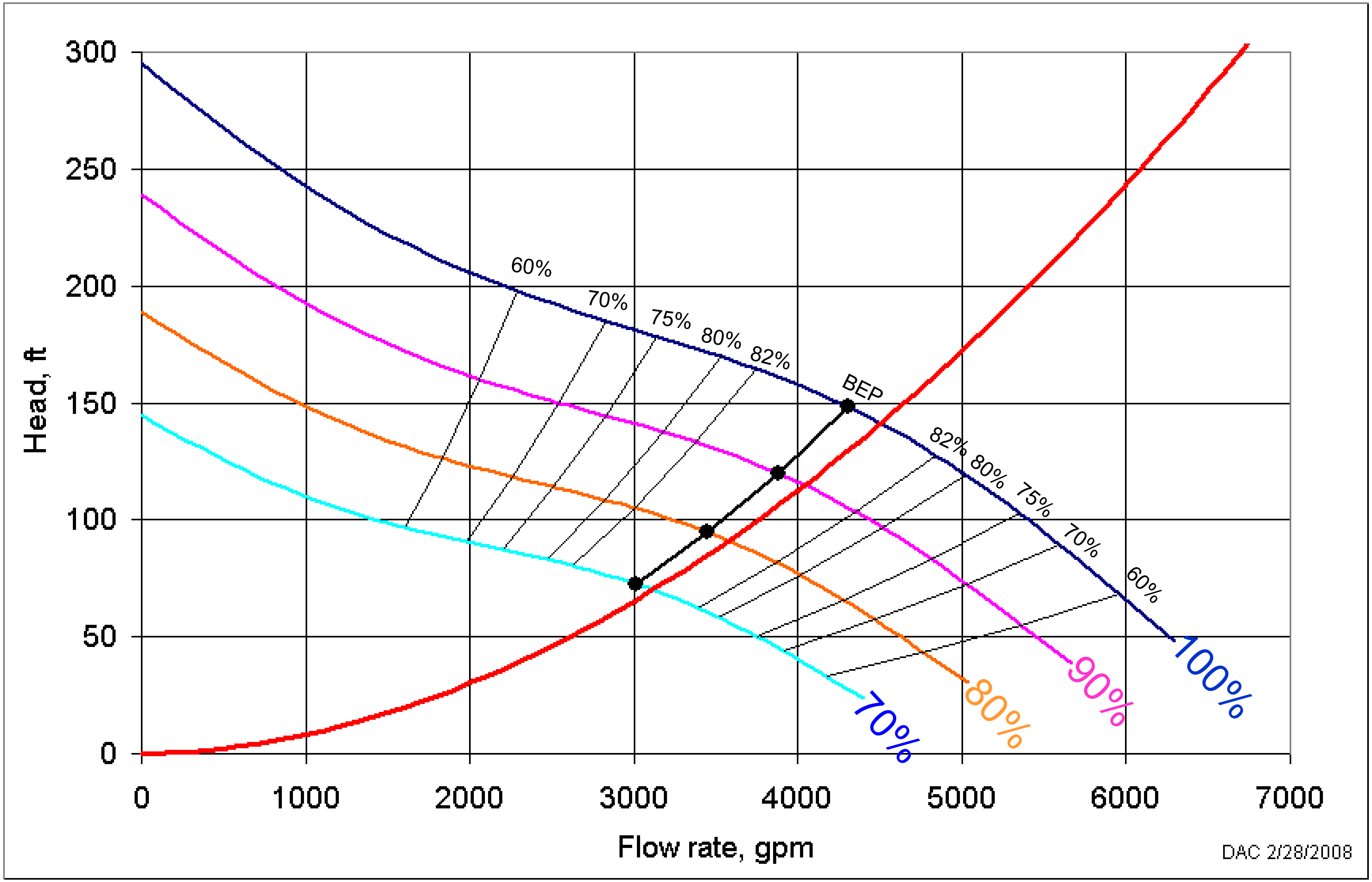


What happens if we reduce pump speed in the three systems types mentioned earlier?

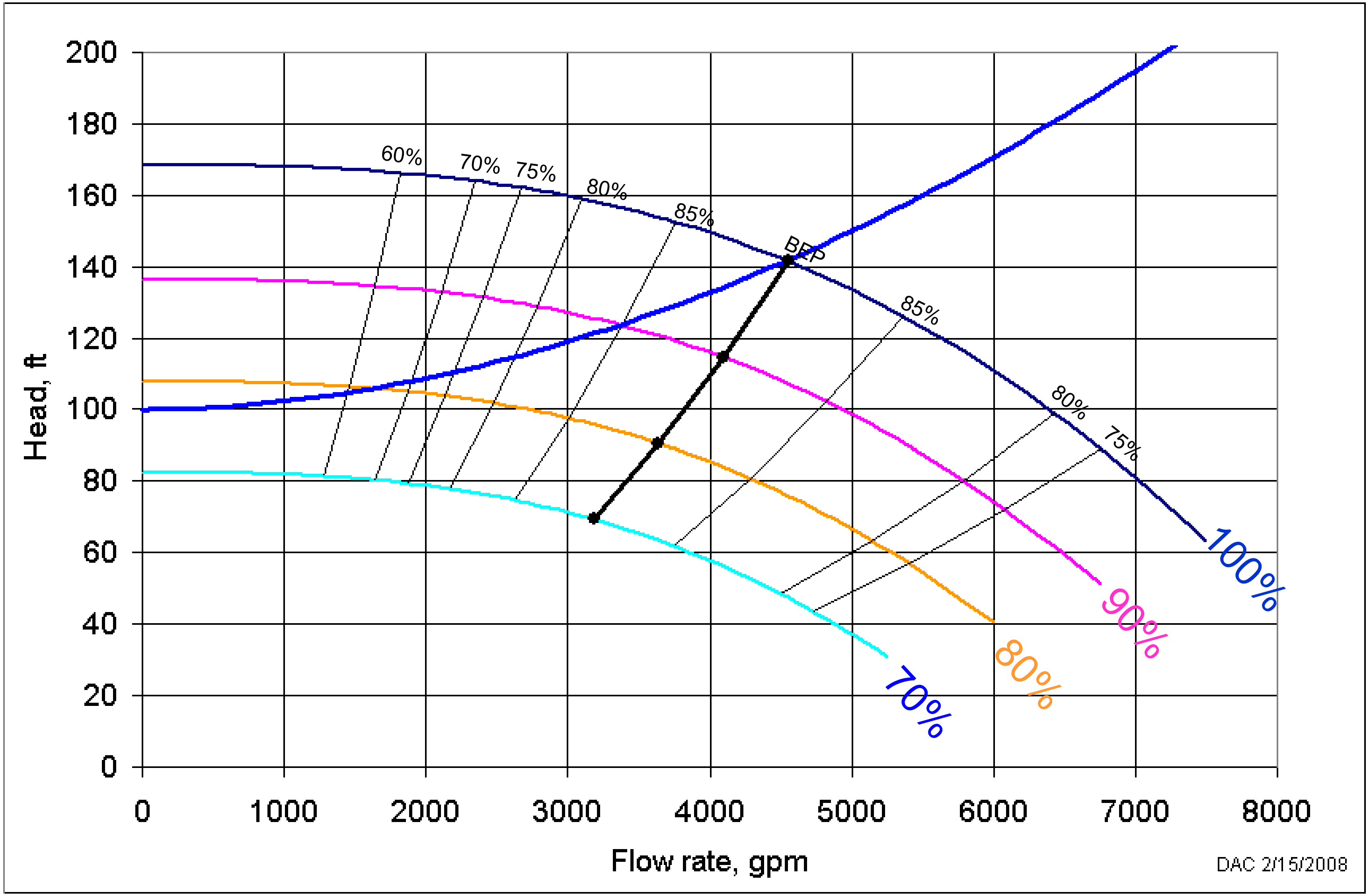
Change in speed for the all frictional system results in maintenance of constant pump efficiency (Pump 2)



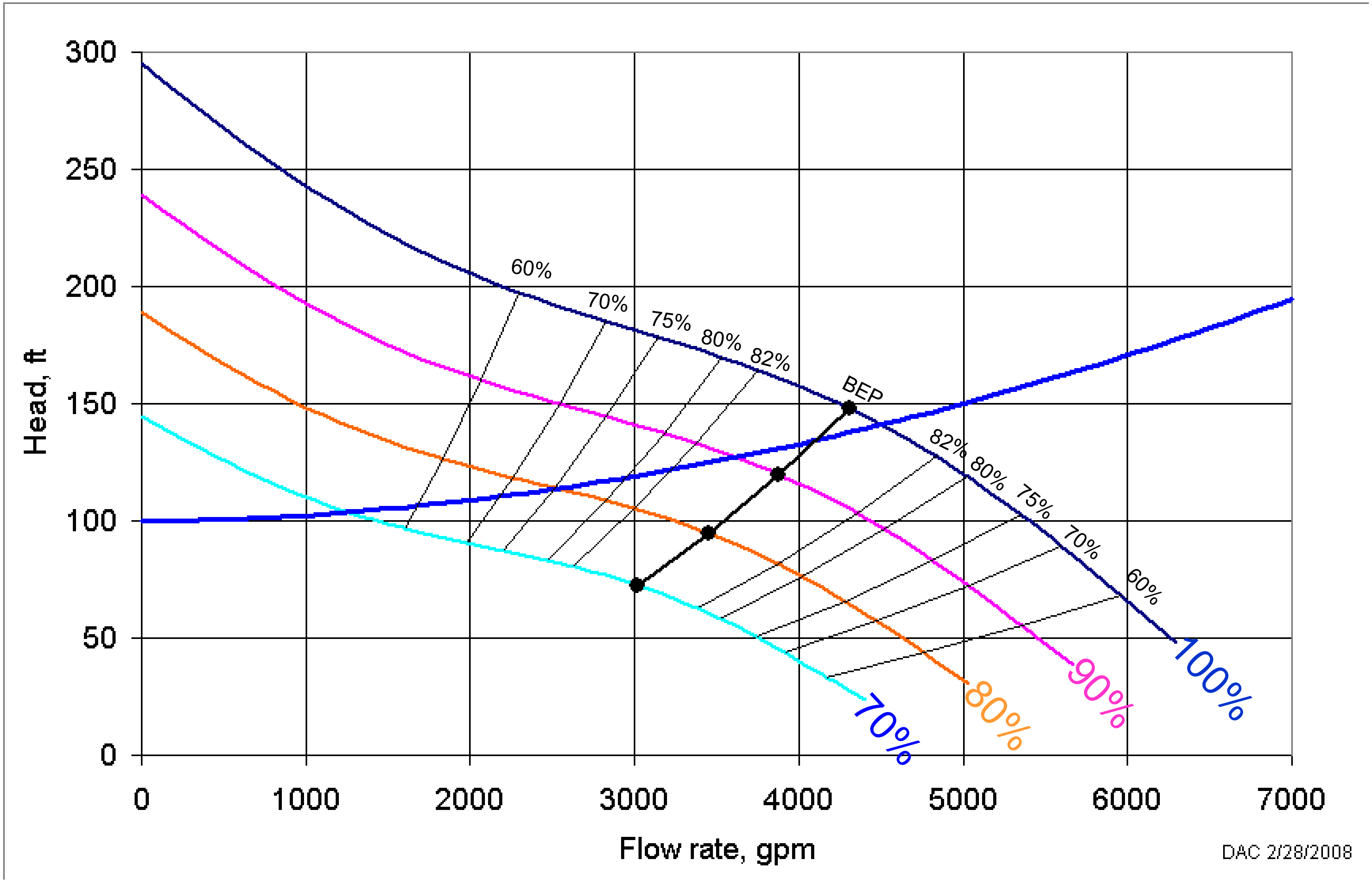
Change in speed for the all frictional system results in maintenance of constant pump efficiency (Pump 3)



