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U.S. DEPARTMENT OF ENERGY

Pumping System Assessment

Summary

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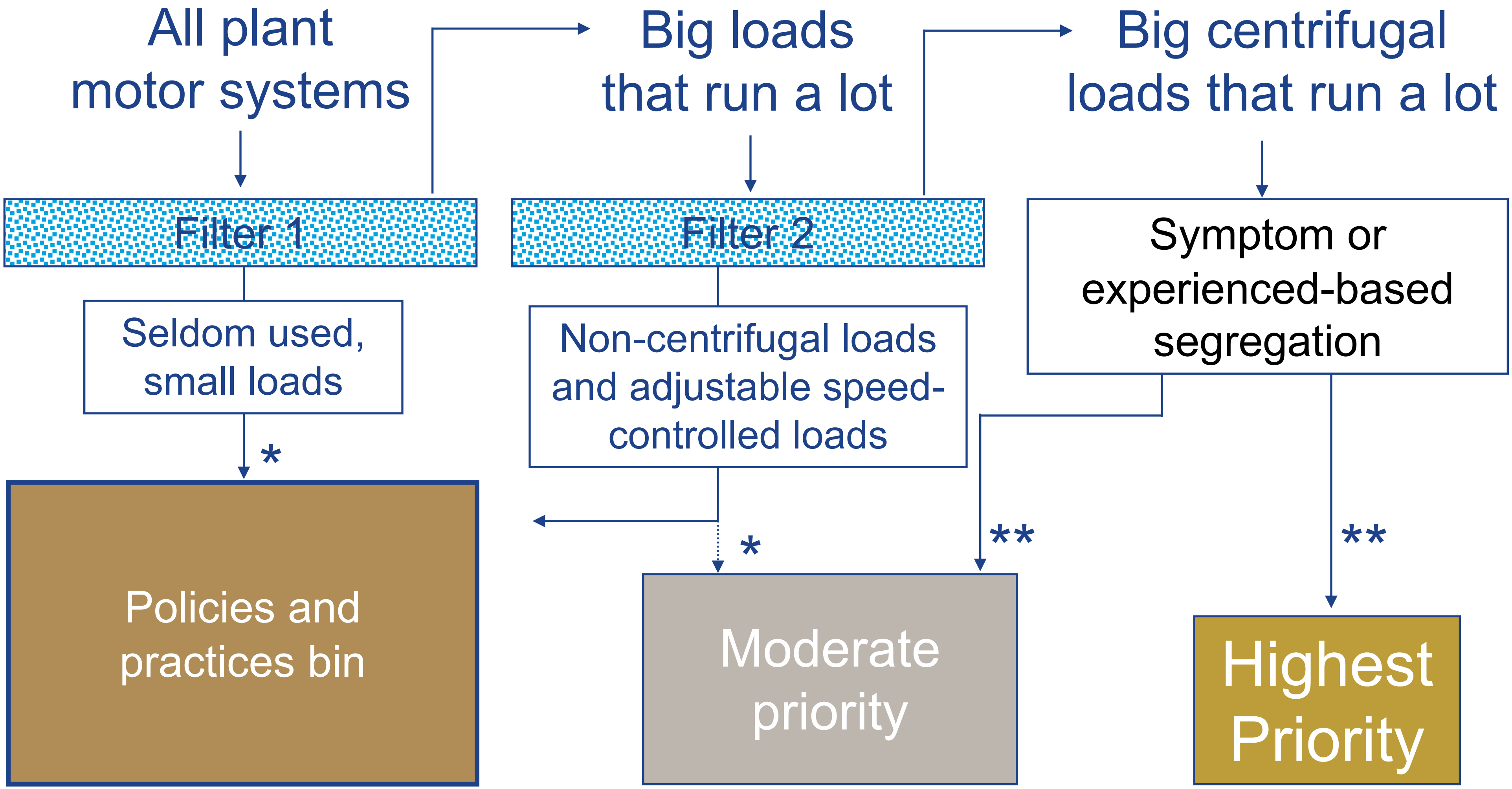
Prescreening to narrow the field of focus - i.e., to select the VITAL FEW for further review



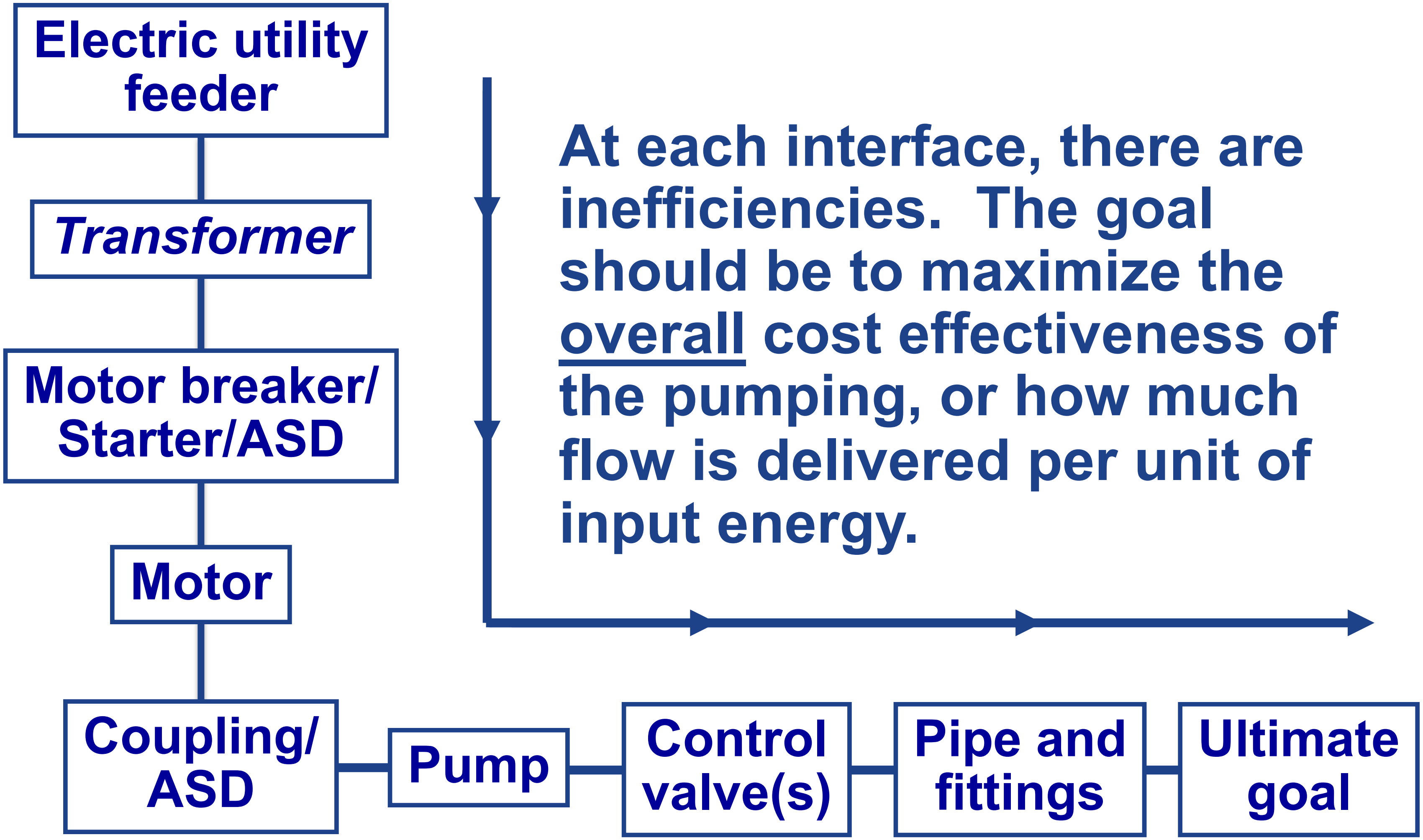
* Productivity/reliability-critical systems sent to higher priority levels

** Policies & practices also apply to moderate & highest priority applications

Example symptoms in pumping systems that indicate potential opportunity

- Throttle valve-controlled systems
- Bypass (recirculation) line normally open
- Multiple parallel pump system with same number of pumps always operating
- Constant pump operation in a batch environment or frequent cycle batch operation in a continuous process
- Cavitation noise (at pump or elsewhere in the system)
- High system maintenance
- Systems that have undergone change in function

First, let's try to get a big picture perspective of energy flow for pumping systems



At each interface, there are inefficiencies. The goal should be to maximize the overall cost effectiveness of the pumping, or how much flow is delivered per unit of input energy.

Observations on losses in some of the power train components

Utility grid – line losses; not our problem (or are they?)

Transformer – Very efficient (typically upper 90's %)

Breaker/starter – Negligible

Electrical ASD – Minor

Motor – Minor

Coupling – Minor

Mechanical ASD – Minor to moderate

Pump – Important

Control valves – Zero to major

Pipe and fittings – Minor to major

Ultimate goal – Always important

One of the single most important fluid energy relationships was identified in the 1700's

Euler

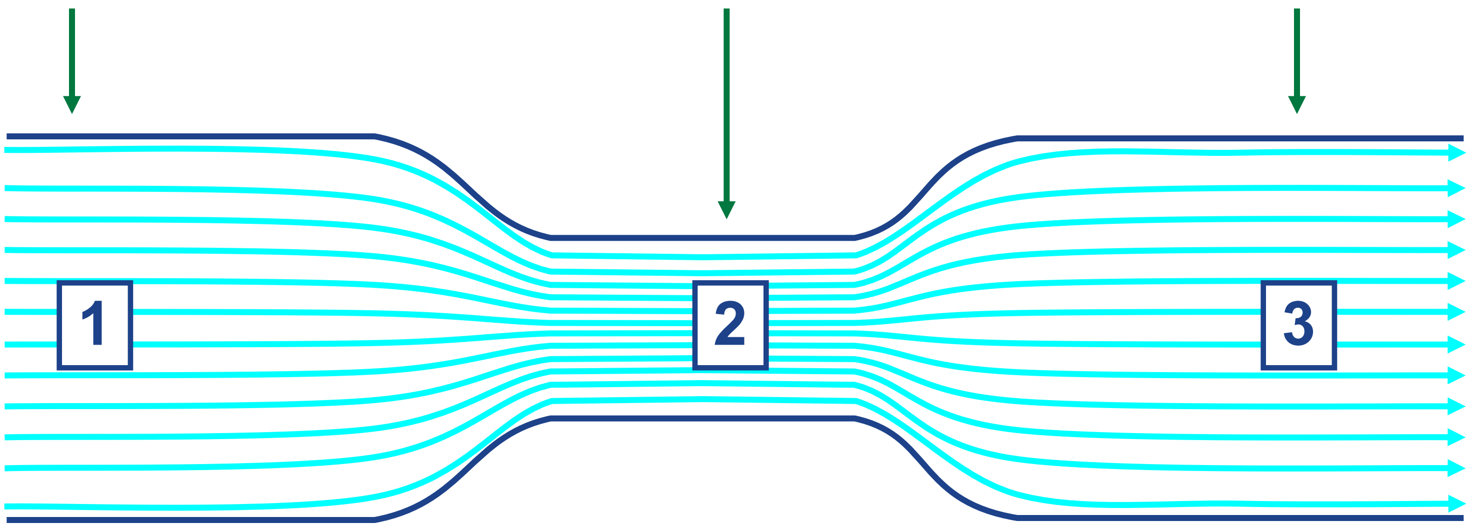
Bernoulli

Component	Symbol
Velocity	V
Pressure	P
Elevation	Z

The combined energy, or head, associated with the fluid velocity, pressure, and elevation along a frictionless streamline is constant, even if the individual components aren't.

Bernoulli's principle: Total energy is constant along a *frictionless* streamline

$$\frac{V_1^2}{2g} + \frac{P_1}{\gamma} + Z_1 = \frac{V_2^2}{2g} + \frac{P_2}{\gamma} + Z_2 = \frac{V_3^2}{2g} + \frac{P_3}{\gamma} + Z_3$$



γ = fluid specific weight (lb_f/ft^3)
g = gravitational acceleration, 32.2 ft/sec^2 (9.81 m/s^2)
Note: Units are in ft (m) of *head*

The Bernoulli relation applies to frictionless, steady, streamline flow

In the real world, friction exists (both within the fluid itself and between the fluid and pipe walls).

So how much does friction cause the real world to deviate from the relationships of the Bernoulli principle?

It depends. Sometimes a little, sometimes a lot.

What are some sources of friction in pumping systems?

Pipe walls

Valves

Elbows

Tees

Reducers/expanders

Expansion joints

Tank inlets/outlets

(i.e., almost everything that the pumped fluid passes through, as well as the fluid itself)

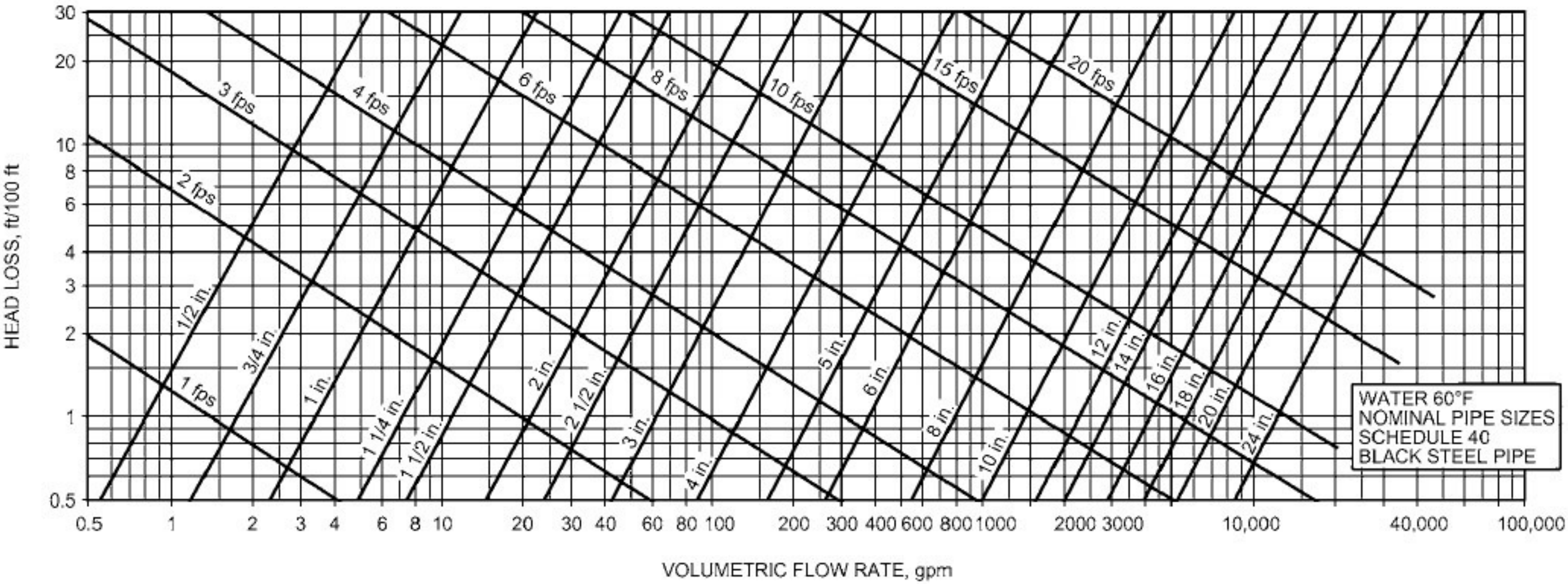
Pipe friction loss estimates are usually based on an equation referred to as Darcy-Weisbach

This equation is very useful to examine to understand what parameters influence *frictional* losses in piping:

$$H_f = f \cdot \frac{L}{d} \cdot \frac{V^2}{2g}$$

H_f	=	head loss due to friction (ft)
f	=	Darcy friction factor
L	=	pipe length (ft)
d	=	pipe diameter (ft)
$\frac{V^2}{2g}$	=	velocity head (ft)

Schedule 40 Steel Pipe Sizing



Piping component frictional losses are also primarily dependent on experimental data

For pipe components, frictional losses have generally been estimated based on the velocity head.

$$H_f = K \bullet \frac{V^2}{2g}$$

K = Loss coefficient

$\frac{V^2}{2g}$ = velocity head

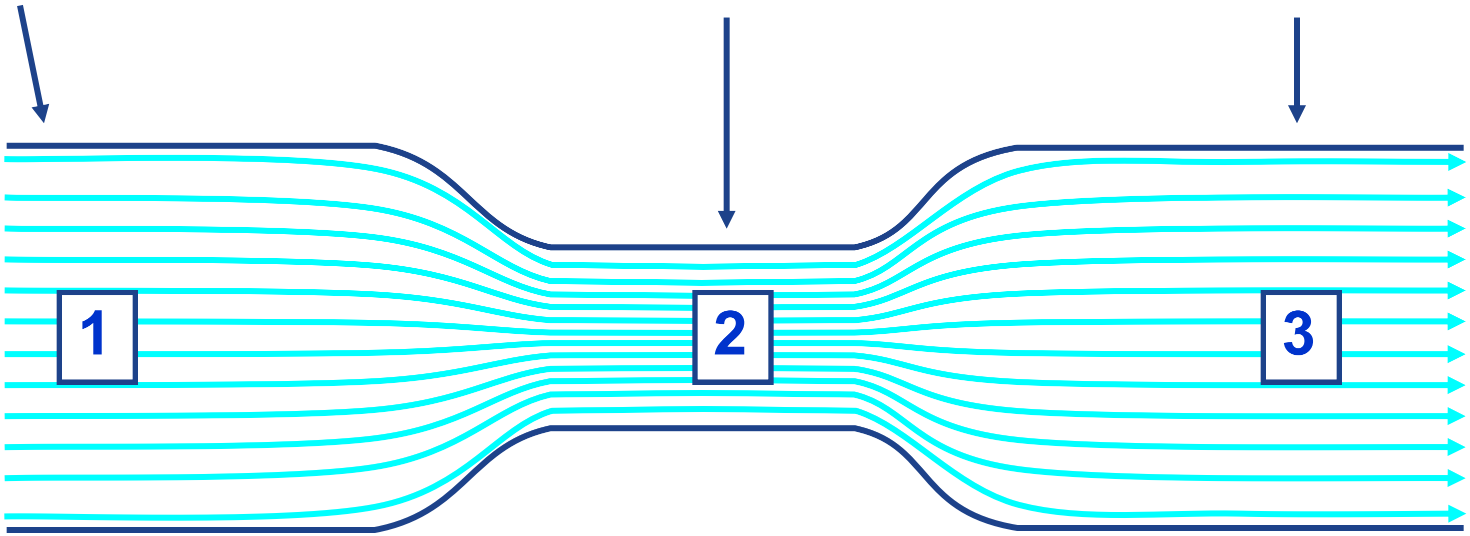
K is a function of size, and for valves, the valve type, and valve % open.

