Pumps and Piping; Design, Performance and Commissioning Issues

Pump Curves, System Curves and Pump Tests

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Pump Performance Presentation

Pumps add energy to the fluid they move

- Elevated mass = stored energy
- Mass in motion = stored energy

Plotting performance in terms of energy added per unit mass makes the performance curve independent of density

$$\frac{\text{Energy}}{\text{Unit Mass}} = \frac{\text{foot} - \cancel{\text{pounds}}}{\cancel{\text{pound}}}$$

Increasing Head

Increasing Flow

Flow = Moving Mass

Pounds per hour

Gallons per minute

Cubic meters per hour

Head = Elevated Mass

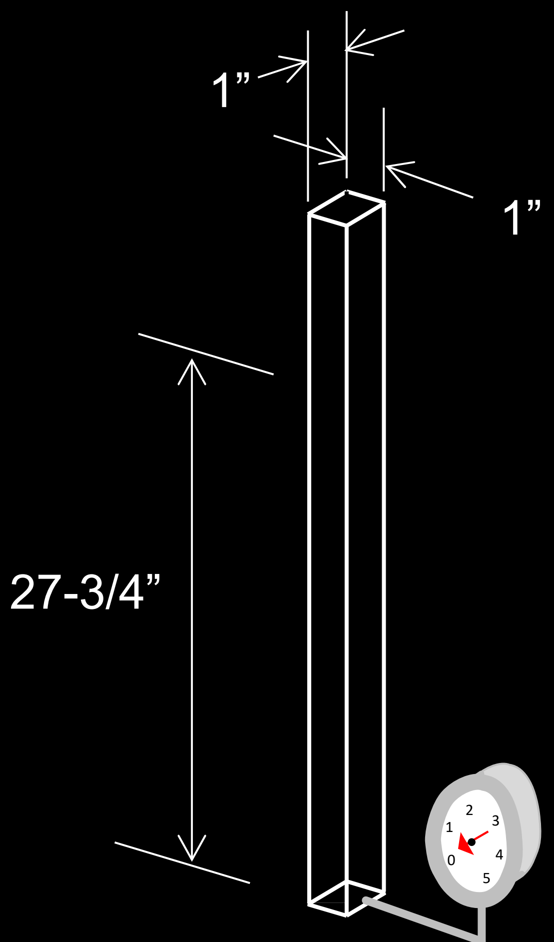
Feet of water

Meters of water

Increasing Head

Increasing Flow

The Relationship Between ft.w.c. and psi



Density of water at 75°F, sea level conditions:

- 62.4 lb./ft.^{3}
- 0.036 lb/ in.^{3}

Volume of a column of water 1 in. square and 27-3/4 in. high:

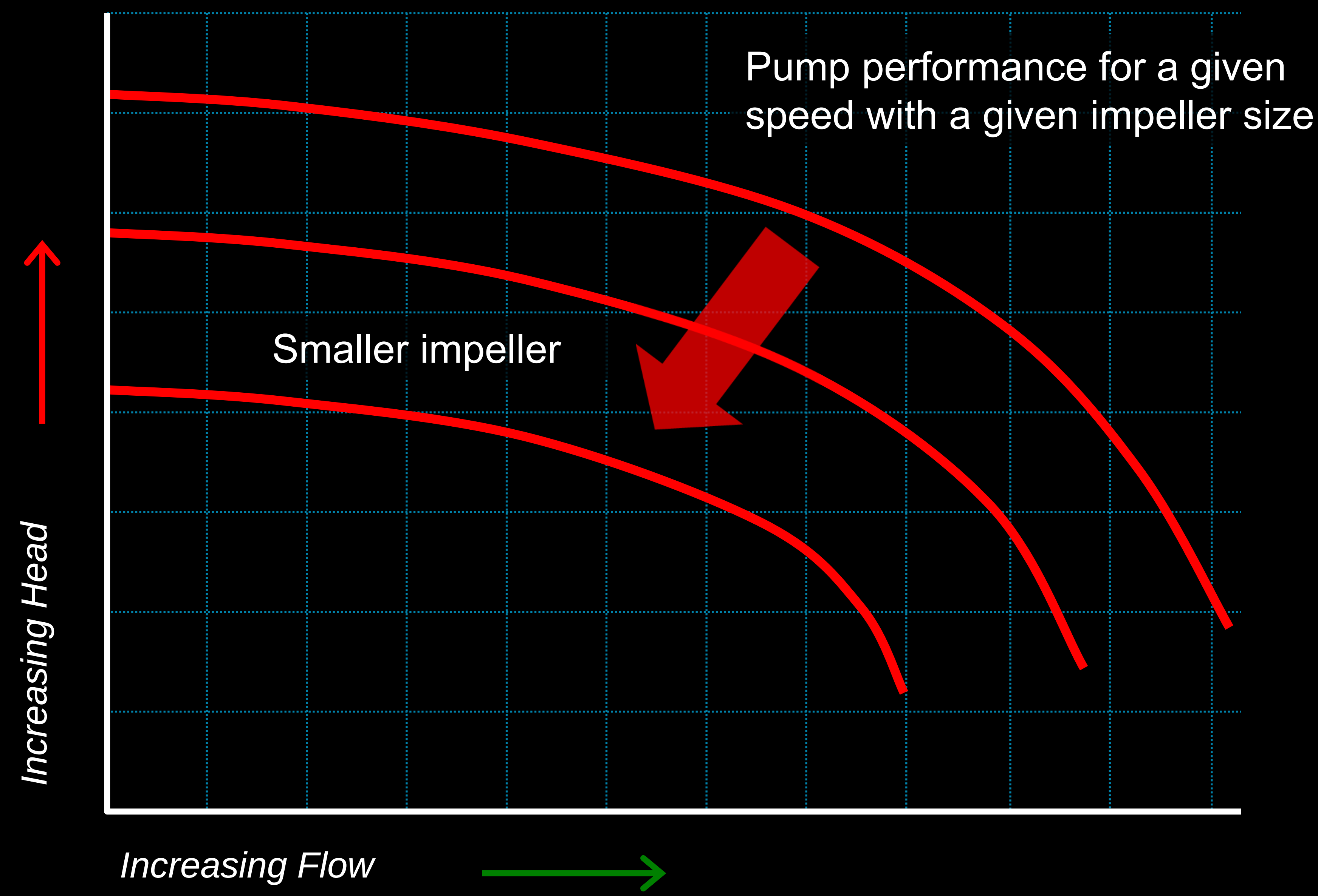
- 27.75 in.^{3}

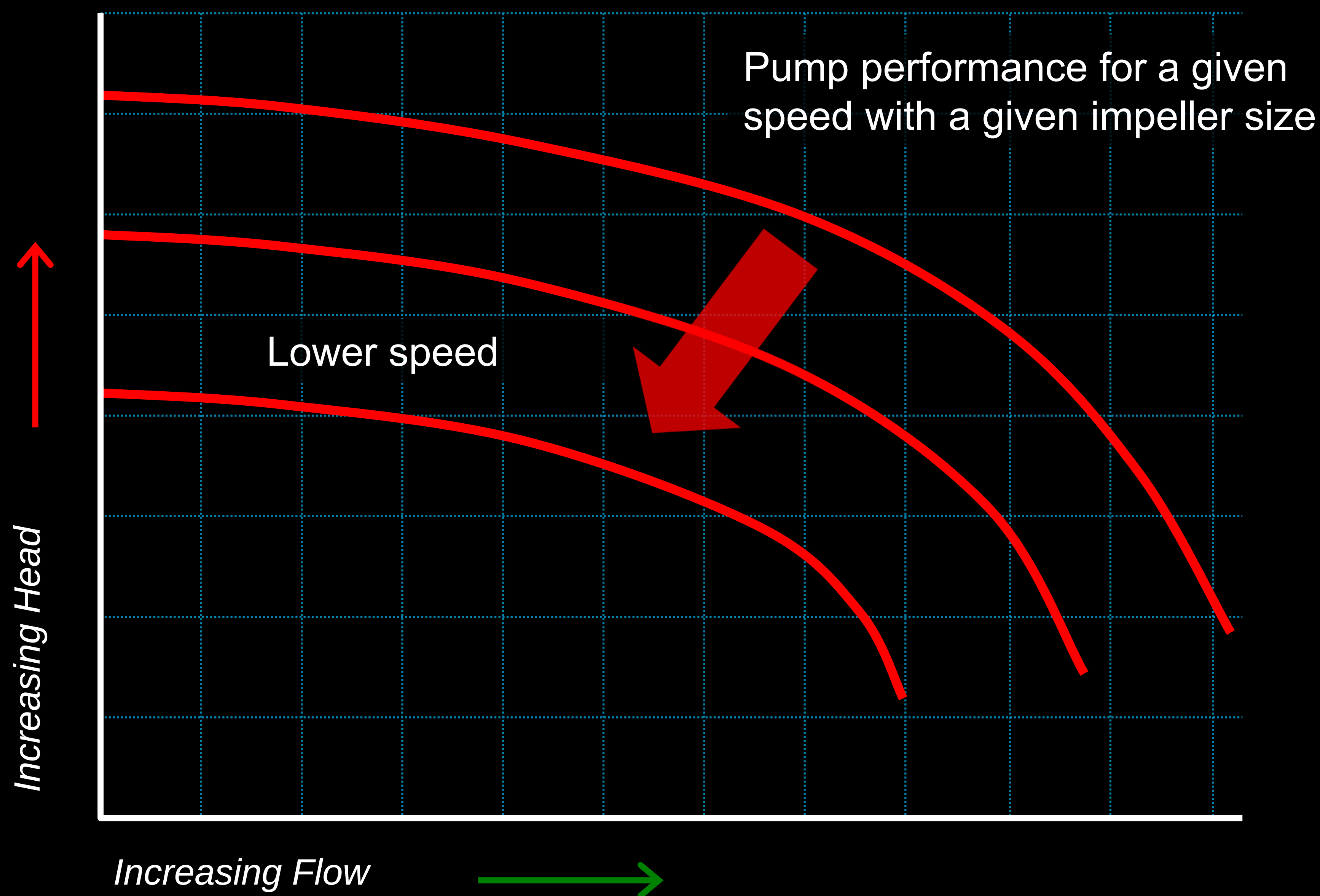
Weight of the column of water:

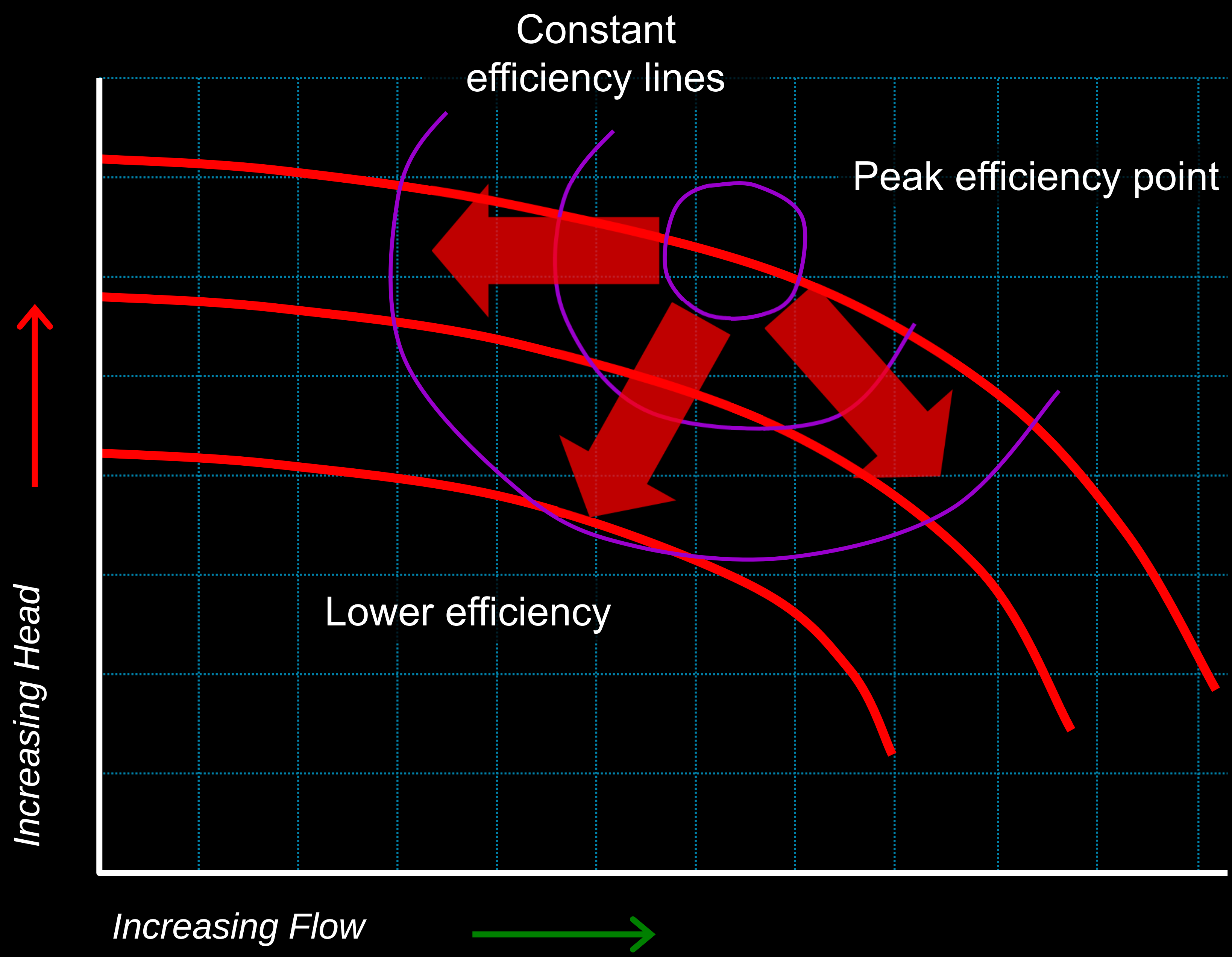
- 27.75 in.^{3} x 0.036 lb/ in.^{3} = 1 lb.

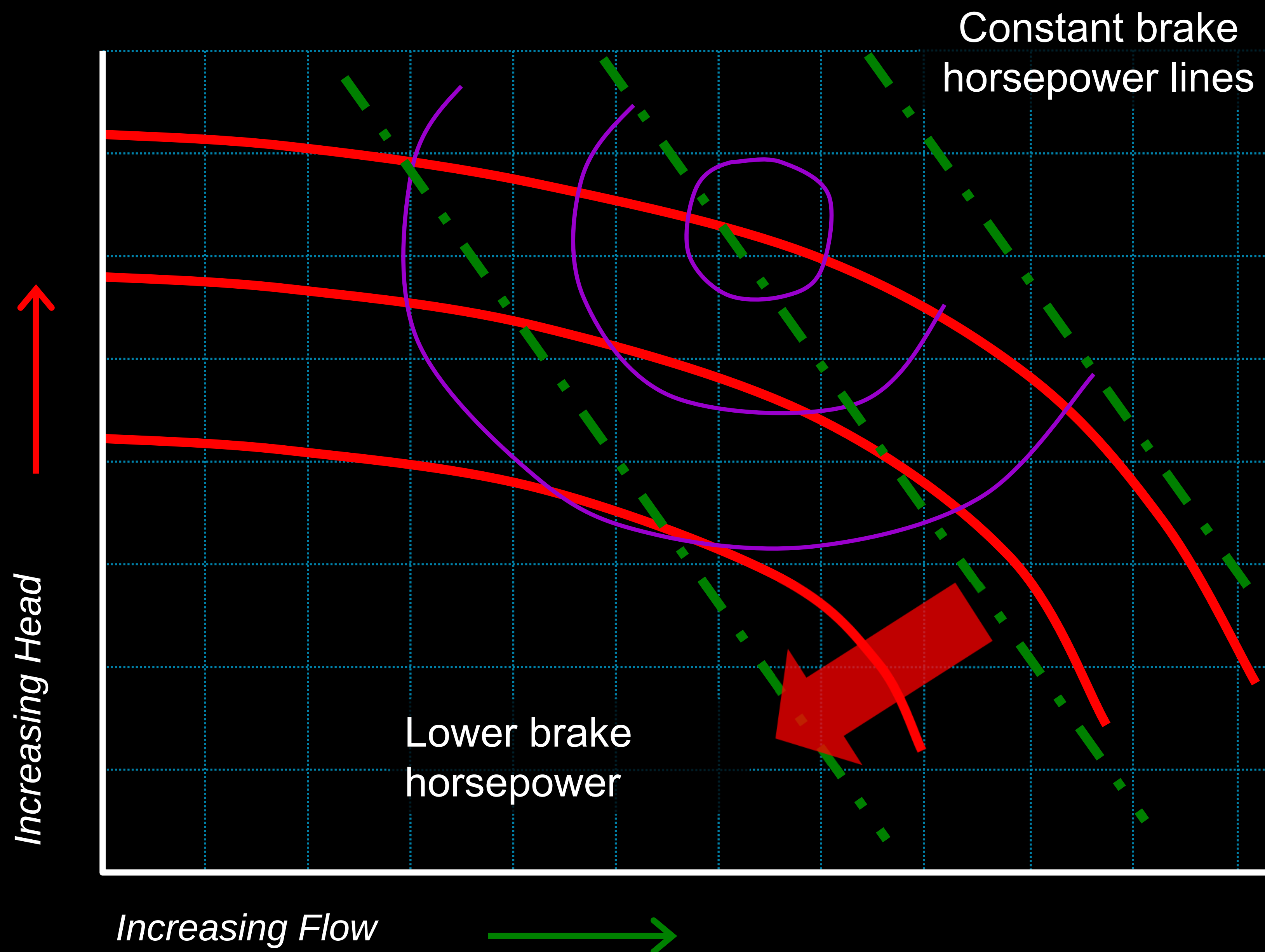
1 lb. of water over 1 in.^{2}:

- 1 lb./in.^{2} (1 psi)

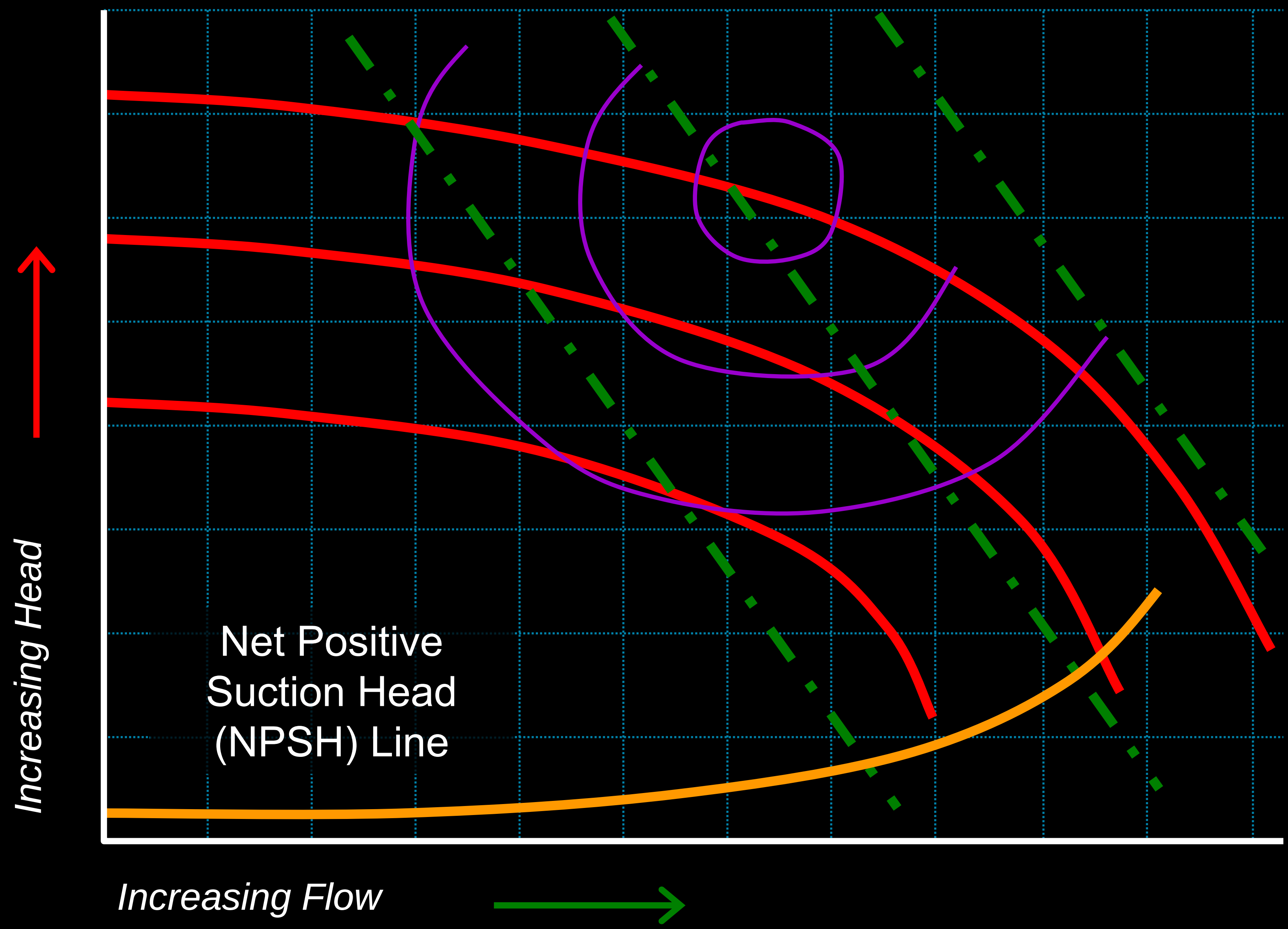

Pump performance for a given speed with a given impeller size
Smaller impeller
Increasing Head
Increasing Flow


Pump performance for a given speed with a given impeller size
Lower speed
Increasing Head
Increasing Flow


Constant
efficiency lines
Peak efficiency point
Lower efficiency
Increasing Head
Increasing Flow



Constant brake horsepower lines
Lower brake horsepower
Increasing Head
Increasing Flow



Net Positive
Suction Head
(NPSH) Line
Increasing Head
Increasing Flow

Net Positive Suction Head

Abstract concept

Related to

- Pressure changes on the suction side of the pump
- Vapor pressure of the fluid
- Absolute vs. gauge pressure

Net Positive Suction Head

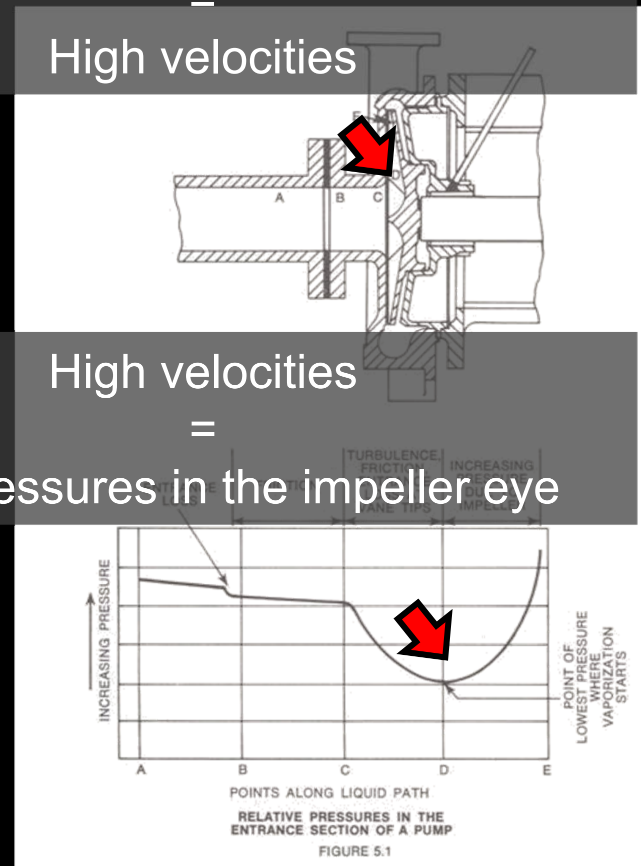
Pressure tends to drop

- As water moves towards the pump
- As water flows through the pump

Lower pressure = tendency to boil

- Pumps move liquid not vapor
- Vapor = cavitation
- Cavitation = loss of flow
- Cavitation = damage!