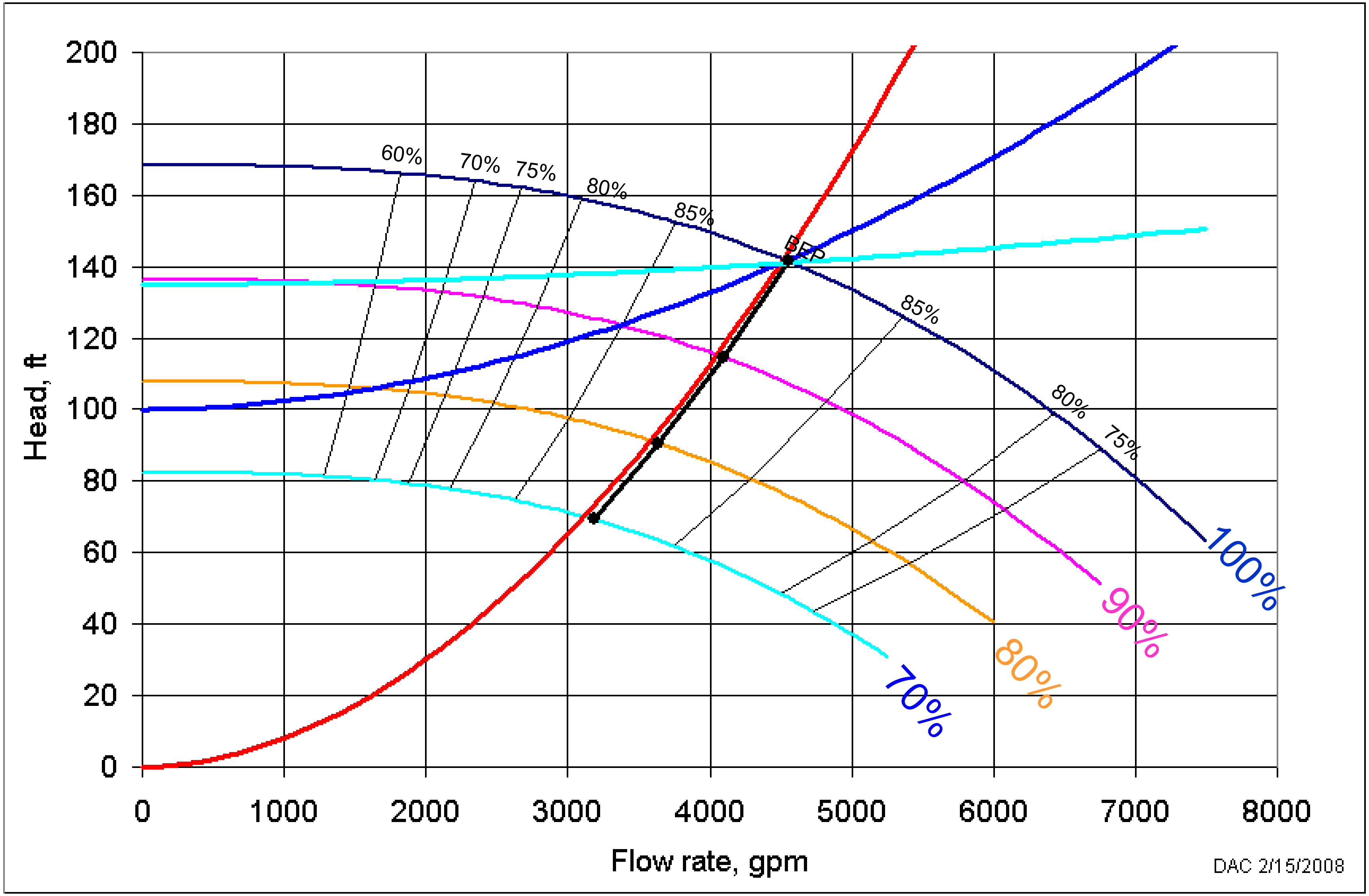
Change in speed for the 100-ft static system with Pump 2 results in loss of flow at ~78% speed



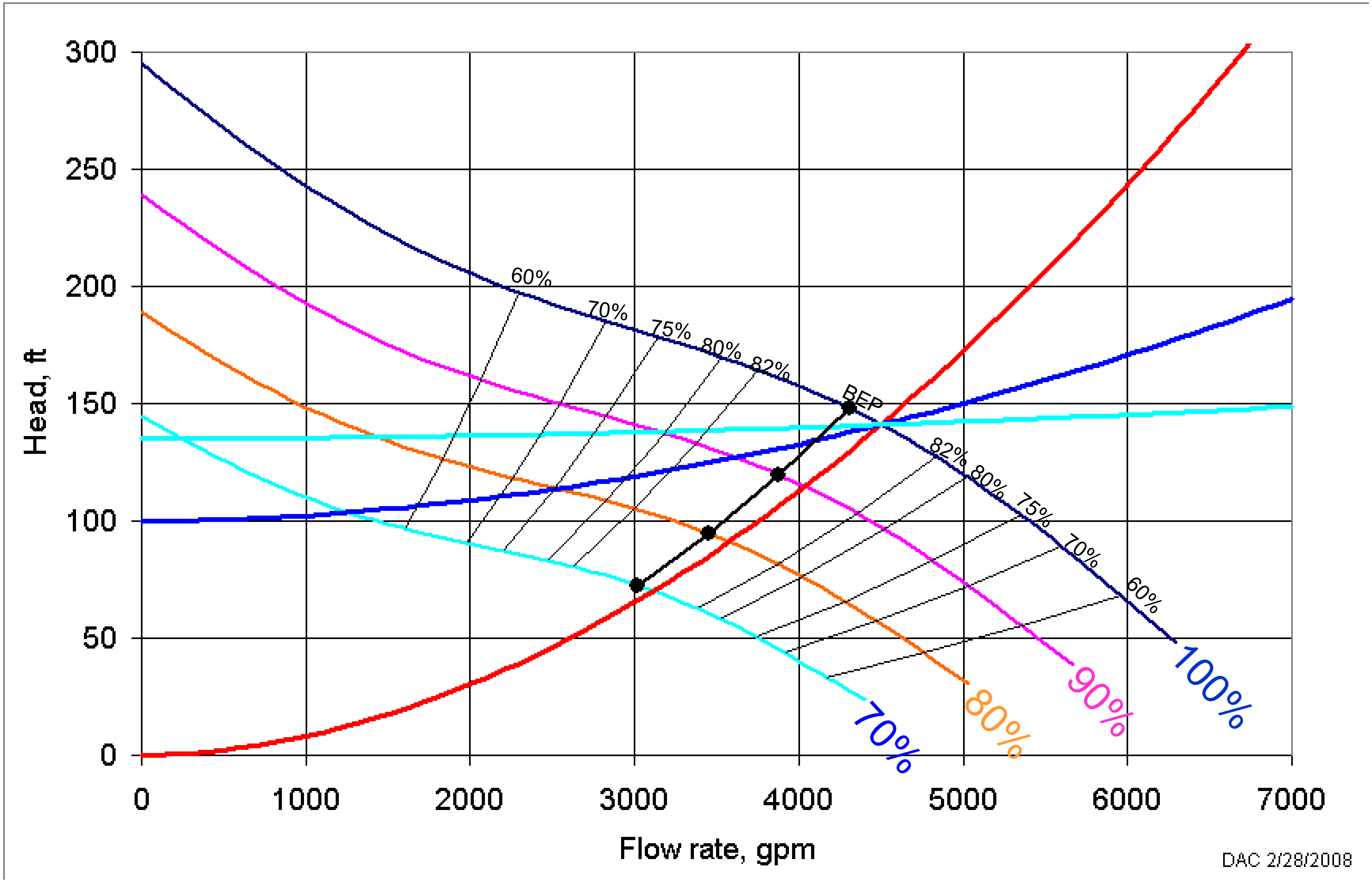
The steeper head-capacity curve for pump 3 makes for improved turndown and controllability



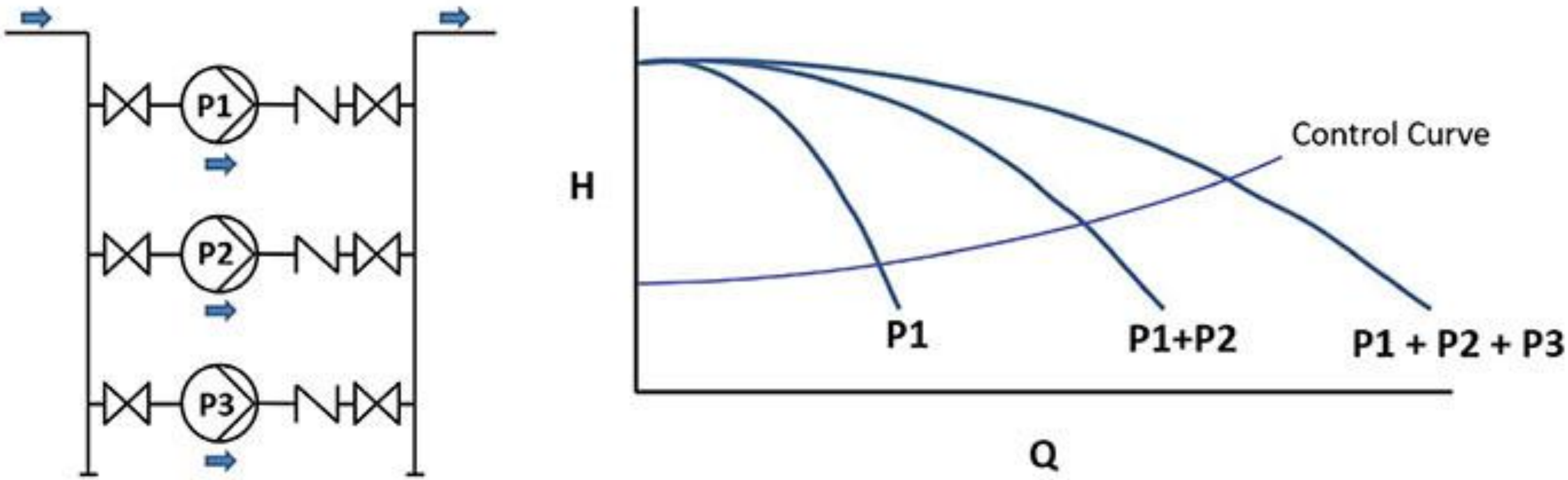
All three system curves with P2, variable speed