Some *typical* K values for miscellaneous pipe components

Component	Component K
90° elbow, standard	0.2 - 0.3
90° elbow, long radius	< 0.1 - 0.3
Square-edged inlet (from tank)	0.5
Discharge into tank	1
Check valve	2
Gate valve (full open)	0.03 - 0.2
Globe valve (full open)	3 - 8
Butterfly valve (full open)	0.5 - 2
Ball valve (full open)	0.04 - 0.1

We can slightly modify the Bernoulli equation to account for friction

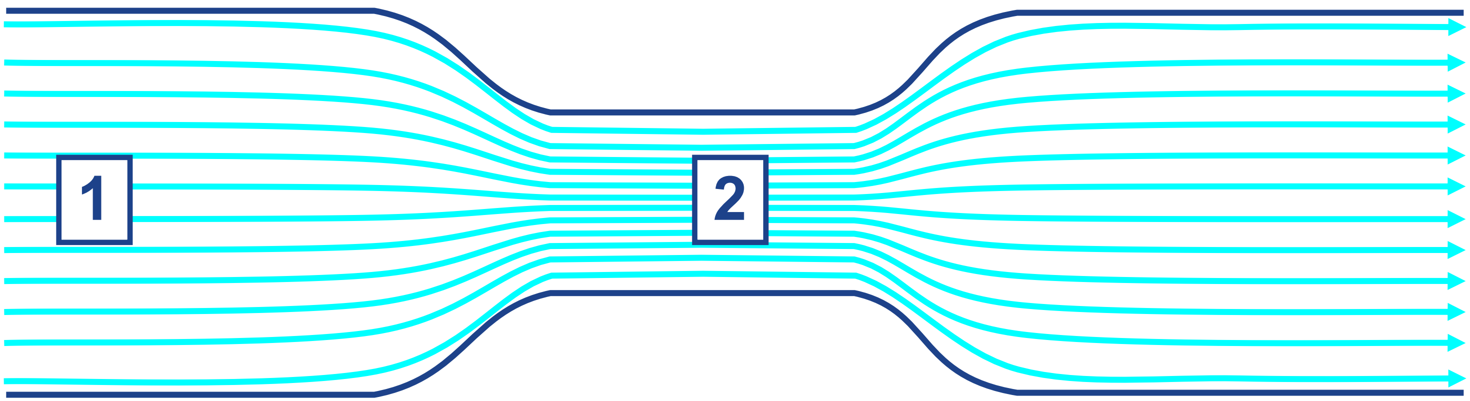
$$\frac{V_1^2}{2g} + \frac{P_1}{\gamma} + Z_1 = \frac{V_2^2}{2g} + \frac{P_2}{\gamma} + Z_2 + H_{f1\text{-}2} = \frac{V_3^2}{2g} + \frac{P_3}{\gamma} + Z_3 + H_{f1\text{-}3}$$



There is less hydraulic head/energy available at points 2 and 3 because of frictional losses

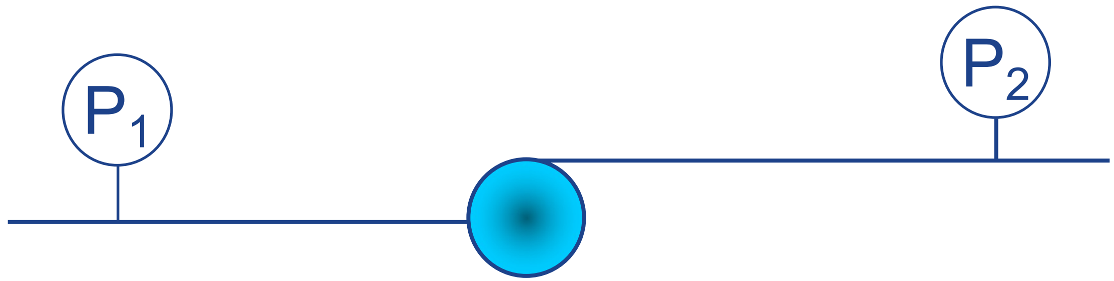
Modified again to accommodate the normal units of pressure in the U.S.A.

$$\frac{V_1^2}{2g} + \frac{2.31\,P_1}{s.g.} + Z_1 = \frac{V_2^2}{2g} + \frac{2.31\,P_2}{s.g.} + Z_2 + H_{f1\text{-}2}$$



Symbol	Represents	Units
V	Velocity	ft/s
g	gravitational acceleration constant	ft/s^2
P	pressure	psig
s.g.	specific gravity	none
Z	Elevation	ft
H_f	Frictional head loss	ft

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

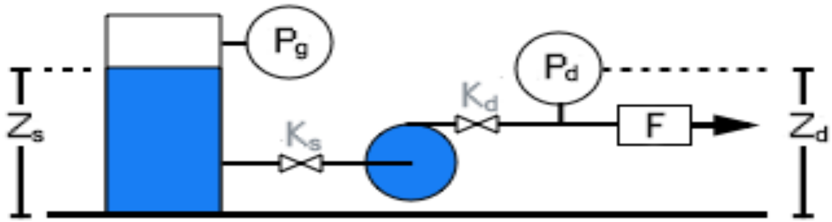
$$\mathrm{H_{pump}} = \left(\frac{V_2^2}{2g} + \frac{2.31\,P_2}{s.g.} + Z_2\right) - \left(\frac{V_1^2}{2g} + \frac{2.31\,P_1}{s.g.} + Z_1\right)$$

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		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

Generate Example | Reset Data

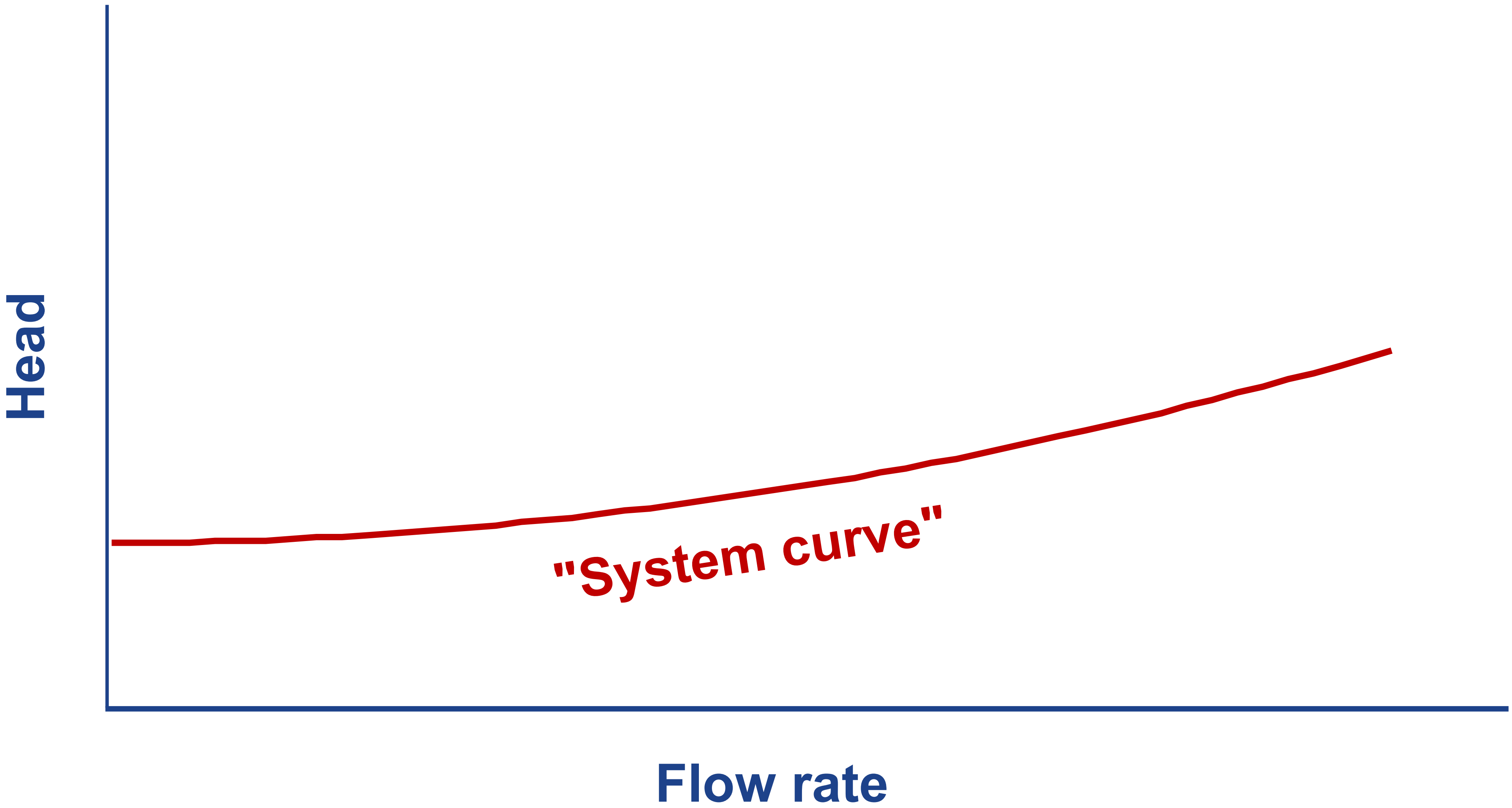
MEASUR Pump Head Calculator Results

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

Let's start with the system curve



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

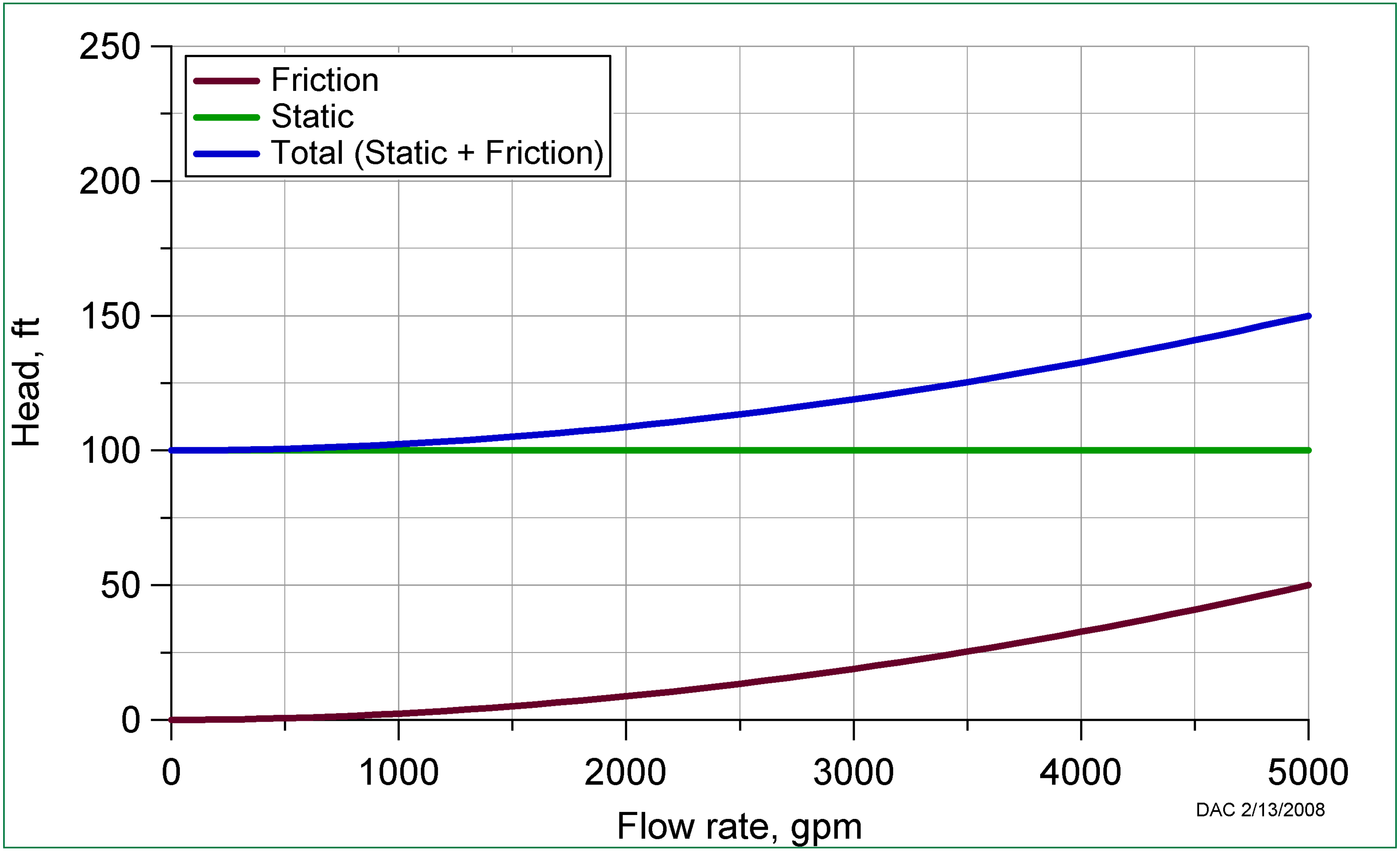
- Static head
- Friction head

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

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

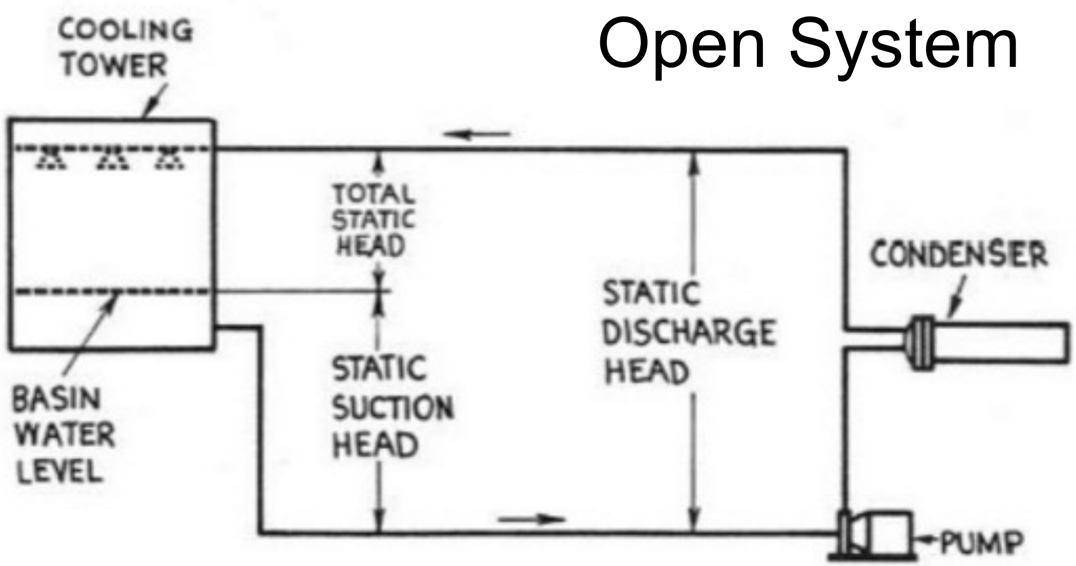
System curves are made up of two fundamental components - static head and frictional head



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



System Curves

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

System curve equations:

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

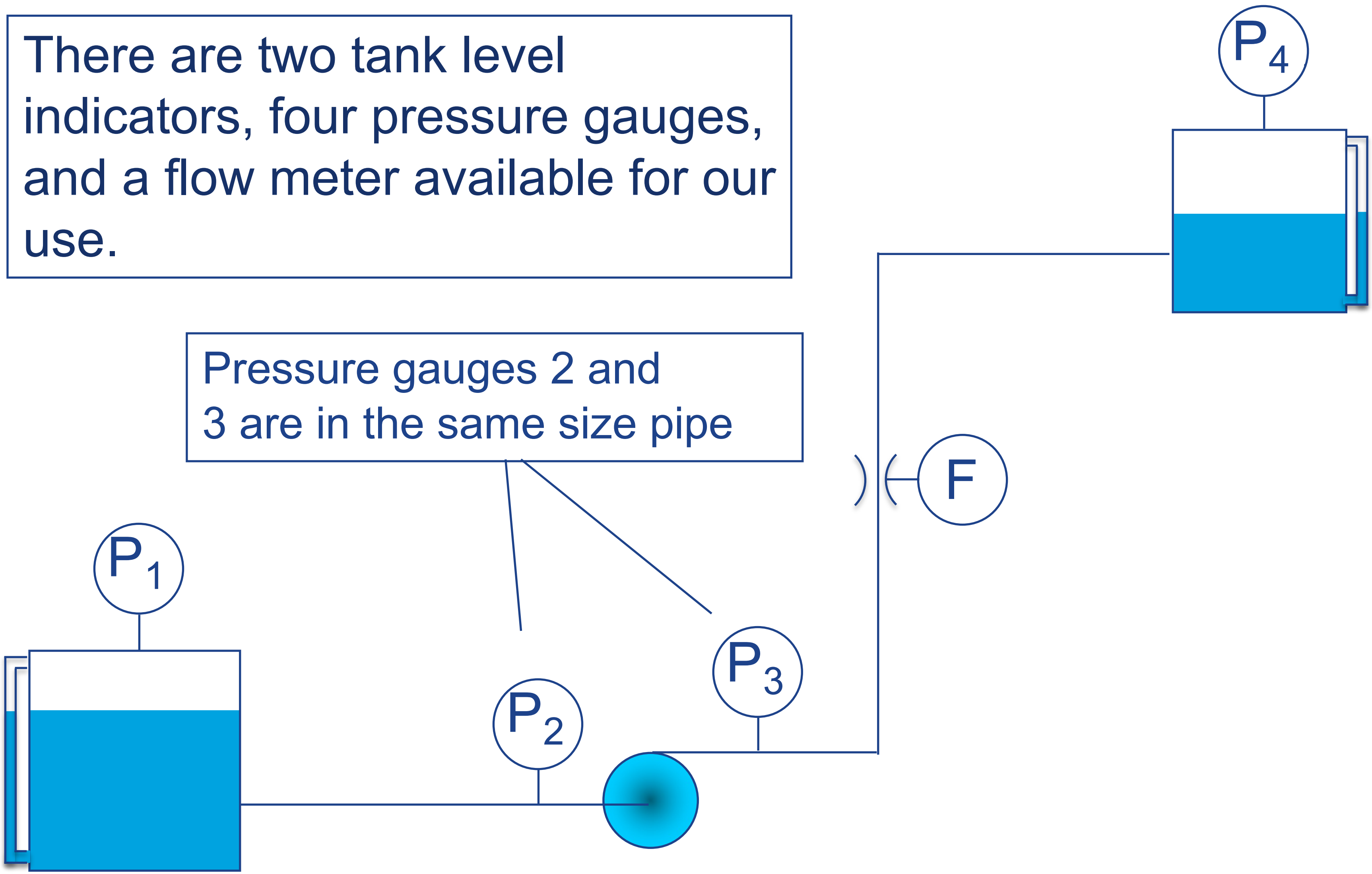
Closed piping systems have zero static head

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.

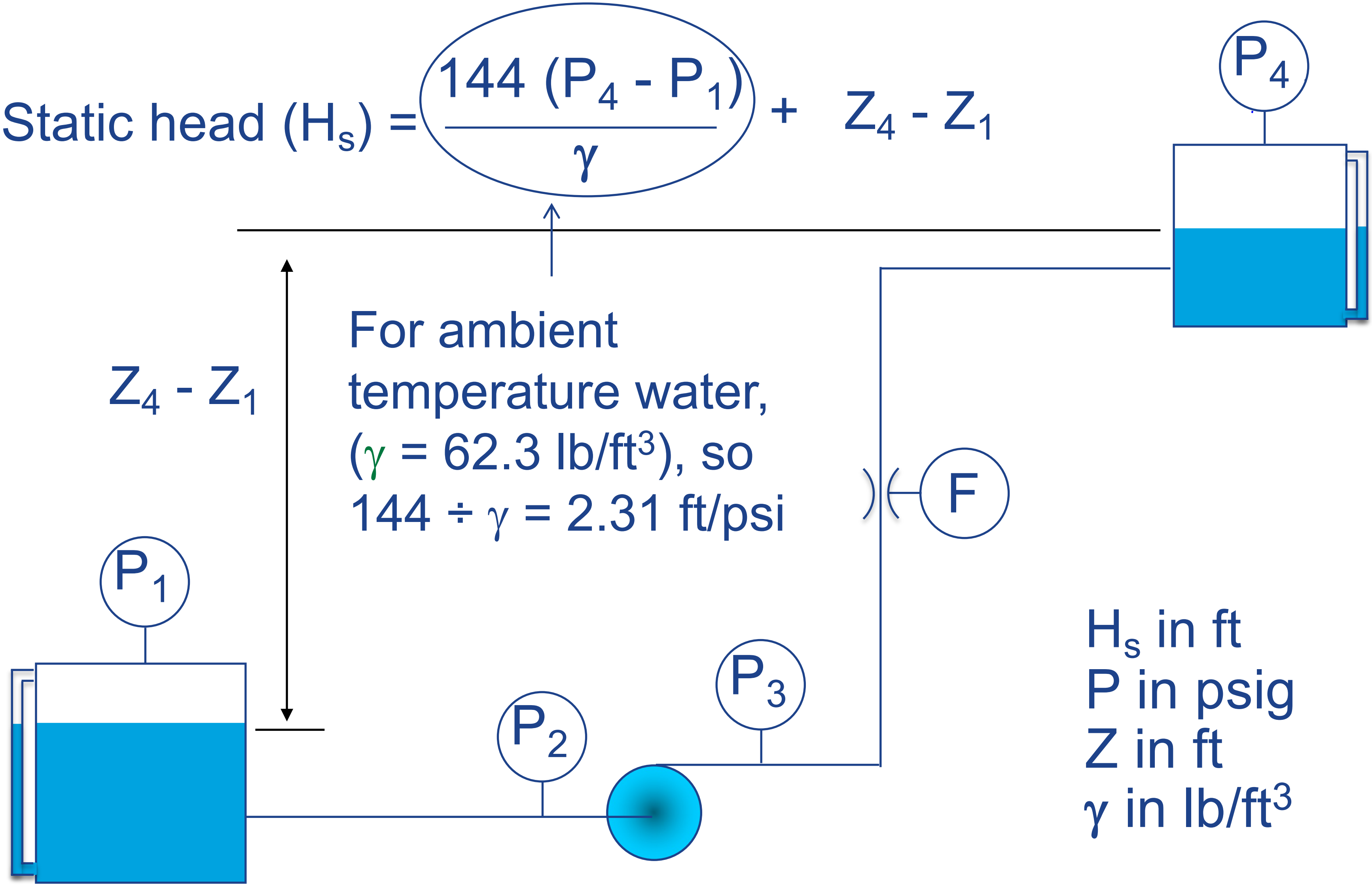
Pressure gauges 2 and 3 are in the same size pipe



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

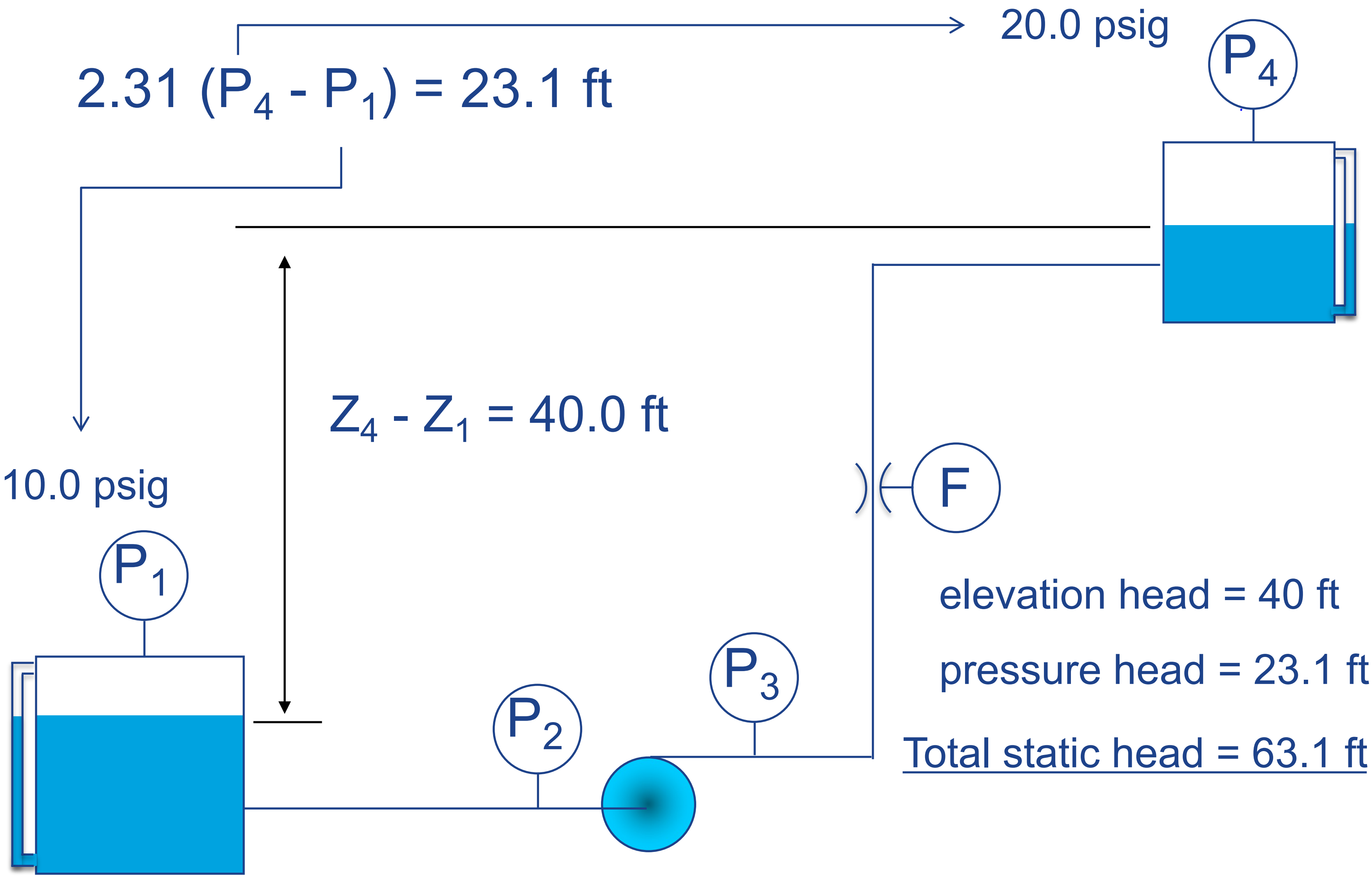
$$\text{Static head } (H_s) = \frac{144\,(P_4 - P_1)}{\gamma} + Z_4 - Z_1$$

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

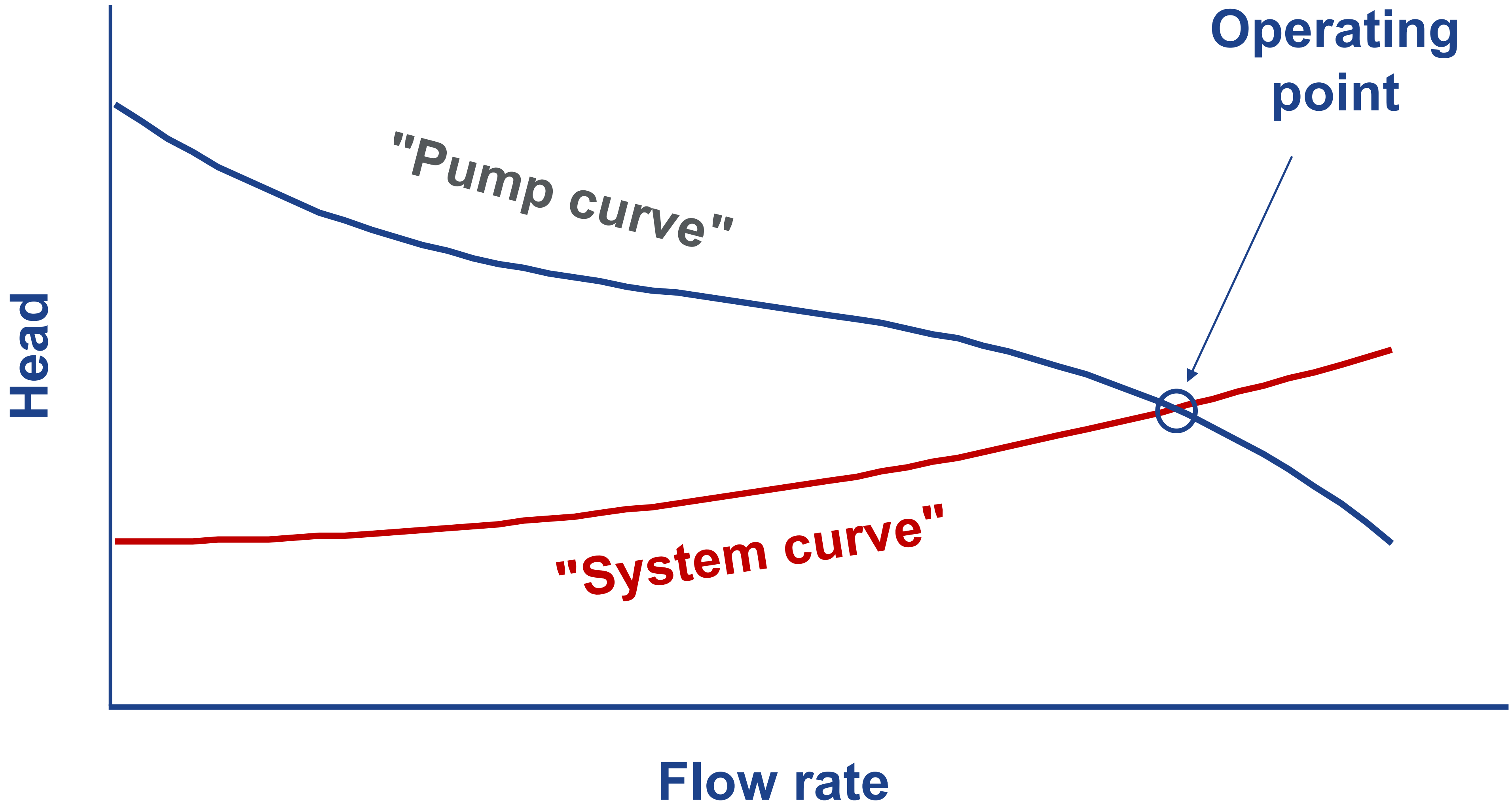


H_s in ft
P in psig
Z in ft
γ in lb/ft^3

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

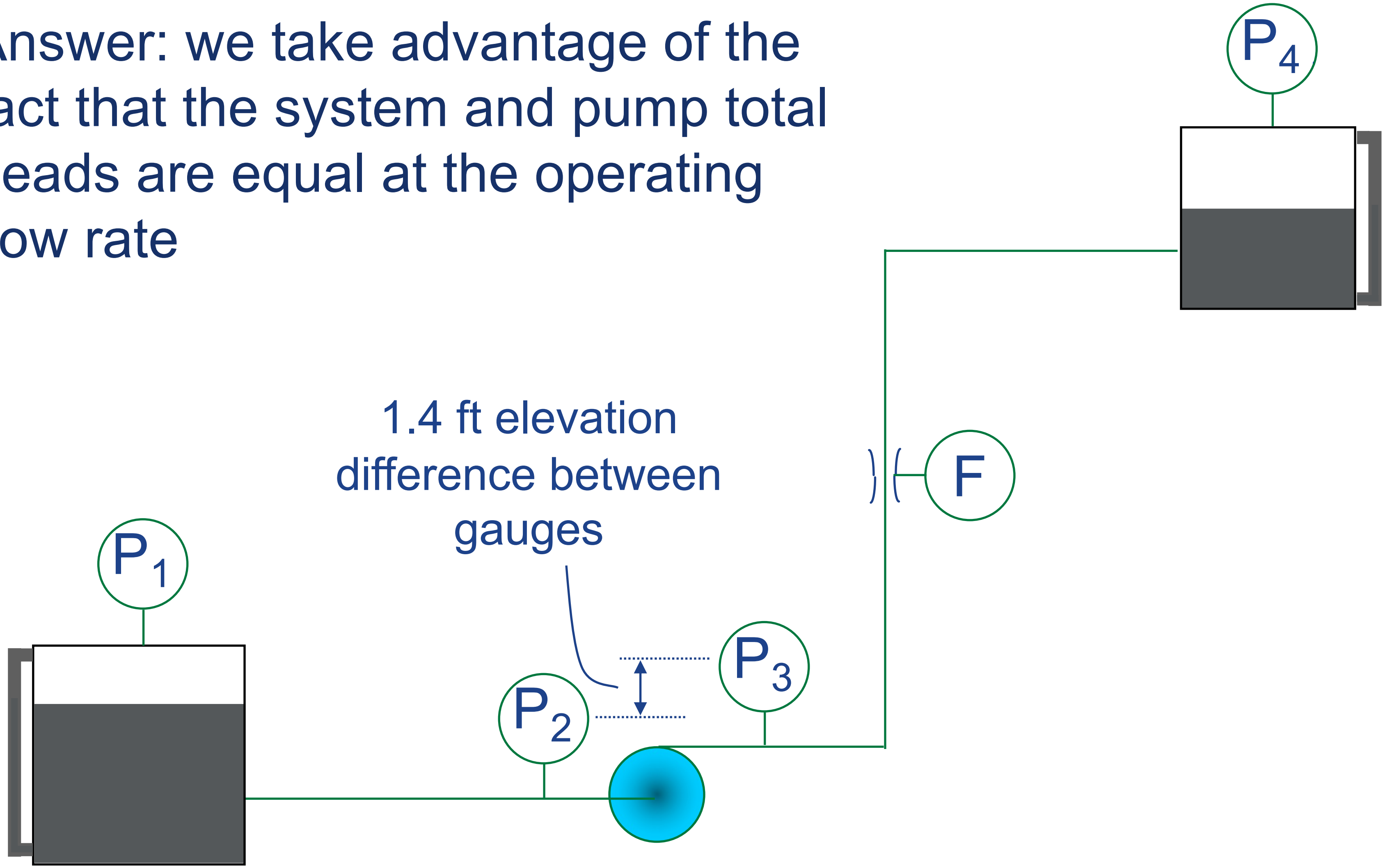


The system operating point is at the intersection of the pump and system head-capacity curves