Small impeller passage cross sections
=
High velocities



High velocities
=
Low pressures in the impeller eye

Data and image taken from the Durco Pump Engineering Manual

Net Positive Suction Head

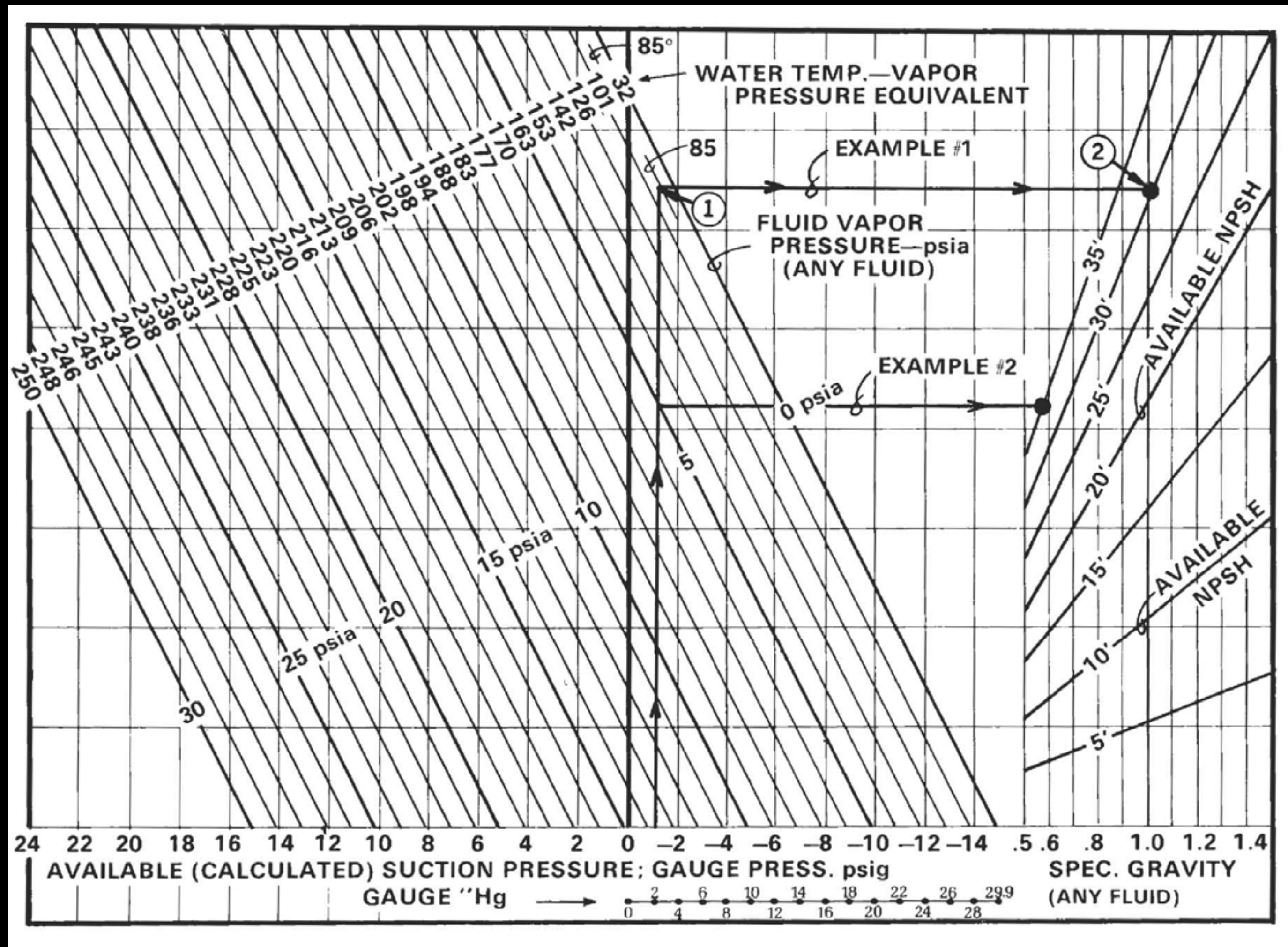
Required

- Head *required* at the suction flange to prevent cavitation
- Characteristic of the *pump*
- Varies with
  - Pump geometry
  - Pump flow rate
  - Pump speed
- Determined by the manufacturer

Available

- Head available at the suction flange above the vapor pressure at the suction flange to keep the fluid in a liquid state
- Characteristic of the *system*
- Varies with
  - System geometry
  - System flow rate
  - Fluid temperature
- Determined by
  - Calculation
  - Field test

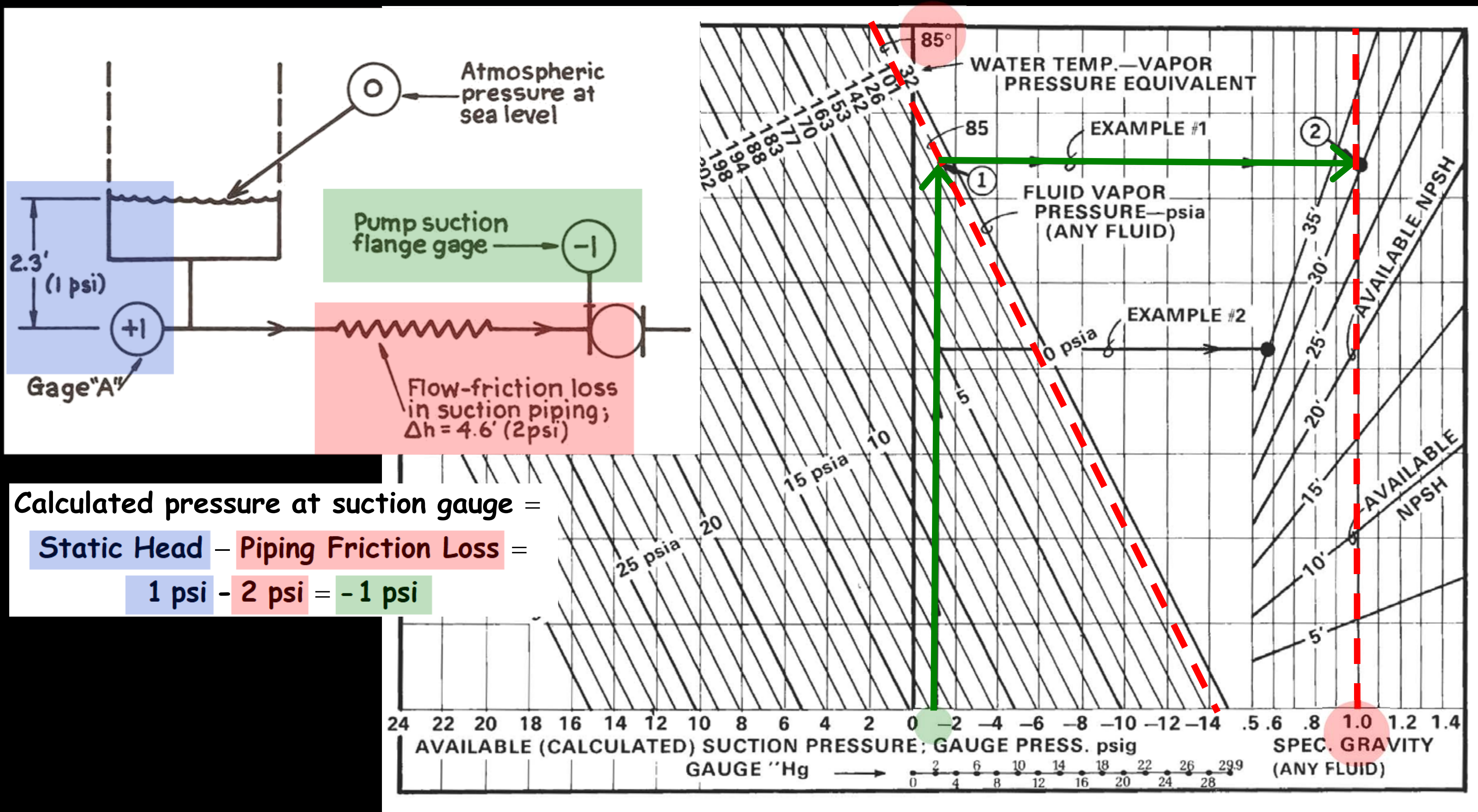
A Practical NPSH Tool



A Practical NPSH Tool

NPSH Available = 31 ft.w.c.

A pump that required less than 31 ft.w.c of NPSH would work!



Calculated pressure at suction gauge =

Static Head – Piping Friction Loss =

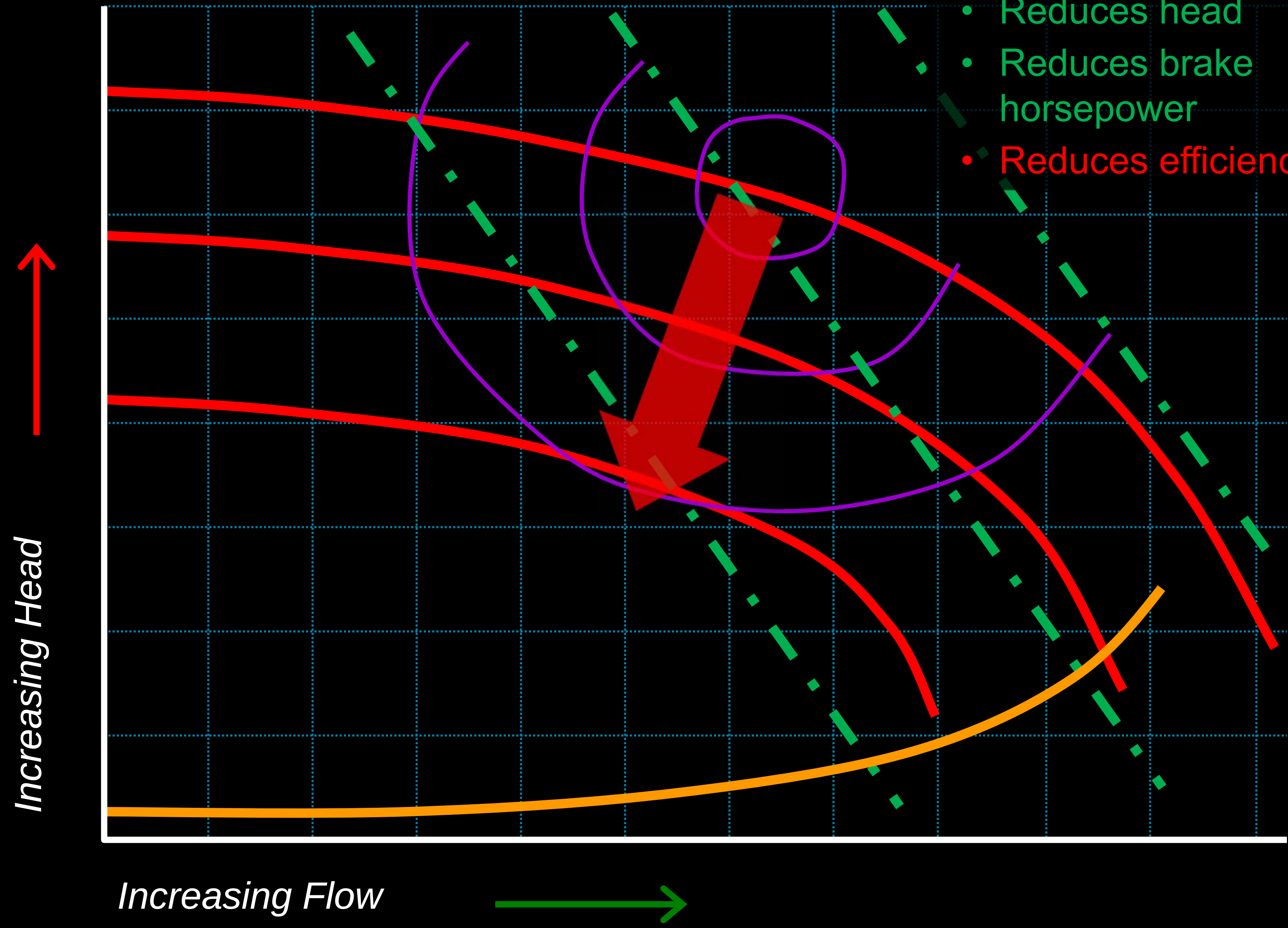
1 psi - 2 psi = - 1 psi

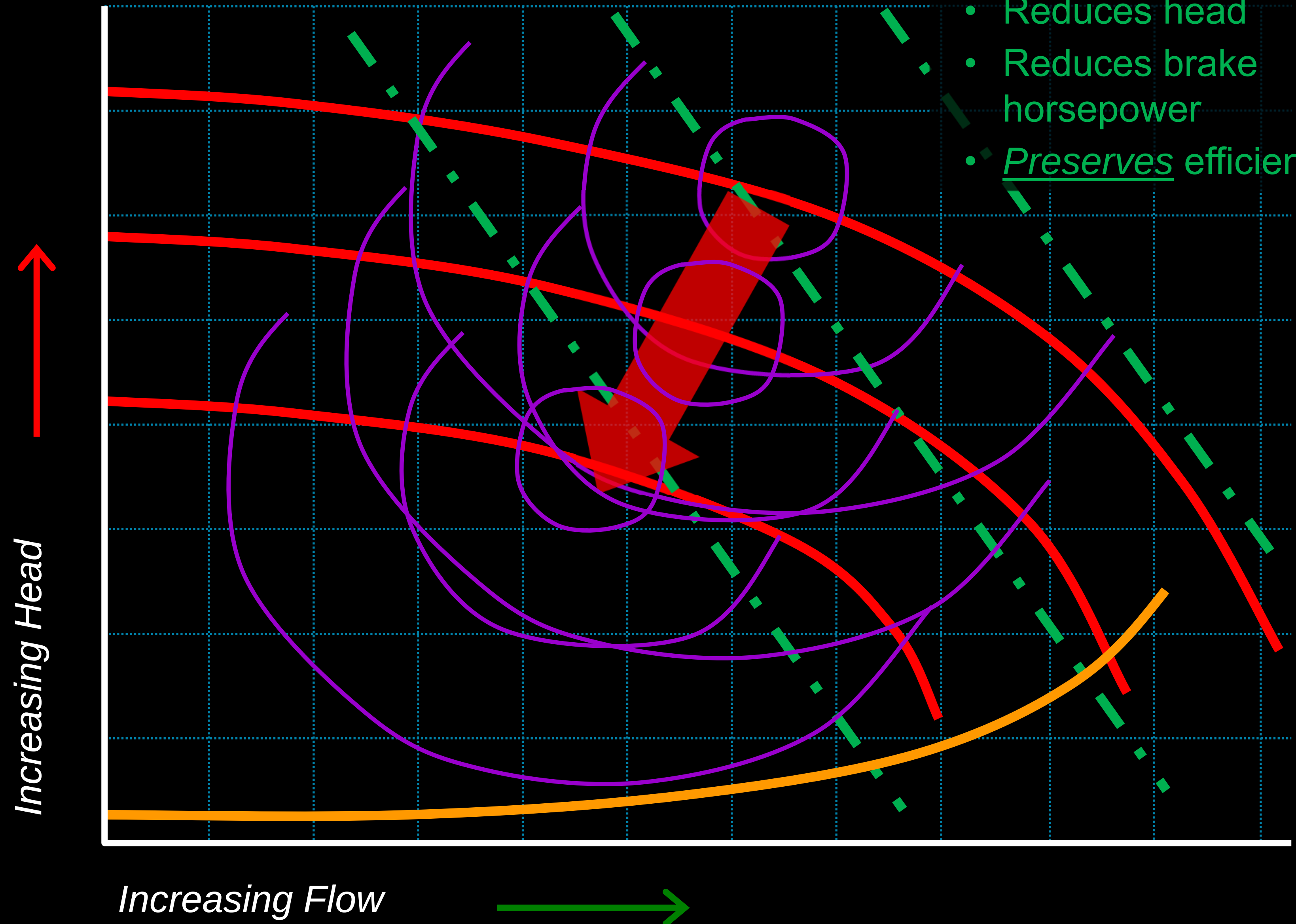
A NPSH Resource

Bell and Gossett's Engineering Design Manual
Bulletin THE-1075 – Cooling Tower Pumping and Piping
Contact Columbia Hydronics
http://www.chchydronics.com/chcpkgs2.htm

Reducing impeller size:

- Reduces head
- Reduces brake horsepower
- Reduces efficiency



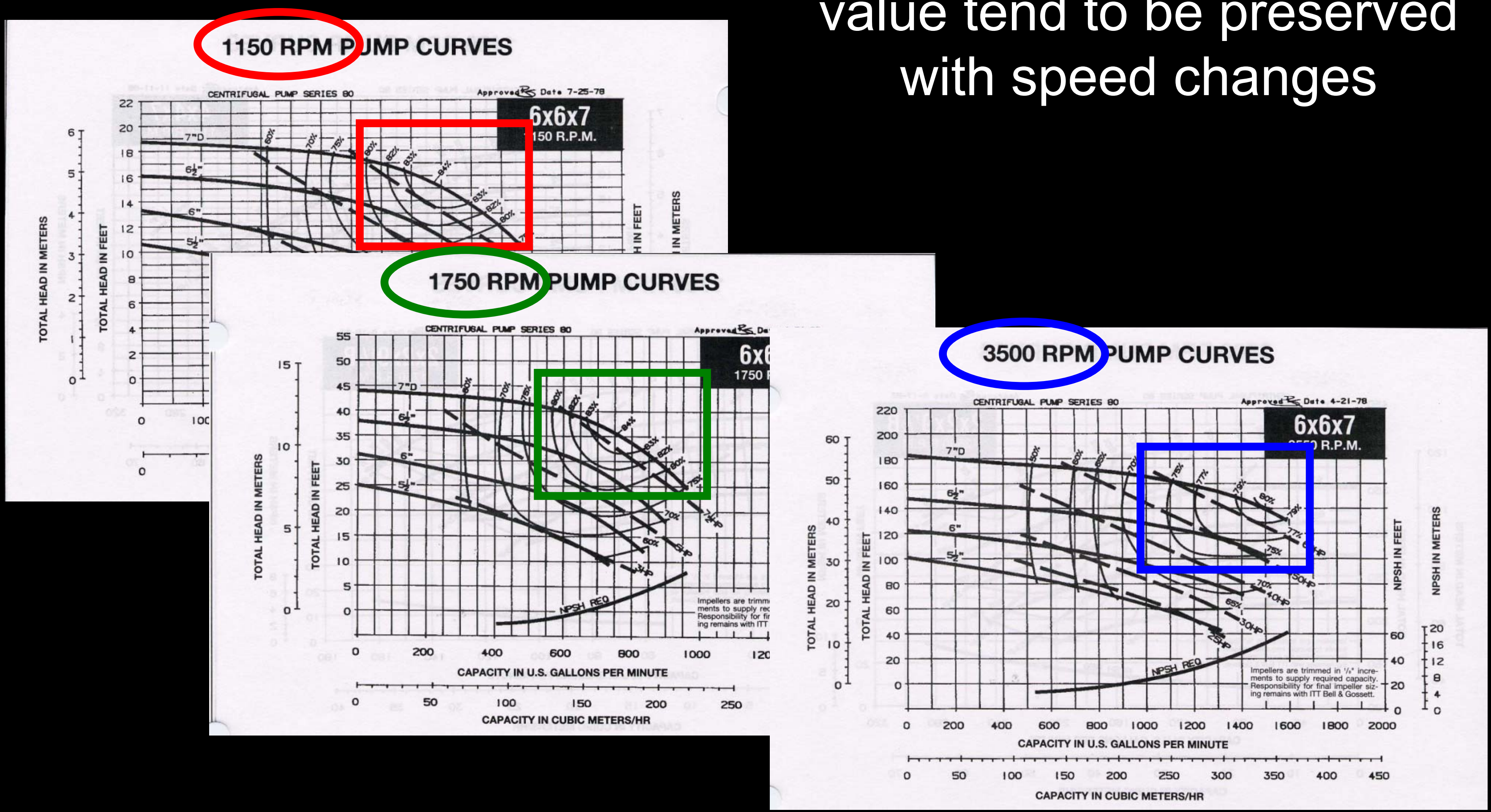


Reducing speed:

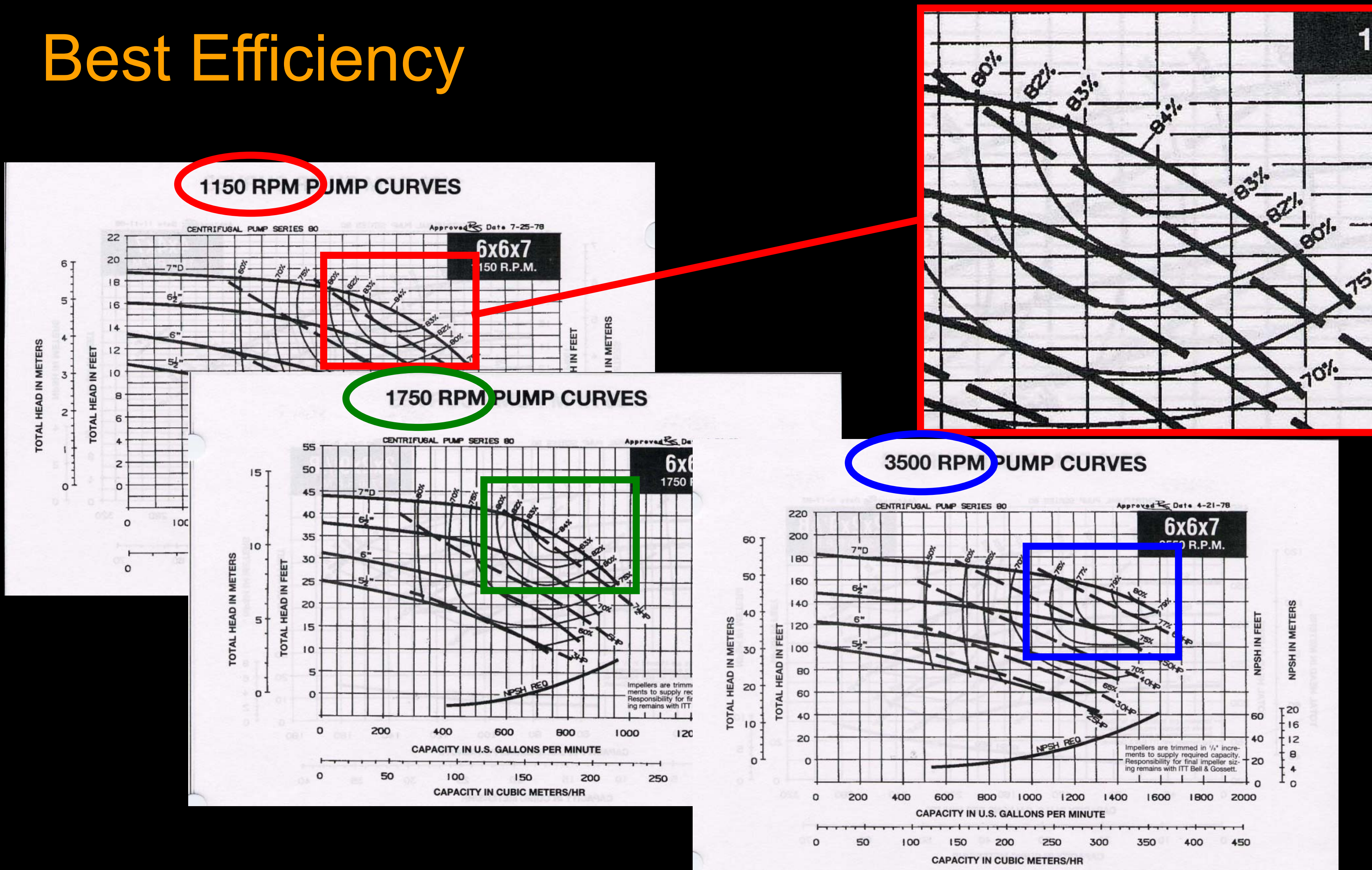
- Reduces head
- Reduces brake horsepower
- *Preserves* efficiency