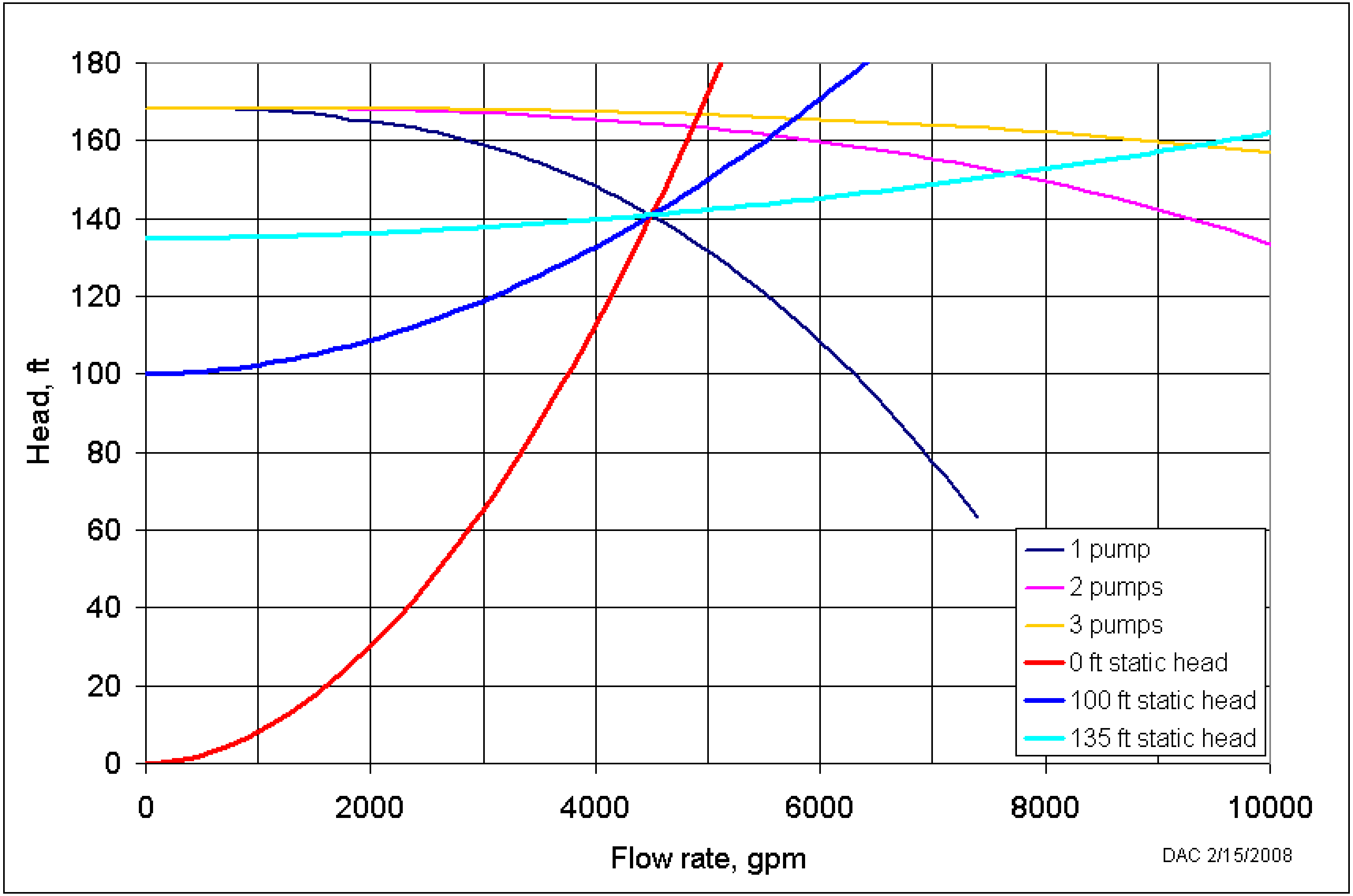
All three system curves with P3, variable speed



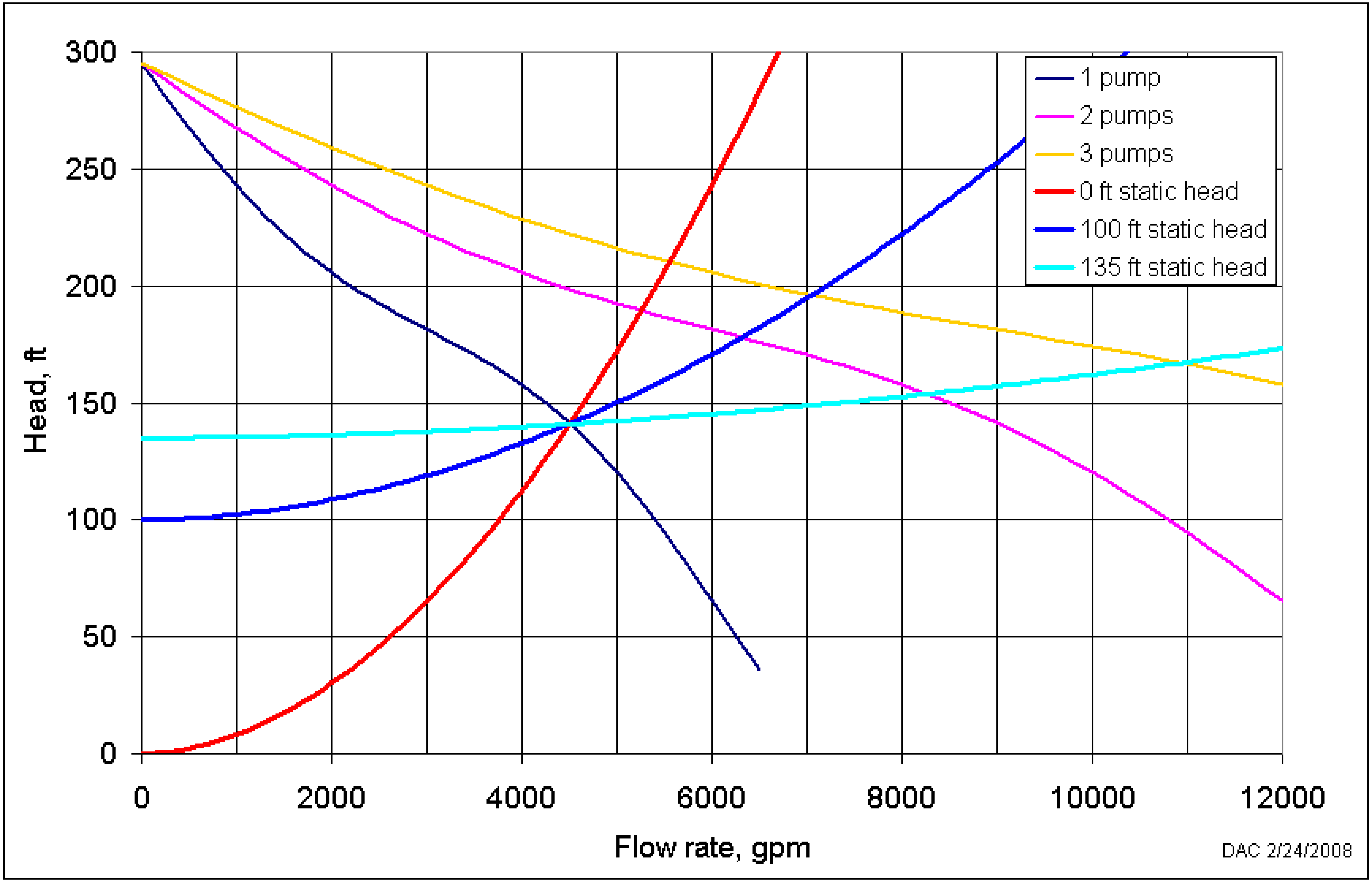
How about parallel pump operation with different system types?



Parallel pump response also depends on the nature of the system and pump curves (P2)



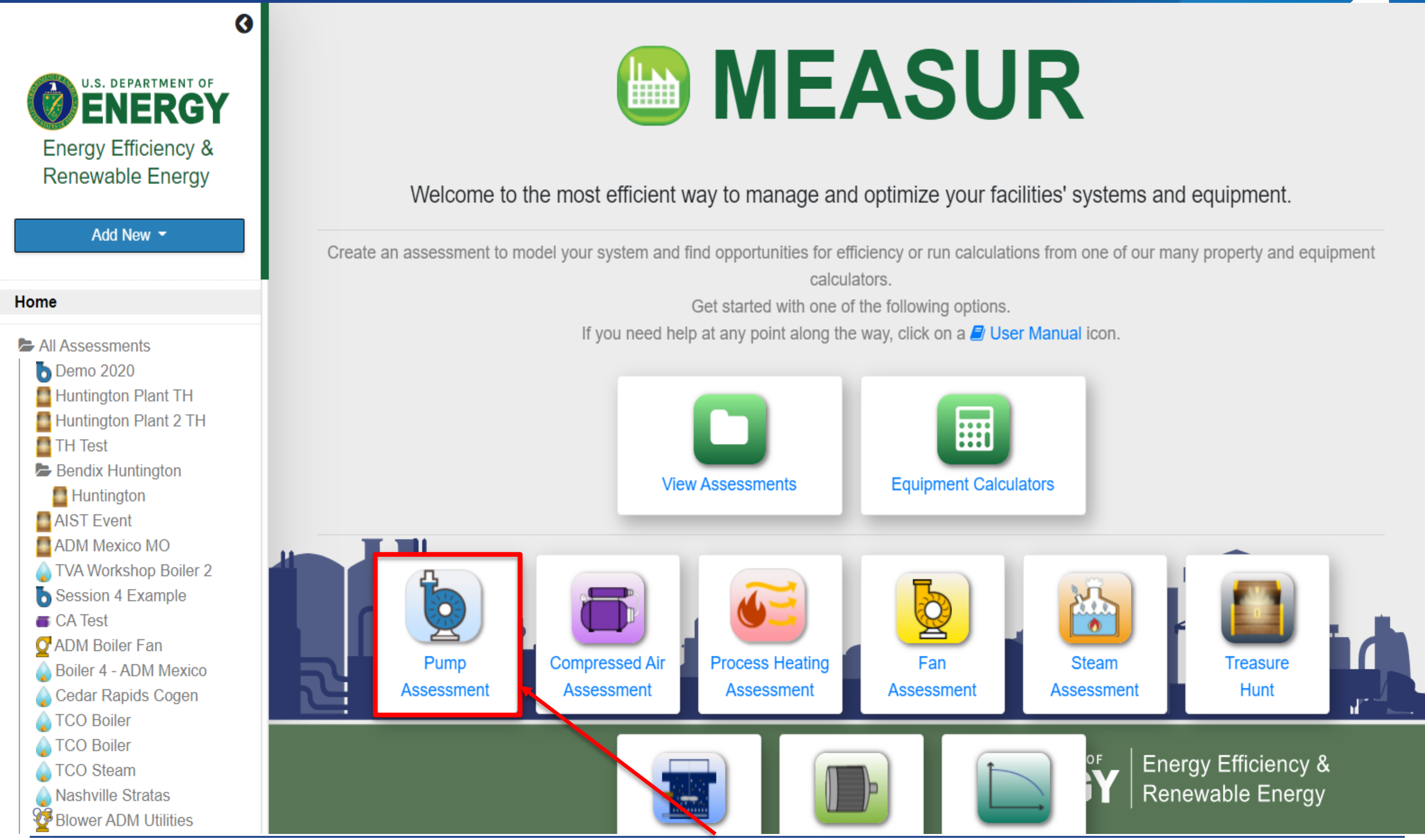
Parallel pump response also depends on the nature of the system and pump curves (P3)



An Introduction to the Pumping Assessment Tool in MEASUR

- Goal: to assist pump users in quantifying potential energy and cost savings
- Relies on process or field-measured fluid and electrical data
- Hydraulic Institute pump efficiency-estimating algorithms used to estimate achievable pump efficiency
- Published motor manufacturer data (motors in the Motormaster database plus other published motor data) were used to develop curve fit-based performance predictions