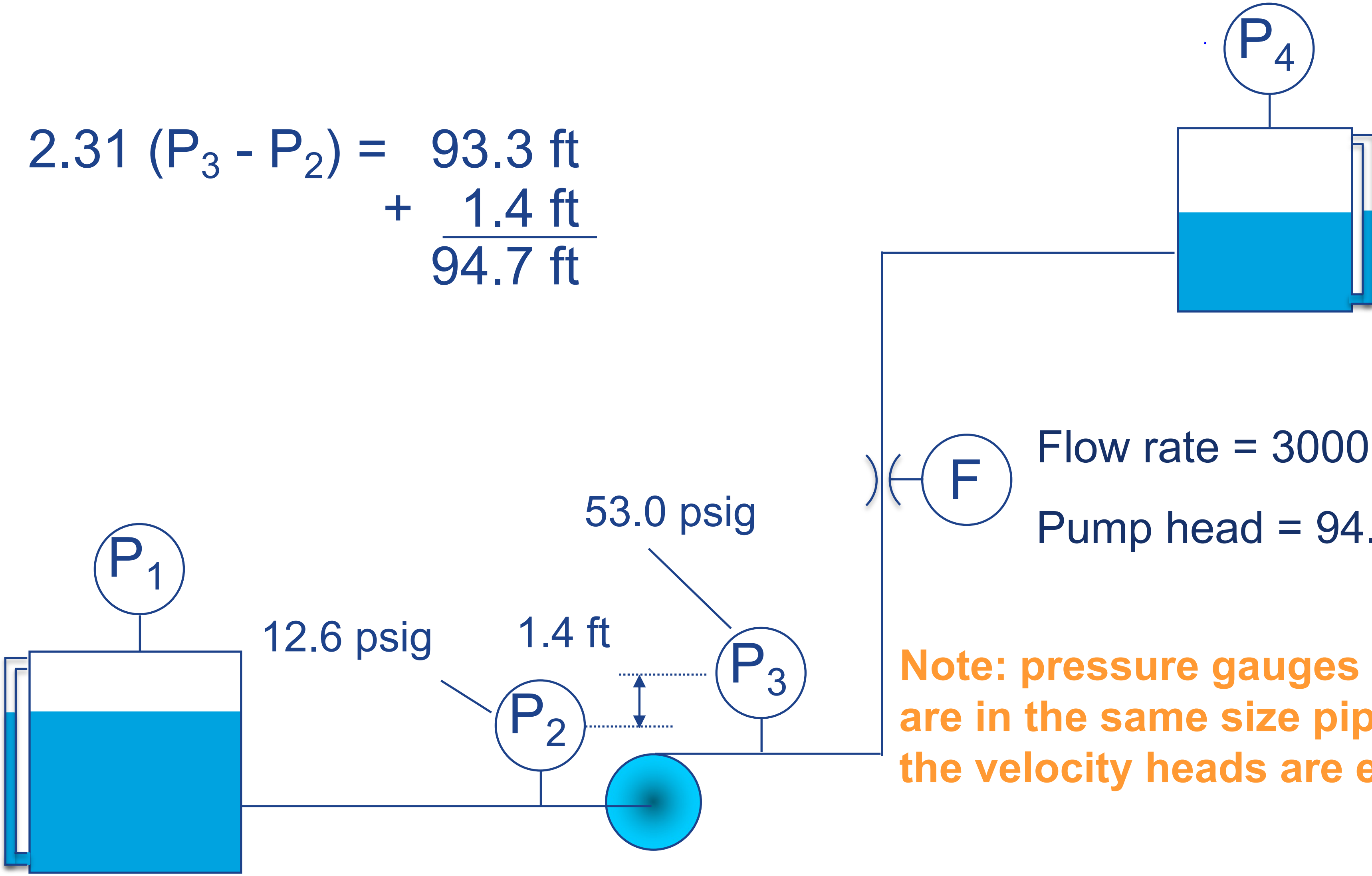
and we can measure the pump head

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

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

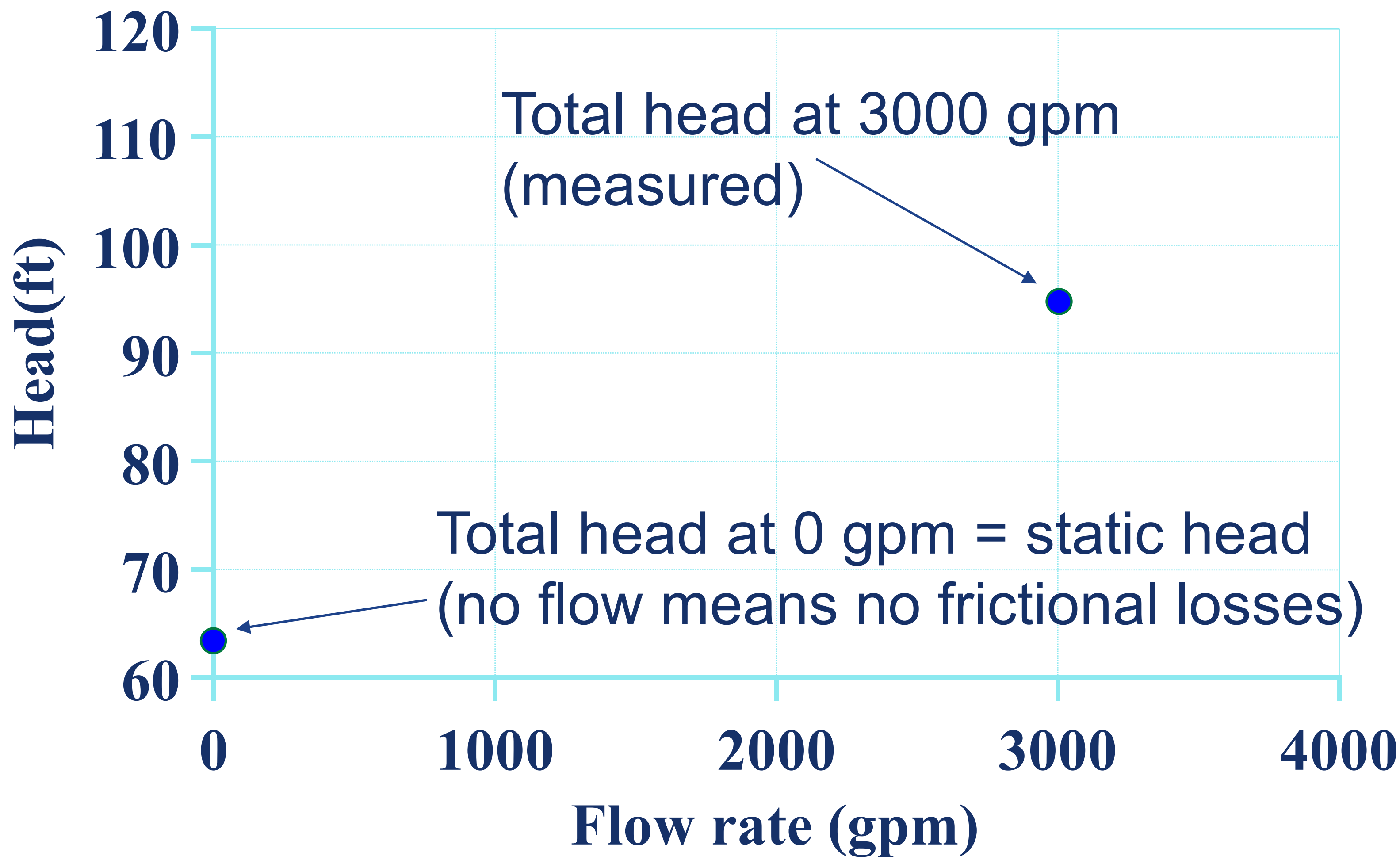


Flow rate = 3000 gpm

Pump head = 94.7 ft

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

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



A little algebra….

$H_2 = H_s + KQ_2^2$

$H_1 = H_s + KQ_1^2$

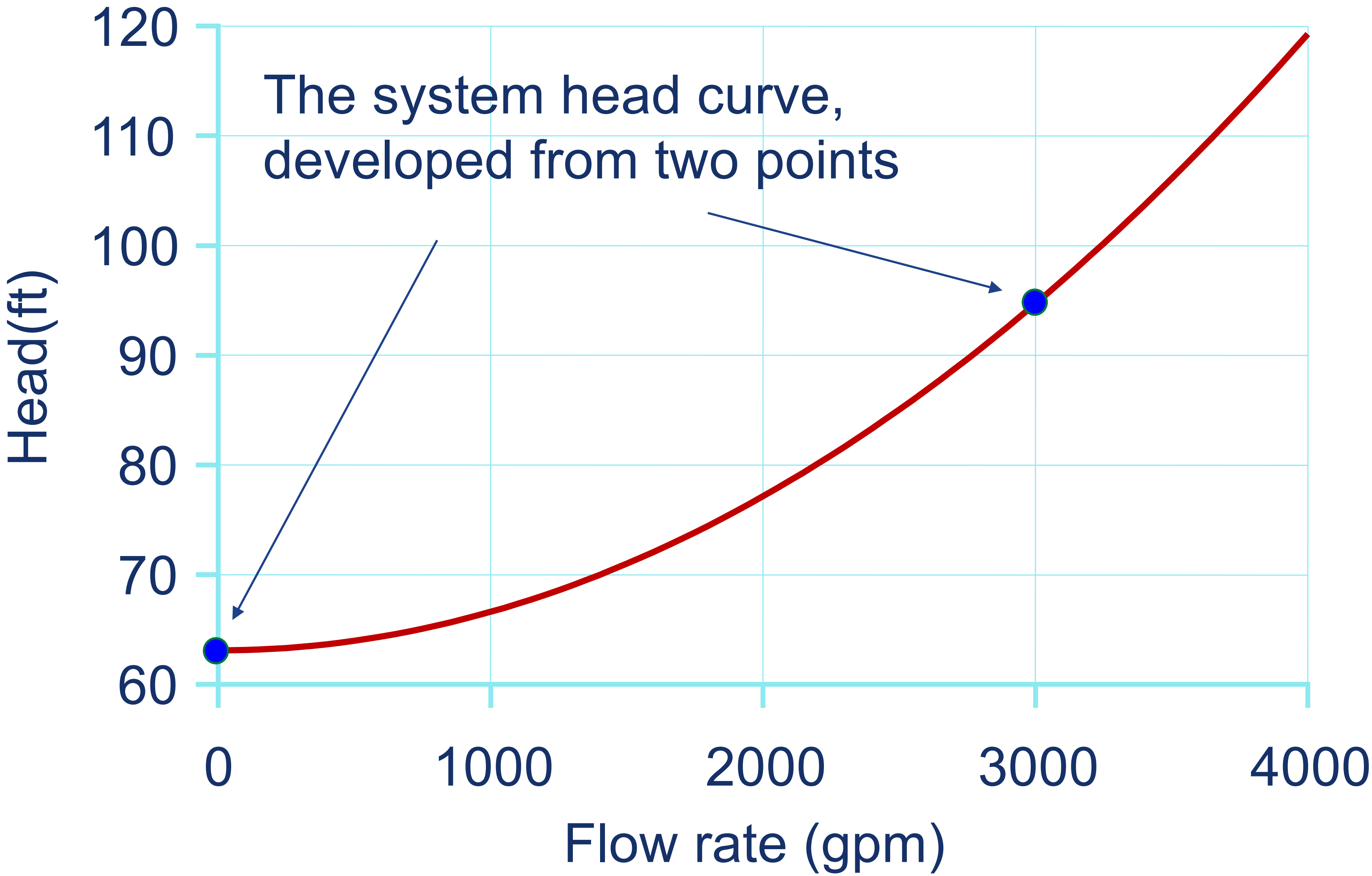
Subtracting yields

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

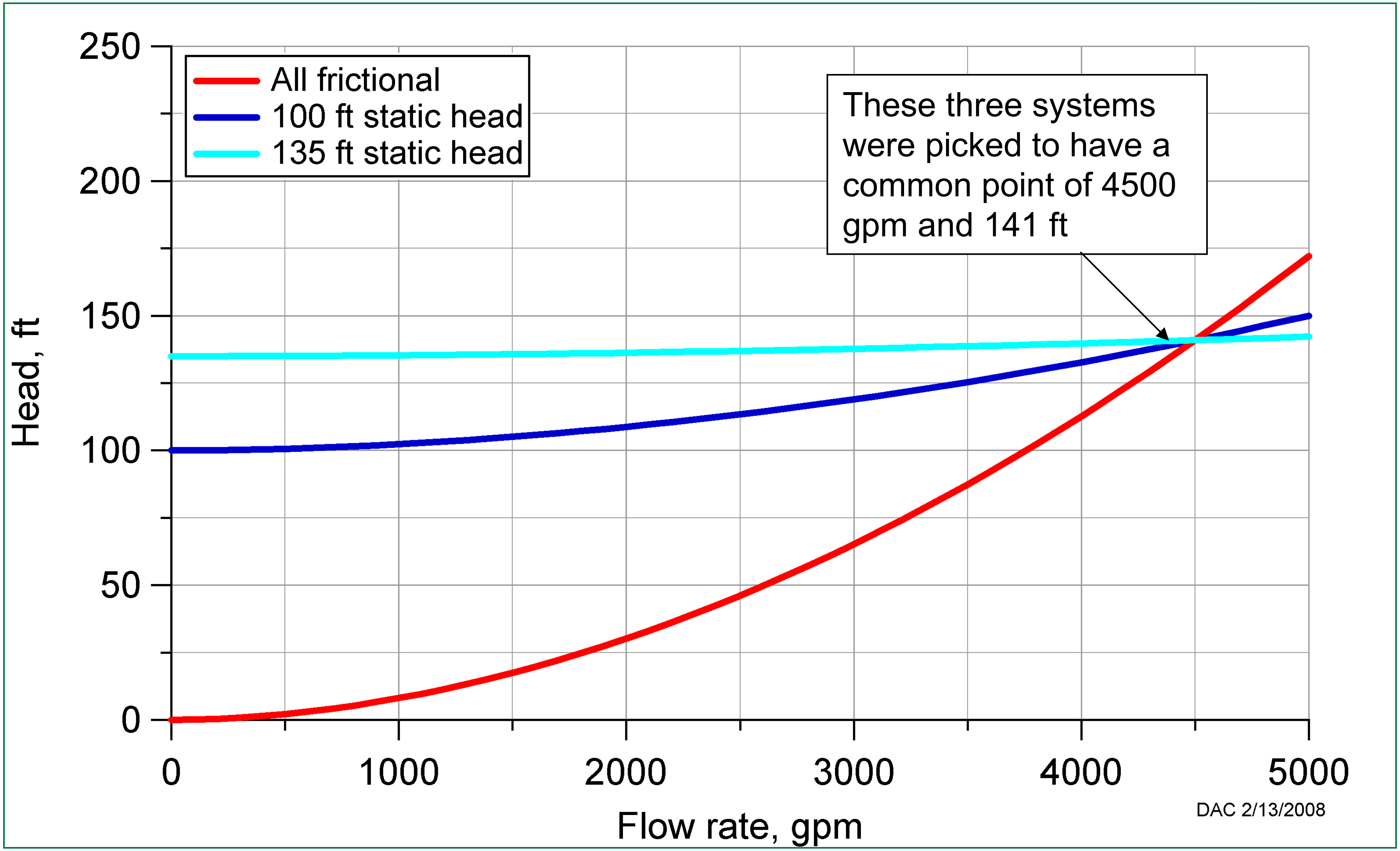
$$K = \frac{(H_2 - H_1)}{(Q_2^2 - Q_1^2)} \quad \text{and } H_s = H_1 - KQ_1^2$$