Best Efficiency

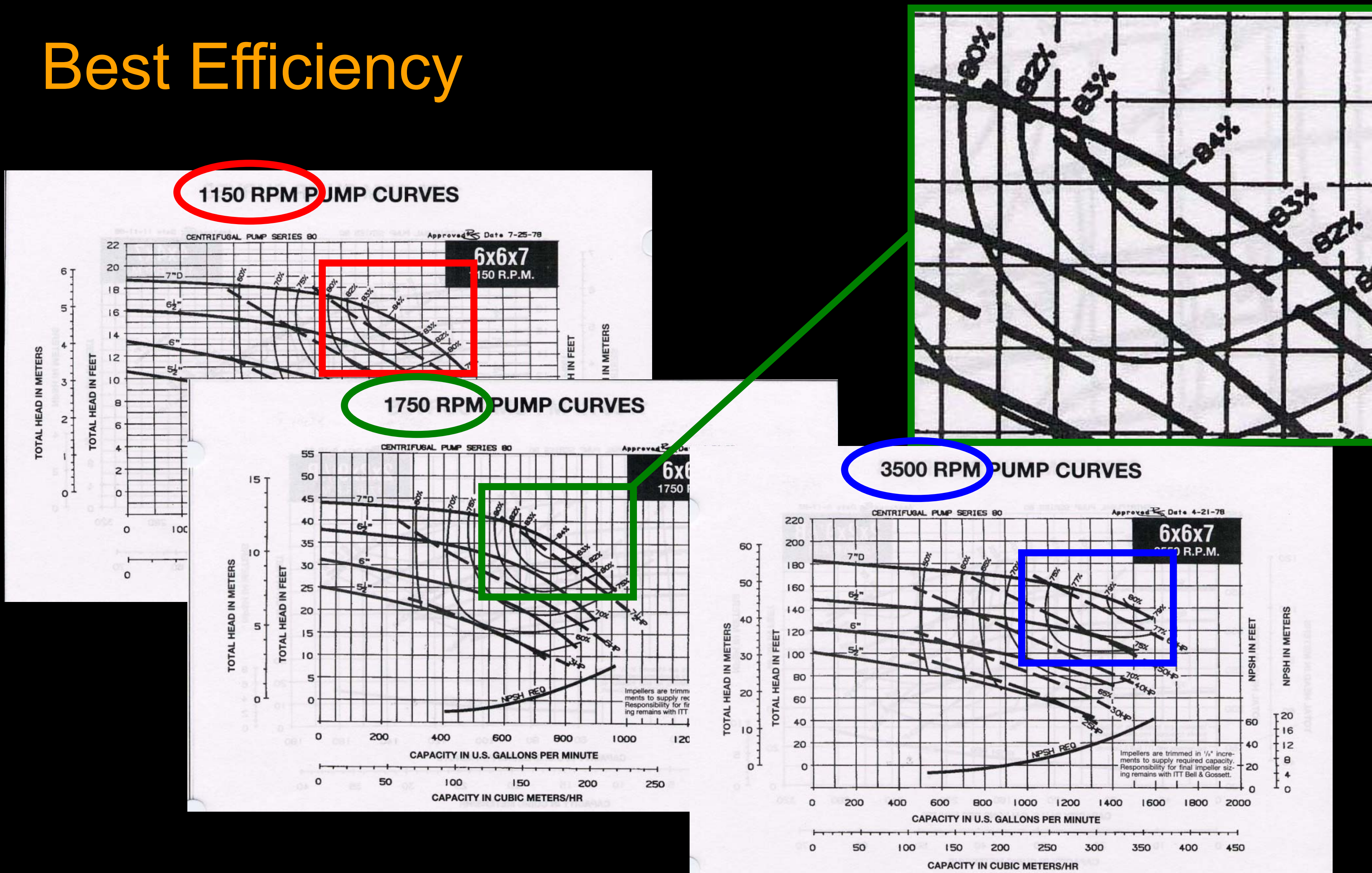
“Sweet spot” location and value tend to be preserved with speed changes



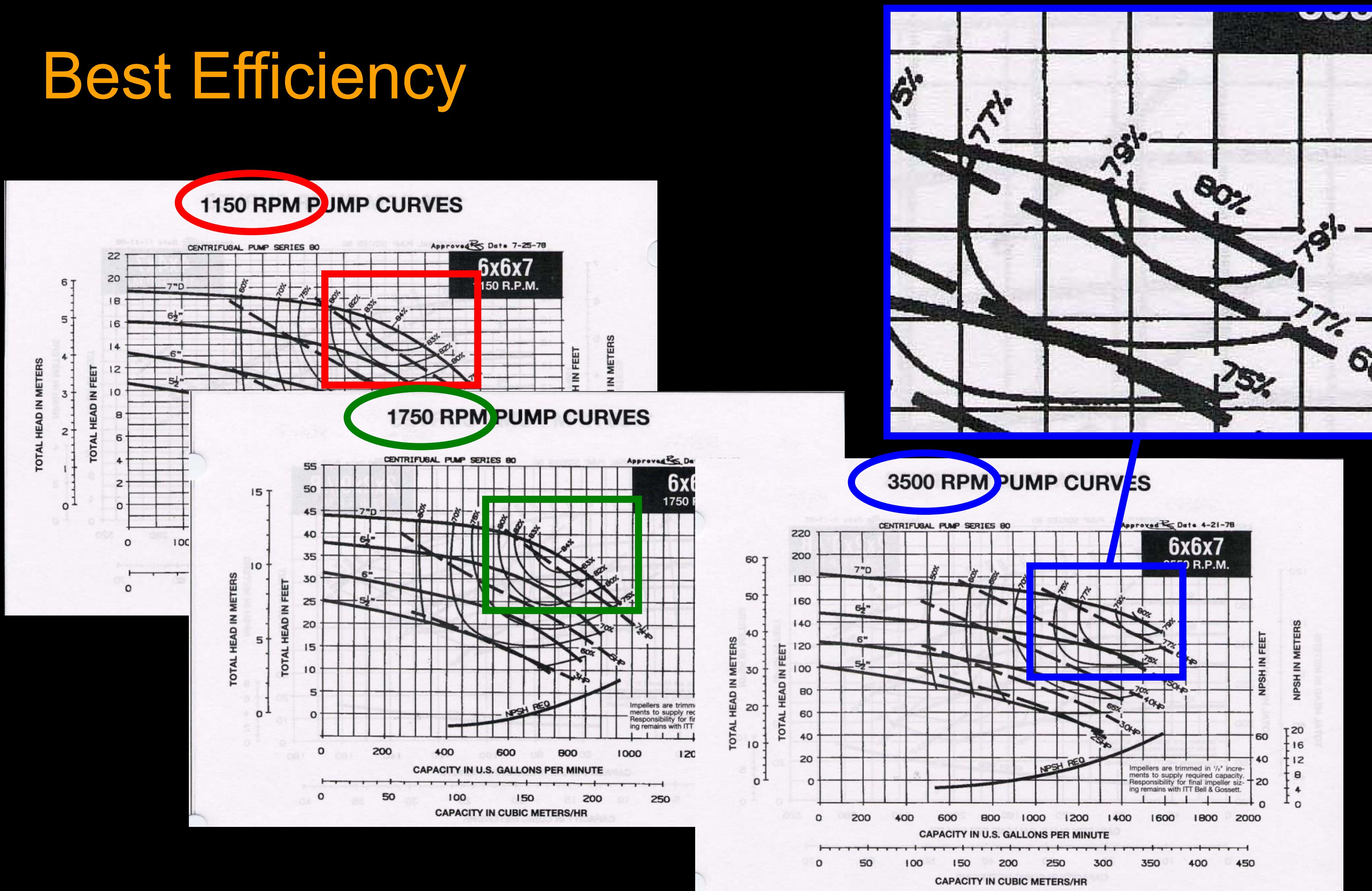
Best Efficiency

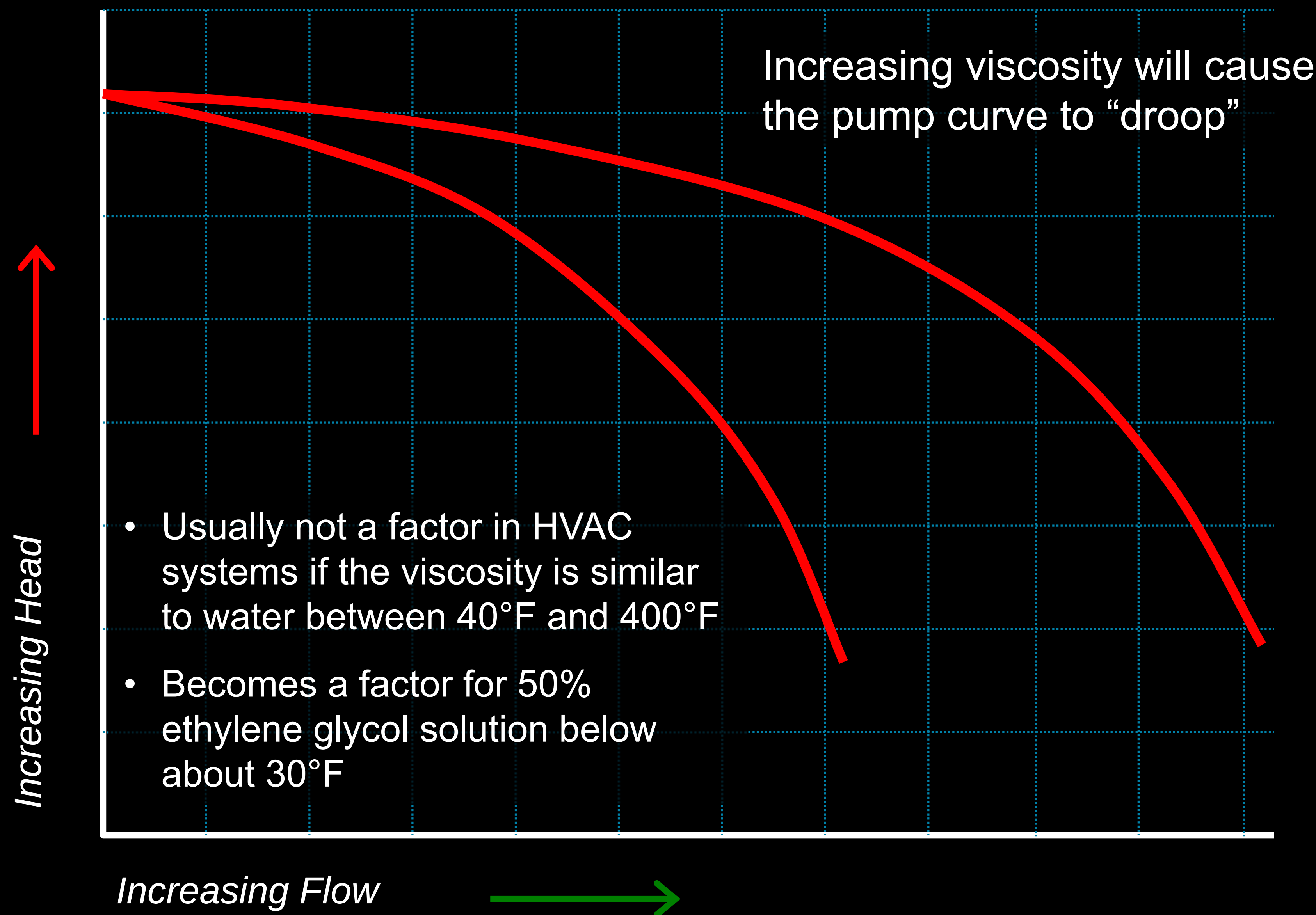


Best Efficiency

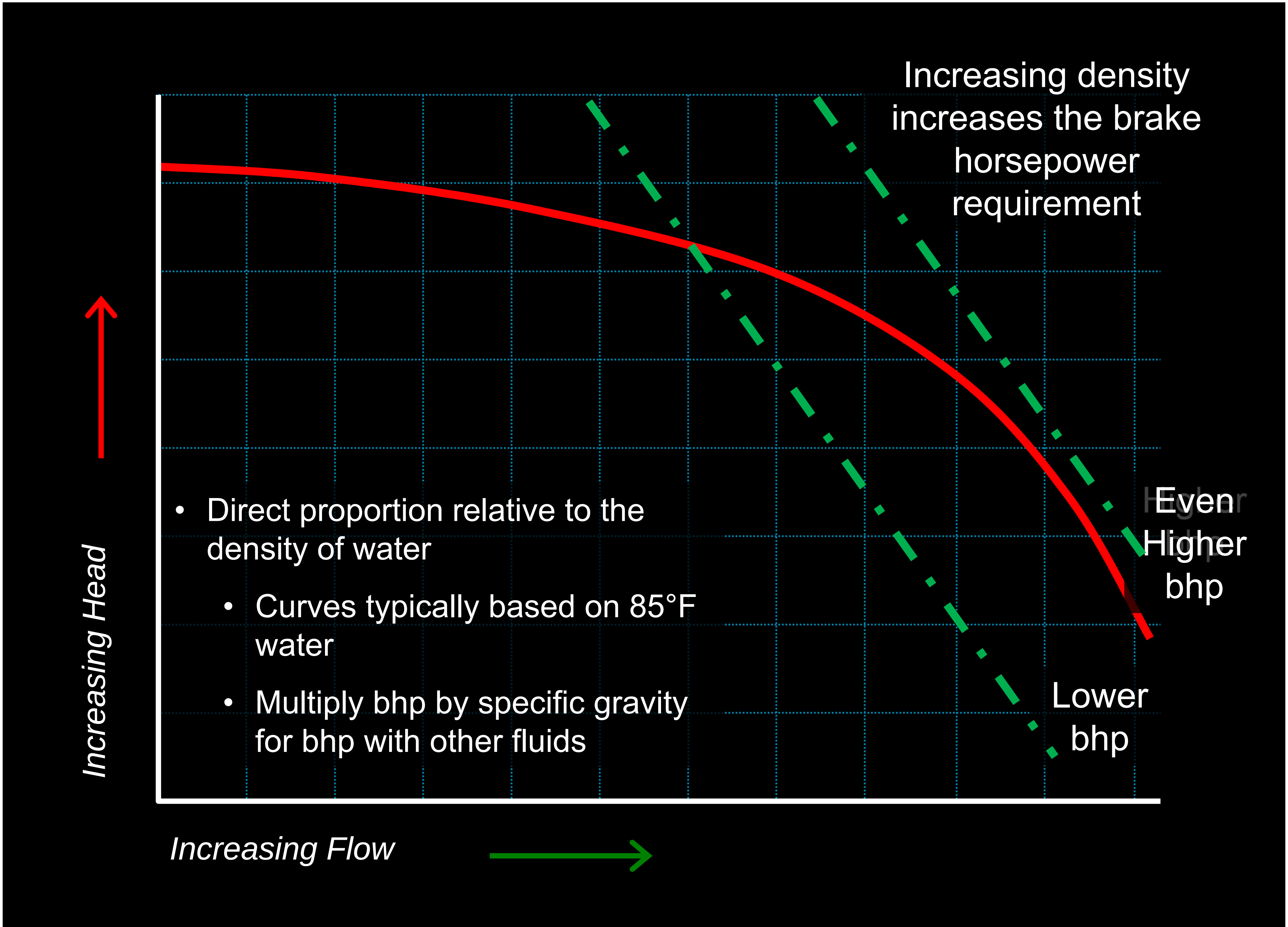


Best Efficiency

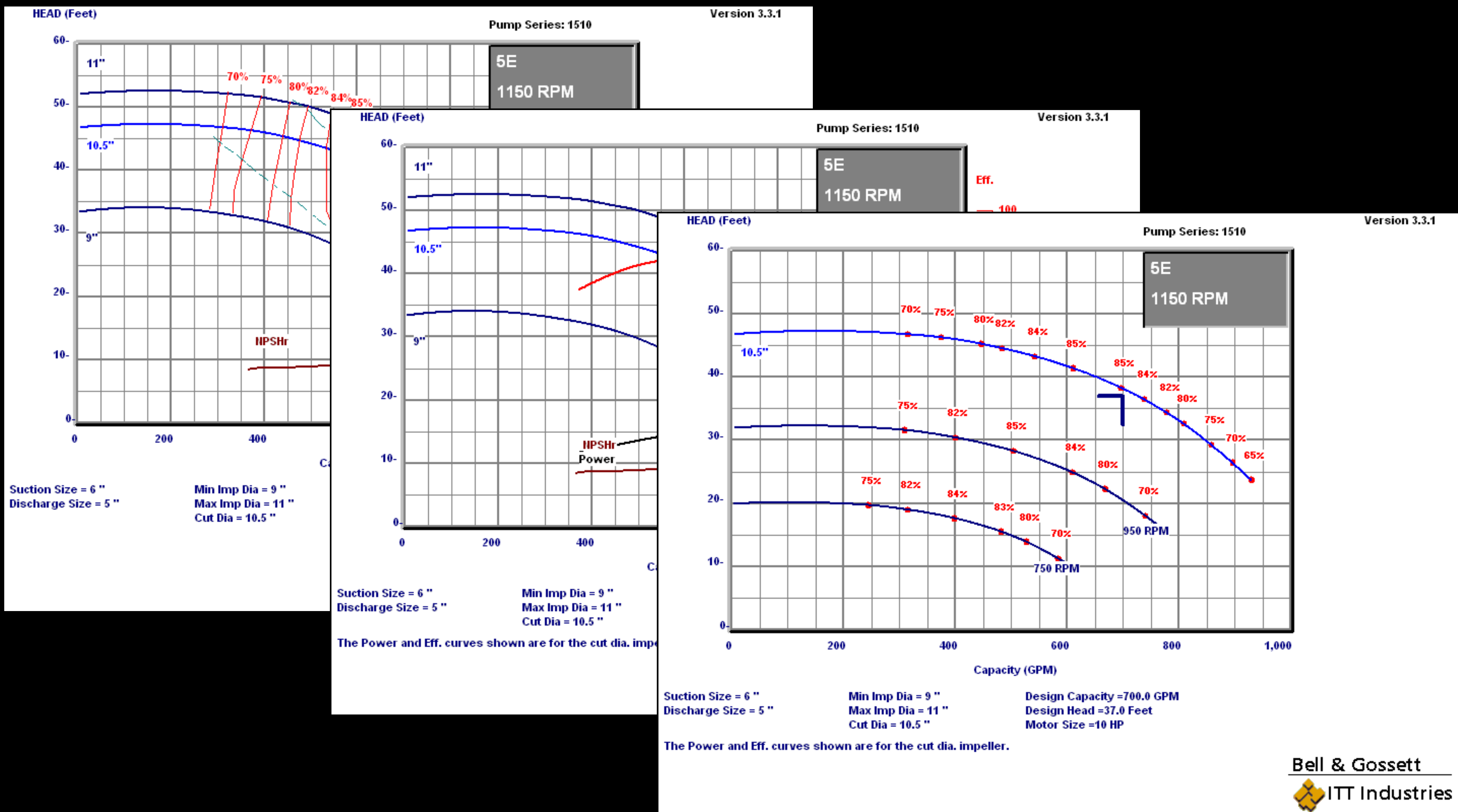




- Usually not a factor in HVAC systems if the viscosity is similar to water between 40°F and 400°F
- Becomes a factor for 50% ethylene glycol solution below about 30°F

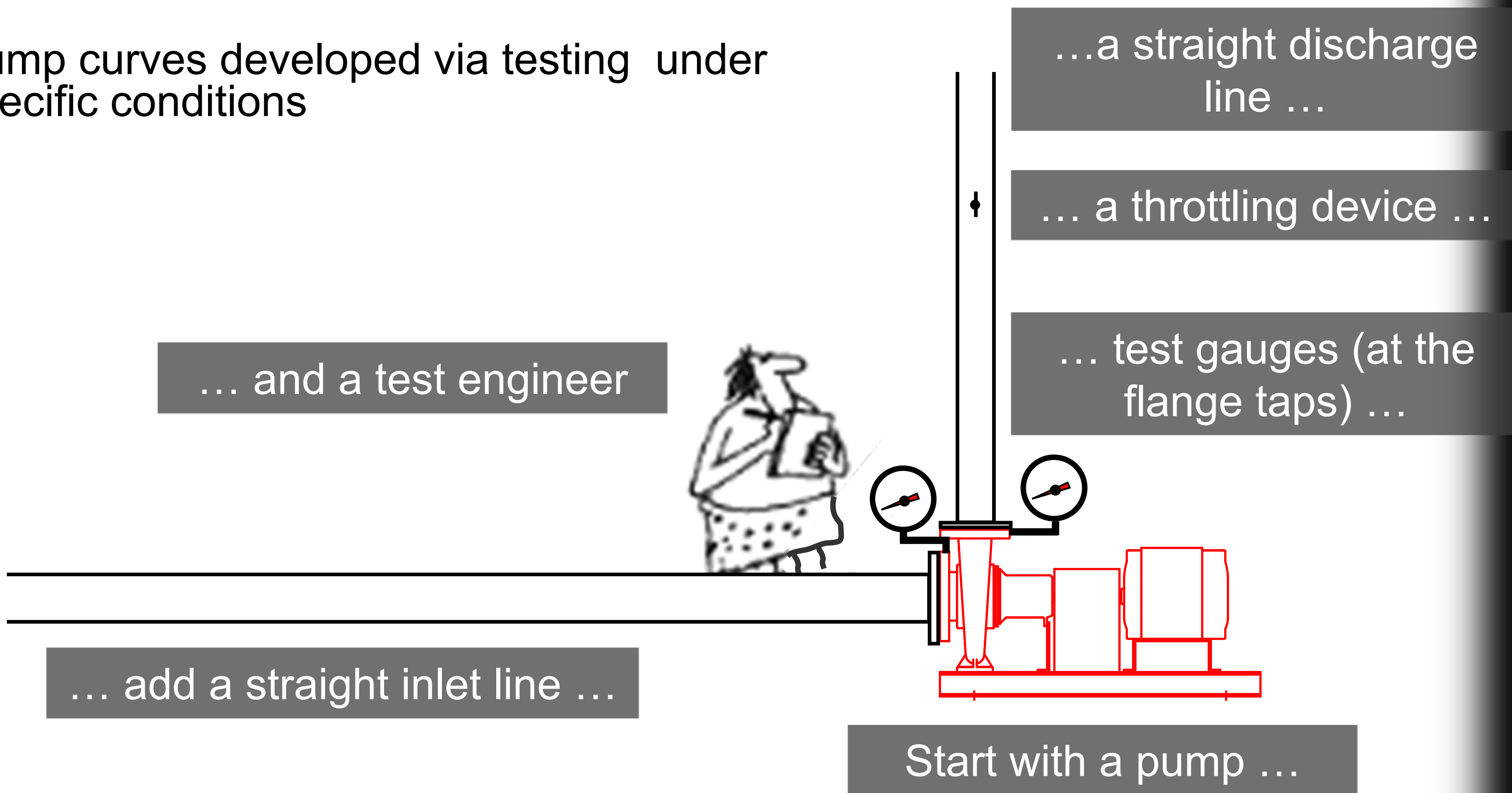

Increasing density increases the brake horsepower requirement
Even Higher bhp
Lower bhp
Direct proportion relative to the density of water
Curves typically based on 85°F water
Multiply bhp by specific gravity for bhp with other fluids
Increasing Head
Increasing Flow

Performance Presentation Variations



Developing a Pump Curve

Pump curves developed via testing under specific conditions



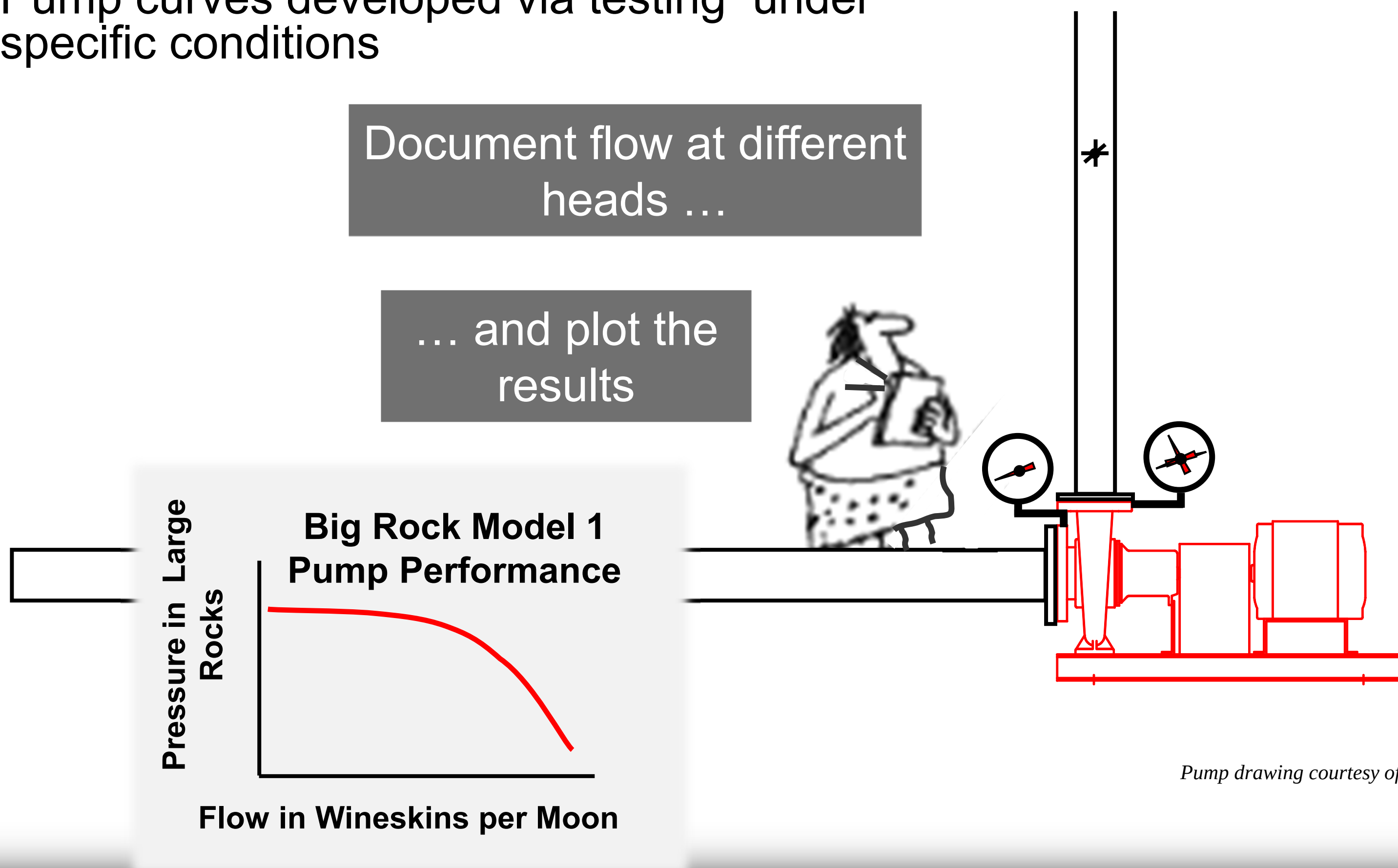
Pump drawing courtesy of Bell and Gossett