Open the MEASUR Software



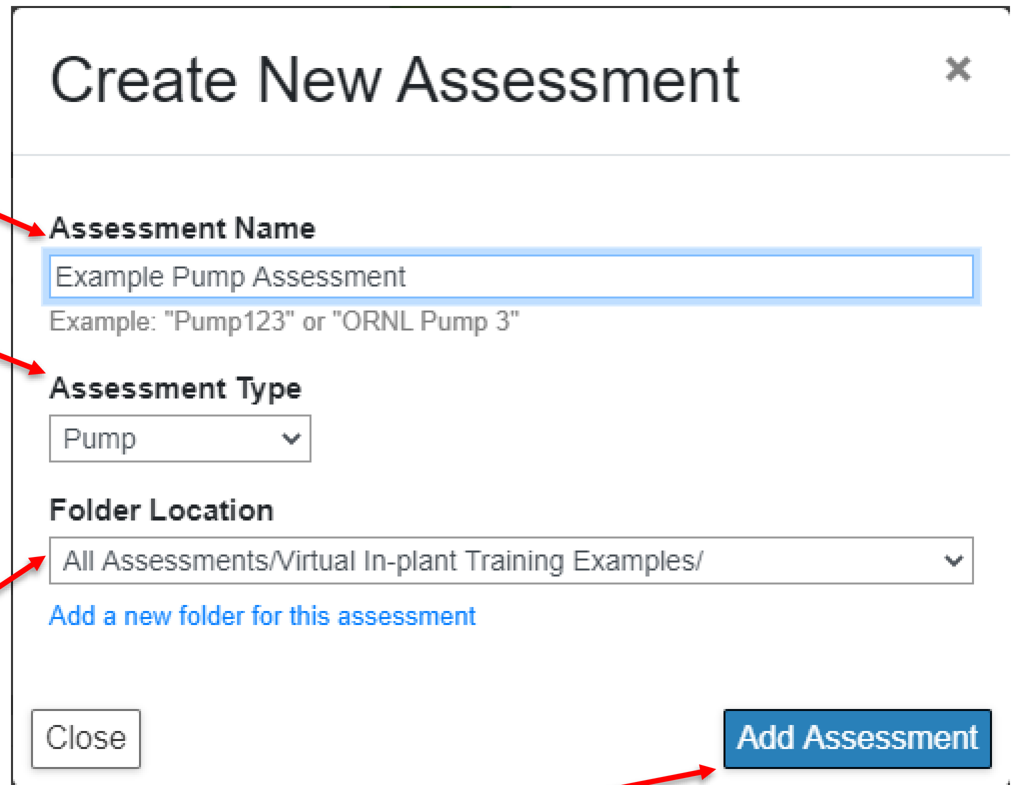
Click on Pump Assessment

Create New Pump Assessment

Name the Assessment

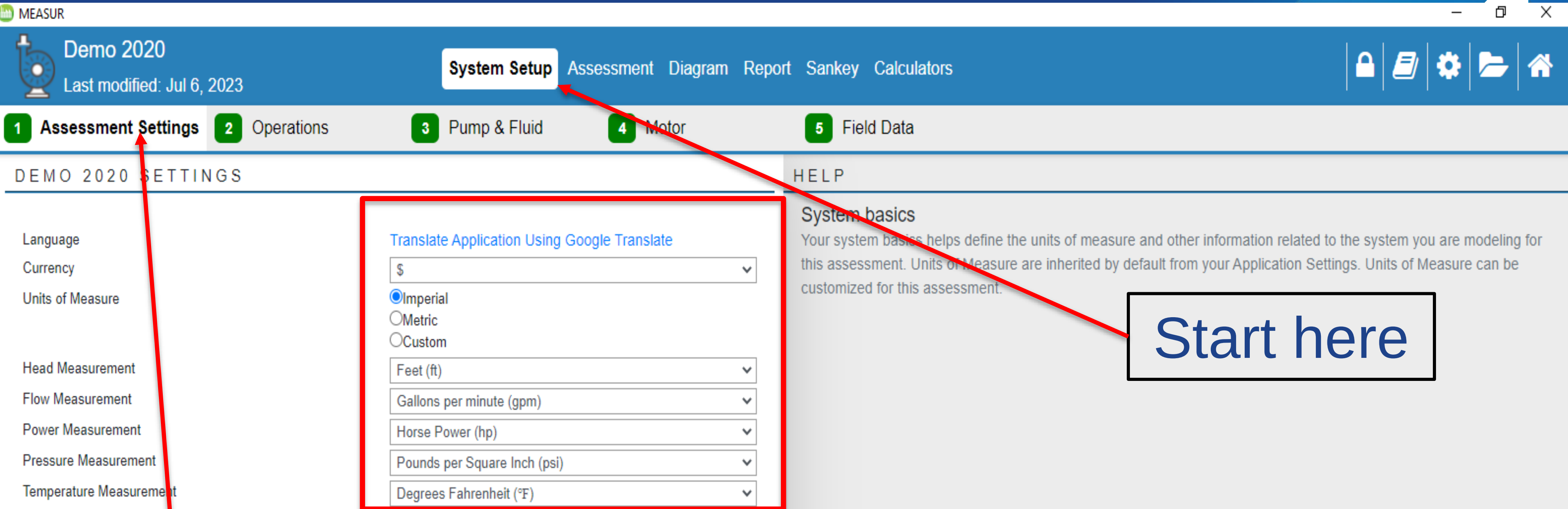
Select the Assessment Type

Select where you want the file saved on your computer



Finally, Click on Add Assessment

System Setup – Assessment Settings



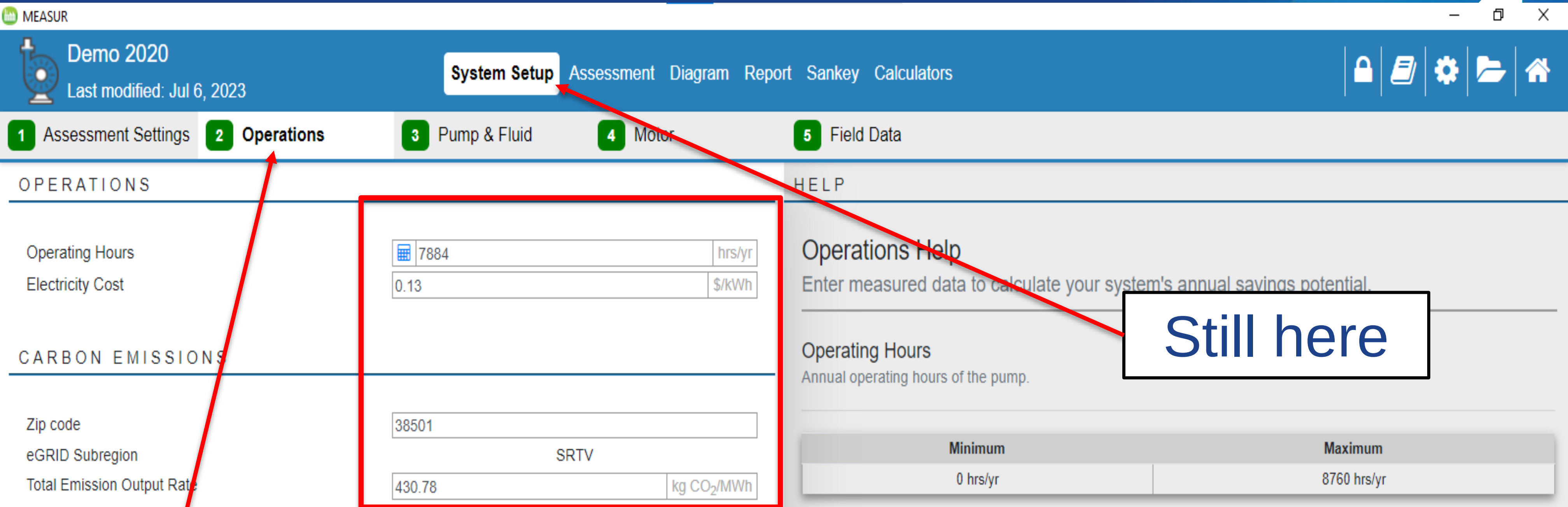
Start here

Then here

Select the language and units you want to work with

Finally, Click on Operations to continue

System Setup – Assessment Settings