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

The resultant system curve

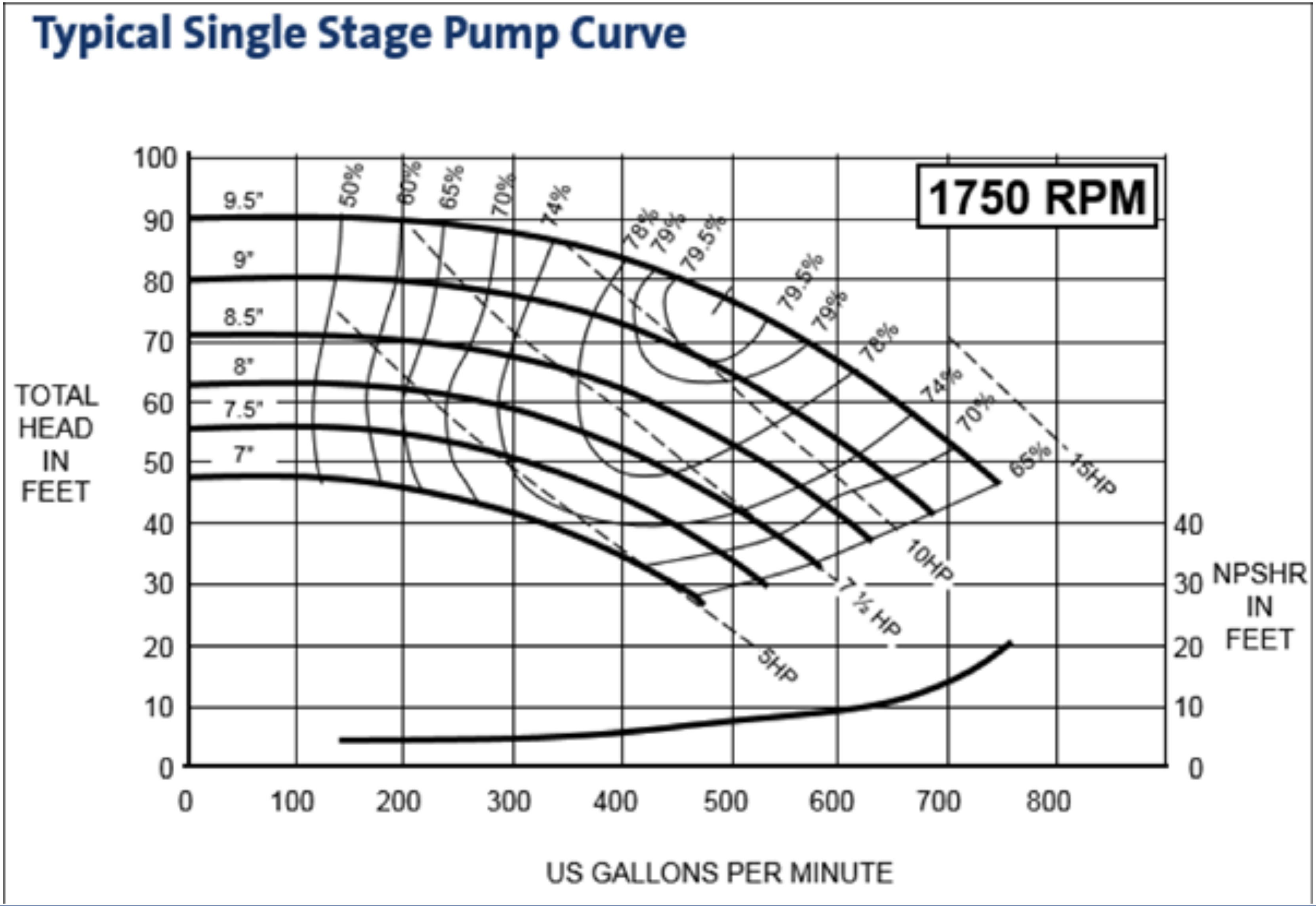


System head curves for three different systems



NOTE: These are three <u>different</u> systems

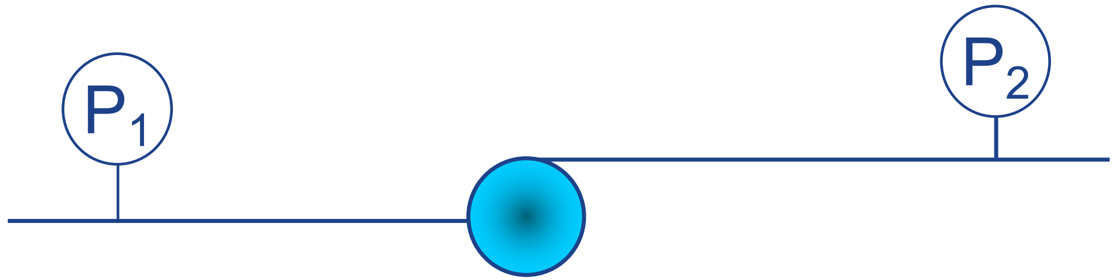
Pump performance characteristics



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



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MEASUR Pump Head Calculator

PUMP HEAD TOOL

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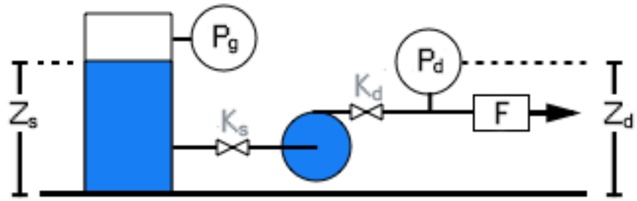

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Pump Head	288.78 ft

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

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

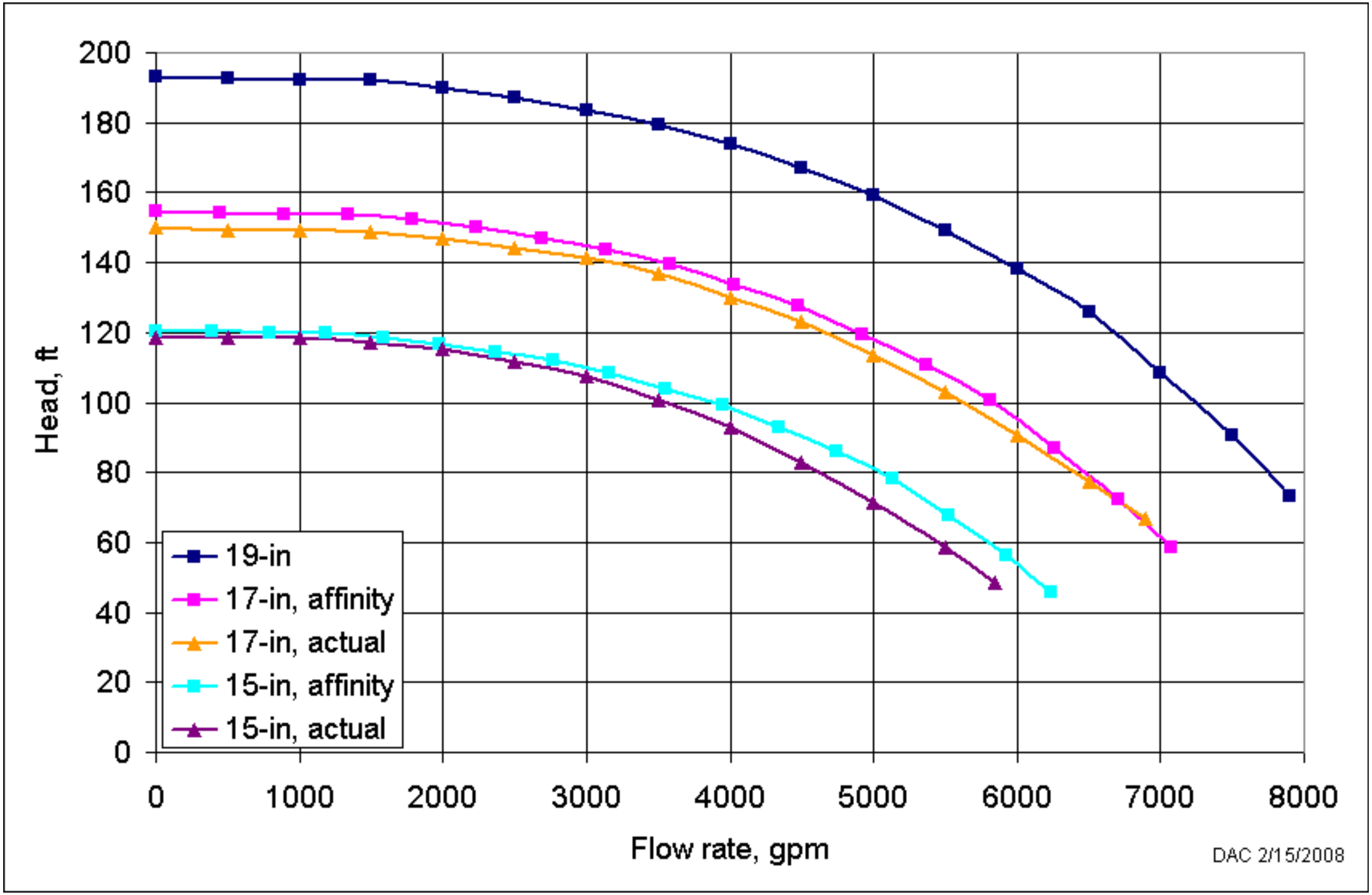
$$\left(\frac{H_1}{H_2}\right) = \left(\frac{D_1}{D_2}\right)^2$$

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

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

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

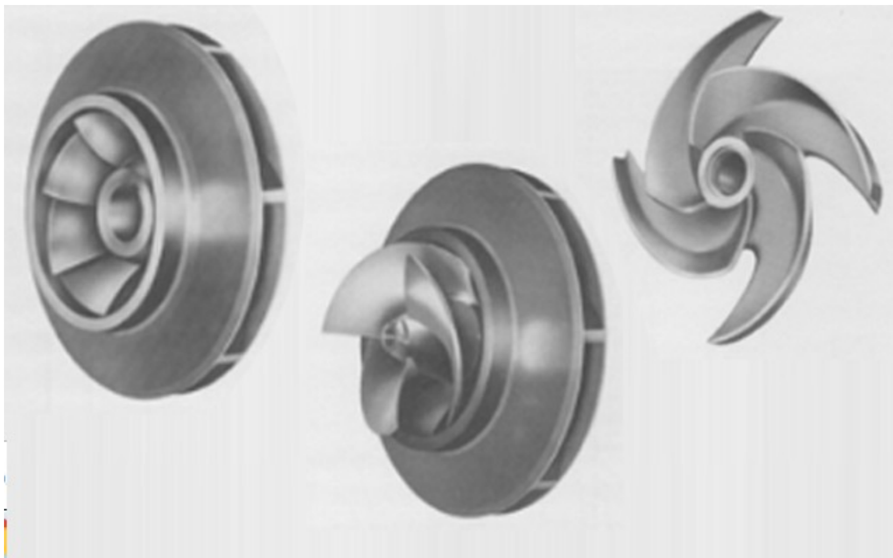
The affinity laws aren't perfect for diameter changes: head curves



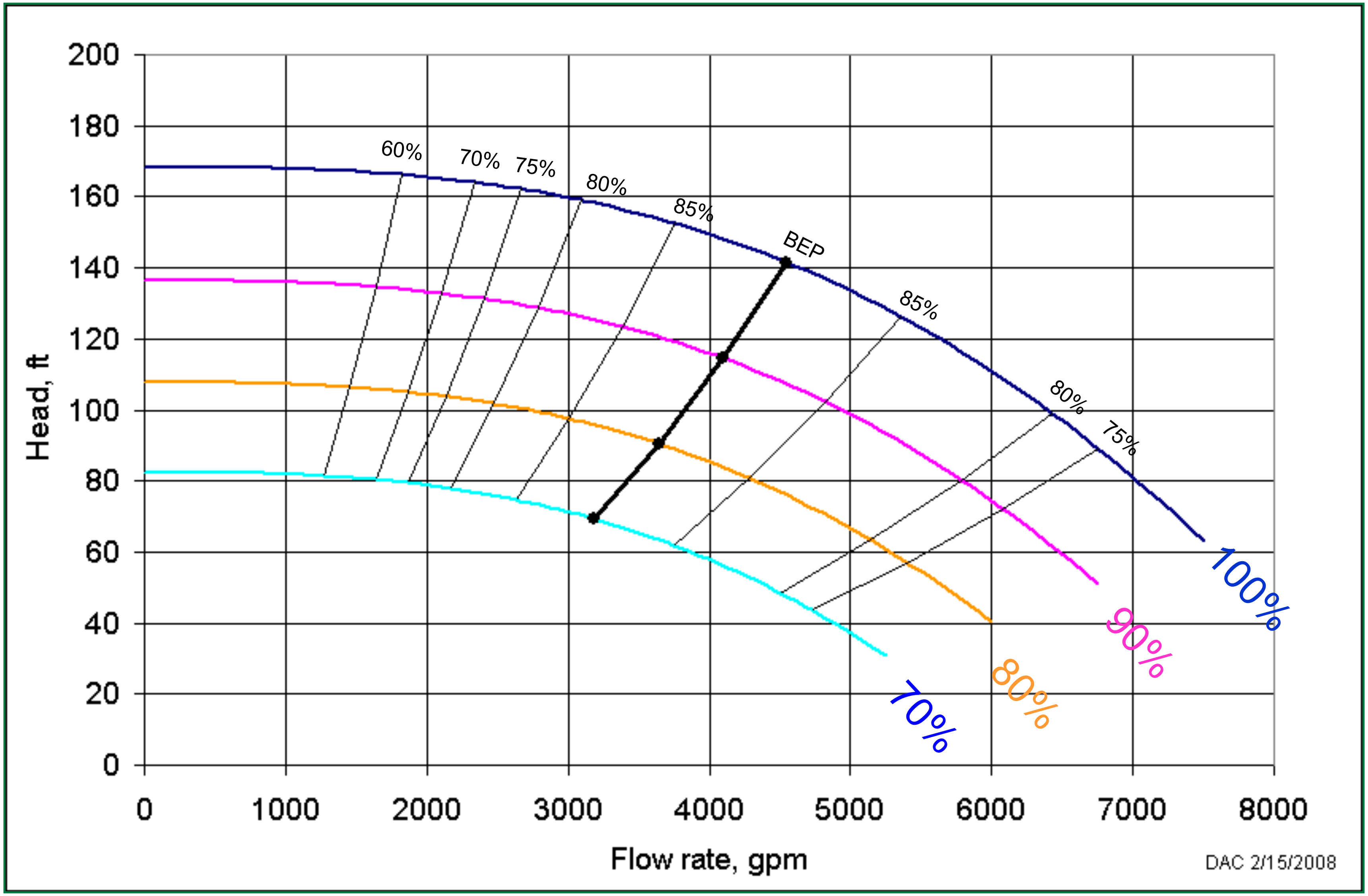
Considering a trim in impeller diameter?