Pump Inlet Conditions and Pressure Taps Matter

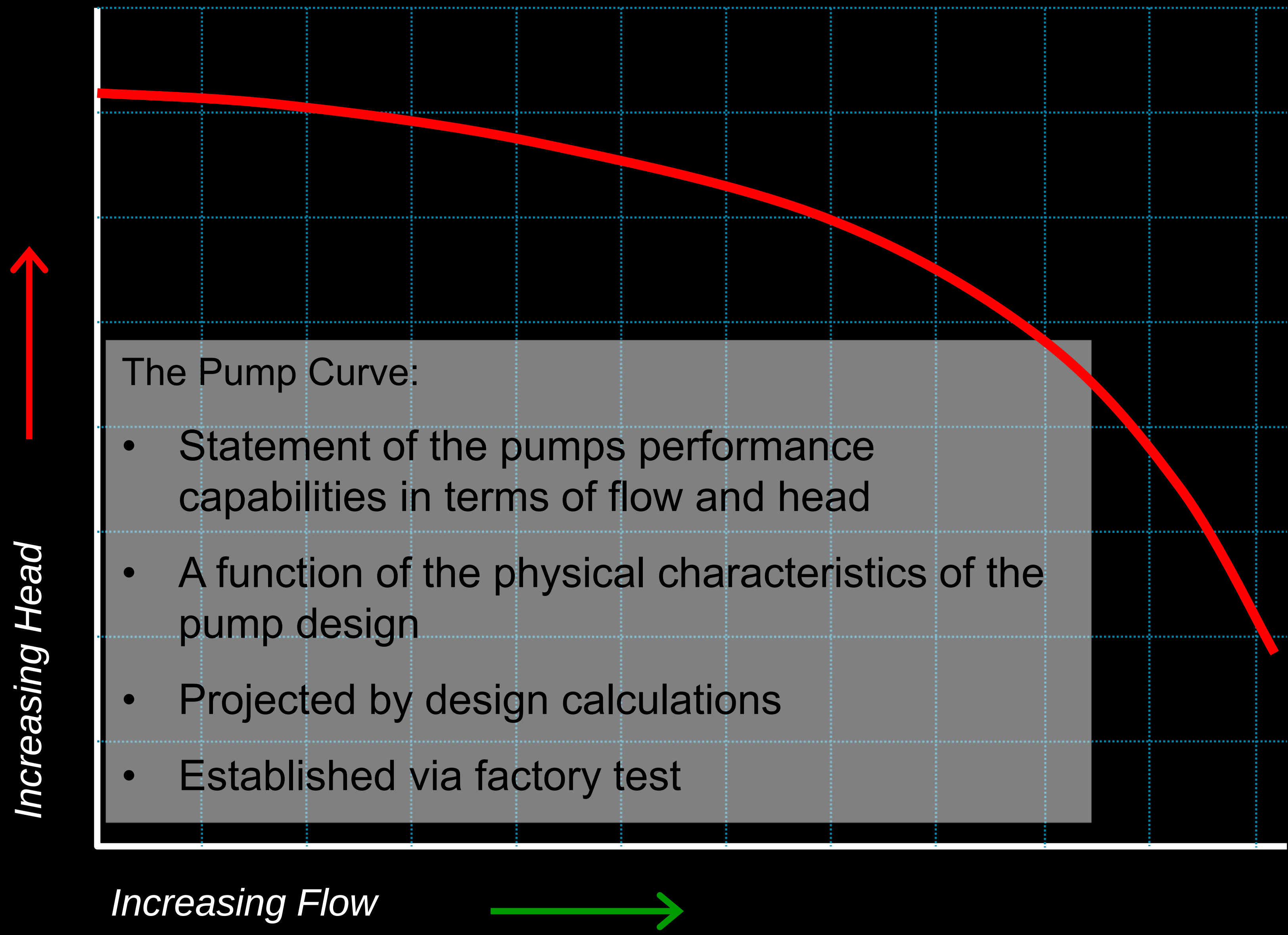
Pump curves developed via testing under specific conditions

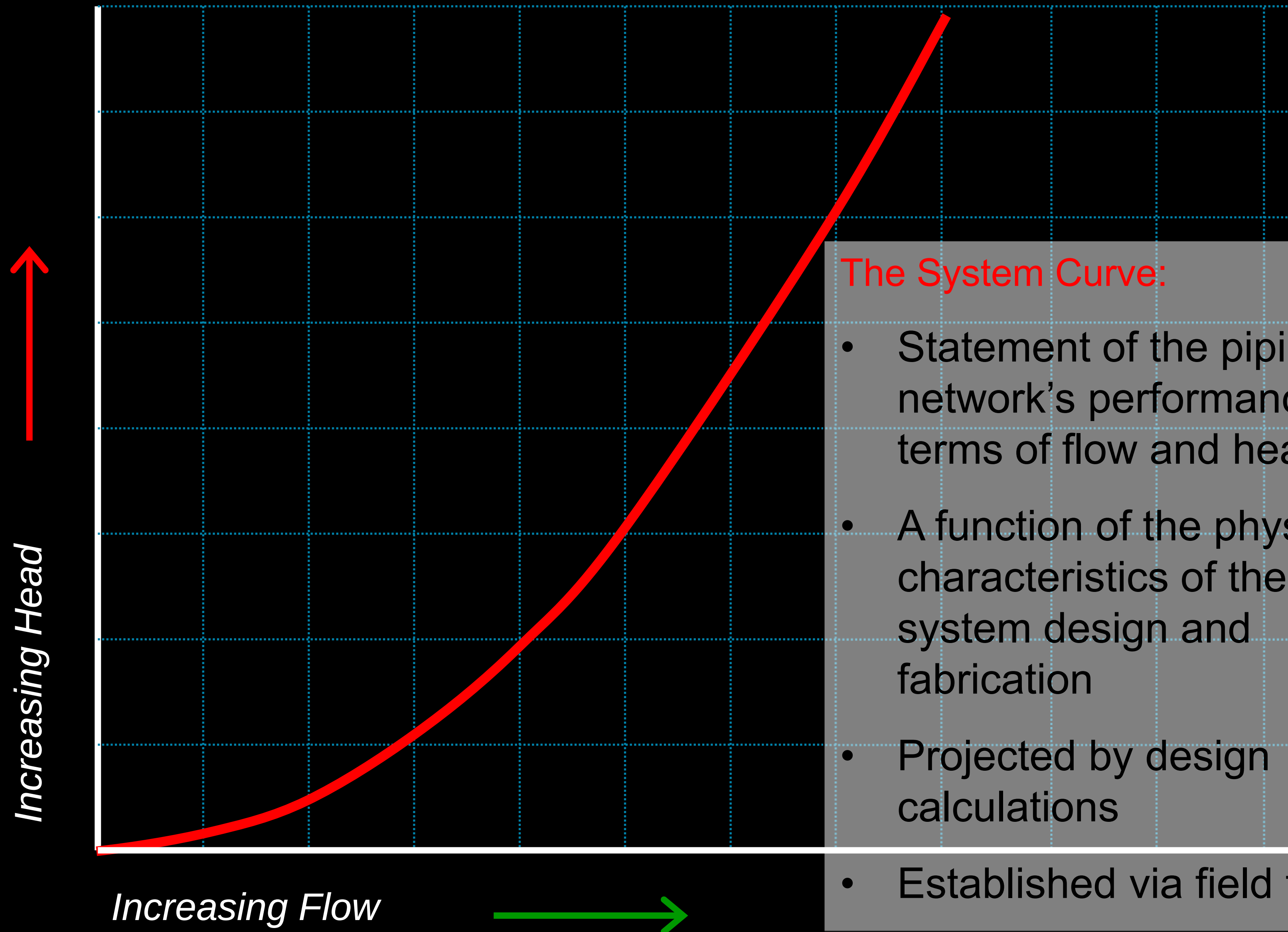
Document flow at different heads …

… and plot the results



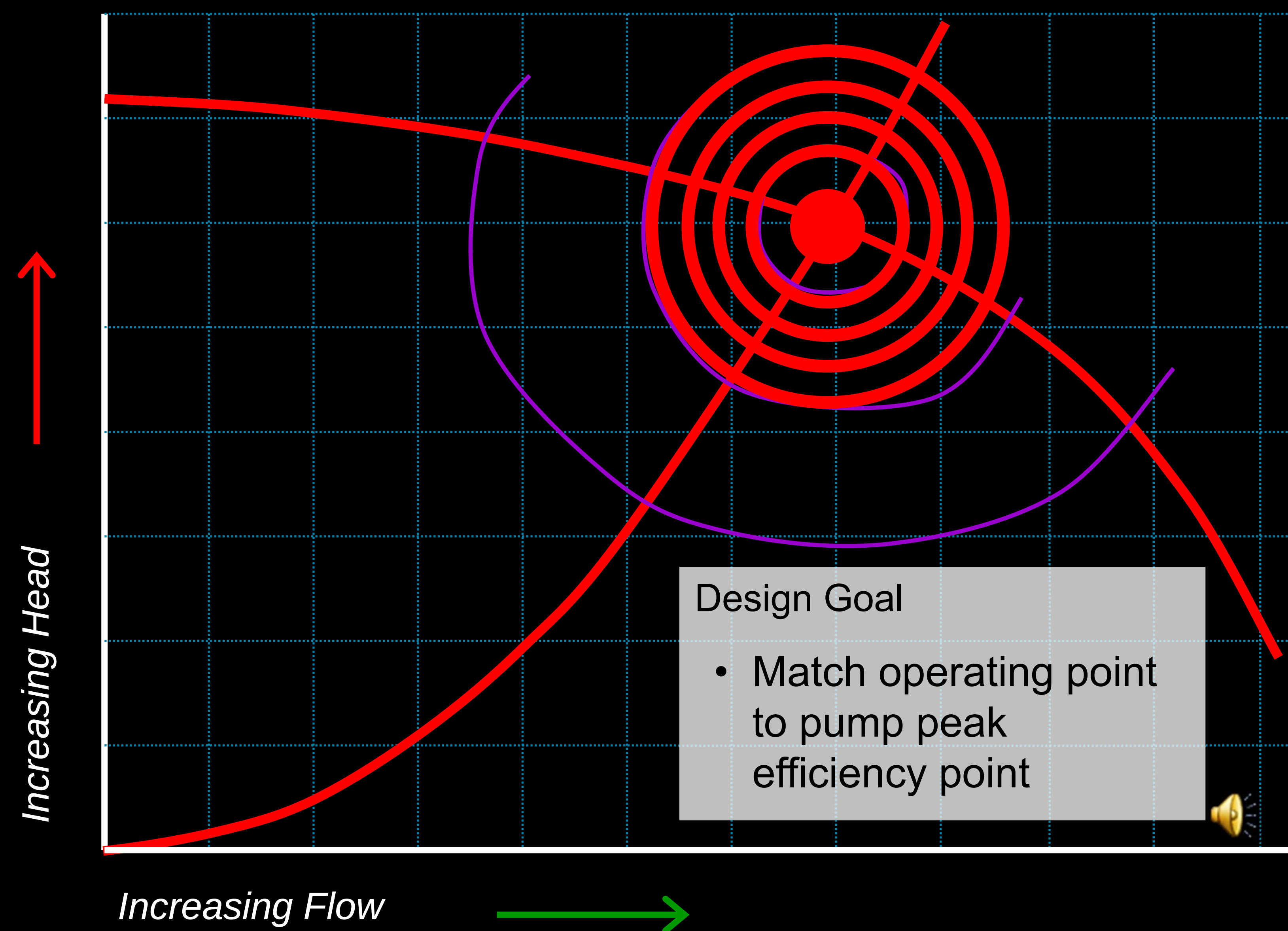
Pump drawing courtesy of Bell and Gossett


The Pump Curve:
• Statement of the pumps performance capabilities in terms of flow and head
• A function of the physical characteristics of the pump design
• Projected by design calculations
• Established via factory test
Increasing Head
Increasing Flow

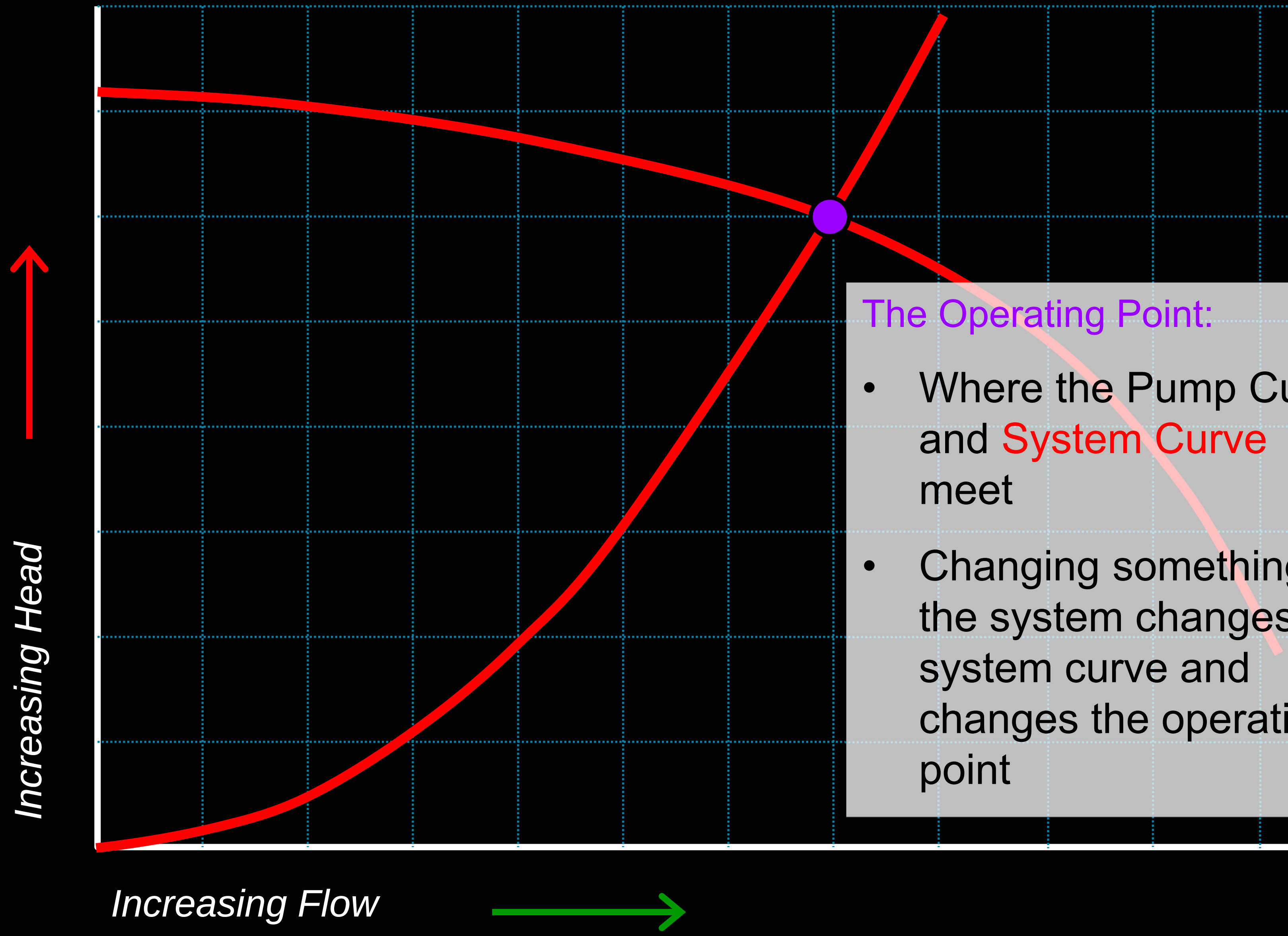


The System Curve:

- Statement of the piping network's performance in terms of flow and head
- A function of the physical characteristics of the system design and fabrication
- Projected by design calculations
- Established via field test

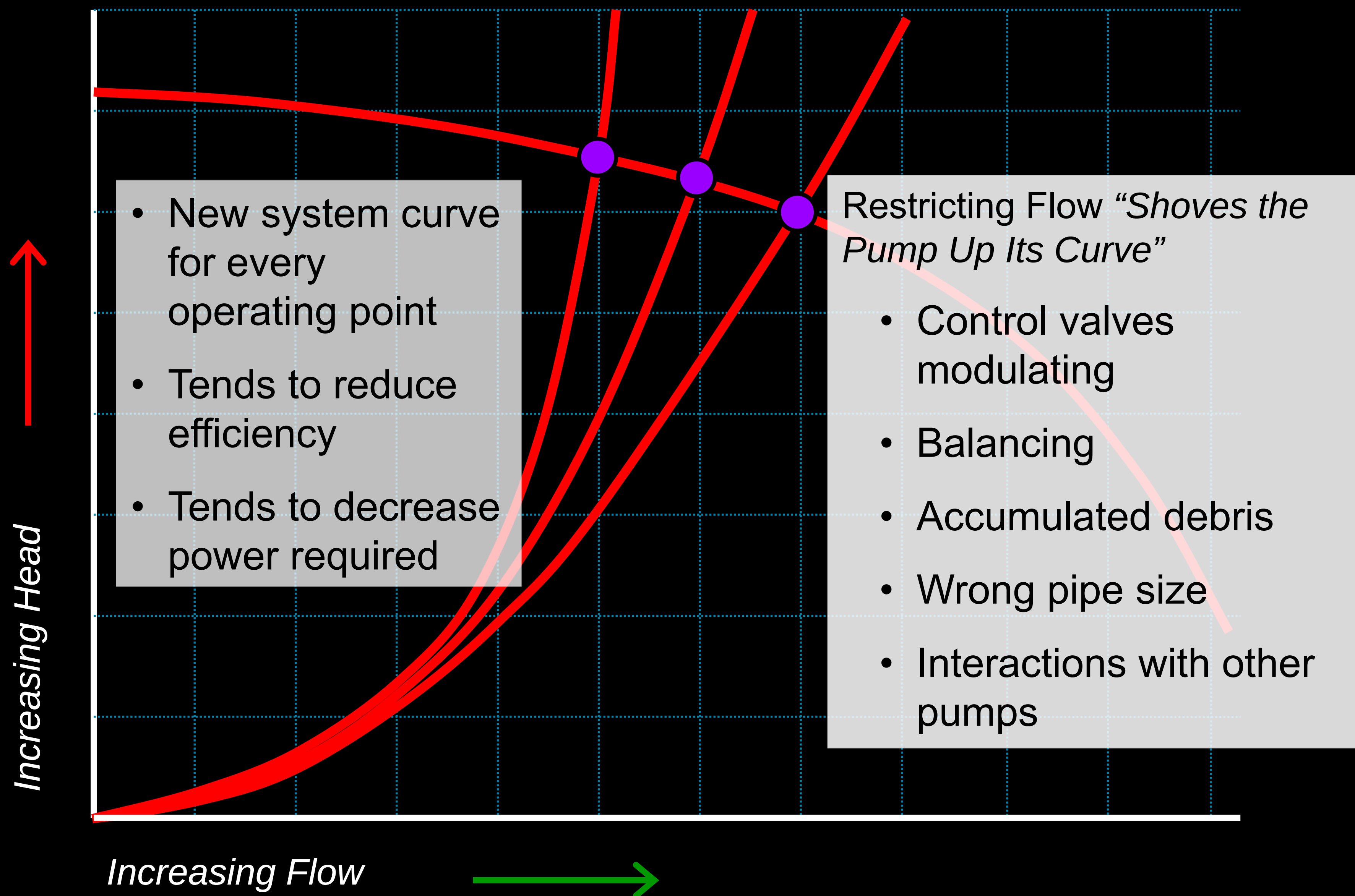


Increasing Head
Increasing Flow
Design Goal
• Match operating point to pump peak efficiency point



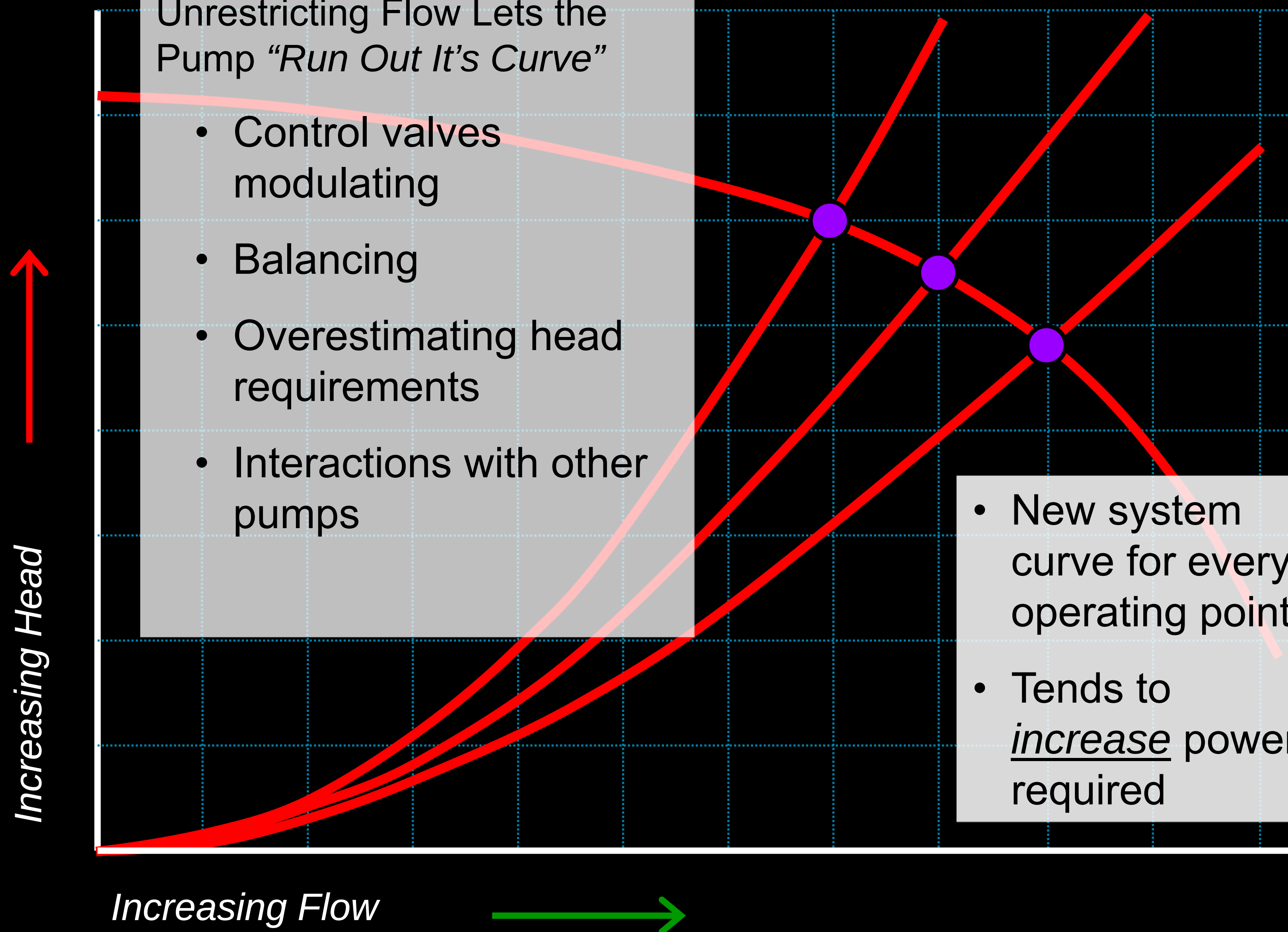
The Operating Point:

- Where the Pump Curve and System Curve meet
- Changing something in the system changes the system curve and changes the operating point

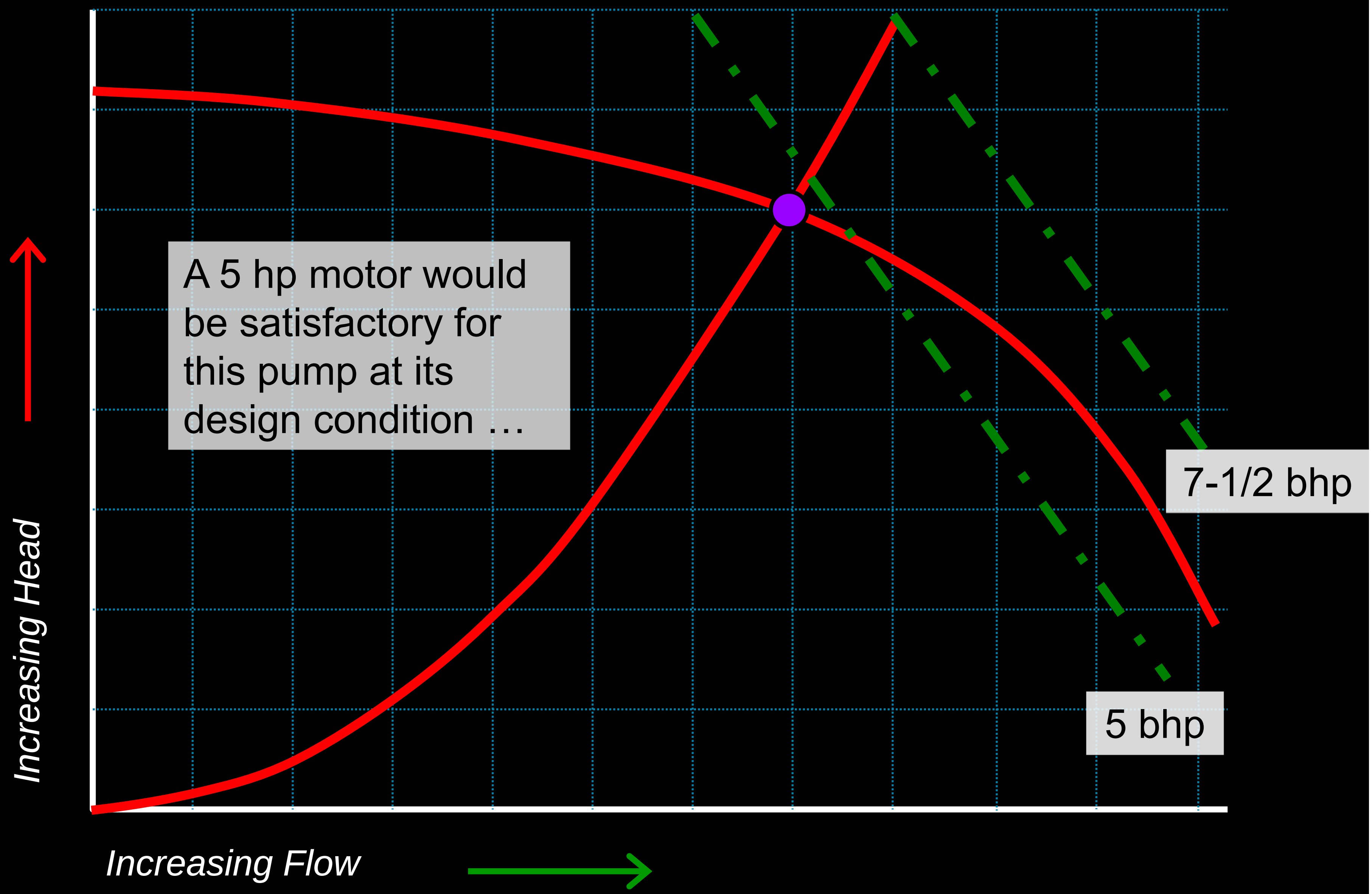

New system curve for every operating point
Tends to reduce efficiency
Tends to decrease power required
Restricting Flow *"Shoves the Pump Up Its Curve"*
Control valves modulating
Balancing
Accumulated debris
Wrong pipe size
Interactions with other pumps
Increasing Head
Increasing Flow

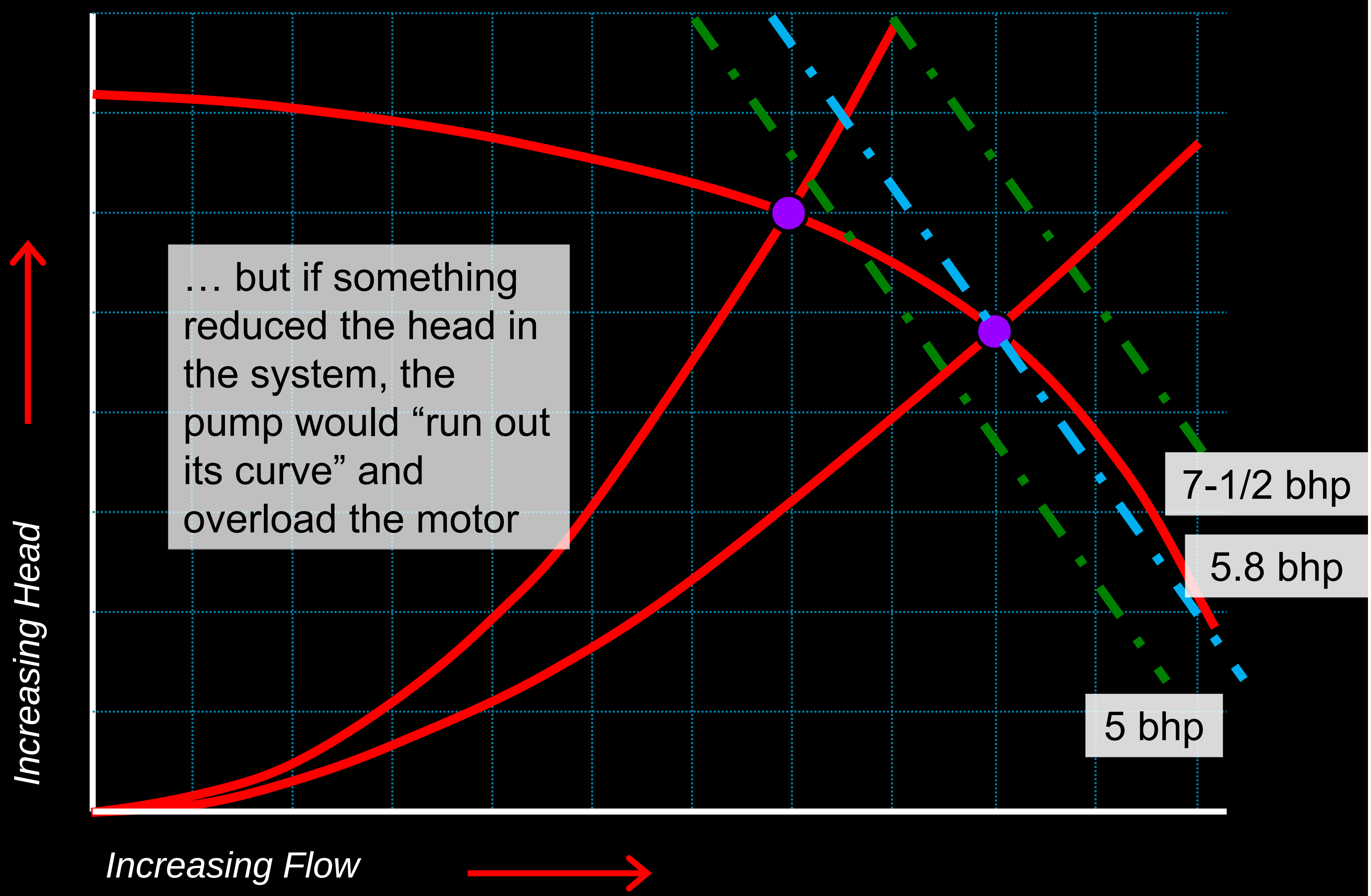
Unrestricting Flow Lets the Pump *"Run Out It's Curve"*

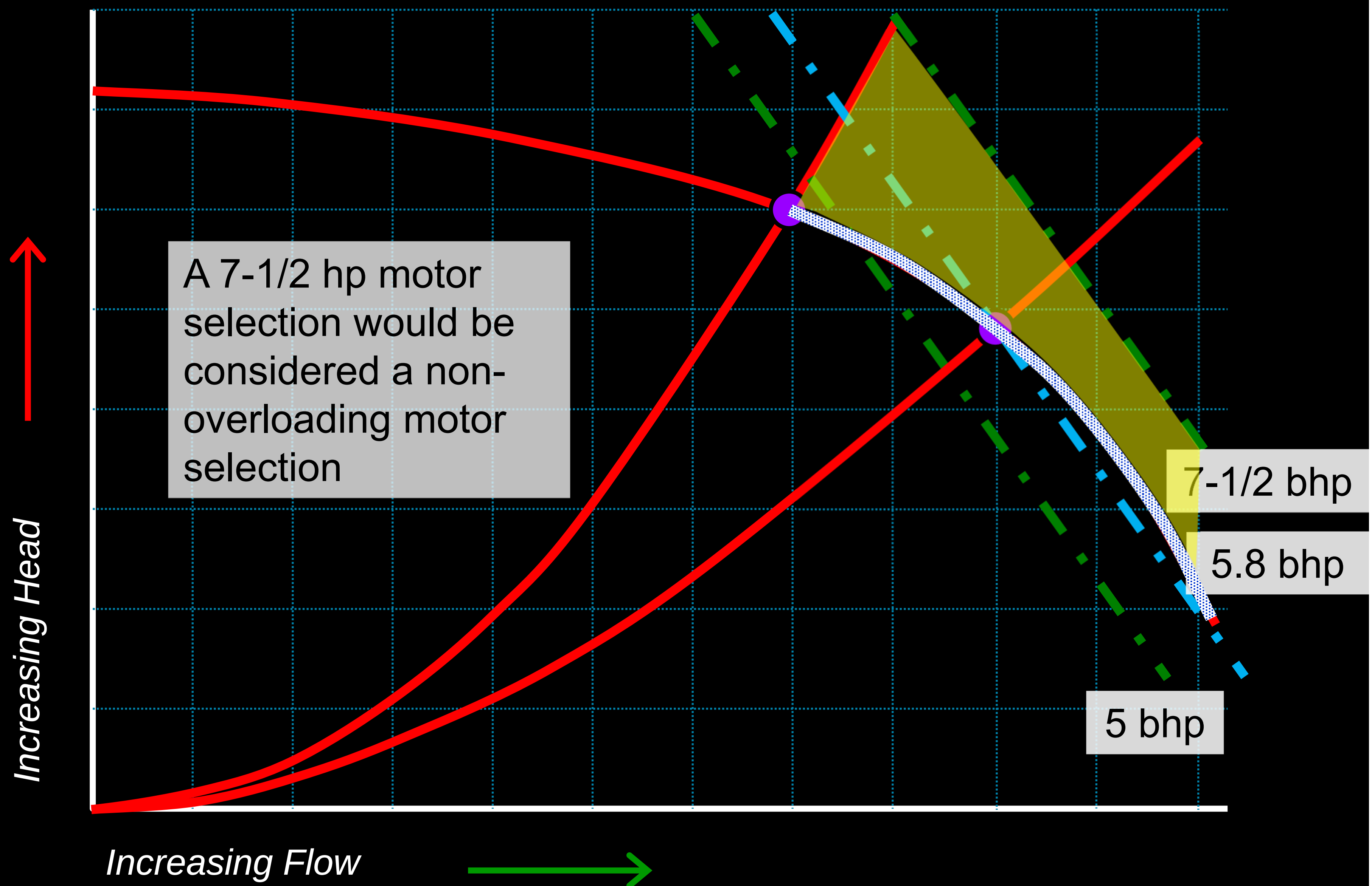
- Control valves modulating
- Balancing
- Overestimating head requirements
- Interactions with other pumps



- New system curve for every operating point
- Tends to *increase* power required


A 5 hp motor would be satisfactory for this pump at its design condition …
7-1/2 bhp
5 bhp
Increasing Head
Increasing Flow


… but if something reduced the head in the system, the pump would “run out its curve” and overload the motor
7-1/2 bhp
5.8 bhp
5 bhp
Increasing Head
Increasing Flow


A 7-1/2 hp motor selection would be considered a non-overloading motor selection
7-1/2 bhp
5.8 bhp
5 bhp
Increasing Head
Increasing Flow

The Square Law:

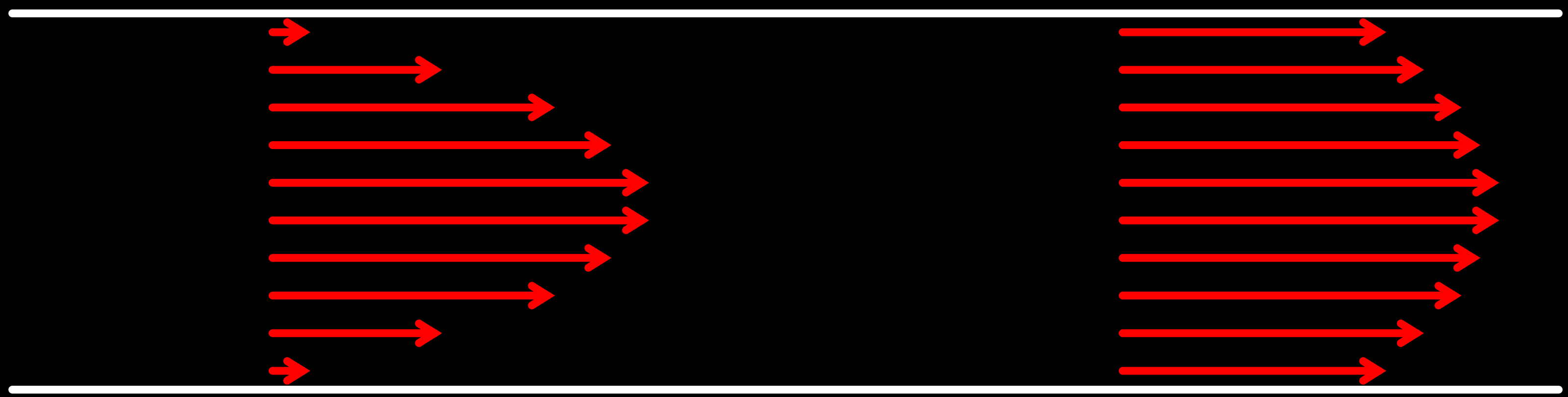
Common to both Air and Water Systems

- Roots in the Darcey – Weisbach equation

$$H_L = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right)$$

- Newtonian fluid
  - "Well behaved fluid"
    - Constant viscosity
    - Water is an example
  - Non-Newtonian fluid
    - Viscosity varies with applied force
    - Corn starch in water is an example
- Applies to fully developed turbulent flow

Turbulent vs. Laminar



Fully Developed Laminar Flow
Average Velocity

Fully Developed Turbulent Flow
Average Velocity

The vectors typically shown to represent the velocity profile in a pipe are usually an indication of the average velocity for a given fluid particle over time not the streamlines

- The actual motion of any given particle could be laminar (parallel lines) or turbulent (swirling lines)
- Laminar flow will tend to have a parabolic average velocity profile shape
- Turbulent flow will have a flatter, fuller velocity profile shape
- Fully developed flow exists when the average flow profile does not change as the fluid moves down the conduit

Nikuardse's Experiment

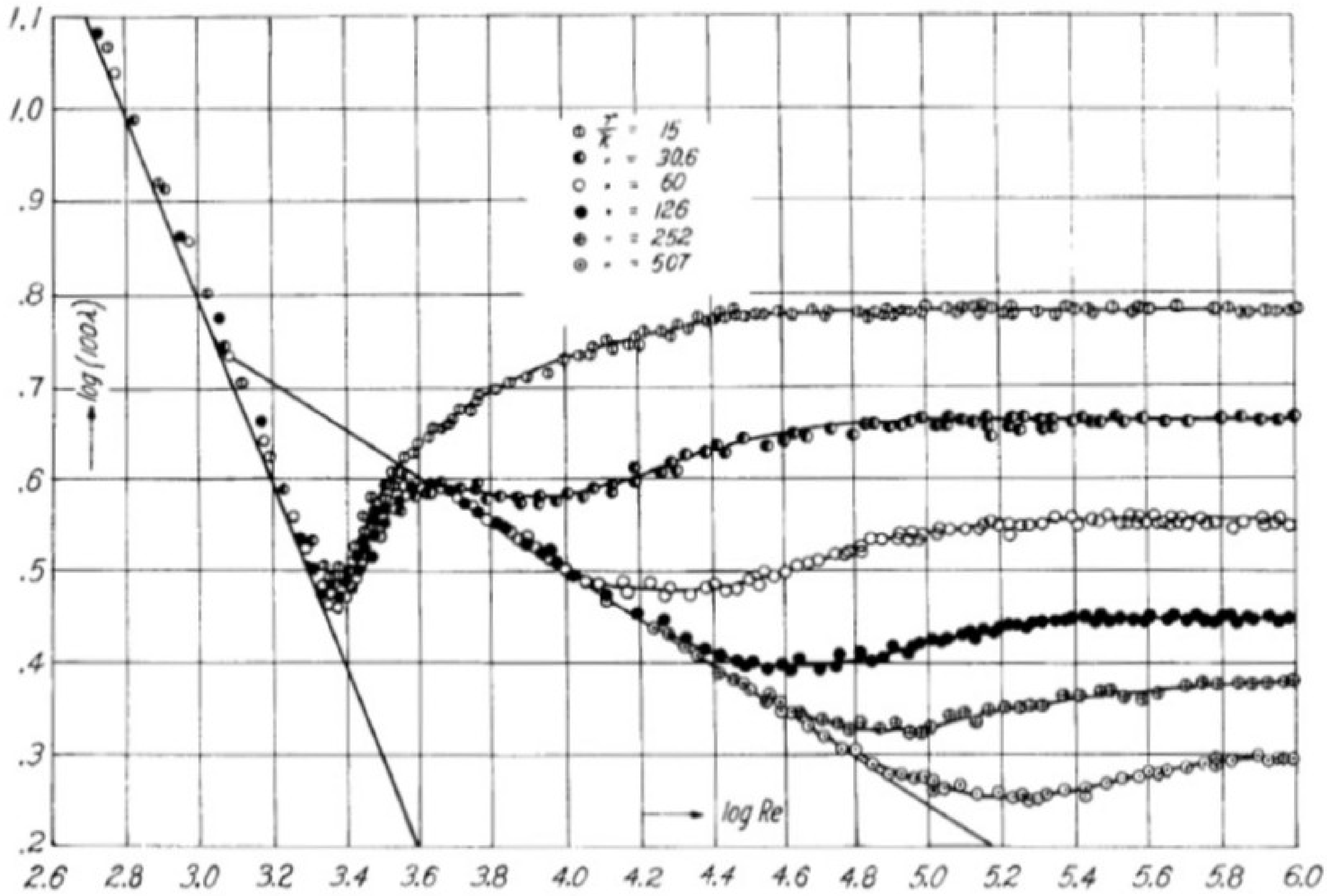
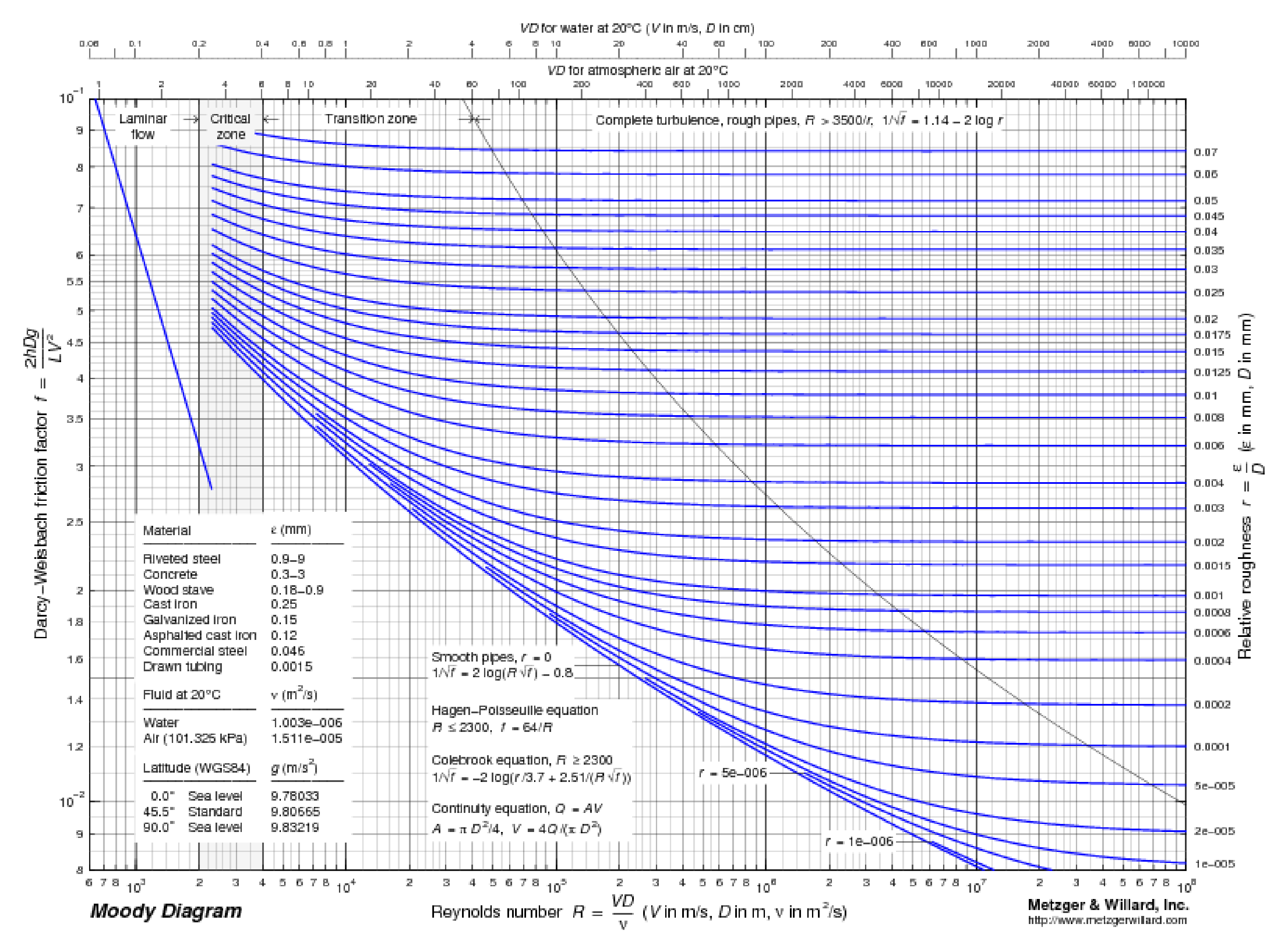


Figure 9.- Relation between log(100 λ) and log Re.