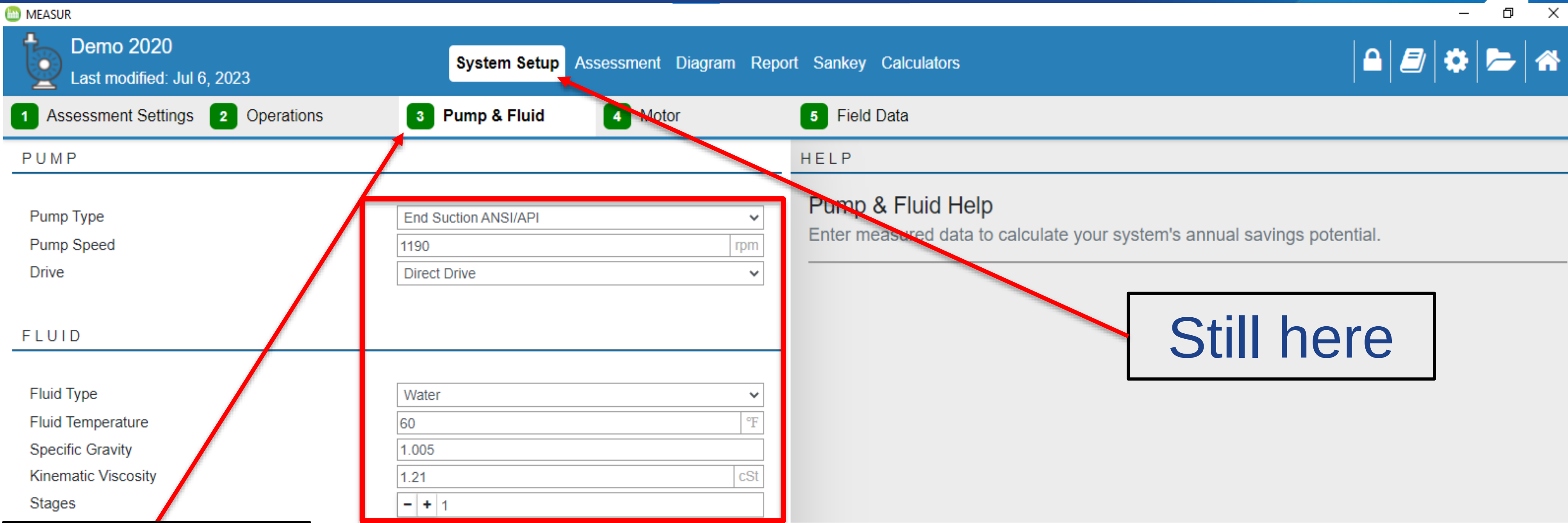
Still here

Now here

Enter Hours of Operation, Electric Cost & Zip Code

Finally, Pump & Fluid to continue

System Setup – Pump & Fluid



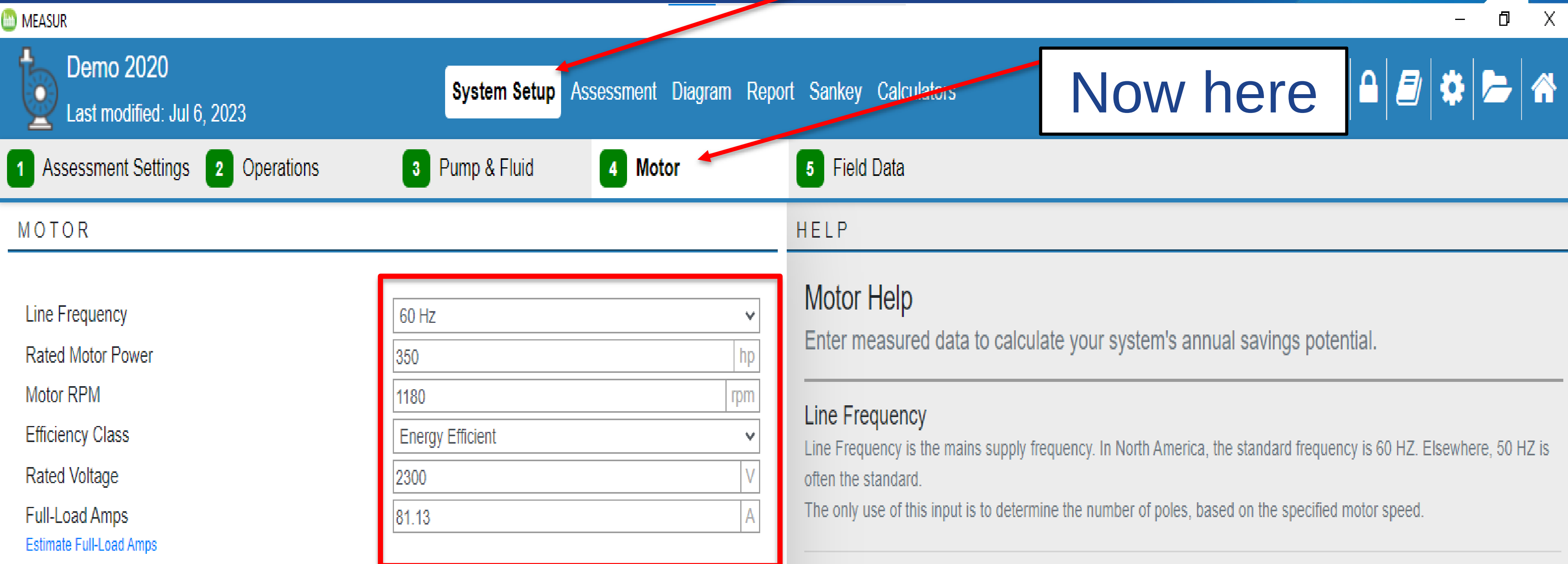
Now here

Input pump and fluid information

Finally, Click on Motor to continue

System Setup – Motor

Still here



Now here

Input Motor information

Finally, Click on Field Data to continue

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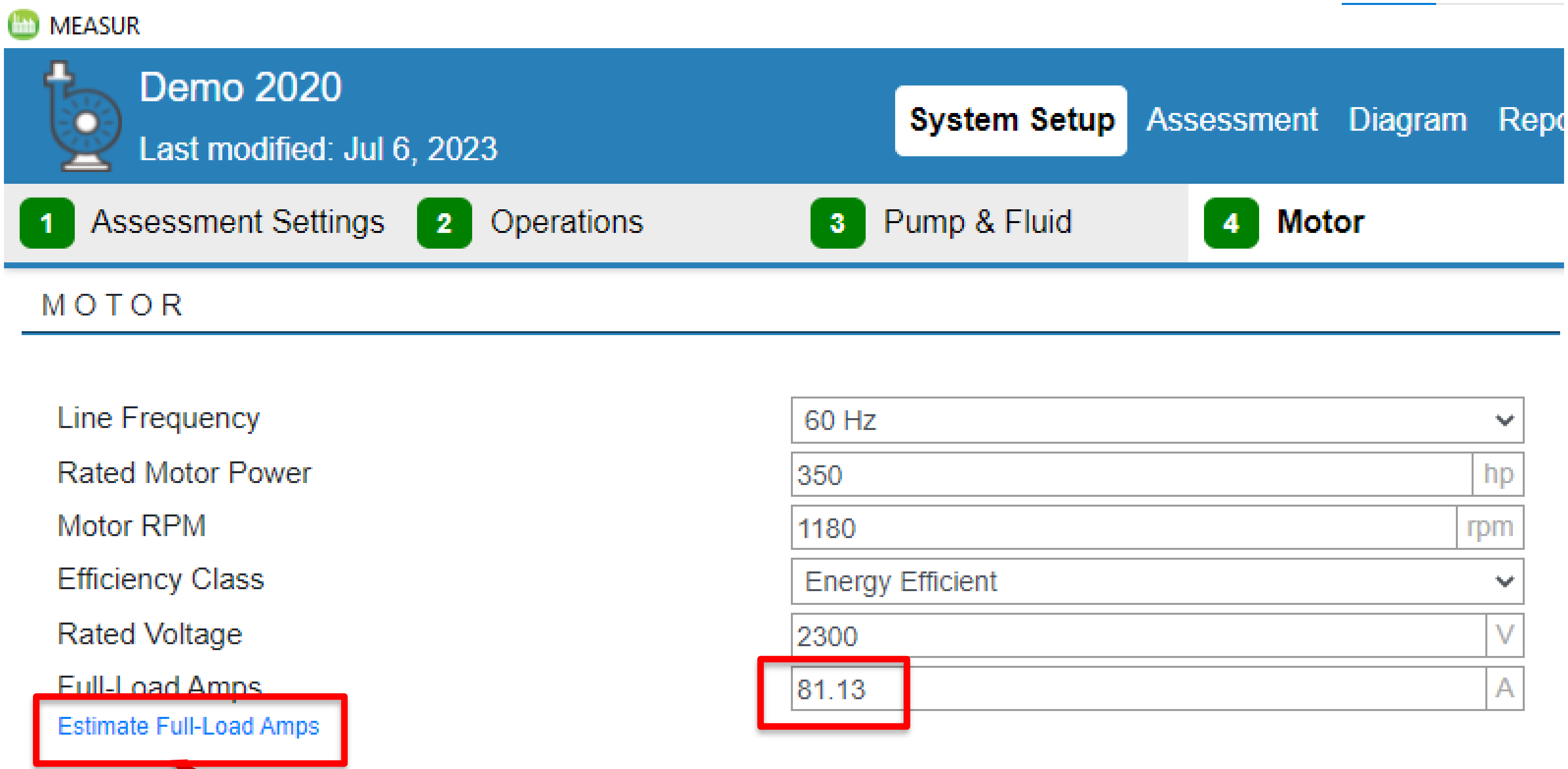
System Setup – Estimate Full Load Amps