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



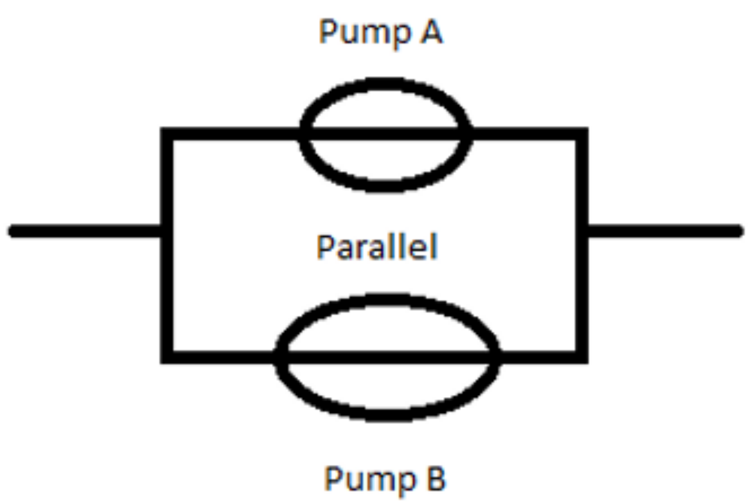
But the affinity laws generally hold up very well with speed changes

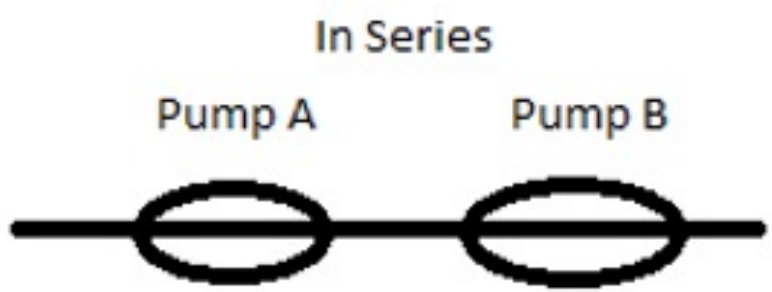


Note: same pump as previous slides, impeller size = 17.9 inches

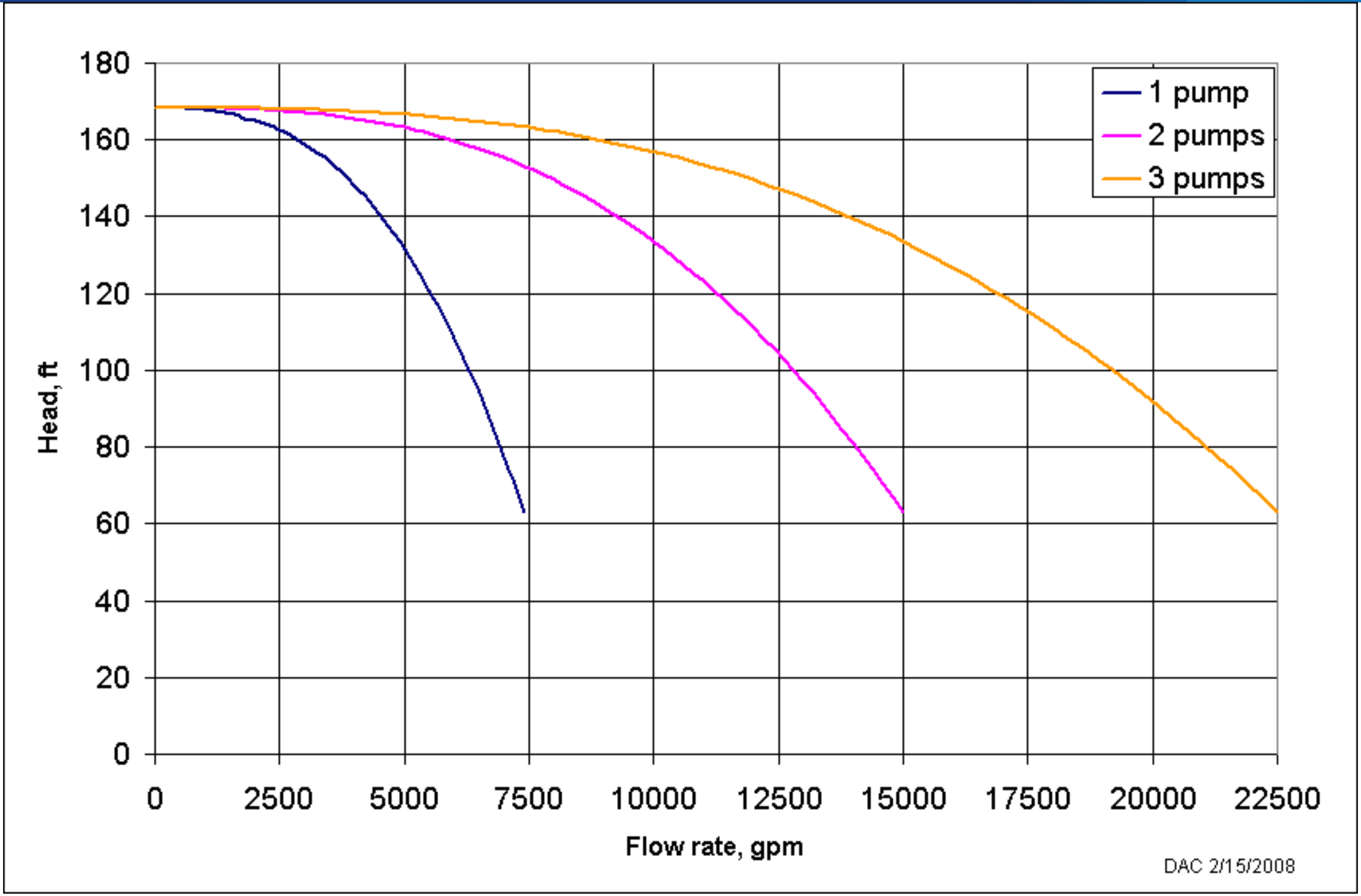
Parallel and series pumping “laws”, like the pump affinity laws apply to the pump curves ***only***

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

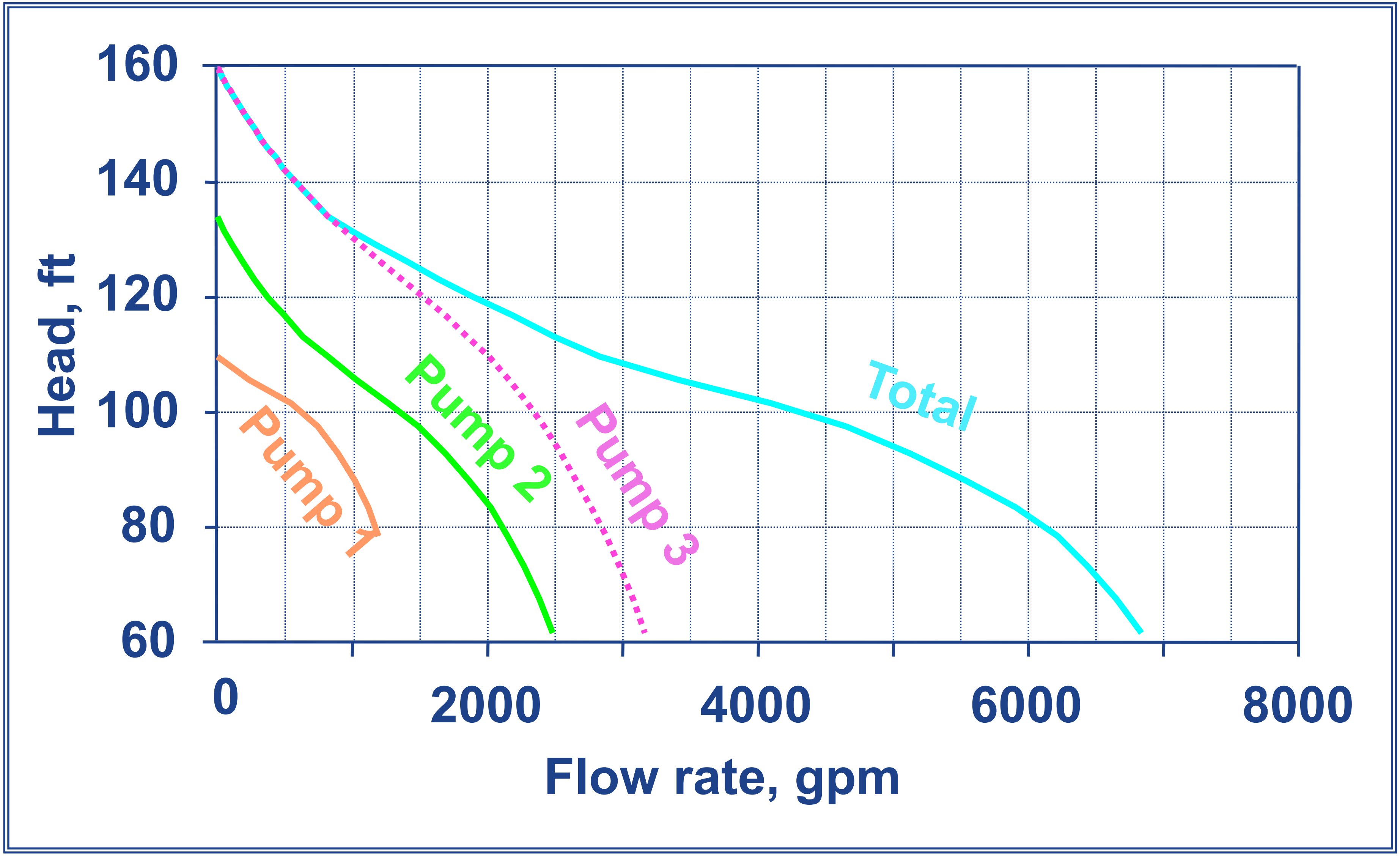




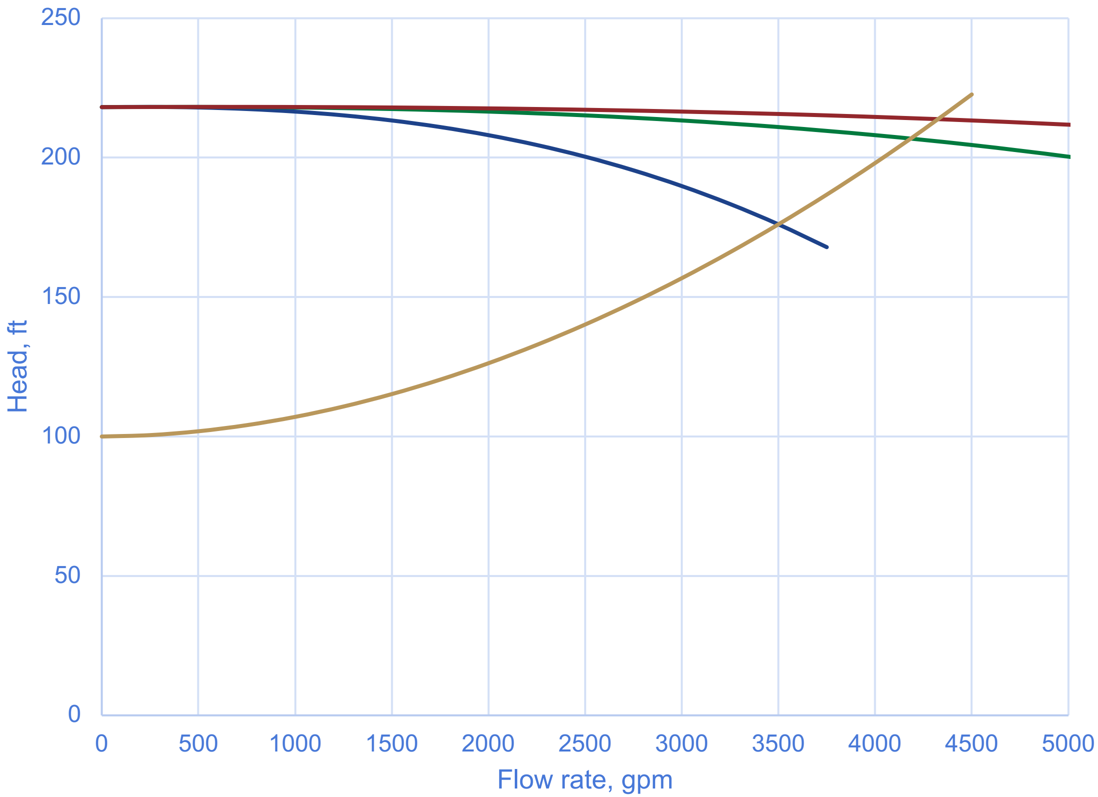
Parallel pumps can help adapt to changing system requirements and provide redundancy



Unlike pumps can also be used in parallel, <u>but with caution</u>

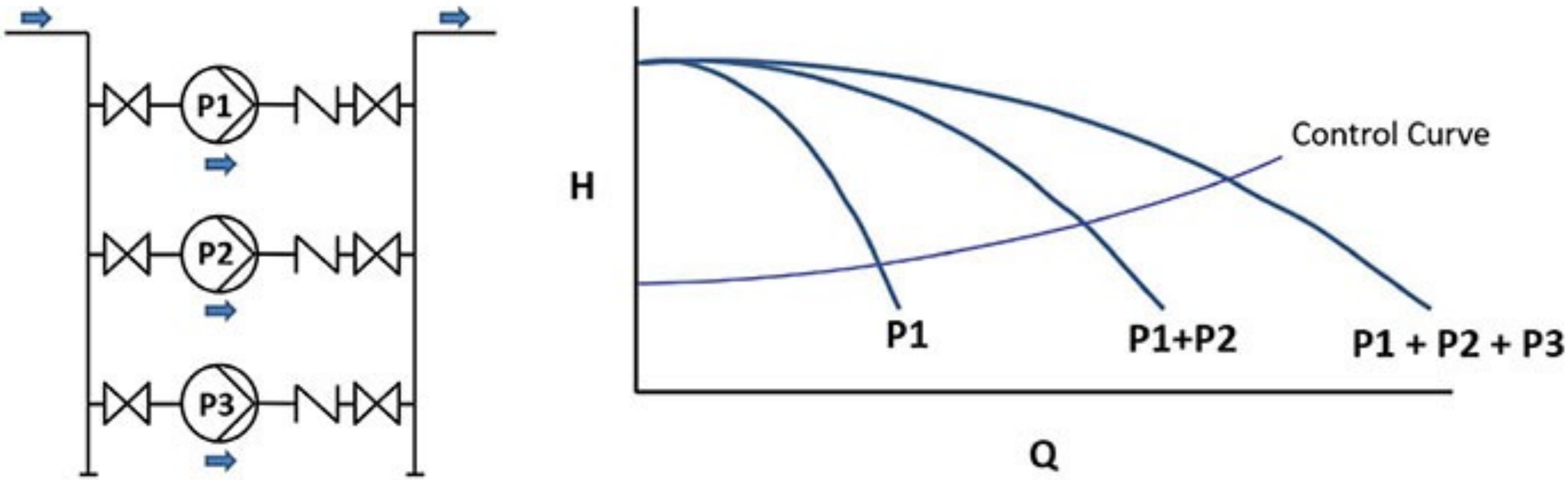


More pumps does not necessarily mean much more flow



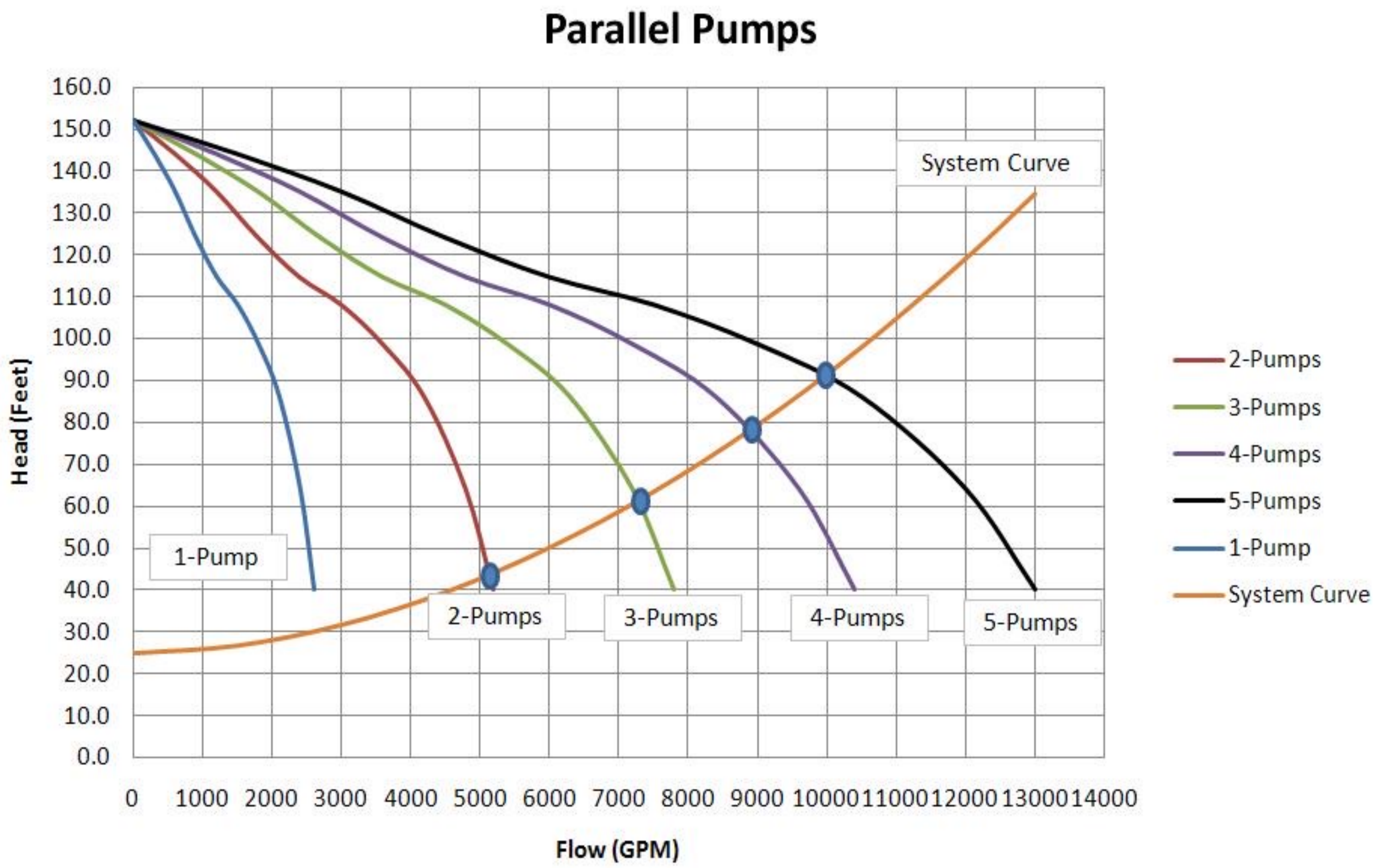
Pumps operating	Flow rate, gpm	Head, ft	% increase in flow
1	3500	176.1	0
2	4185	206.8	19.6%
3	4325	213.8	23.6%

How about parallel pump operation with different system types?