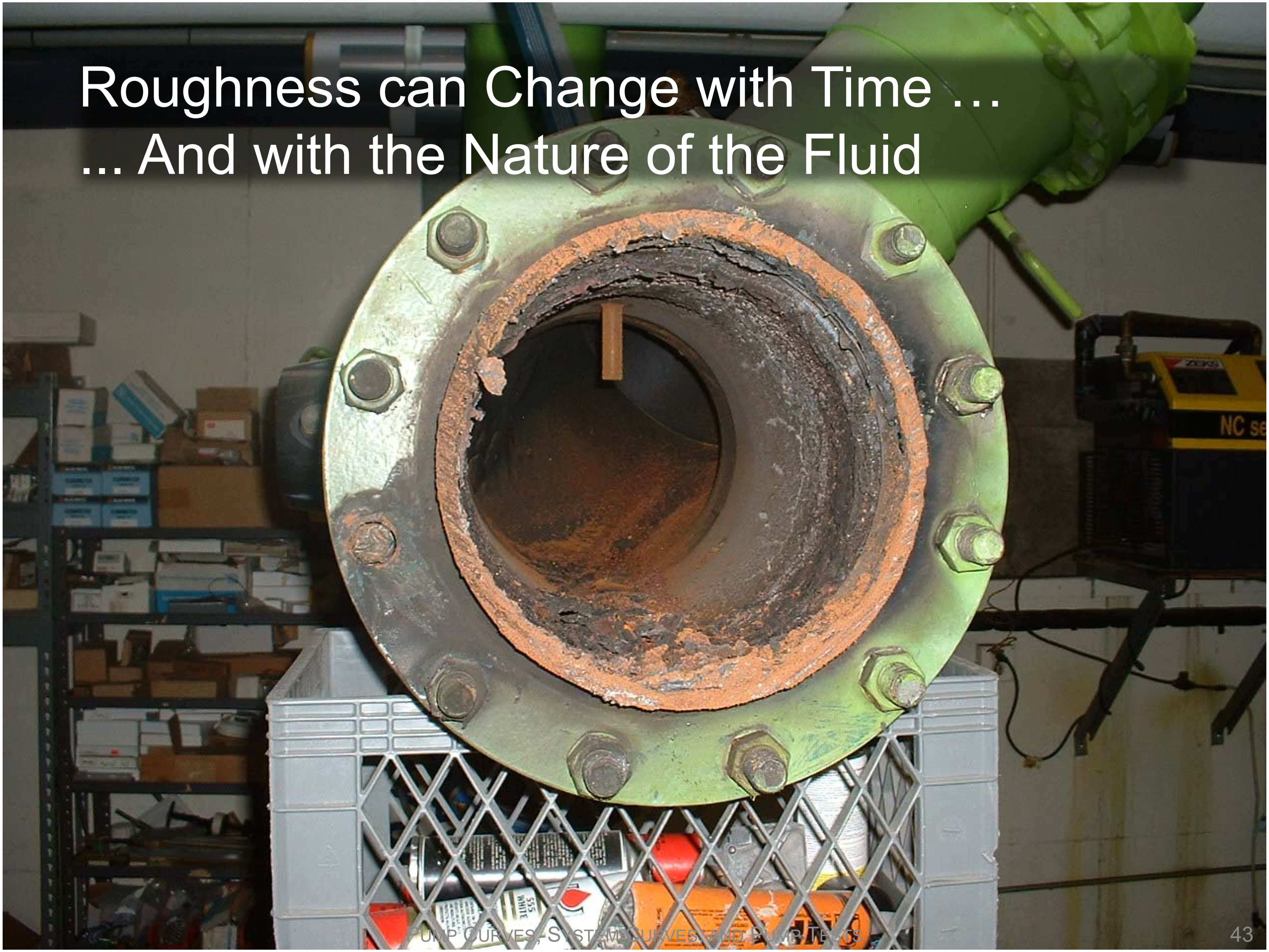
Moody Diagram

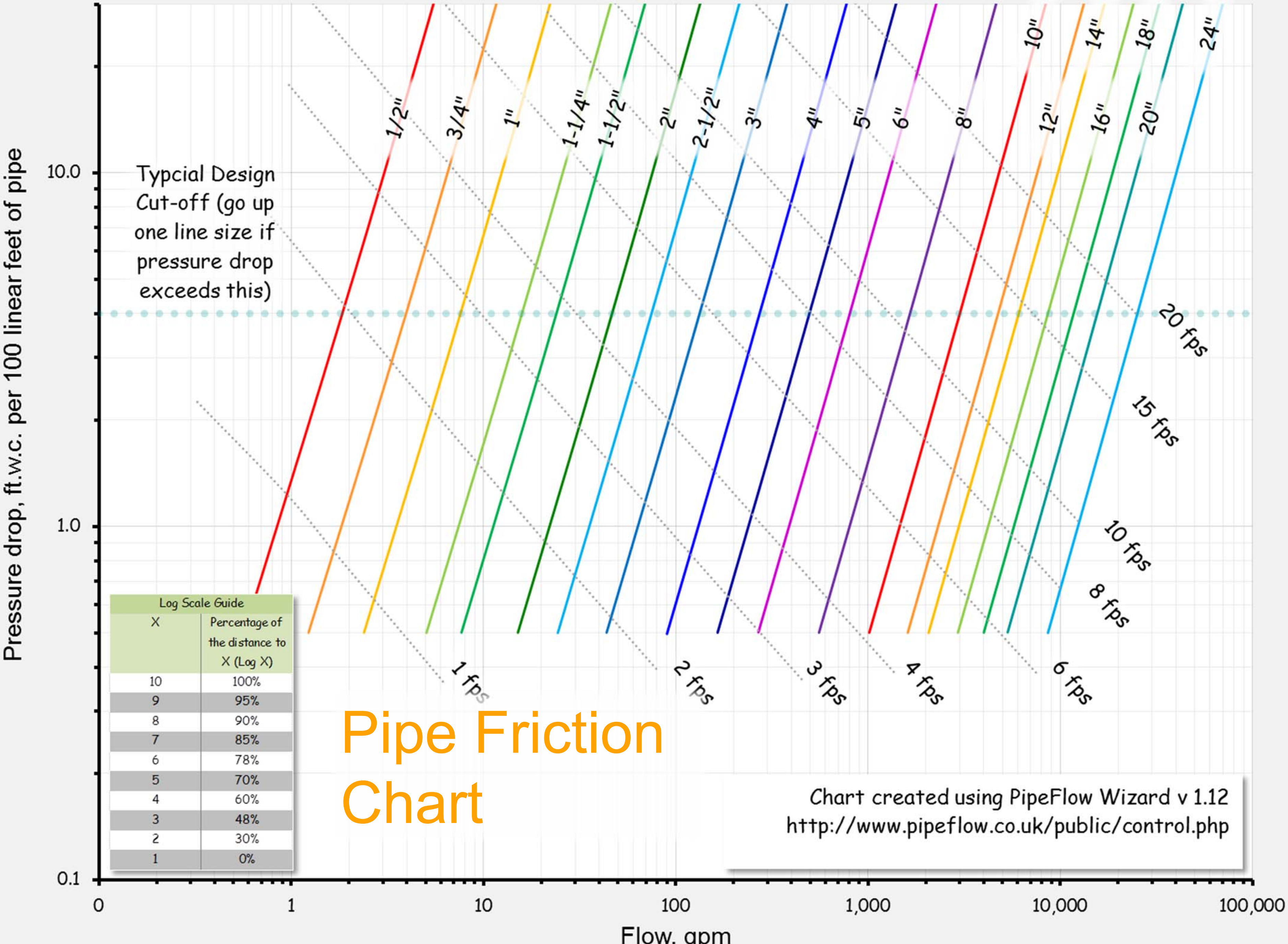


Pipe May Not Be Perfectly Smooth from the Start

Roughness can Change with Time …

Roughness can Change with Time …
... And with the Nature of the Fluid





Log Scale Guide

X	Percentage of the distance to X (Log X)
10	100%
9	95%
8	90%
7	85%
6	78%
5	70%
4	60%
3	48%
2	30%
1	0%

Pipe Friction Chart

Give it a Try

Given:

- 2,800 gpm flow rate
- 1,000 feet of steel pipe

What line size would you select?

What would the friction rate be?

What would the pressure drop be?

Give it a Try

Given:

- 2,800 gpm flow rate
- 1,000 feet of steel pipe

What line size would you select?

What would the friction rate be?

What would the pressure drop be?

- If you reduced the flow to 1,400 gpm in the line that you had selected based on the 2,800 gpm design parameter, what is the new pressure drop?

Give it a Try

Given:

- 2,800 gpm flow rate
- 1,000 feet of steel pipe

What line size would you select?

What would the friction rate be?

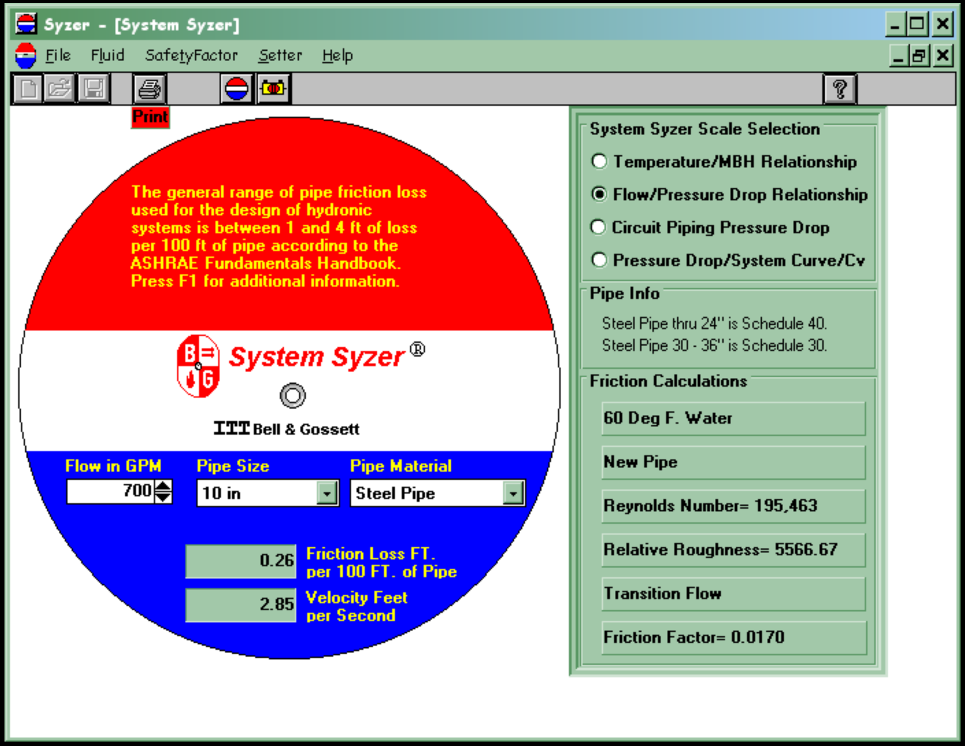
What would the pressure drop be?

If you reduced the flow to 1,400 gpm in the line that you had selected based on the 2,800 gpm design parameter, what is the new pressure drop?

What if the flow drops to 700 gpm?

B&G Syzer

Another way to get an answer



http://www.bellgossett.com/BG-SystemSyzer.asp

The Square Law:
Common to both Air and Water Systems

$$Pressure_{New} = Pressure_{Old} \times \left(\frac{Flow_{New}}{Flow_{Old}} \right)^2$$

Where:

$Pressure_{New}$ = The pressure you want to know in consistent units

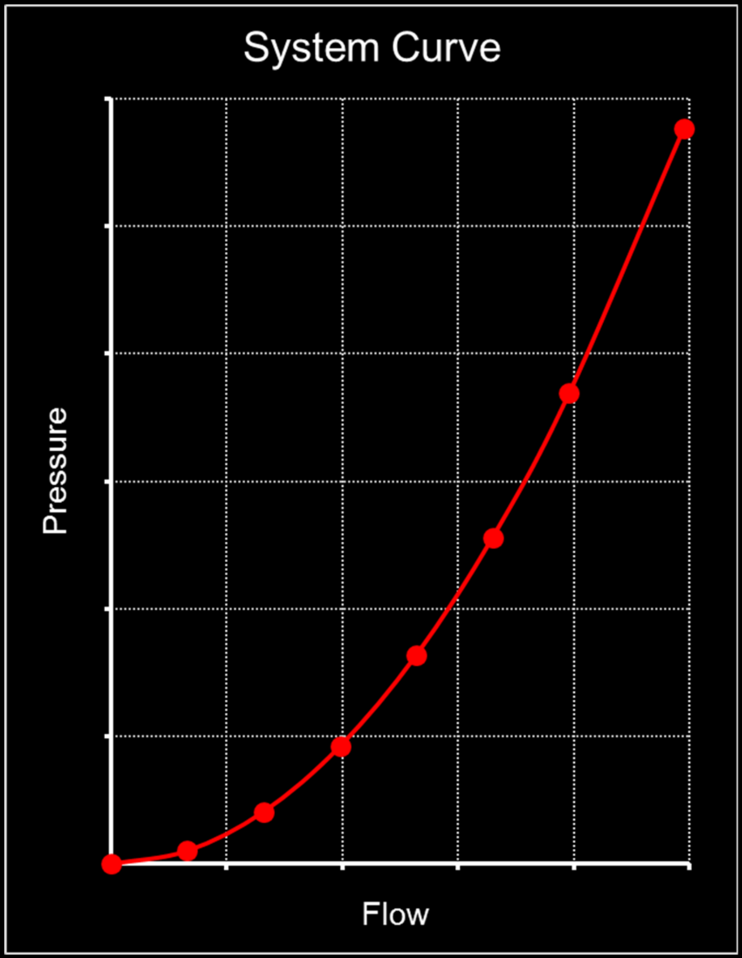
$Pressure_{Old}$ = The pressure you know in consistent units

$Flow_{New}$ = The pressure you want to know in consistent units

$Flow_{Old}$ = The pressure you want to know in consistent units

The Square Law:
Common to both Air and Water Systems

- Applies to a fixed system
  - If a valve moves in a water system you generate a new system curve
  - If a damper moves in an air system, you generate a new system curve
- There are places in our systems where the flow is not fully developed turbulent flow
  - ASHRAE research suggests the nominal exponent is 1.85 – 1.89
  - Using 2 is close enough for field work most of the time



Why This Matters

Pump power is a function of flow and static pressure

$$bhp = \left(\frac{Flow \times Head}{3{,}960 \times Efficiency_{Pump}} \right)$$

Where:

$Flow =$ Flow produced by the pump in gpm

$Head =$ Head produced by the pump in feet water column

3,960 = A units conversion constant that will work for water at the temperatures and pressures typically encountered in HVAC systems.

$Efficiency_{Pump} =$ Pump efficiency, read from the pump curve or estimated from past experience; .40 - .70 for small (under 500 gpm) pumps, .70 - .85 for large pumps

Divide by motor efficiency and multiply by .746 kW per horse power to get killoWatts

Why This Matters

The Square Law says that if we reduce the flow rate in a given system, the head required to deliver the flow will be reduced exponentially

- Cut the flow by 50%, then you cut the head required to 25% of what it was (.5 x .5 or $.5^2$)

$$Pressure_{New} = Pressure_{Old} \times \left(\frac{Flow_{New}}{Flow_{Old}} \right)^2$$

Where:

$Pressure_{New}$ = The pressure you want to know in consistent units

$Pressure_{Old}$ = The pressure you know in consistent units

$Flow_{New}$ = The pressure you want to know in consistent units

$Flow_{Old}$ = The pressure you want to know in consistent units

Why This Matters if You are Working with Control Systems

As a result, for a fixed system, pump power varies as the cube of the flow rate

$$bhp \propto Flow^3$$

- *Control systems can optimize both the flow and the head required by a system, thus control systems can optimize the pump power required by a system*
- *Control systems can also mess this up if we are not careful and as a result waste energy and resources*

Note Also

- Velocity and flow are related
- You can measure flow by measuring velocity and multiplying by the area
- The velocity is not perfectly uniform across the pipe
- Fittings distort the velocity profile
- The flow profile is re-established by interactions with the pipe

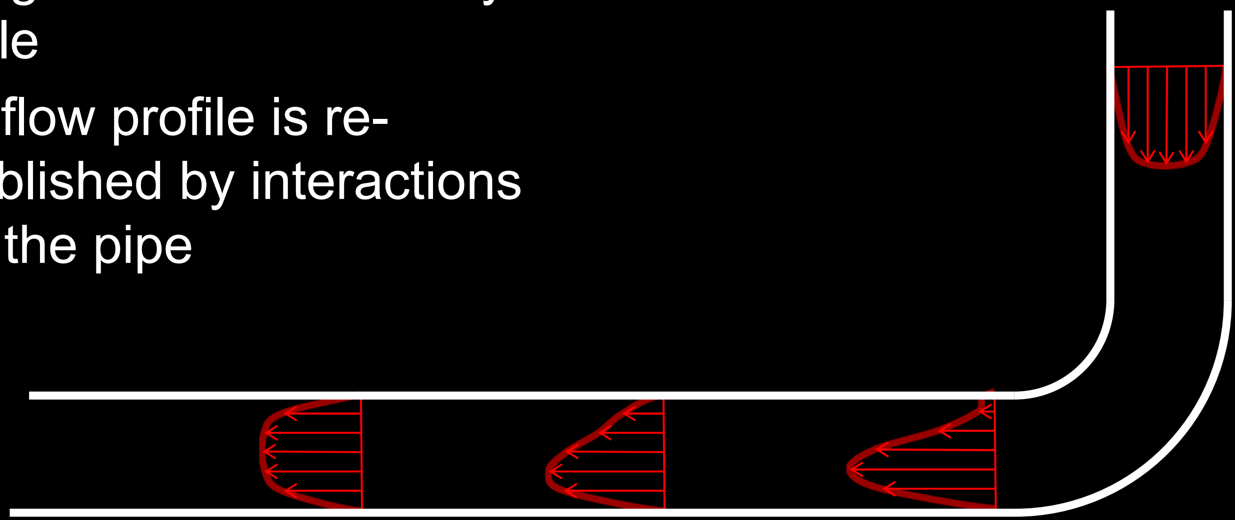
$$Flow = Velocity \times Area$$

With consistent units, for instance:

Flow rate in ft.^{3} per minute

Velocity in ft. per minute

Area in ft.^{2}



Pump Affinity Laws

Apply to a fixed system

- Allow performance to be predicted up and down the system curve
- Allow new impeller curves to be generated based on an existing impeller curve

Pump Affinity Laws

Fundamental relationships:

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

Where :

Q = Flow

N = Impeller speed

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

Where :

H = Head

$$BHP_2 = BHP_1\left(\frac{N_2}{N_1}\right)^3$$

Where :

BHP = Brake horse power

Pump Affinity Laws

Fundamental relationships:

$$Q_2 = Q_1\left(\frac{N_2}{N_1}\right) \qquad H_2 = H_1\left(\frac{N_2}{N_1}\right)^2 \qquad BHP_2 = BHP_1\left(\frac{N_2}{N_1}\right)^3$$

Useful derived relationships:

$$Q_2 = Q_1\left(\frac{D_2}{D_1}\right) \qquad H_2 = H_1\left(\frac{Q_2}{Q_1}\right)^2 \qquad BHP_2 = BHP_1\left(\frac{Q_2}{Q_1}\right)^3$$

Where :

$D = \text{Impeller diameter}$

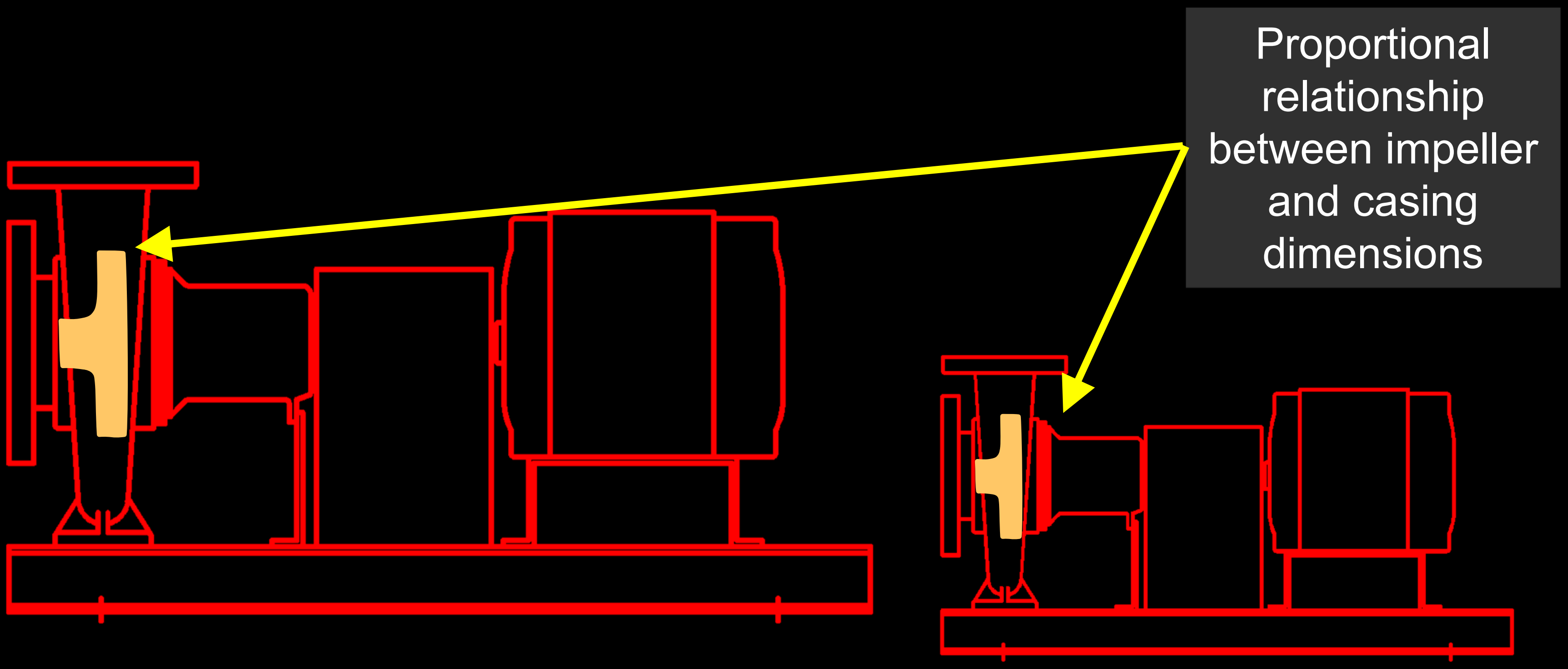
Applying the Affinity Laws To Predict Performance

Approximate relationships; Consider an impeller trim

- In most practical applications, only the pump impeller is trimmed
  - Other dimensions do not change in proportion to the impeller changes
  - Leakage losses impacted
  - Hydraulic losses impacted

Applying the Affinity Laws To Predict Performance

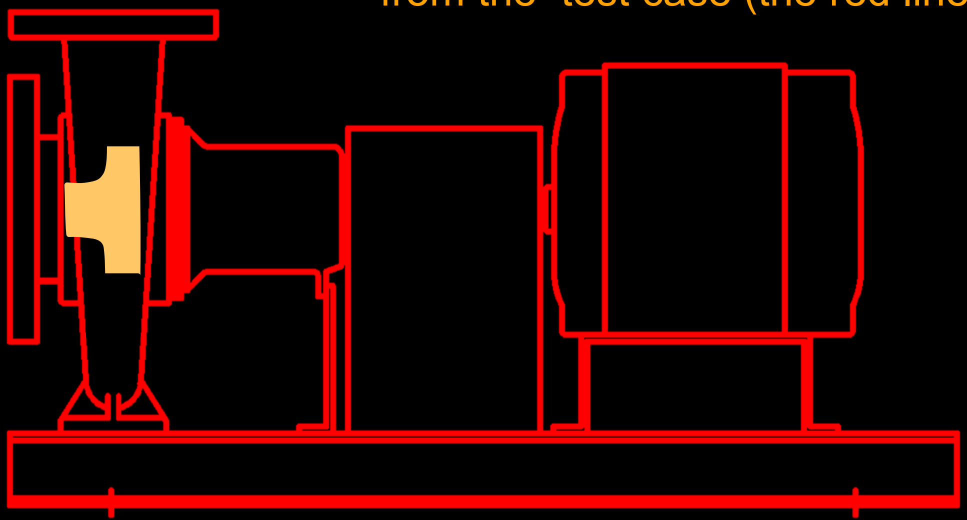
The affinity laws assume geometric similarity

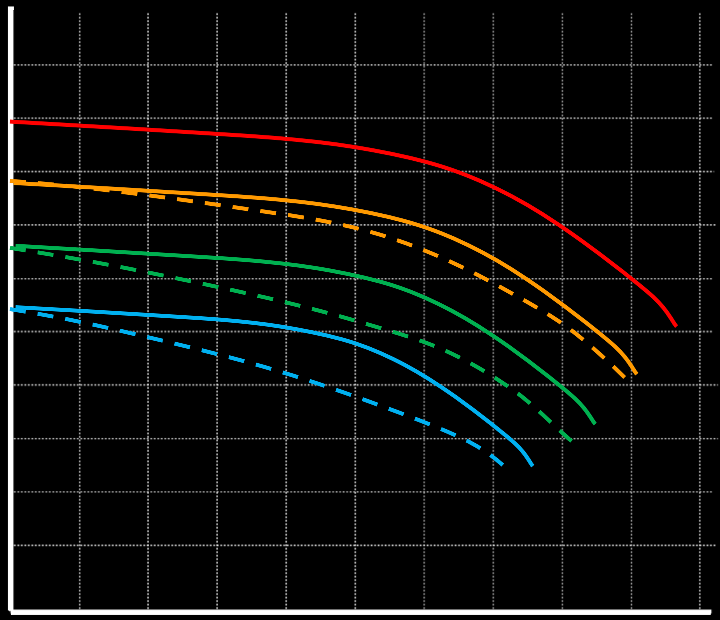


Applying the Affinity Laws To Predict Performance

Changing the impeller outside diameter with out changing the eye diameter and casing size is different