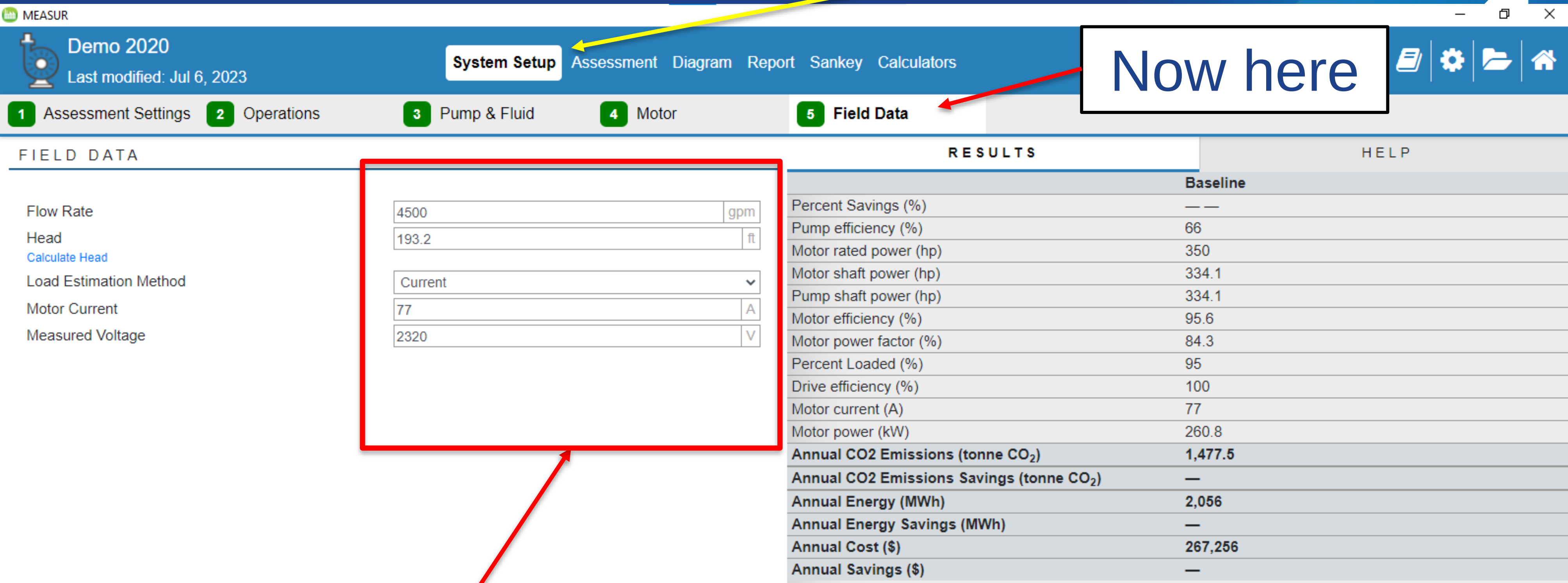


Can estimate full load motor amps by clicking here

System Setup – Field Data

Still here

Now here

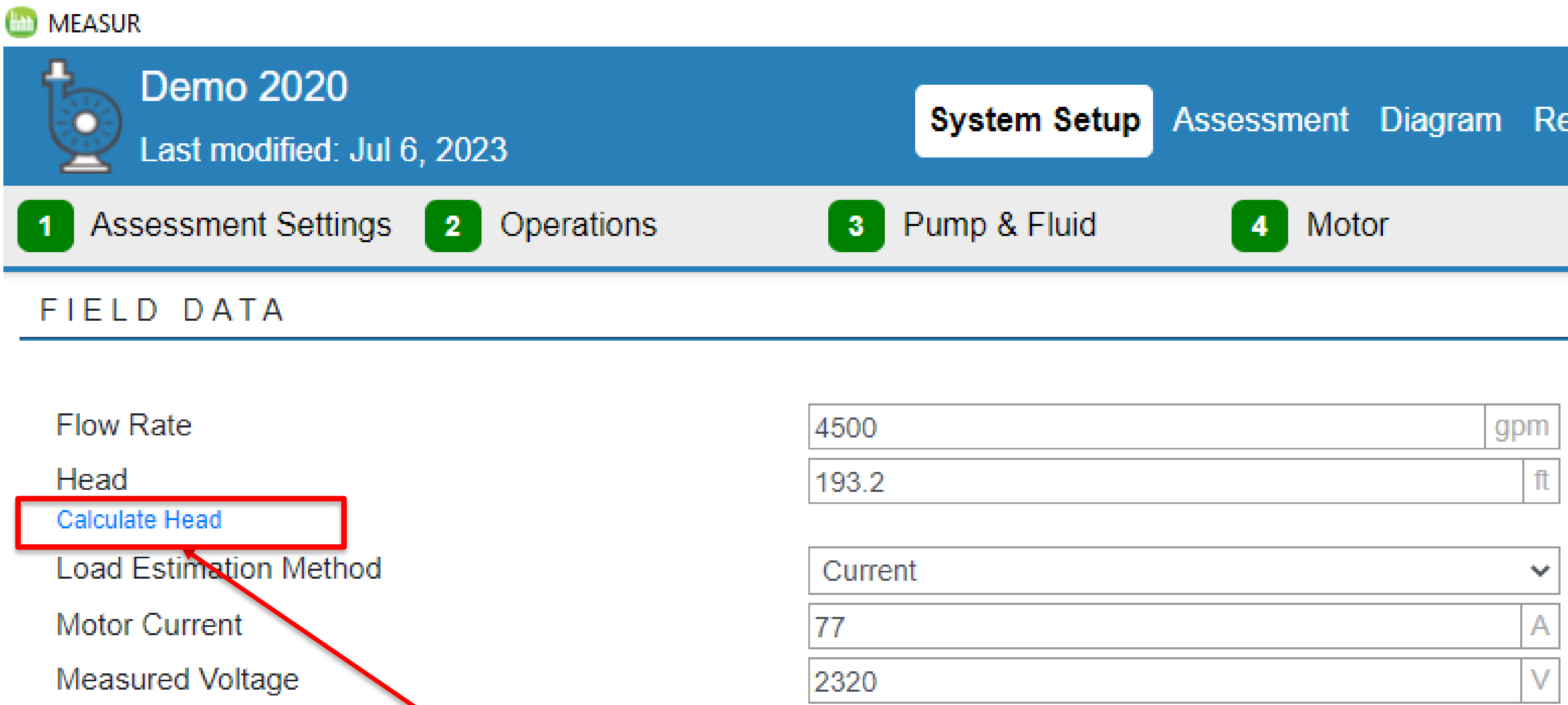


Input Field Data

Baseline Results

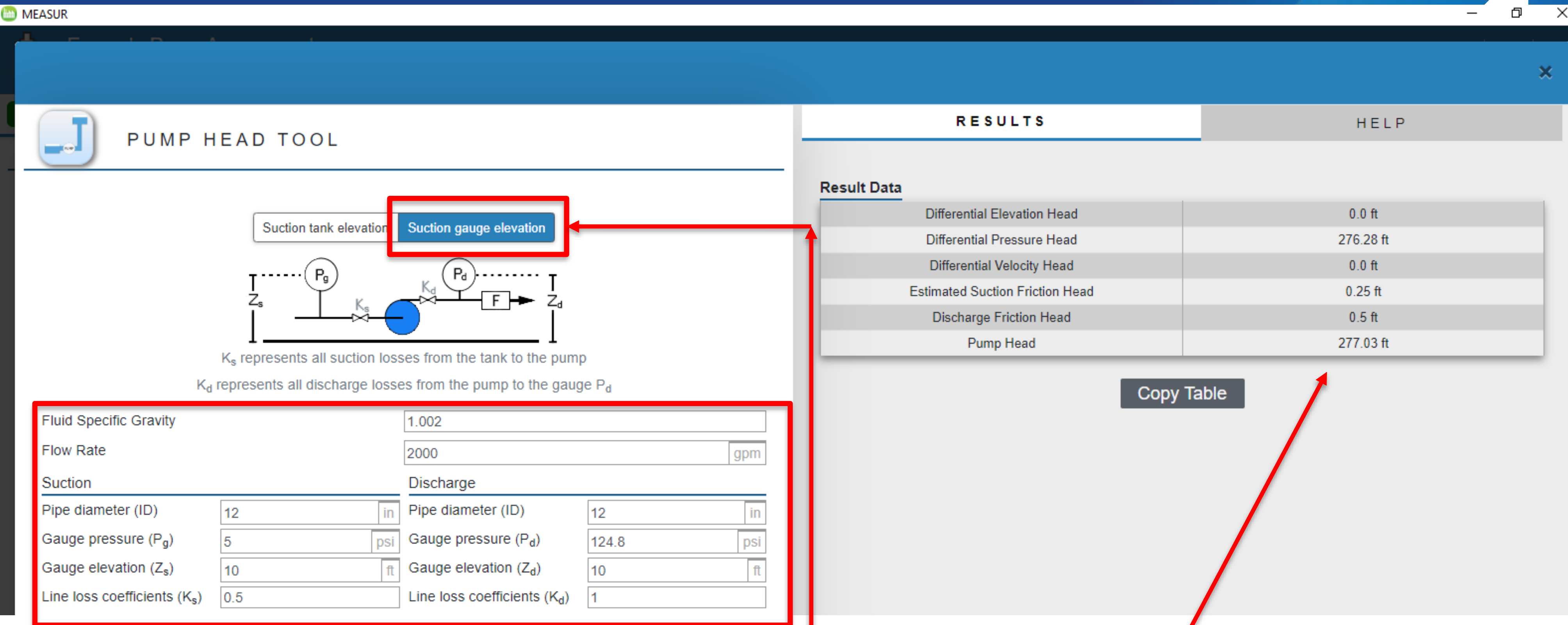
After Field Data, move on to the Assessment

System Setup – Calculate Pump Head



Go to the pump head calculator by clicking here

System Setup – Pump Head Calculator



Input Field Data

Pump Head

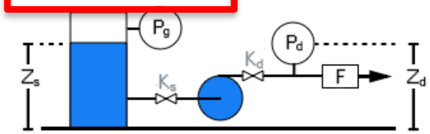
Two Different Geometries: Suction Gauge

System Setup – Pump Head Calculator

MEASUR

PUMP HEAD TOOL

Suction tank elevation | Suction gauge elevation



K_s represents all suction losses from the tank to the pump

K_d represents all discharge losses from the pump to the gauge P_d

Fluid Specific Gravity: 1.002

Flow Rate: 2000 gpm

Suction		Discharge	
Pipe diameter (ID)	12 in	Pipe diameter (ID)	12 in
Tank gas overpressure (P_g)	0 psi	Gauge pressure (P_d)	124 psi
Tank fluid surface elevation (Z_s)	10 ft	Gauge elevation (Z_d)	10 ft
Line loss coefficients (K_s)	0.5	Line loss coefficients (K_d)	1

RESULTS | HELP

Result Data

Differential Elevation Head	0.0 ft
Differential Pressure Head	285.97 ft
Differential Velocity Head	0.5 ft
Estimated Suction Friction Head	0.25 ft
Discharge Friction Head	0.5 ft
Pump Head	287.22 ft

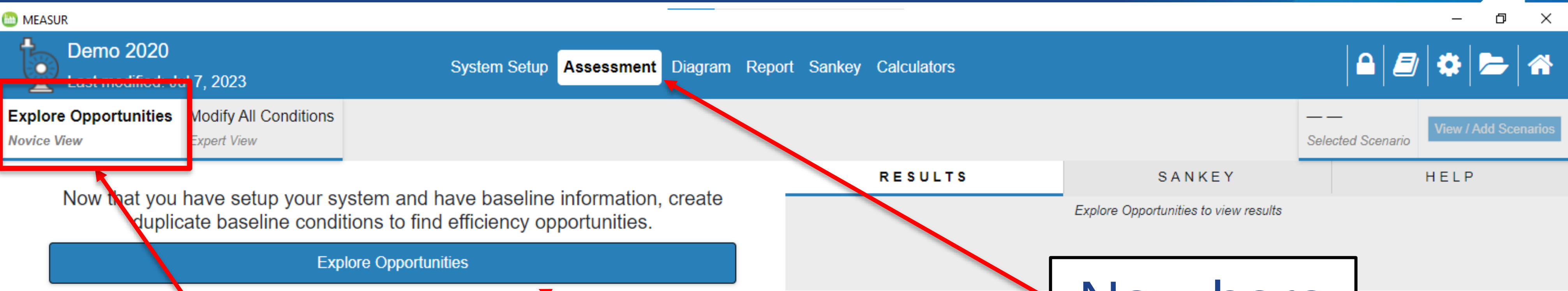
Copy Table

Input Field Data

Pump Head

Two Different Geometries: Suction Tank

Assessment View – Novice



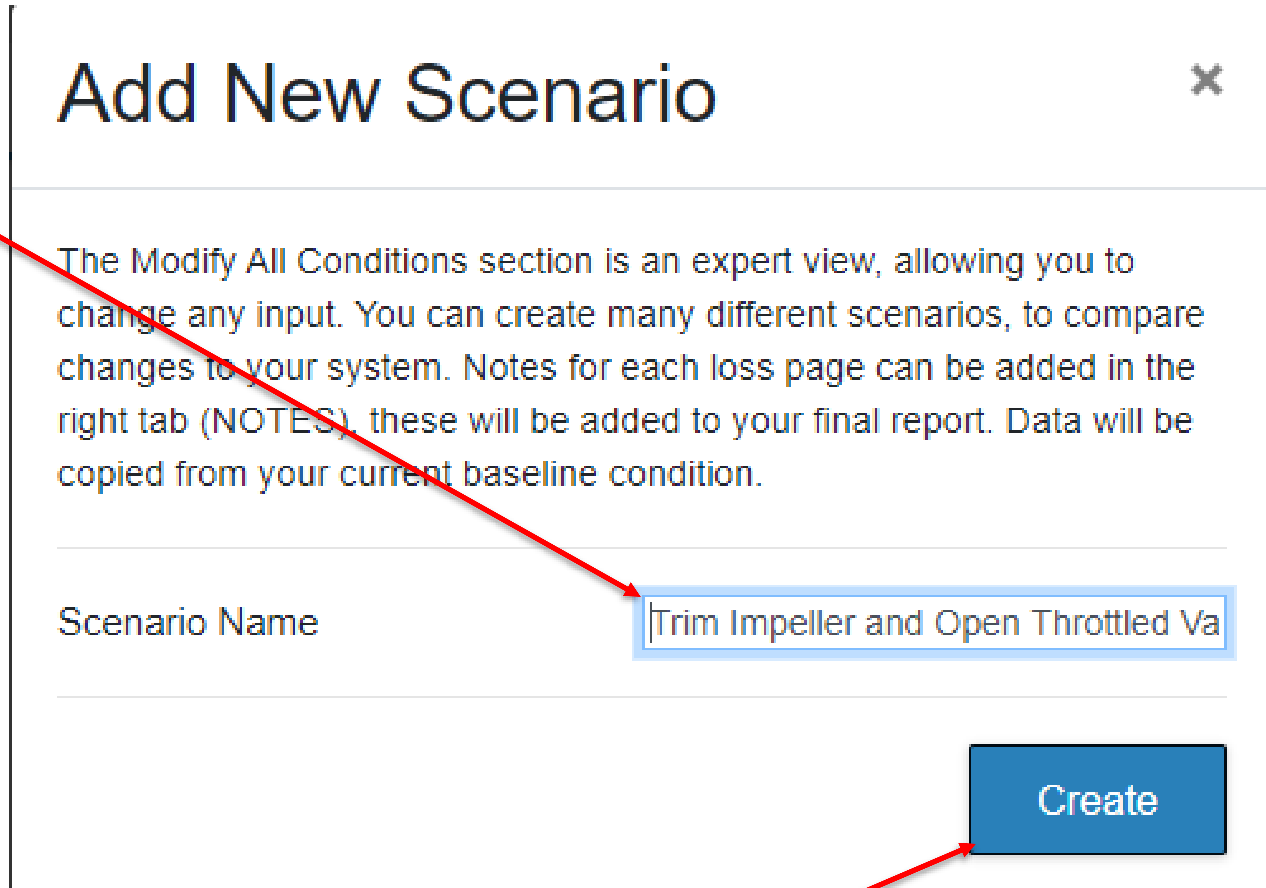
Now here

Novice View

Click Explore Opportunities to evaluate a potential project

Evaluate Potential Project

Name the Opportunity



Click on Create

Assessment View – Novice

MEASUR

Demo 2020
Last modified: Jul 7, 2023

System Setup | **Assessment** | Diagram | Report | Sankey | Calculators

Explore Opportunities *Novice View* | Modify All Conditions *Expert View*

Trim Impeller *Selected Scenario* | View / Add Scenarios

SELECT POTENTIAL ADJUSTMENT PROJECTS

Select potential adjustment projects to explore opportunities to increase efficiency and the effectiveness of your system.

Add New Scenario

Modification Name: Trim Impeller

- [ ] Install VFD
- [ ] Install More Efficient Drive
- [x] Install More Efficient Pump

Baseline Pump Type: End Suction ANSI/API

Modification Pump Efficiency (Optimize Pump): 62 %

The efficiency of your pump has been calculated based on your system setup. Either directly modify your efficiency or click **"Optimize Pump"** to estimate your pump efficiency based on a different pump type.