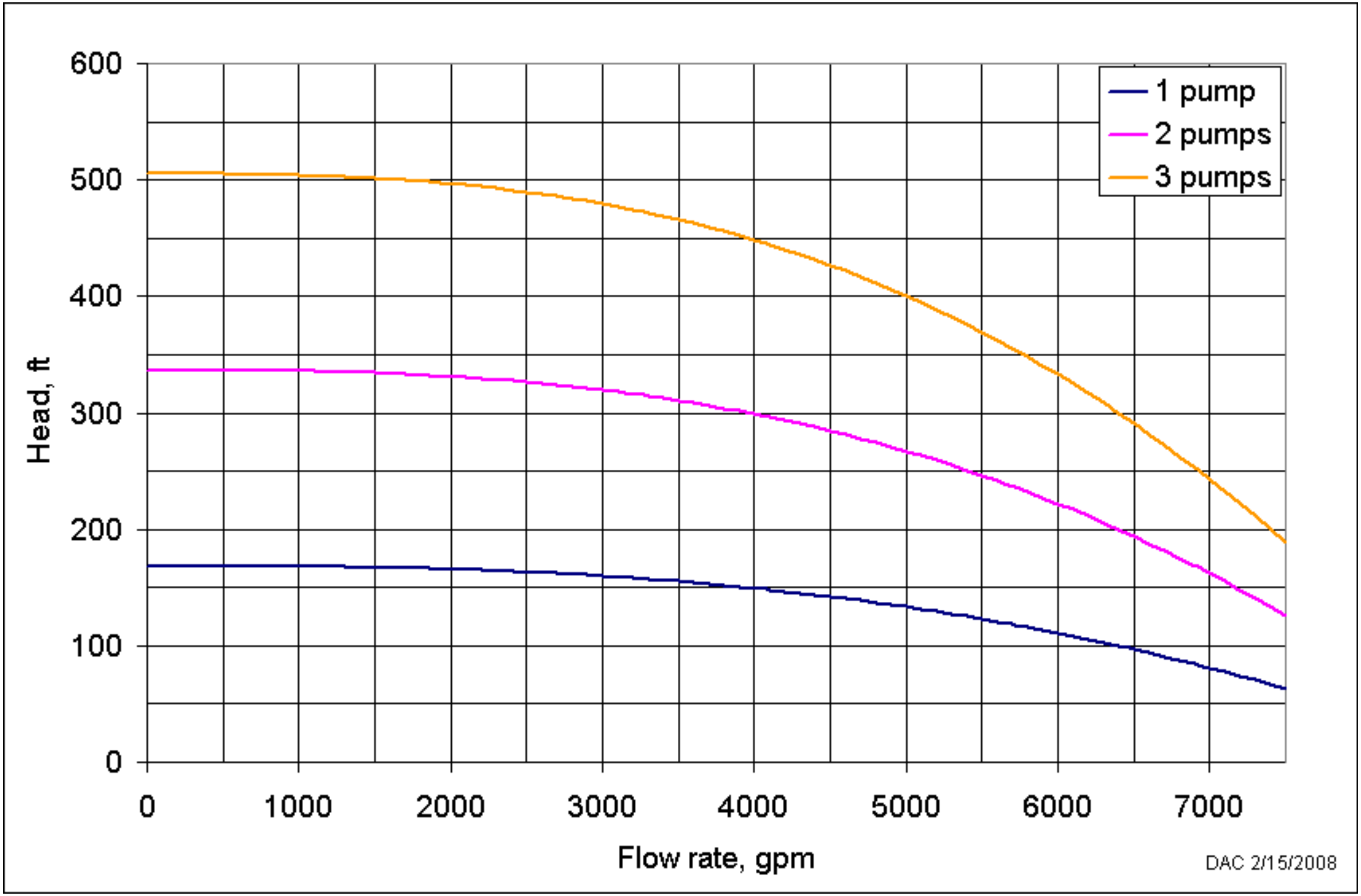


Parallel Pumping Example

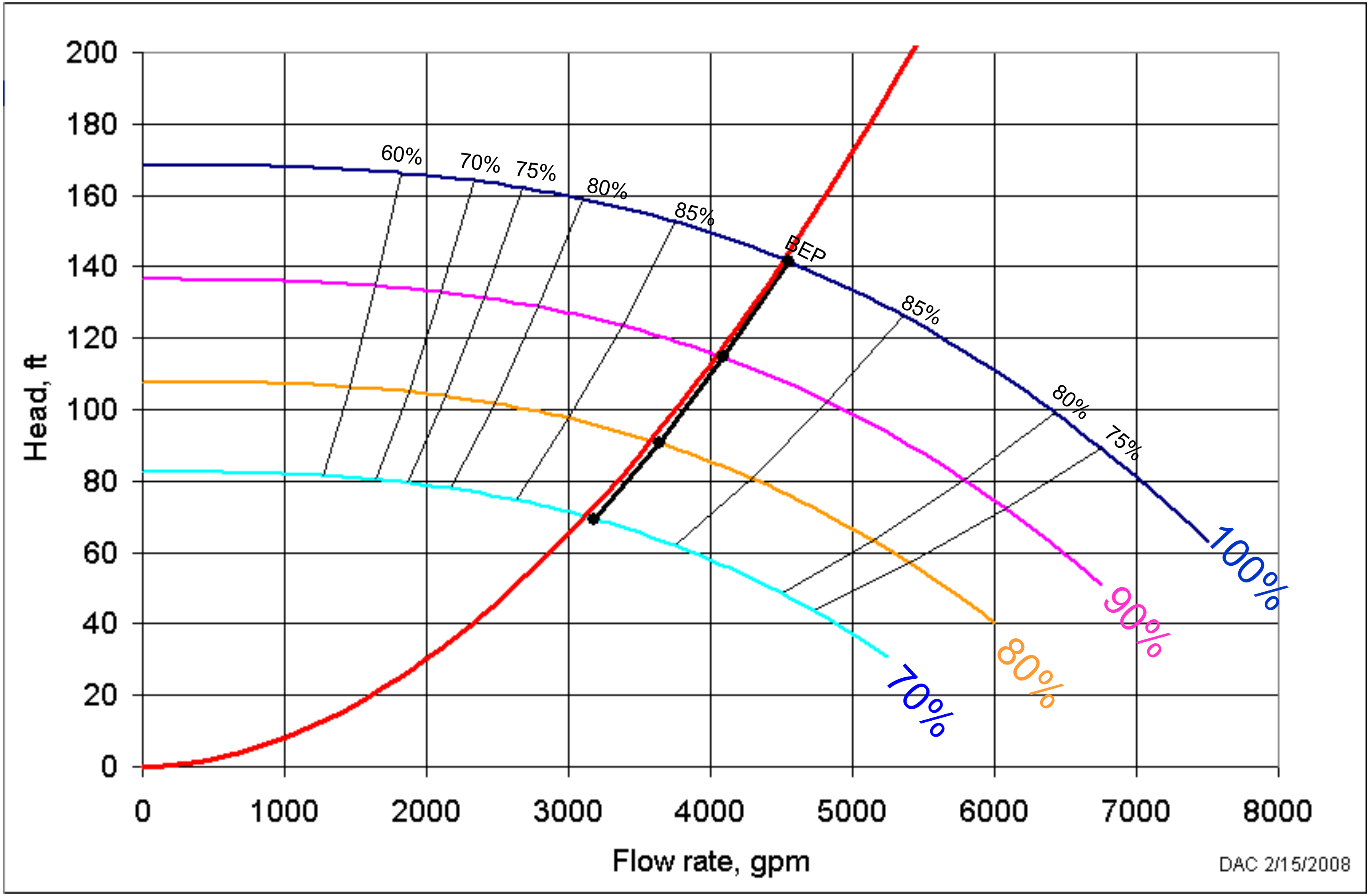
Parallel Pumping Example



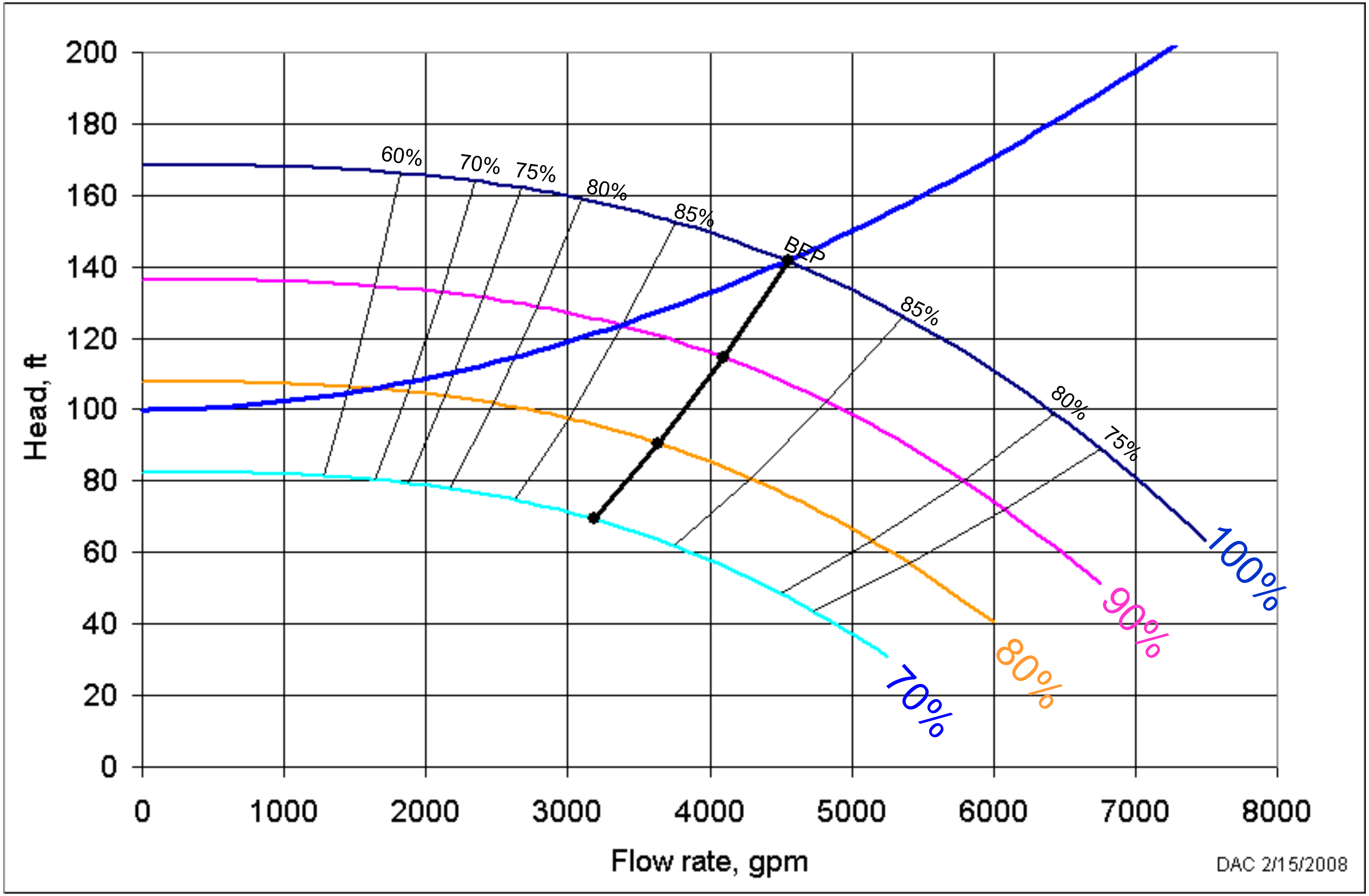
Identical pumps in series; add head at a given flow rate to estimate overall performance



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



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



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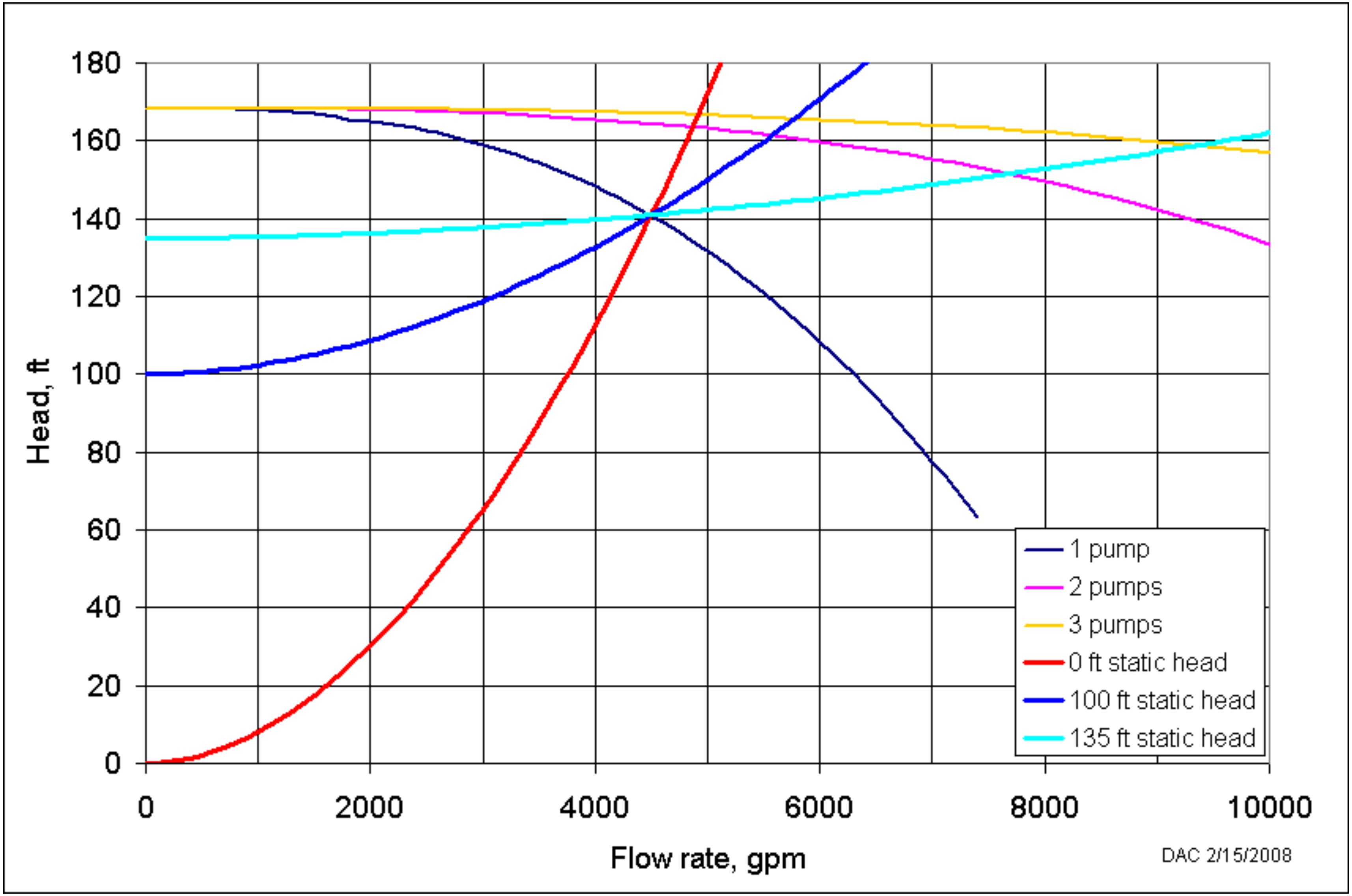
Parallel pump response also depends on the nature of the system and pump curves (P2)



Pumping faster than necessary increases friction losses – Homework Problem

A municipal water treatment plant needs to deliver 1.5 million gallons per day of fresh water into the system. An energy study has suggested the plant pump at a slower rate for a longer time to reduce the cost of pumping. The data below applies to this system. If electricity costs $0.08/kWh and demand costs $15.25/kW, calculate the annual operating cost for each flow rate.