The solid curves are the impeller lines predicted by the affinity laws from the test case (the red line)

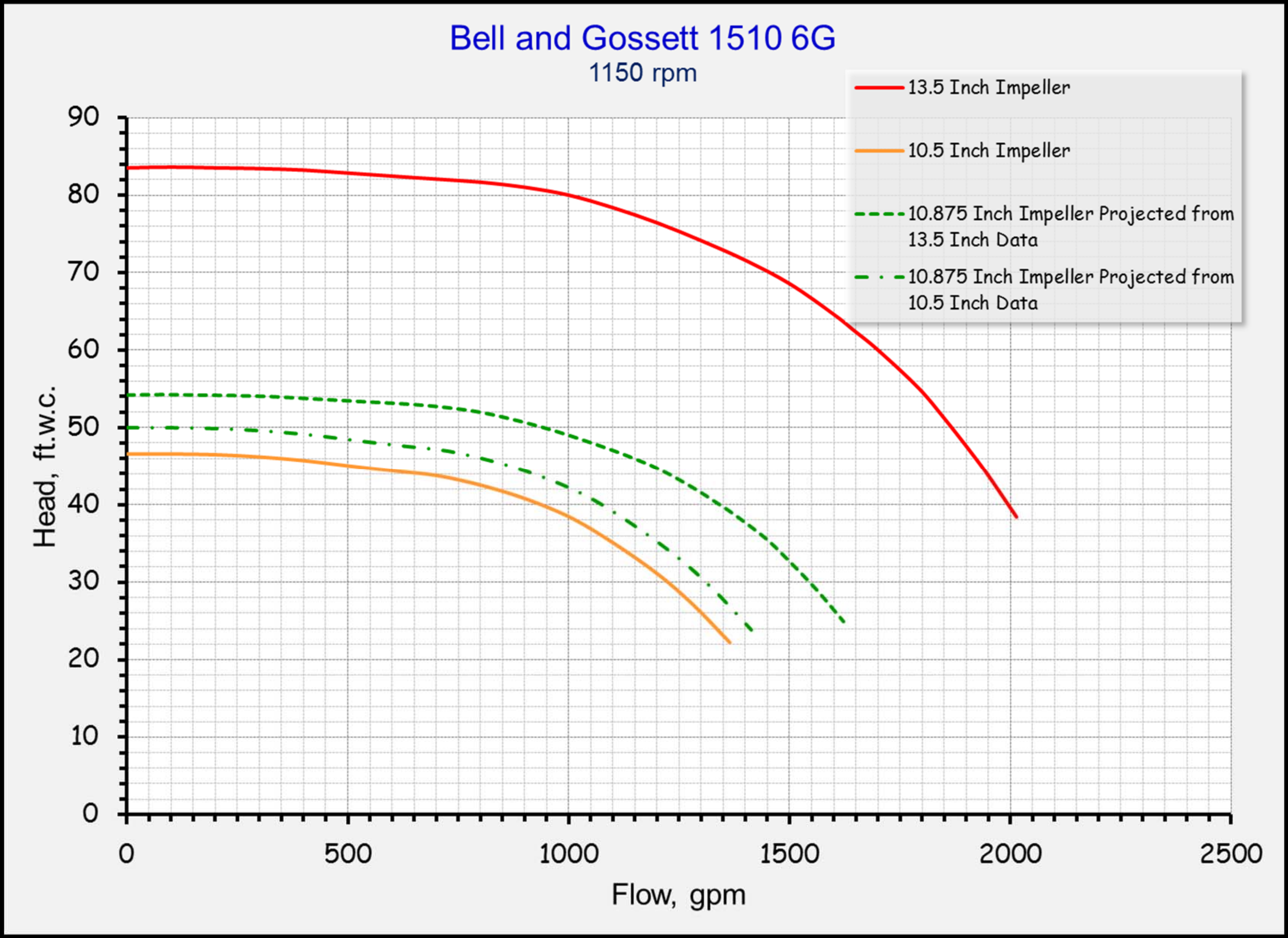




The dashed lines are the actual measured curves with trimmed impellers

Graphic based on the curves for a Bell and Gossett 1510 6x6x7 at 1750 rpm

Applying the Affinity Laws To Predict Performance



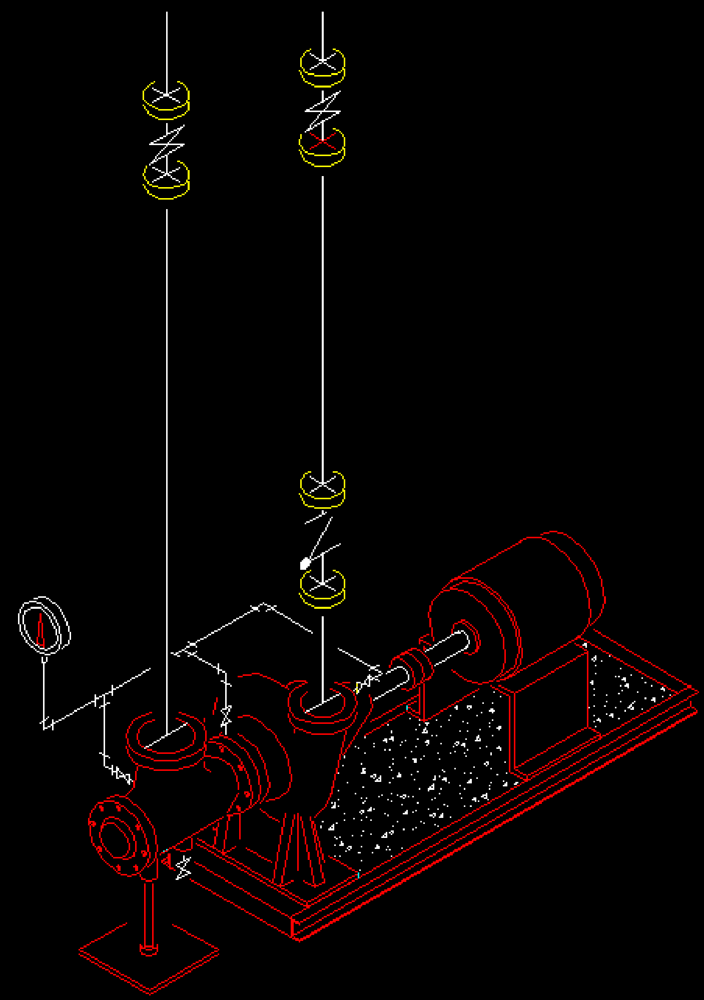
Pump Tests;

Advantages

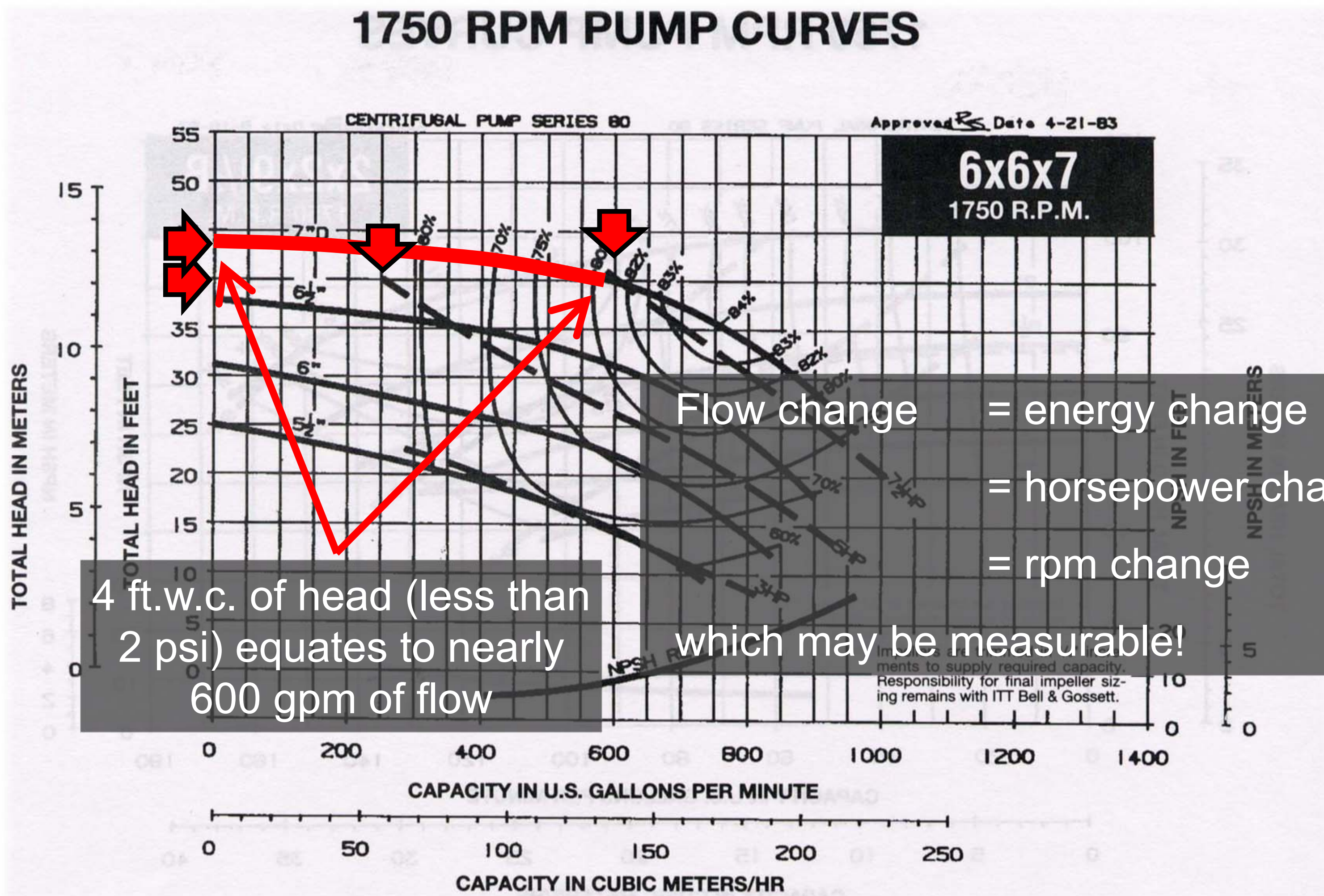
- Have pump, will test
- Simple
  - Procedure
  - Test equipment requirement

Disadvantages

- Only as good as the curve
- No curve = No way to test
- Results difficult to interpret on the “flat” part of the curve



A Closer Look at Some of the Disadvantages



4 ft.w.c. of head (less than 2 psi) equates to nearly 600 gpm of flow

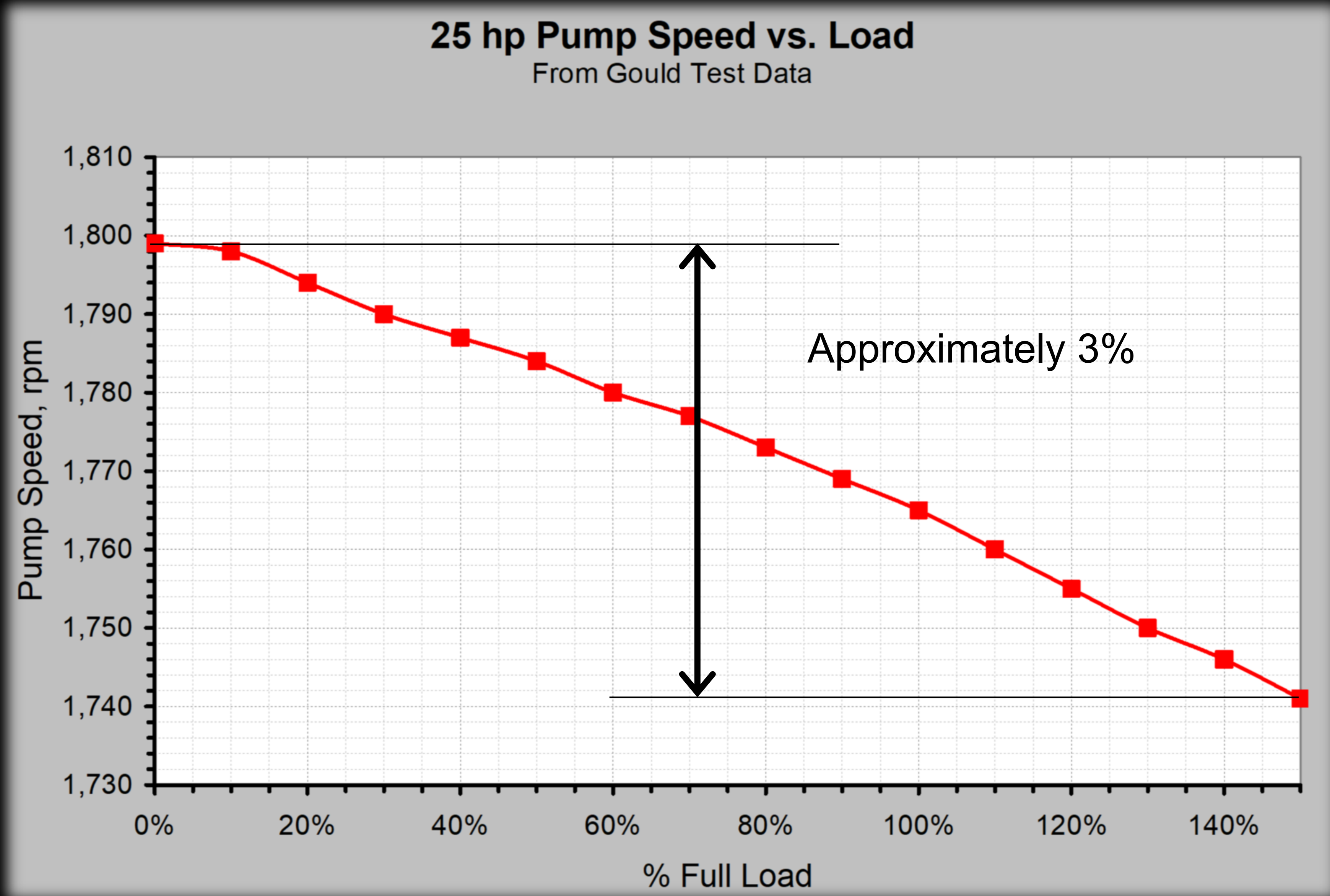
Flow change = energy change

= horsepower change

= rpm change

which may be measurable!

Pump curve courtesy of Bell and Gossett


25 hp Pump Speed vs. Load
From Gould Test Data
Pump Speed, rpm
1,810
1,800
1,790
1,780
1,770
1,760
1,750
1,740
1,730
0%
20%
40%
60%
80%
100%
120%
140%
% Full Load
Approximately 3%

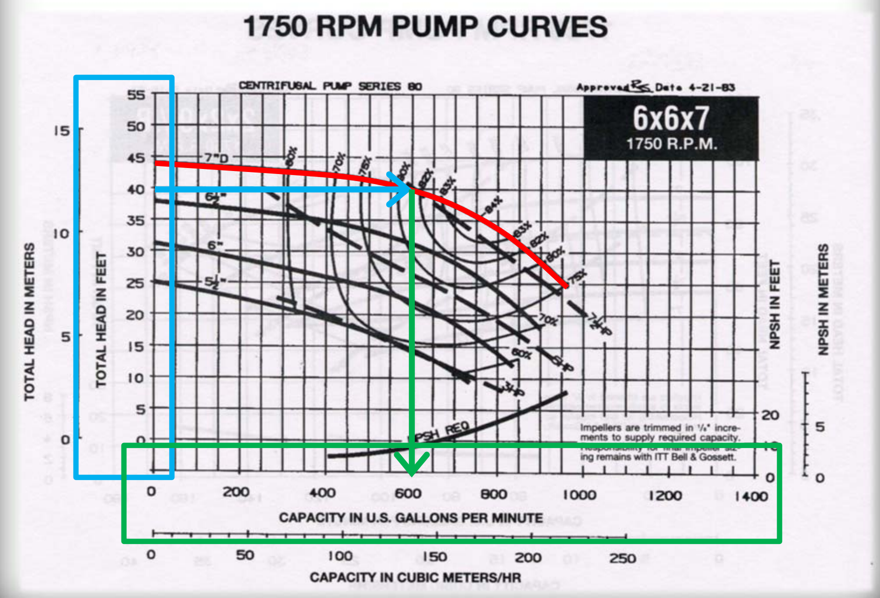
http://tinyurl.com/PumpTestr1

Performing a Pump Test

Performing a Pump Test

Pump curves are certified performance

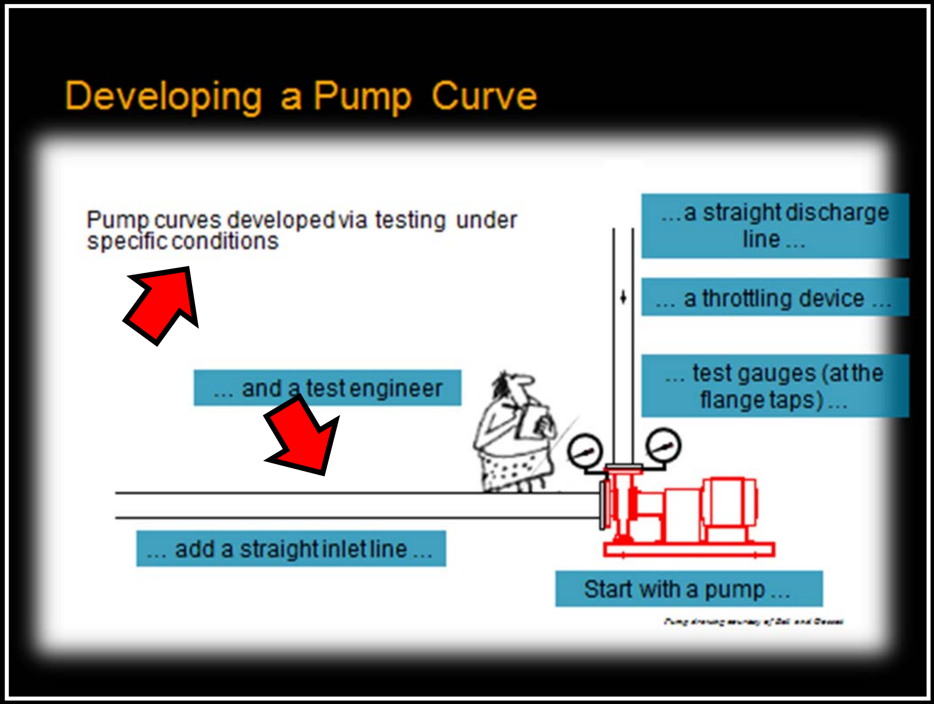
- Known impeller size
- Read differential pressure across the pump
- Use differential pressure and impeller size to determine flow



Performing a Pump Test

Inlet conditions are important

- Velocity profile
- Strainer condition



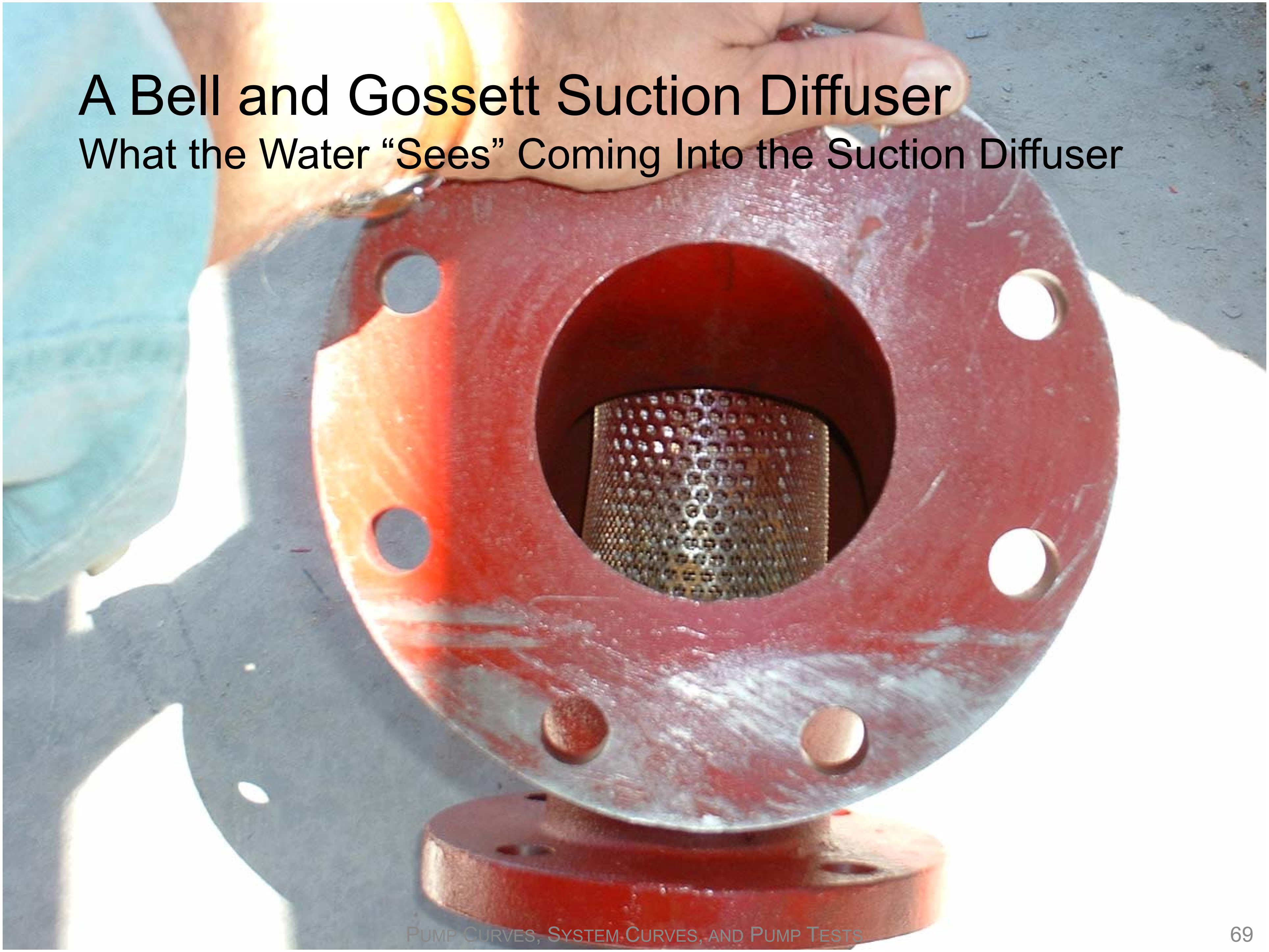
Performing a Pump Test

Inlet conditions are important

- Velocity profile
- Strainer condition
  - Suction diffusers
    - Preserve “real estate”
    - Ensure a uniform flow profile into the pump impeller
    - Serve as a strainer