- [ ] Reduce System Flow Rate
- [x] Reduce System Head Requirement

Baseline Head: 193 ft

Modification Head: 160 ft (Calculate Head)

- [ ] Adjust Operational Data
- [ ] Install More Efficient Motor

Back

RESULTS | SANKEY | HELP

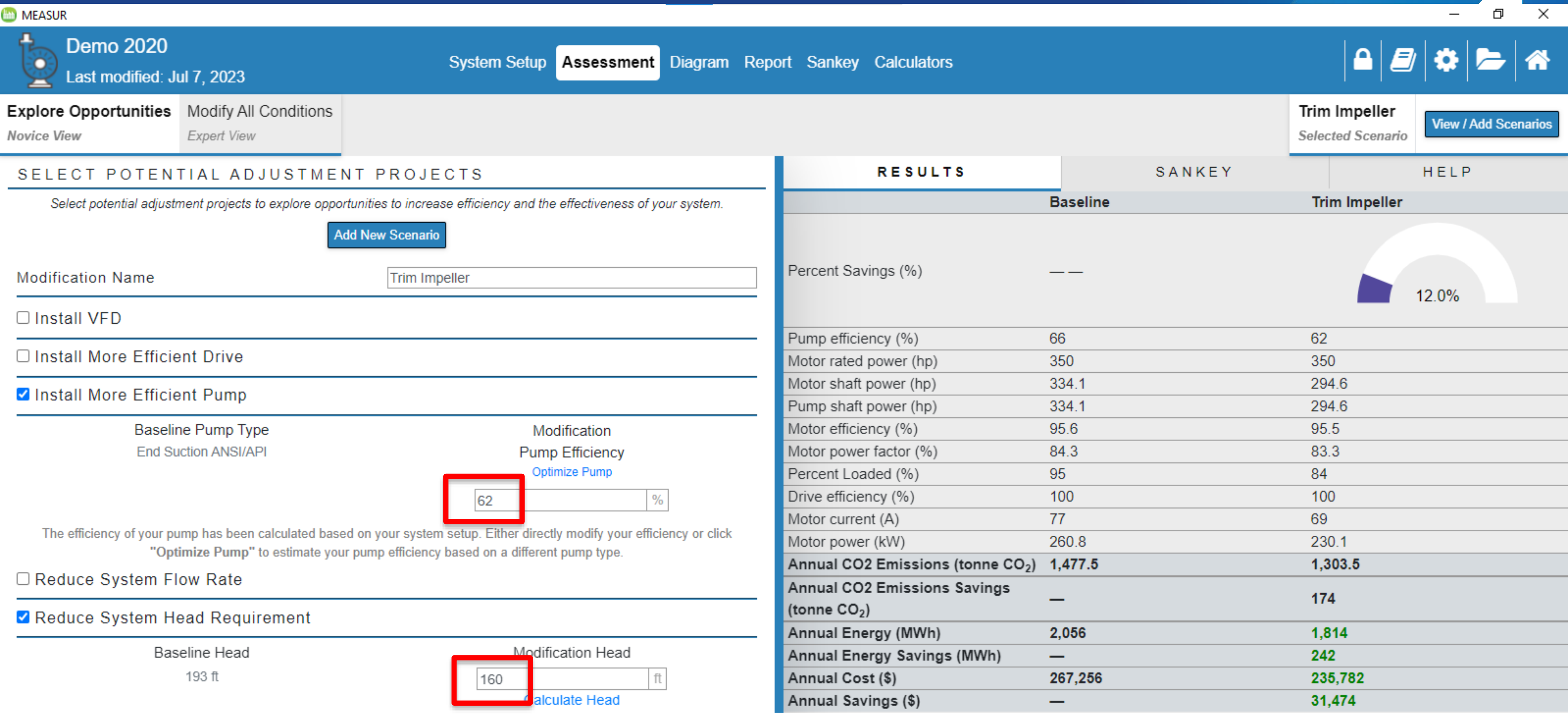
	Baseline	Trim Impeller
Percent Savings (%)	— —	12.0%
Pump efficiency (%)	66	62
Motor rated power (hp)	350	350
Motor shaft power (hp)	334.1	294.6
Pump shaft power (hp)	334.1	294.6
Motor efficiency (%)	95.6	95.5
Motor power factor (%)	84.3	83.3
Percent Loaded (%)	95	84
Drive efficiency (%)	100	100
Motor current (A)	77	69
Motor power (kW)	260.8	230.1
Annual CO2 Emissions (tonne CO_2)	**1,477.5**	**1,303.5**
Annual CO2 Emissions Savings (tonne CO_2)	**—**	**174**
Annual Energy (MWh)	**2,056**	**1,814**
Annual Energy Savings (MWh)	**—**	**242**
Annual Cost ($)	**267,256**	**235,782**
Annual Savings ($)	**—**	**31,474**

View Report

Select the type of project

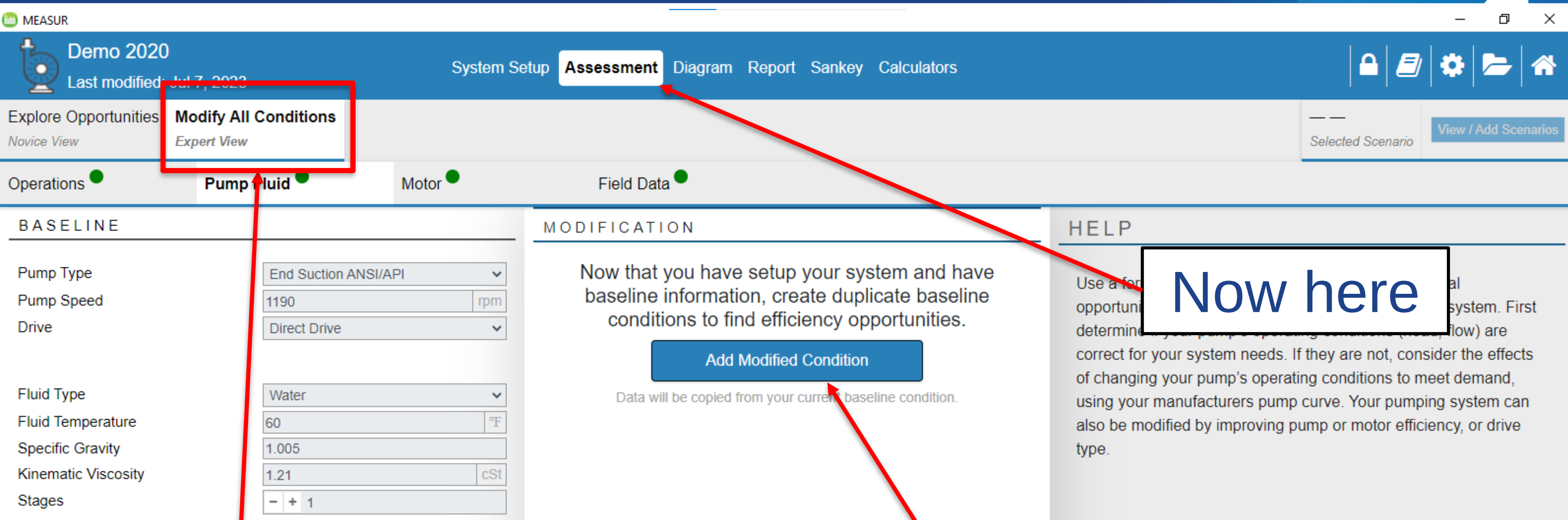
Have throttled pump with constant flow

Assessment View – Novice



Reduce Pump Head by 33 Feet by Trimming the Impeller and Opening the Throttled Valve. Pump efficiency falls by 4%.