Flow Rate (gpm)	Head (feet)	Time (hr/day)
1700	294.1	14.71
1900	302.3	13.16
2100	311.4	11.90
2300	321.5	10.87
2500	332.5	10.00

Pump and motor efficiencies

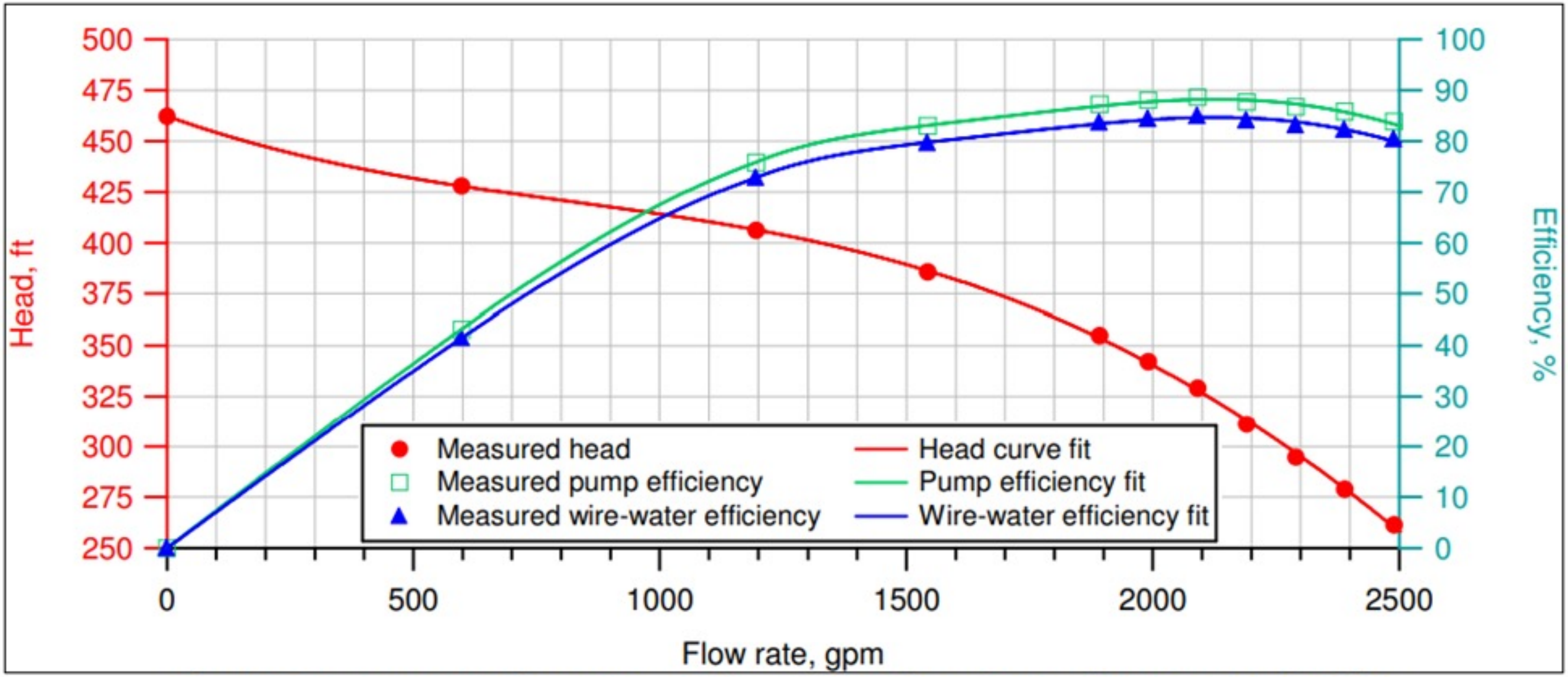


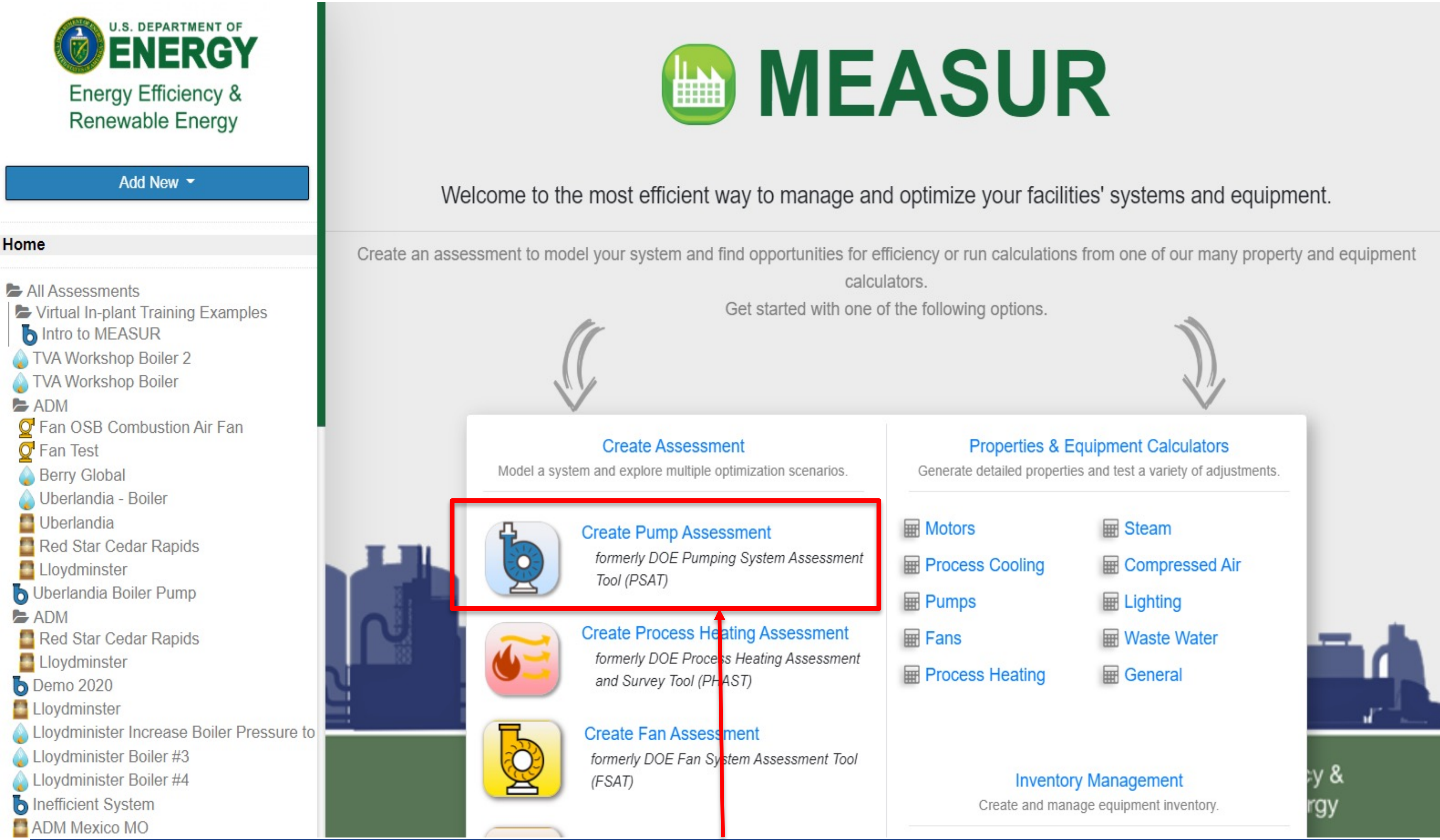
Figure 21. Pump and motor performance data from Floway test facility

The analysis

Flow Rate (gpm)	Head (feet)	Time (hr/day)	Wire to Water Efficiency (%)	Required Pump Power (kW)	Annual Energy (MWh)	Annual Demand (kW)	Annual Energy Cost ($)	Annual Demand Cost ($)	Total Annual Cost ($)	Savings vs. 2500 gpm Rate
1700	294.1	14.71	81.5	115.57	620.49	1386.79	49639	21149	70788	22190
1900	302.3	13.16	83.5	129.58	622.44	1555.00	49795	23714	73509	19469
2100	311.4	11.9	85.0	144.93	629.51	1739.18	50361	26522	76883	16094
2300	321.5	10.87	83.0	167.83	665.88	2013.98	53270	30713	83984	8994
2500	332.5	10	80.0	195.74	714.46	2348.91	57157	35821	92978	0

Pumping slower for longer reduces the frictional losses and reduces the operating cost

Open the MEASUR Software

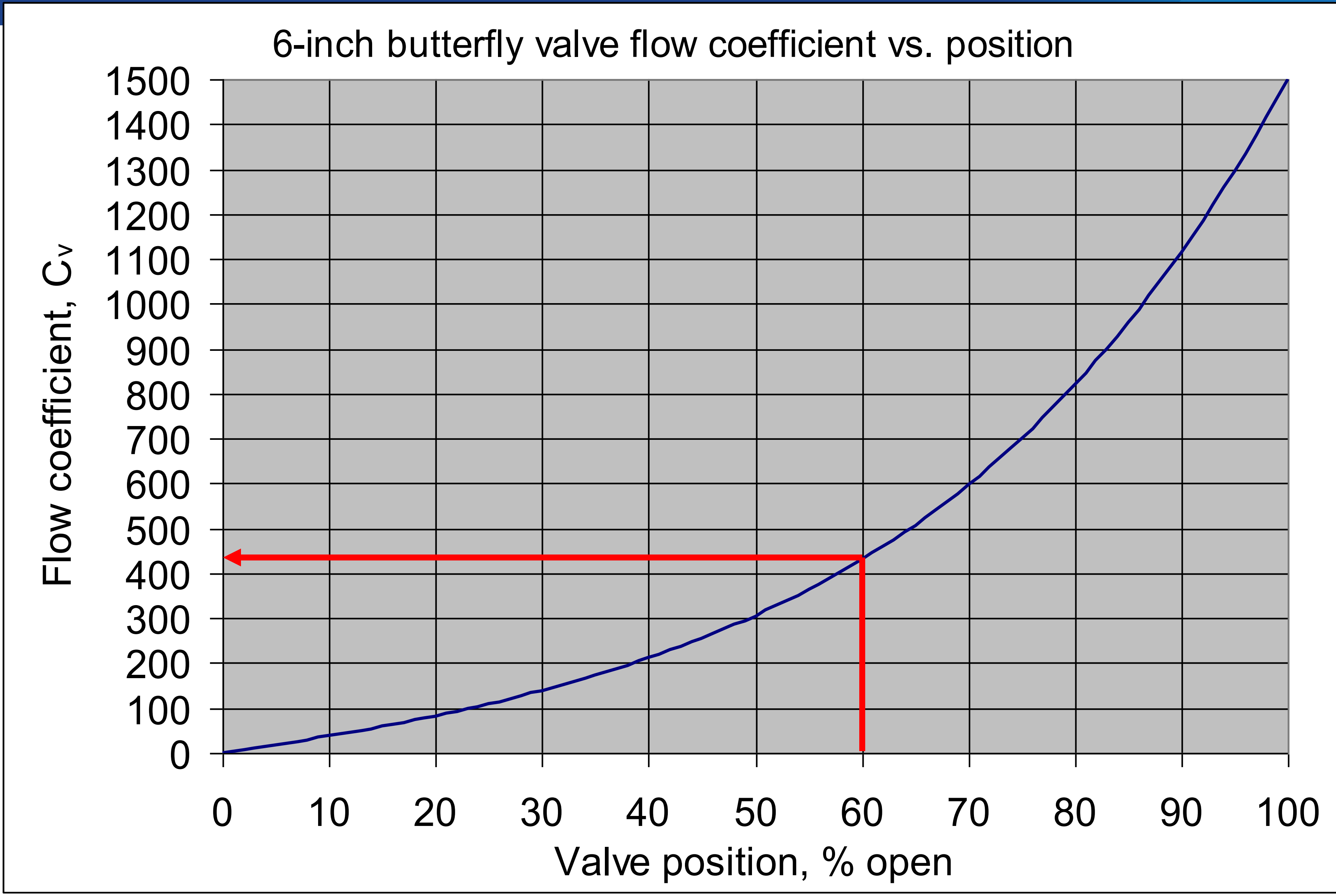


Click on Create Pump Assessment

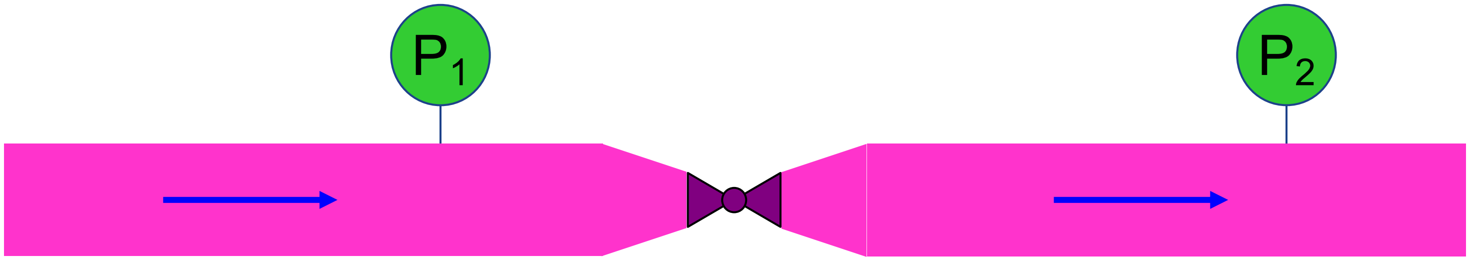
Pumping tool before MEASUR was PSAT

- The first Pumping System Analysis Tool developed by US DOE was PSAT
- PSAT download comes with another program, ***Valve Tool***, that is very useful
- Valve Tool has not been added to MEASUR yet
- PSAT and Valve Tool can be downloaded from the following website
- https://www.energy.gov/eere/amo/downloads/pumping-system-assessment-tool-psat

Valve flow coefficient curve



The valve tool works from the fundamental valve relationships



$$Q = F_p C_v \sqrt{\frac{\Delta P}{s.g.}}$$

In U.S. units:

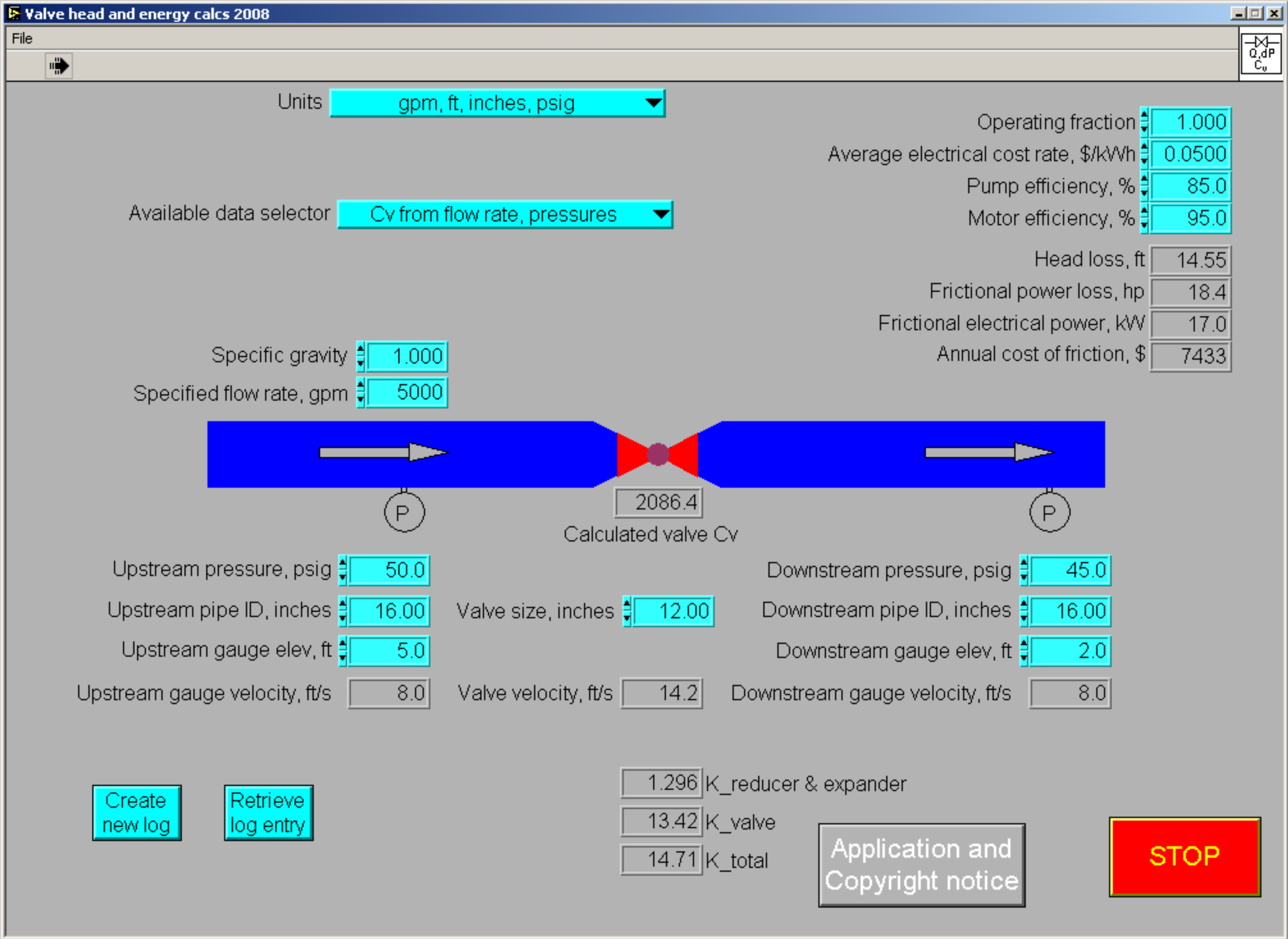
Q = Flow rate (gpm)

F_p = Geometry factor

C_v = Valve flow coefficient

ΔP = pressure drop, psi

s.g. = specific gravity


Valve head and energy calcs 2008
File
Units
gpm, ft, inches, psig
Available data selector
Cv from flow rate, pressures
Operating fraction
1.000
Average electrical cost rate, $/kWh
0.0500
Pump efficiency, %
85.0
Motor efficiency, %
95.0
Head loss, ft
14.55
Frictional power loss, hp
18.4
Frictional electrical power, kW
17.0
Annual cost of friction, $
7433
Specific gravity
1.000
Specified flow rate, gpm
5000
P
2086.4
Calculated valve Cv
P
Upstream pressure, psig
50.0
Downstream pressure, psig
45.0
Upstream pipe ID, inches
16.00
Valve size, inches
12.00
Downstream pipe ID, inches
16.00
Upstream gauge elev, ft
5.0
Downstream gauge elev, ft
2.0
Upstream gauge velocity, ft/s
8.0
Valve velocity, ft/s
14.2
Downstream gauge velocity, ft/s
8.0
Create new log
Retrieve log entry
1.296 K_reducer & expander
13.42 K_valve
14.71 K_total
Application and Copyright notice
STOP


The End