Assessment View – Expert

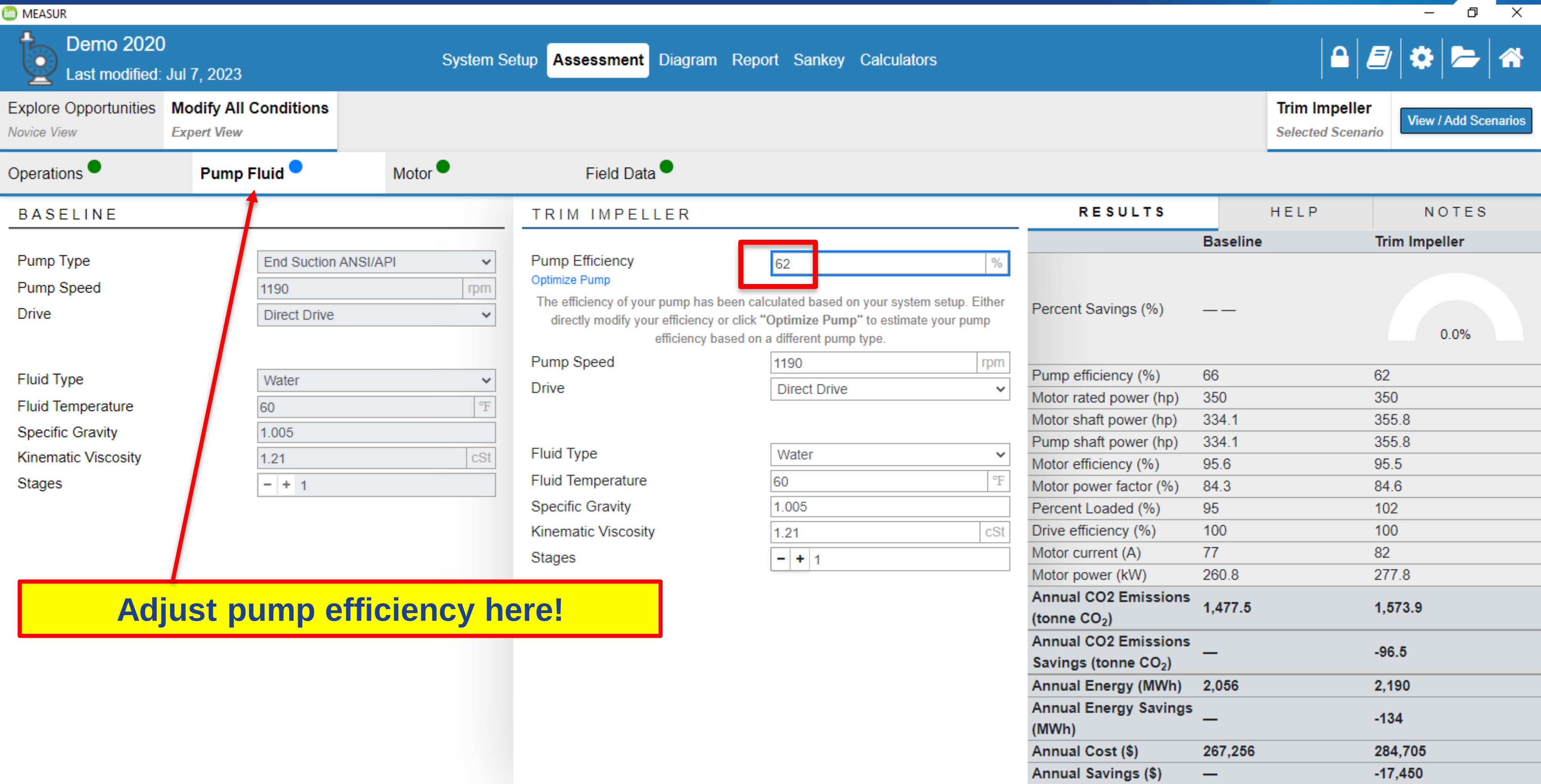


Now here

Expert View

Click Modified Condition to evaluate a potential project

Assessment View – Expert



Pump efficiency dropped to 62%

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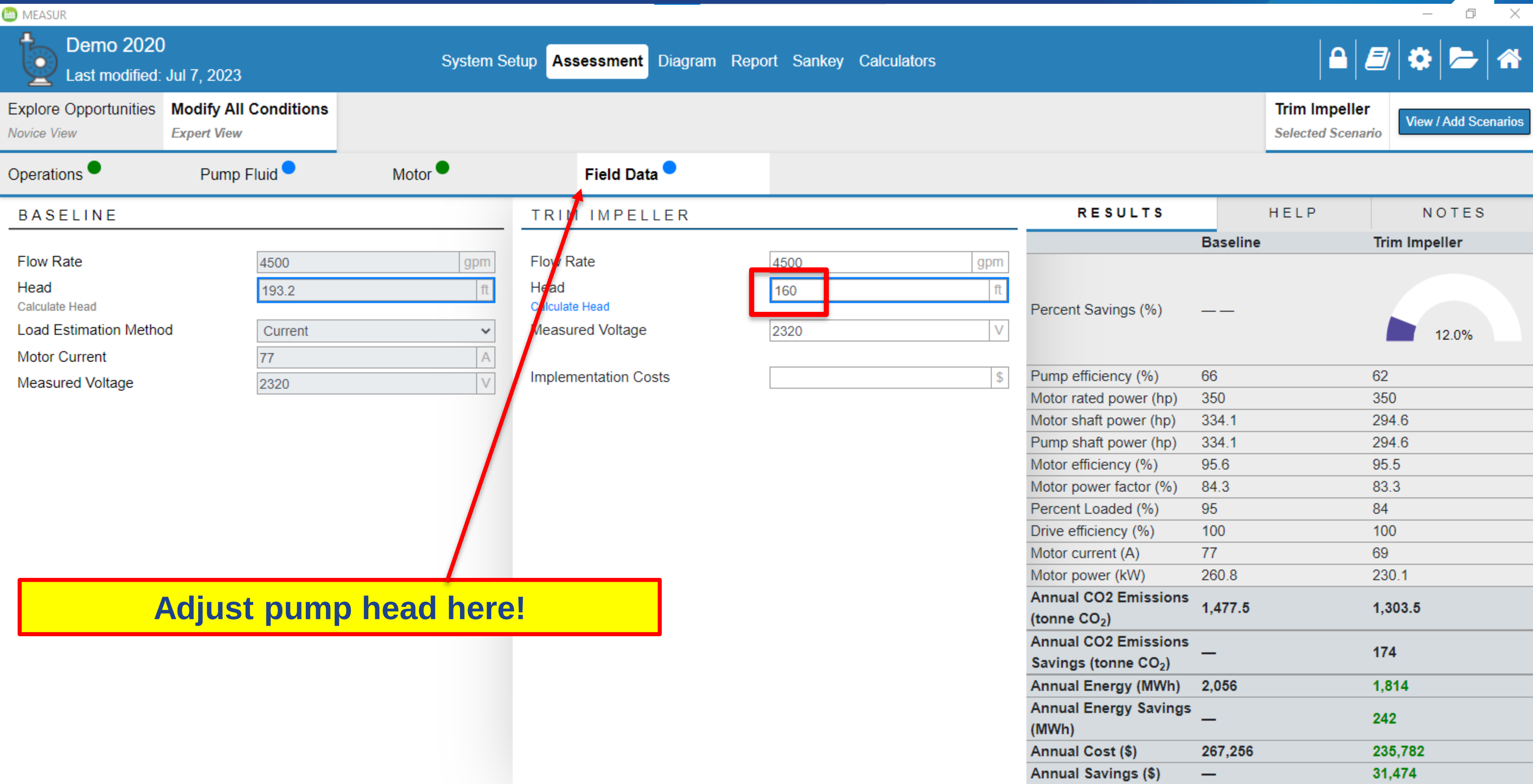
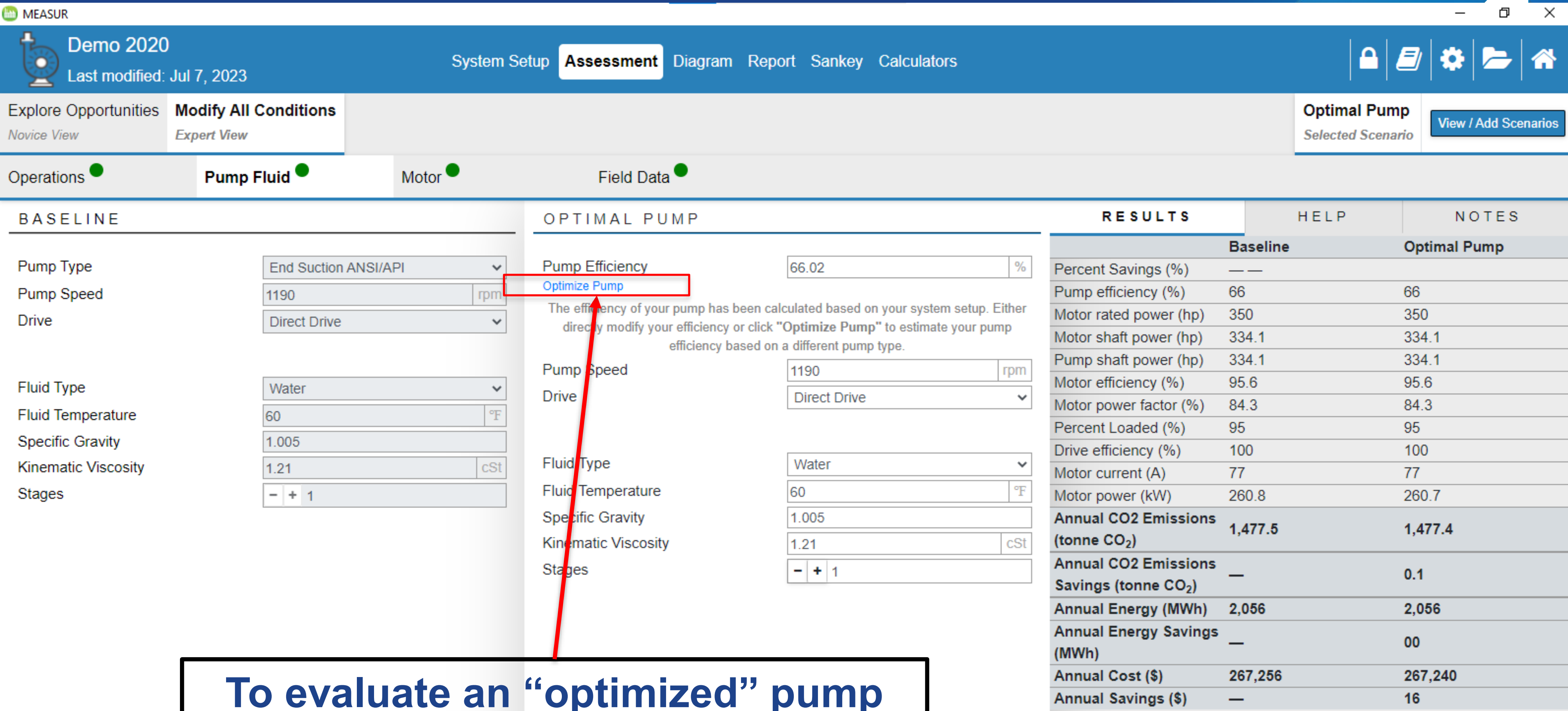
Assessment View – Expert



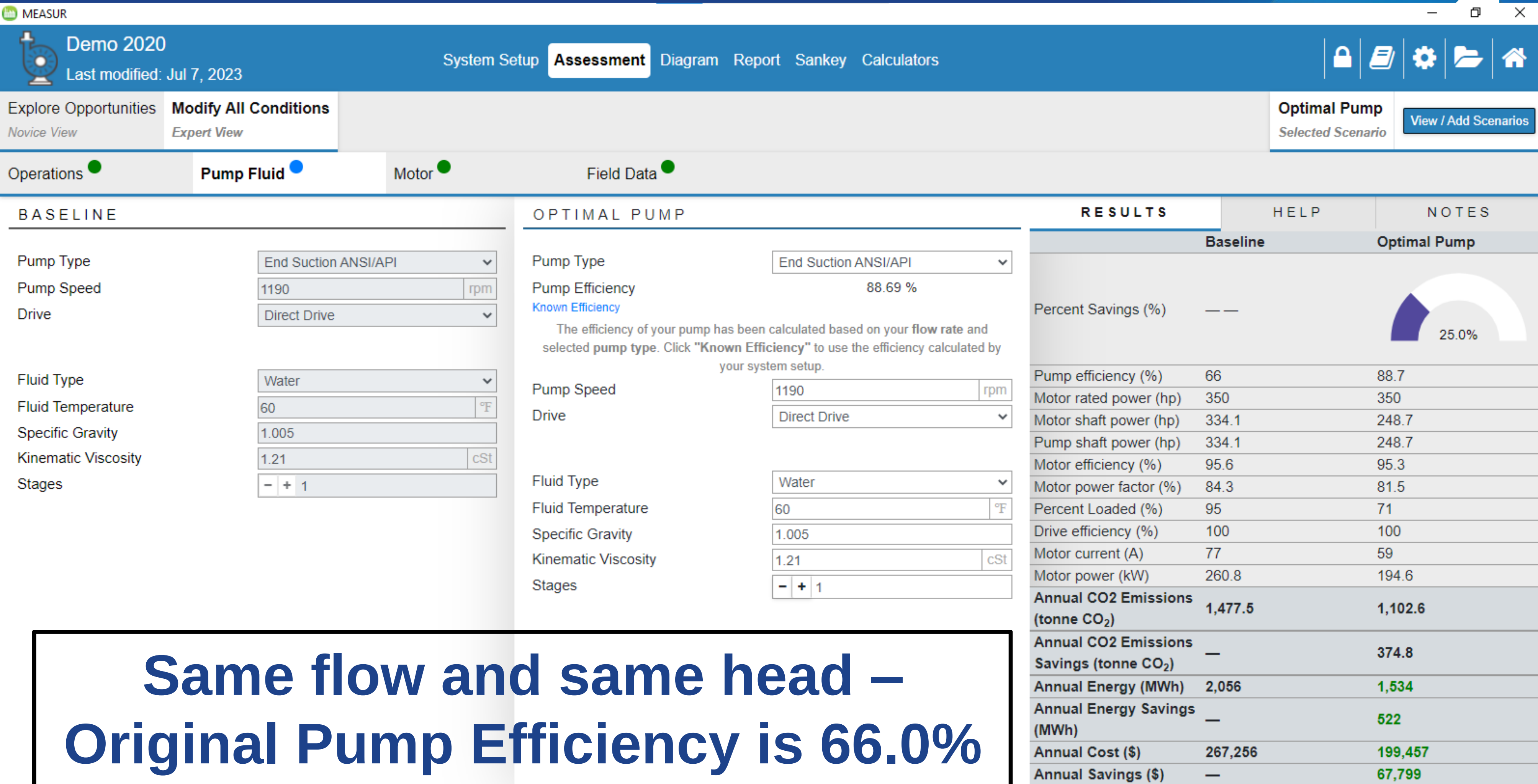
Pump head dropped to 160 feet

Compare Existing Pump to Optimal Pump



To evaluate an "optimized" pump based on Hydraulic Institute algorithms click here

Optimize Pump w/ Hydraulic Institute Algorithms



Same flow and same head –
Original Pump Efficiency is 66.0%
Optimal Pump is 88.7%

The End for Session 2