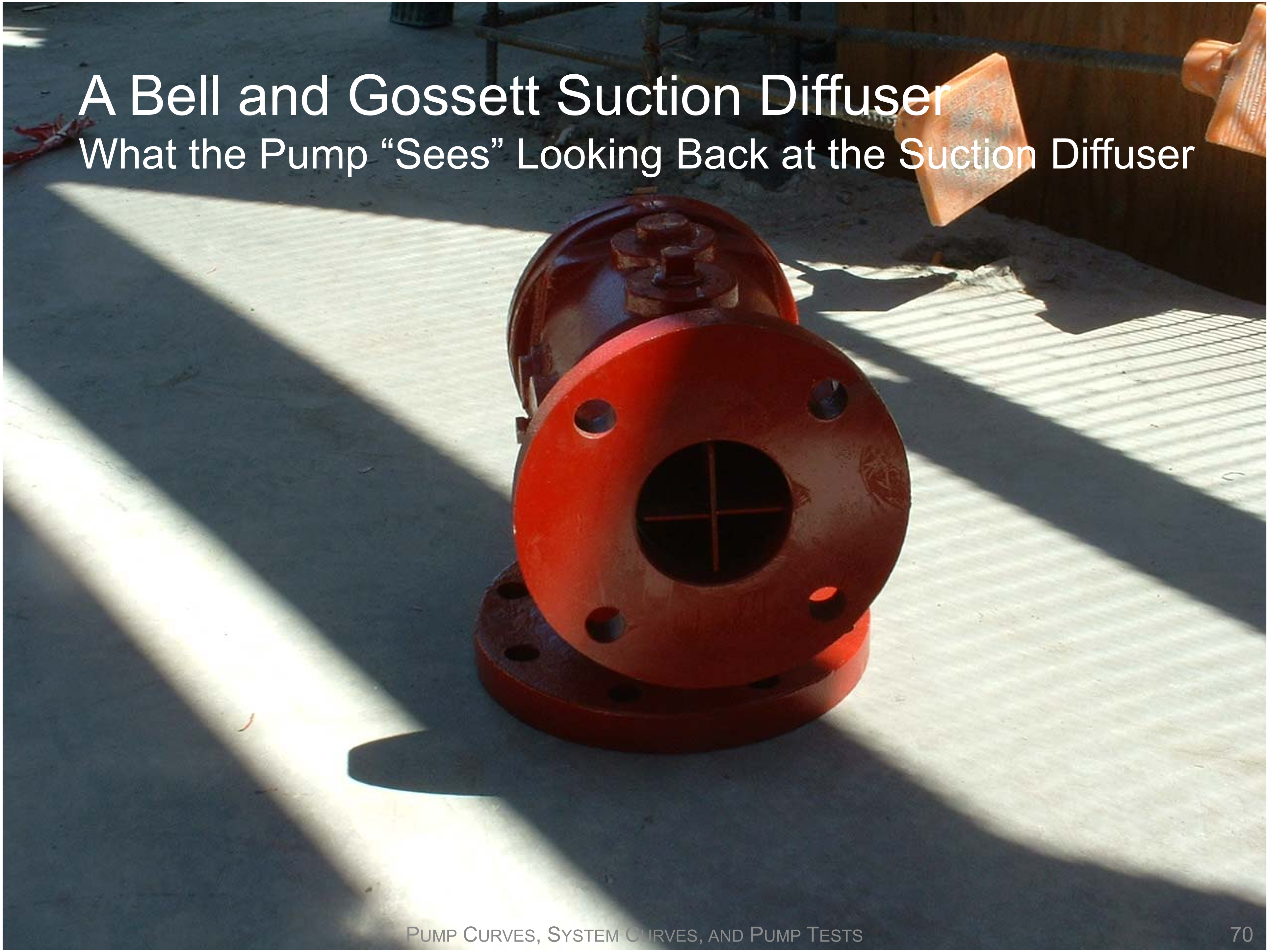
A Bell and Gossett Suction Diffuser

What the Water "Sees" Coming Into the Suction Diffuser

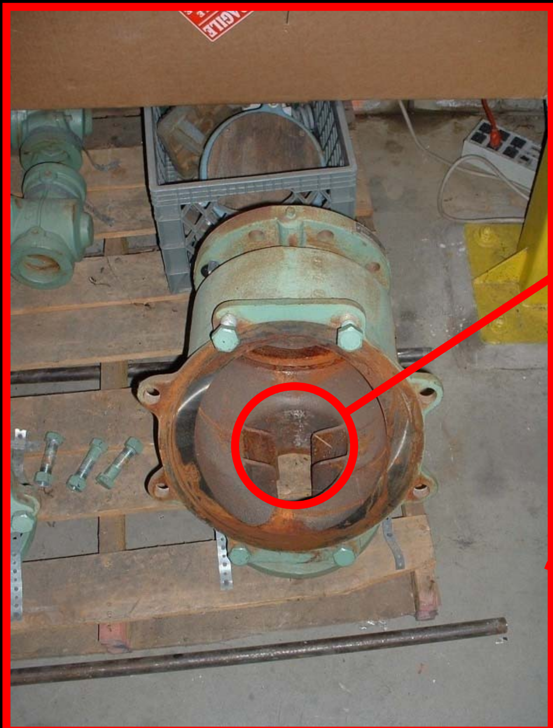


A Bell and Gossett Suction Diffuser

What the Pump “Sees” Looking Back at the Suction Diffuser



Inside a Taco Suction Diffuser



Note straightening vanes in the outlet

Strainer screen typically installed in this area

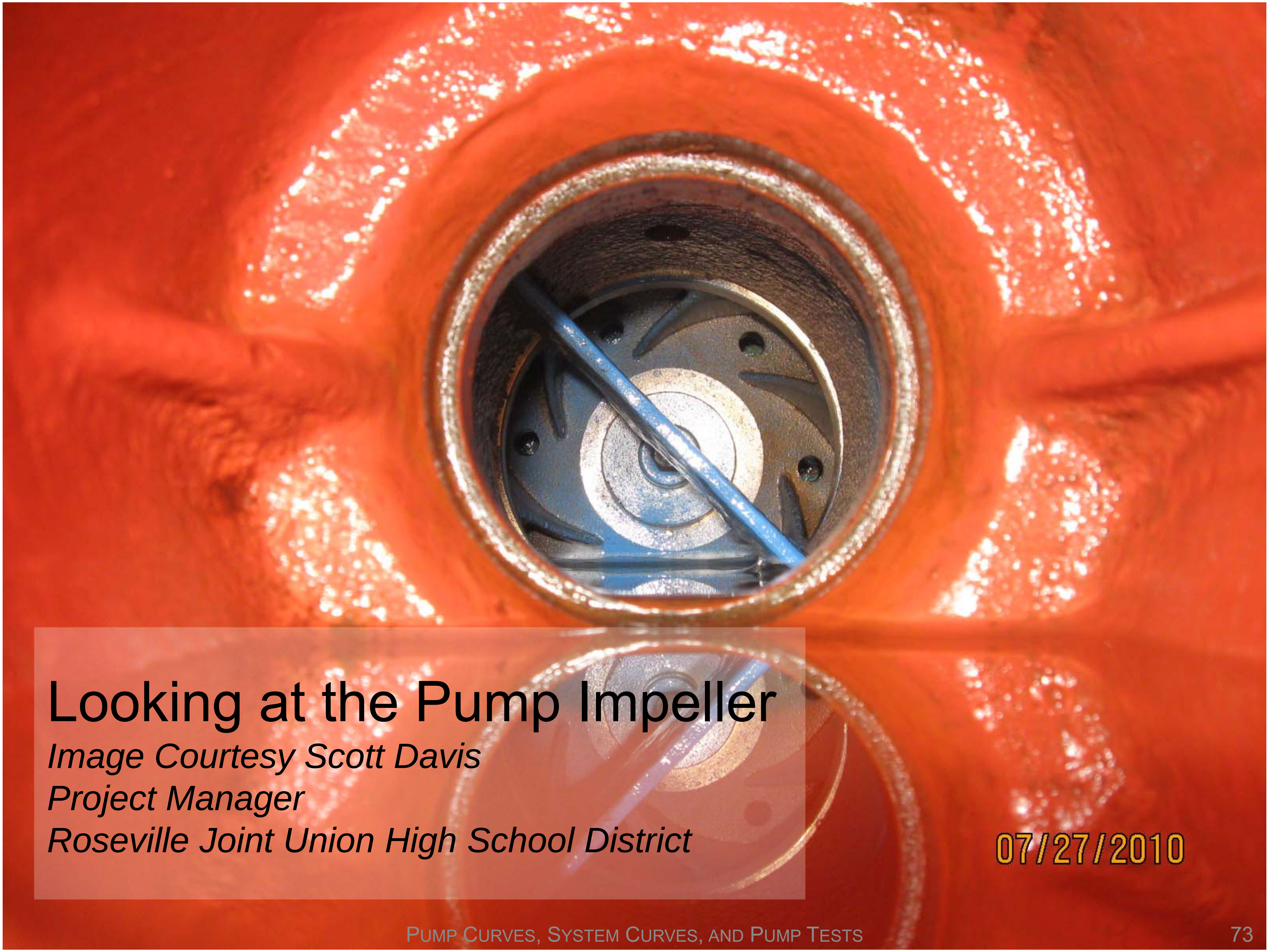
Inlet

Outlet

Installed on a typical end suction pump

Victaulic Suction Diffuser on Paco Pump

Image Courtesy Scott Davis
Project Manager
Roseville Joint Union High School District

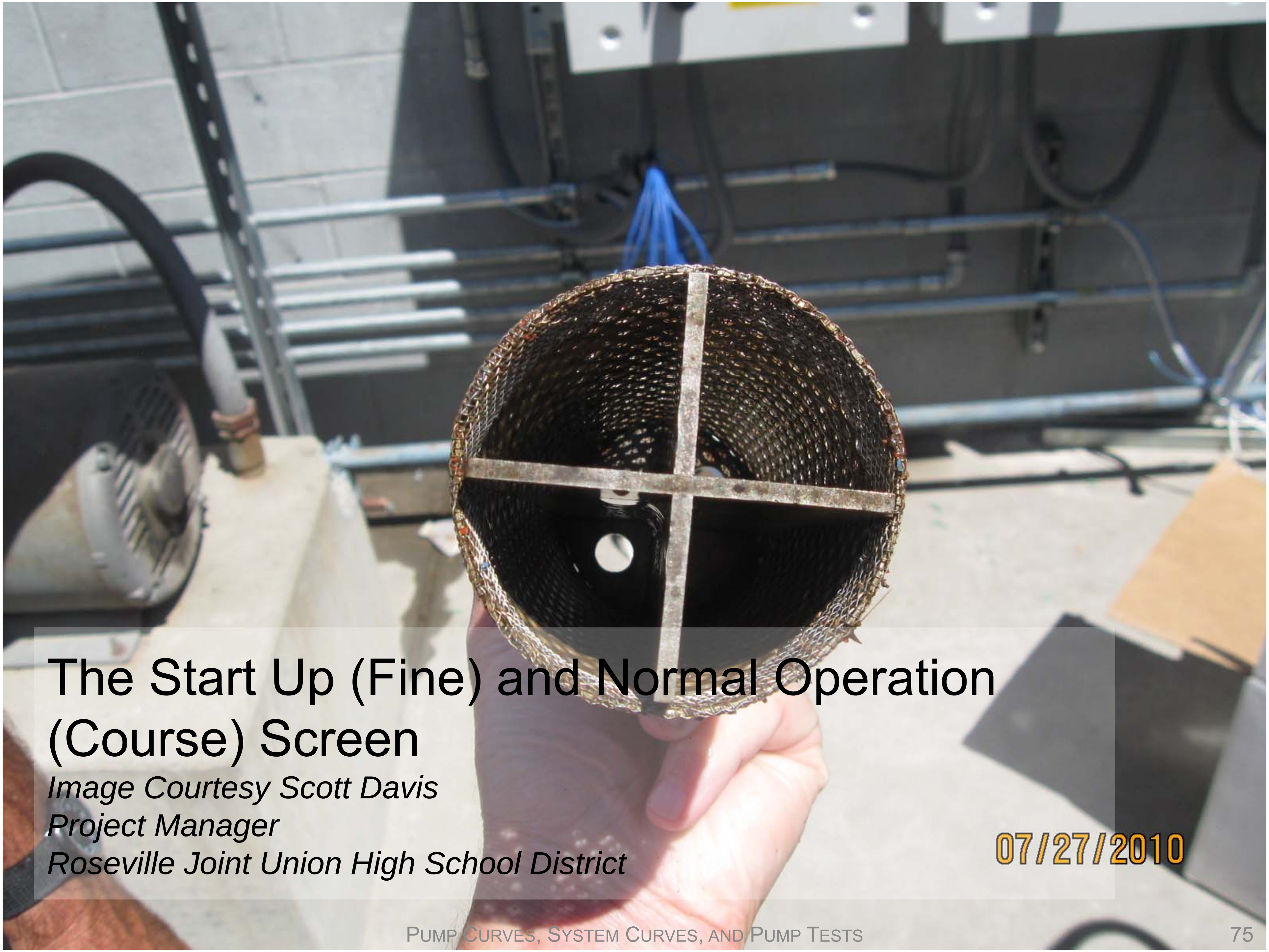


Looking at the Pump Impeller

Image Courtesy Scott Davis
Project Manager
Roseville Joint Union High School District

The Start Up (Fine) and Normal Operation (Course) Screen

Image Courtesy Scott Davis
Project Manager
Roseville Joint Union High School District



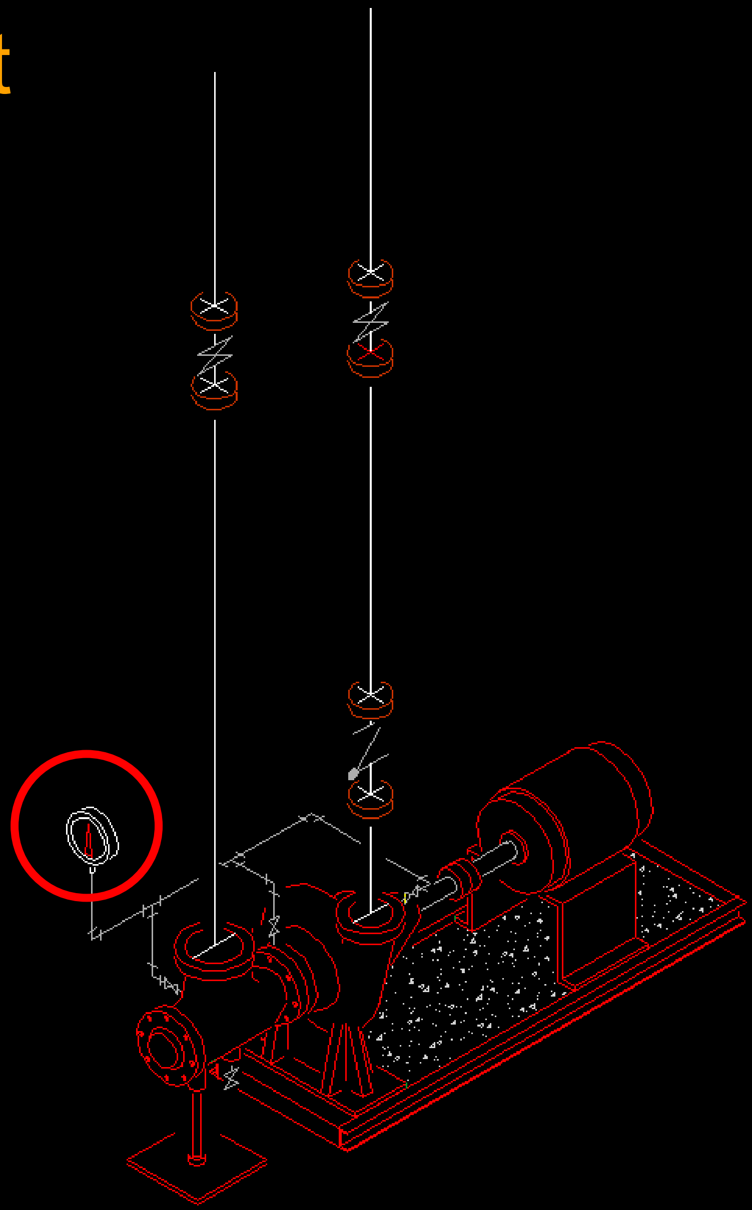
The Start Up (Fine) and Normal Operation (Course) Screen

Image Courtesy Scott Davis
Project Manager
Roseville Joint Union High School District

Performing a Pump Test

Accurate Pressure Measurements are Important

- High quality gauges
  - High accuracy
  - Large dial size
  - Useful features



Pressure Gauge Accuracy

Accuracy is defined as the conformity of an indication to its true value. Accuracy is a percentage of the full range. For example, a gauge that has a scale of 0-300 psi with an accuracy of ±1% would mean that the gauge is accurate to within ± (plus or minus) 3 psi.

Accuracy Grades - ASME B40.1 (American Society of Mechanical Engineers)

Accuracy grade	Lower 1/4 of scale	Middle 1/2 of scale	Upper 1/4 of scale	Maximum Friction Percent of Span
4A	0.1	0.1	0.1	(NOTE)
3A	0.25	0.25	0.25	0.25
2A	0.5	0.5	0.5	0.5
1A	1	1	1	1.0
A	2	1	2	1.0
B	3	2	3	2.0
C	4	3	4	3.0
D	5	5	5	3.0

NOTE: Grade 4A gauges must remain within specified tolerance before and after being lightly tapped.

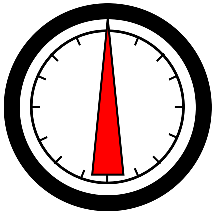
Accuracy is not consistent across the scale for the lower accuracy classes

Pressure Gauge Resolution

Standard Ranges

psi Ranges (A)

Range Code	Specific Range (psi)	Figure Intervals	Minor Divisions
010	30" Hg to 0	5	0.2
020	30" Hg to 15 psi	5/5	0.5/0.2
030	30" Hg to 30 psi	10/5	1/0.5
040	30" Hg to 60 psi	10/10	1/1
050	30" Hg to 100 psi	30/10	2/1
060	30" Hg to 150 psi	30/20	5/2
070	30" Hg to 300 psi	30/50	5/2
080	0 to 15 psi	3	0.1
090	0 to 30 psi	5	0.2
100	0 to 60 psi	10	0.5
110	0 to 100 psi	10	1
120	0 to 160 psi	20	1
130	0 to 200 psi	20	2
140	0 to 300 psi	50	2
150	0 to 400 psi	50	5
160	0 to 600 psi	50	5
180	0 to 1000 psi	100	10



Pressure Gauge Resolution

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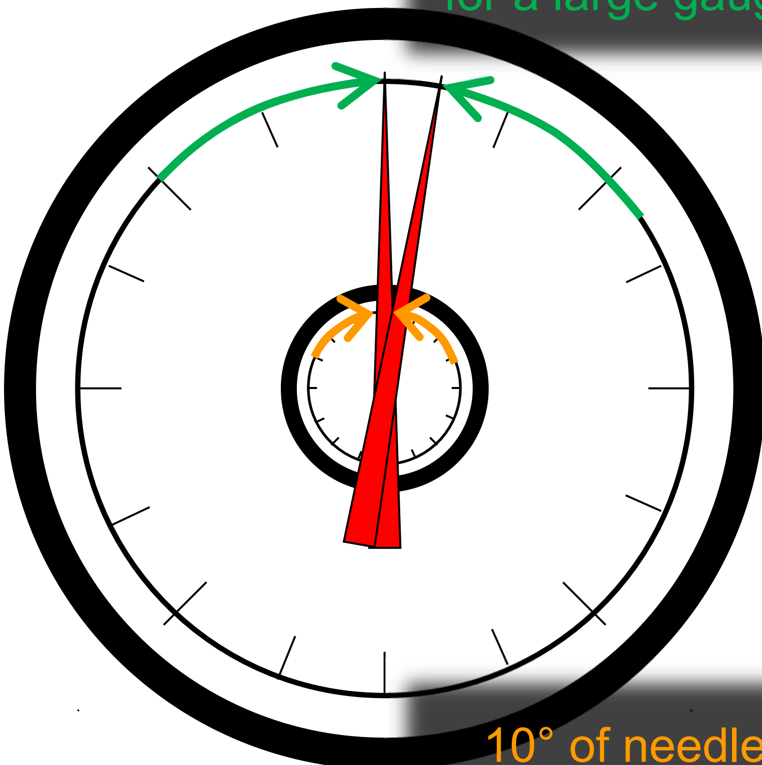
070	30" Hg to 300 psi	30/50	5/2
080	0 to 15 psi	3	0.1
090	0 to 30 psi	5	0.2
100	0 to 60 psi	10	0.5
110	0 to 100 psi	10	1
120	0 to 160 psi	20	1
130	0 to 200 psi	20	2
140	0 to 300 psi	50	2
150	0 to 400 psi	50	5
160	0 to 600 psi	50	5
180	0 to 1000 psi	100	10



10° of needle rotation = less than 1/2 of a graduation for a large gauge

10° of needle rotation = 1 graduation for a small gauge

Accuracy and Diameter vs. Price

Spec

- 0 to 300 psi
- ANSI 2A accuracy (0.5% across the range)
- 6” diameter
- Max indication feature

Price

- $99

Spec

- 0 to 300 psi
- 1.6% accuracy at mid range, 3% accuracy at ends of range
- 4-1/2” diameter

Price

- $9

Spec

- 0 to 300 psi
- 1.6% accuracy at mid range, 3% accuracy at ends of range
- 2” diameter

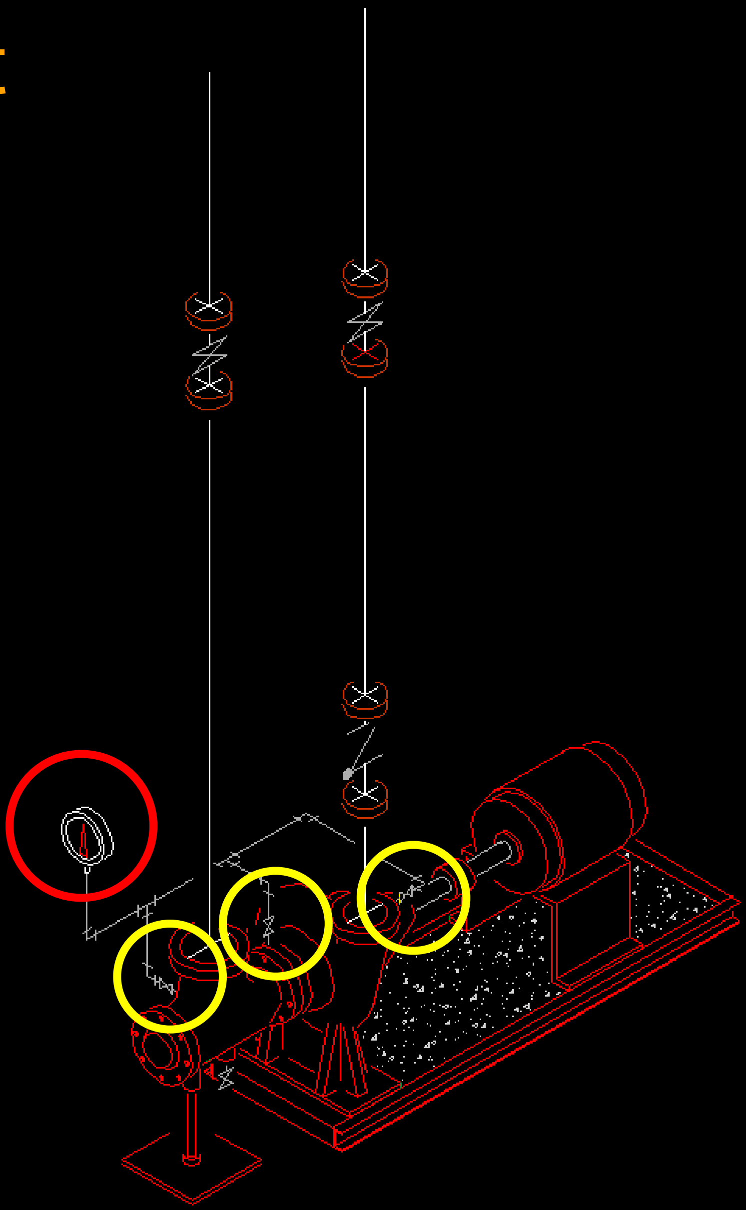
Price

- $4

Performing a Pump Test

Accurate Pressure Measurements are Important

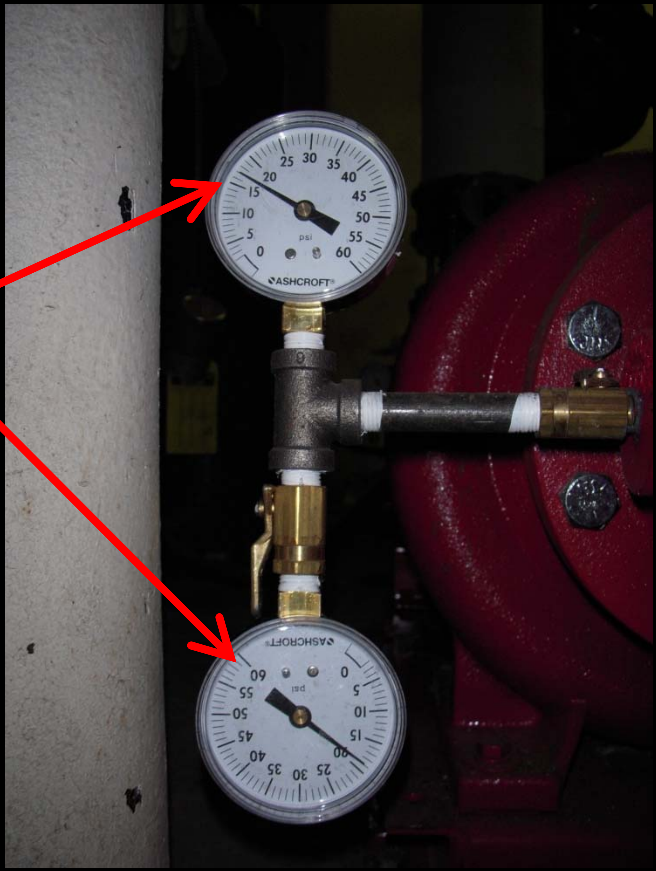
- High quality gauges
  - High accuracy
  - Large dial size
  - Useful features
- Less is More
  - Reading all pressures with the same gauge through a manifold cancels out gauge error and saves a gauge

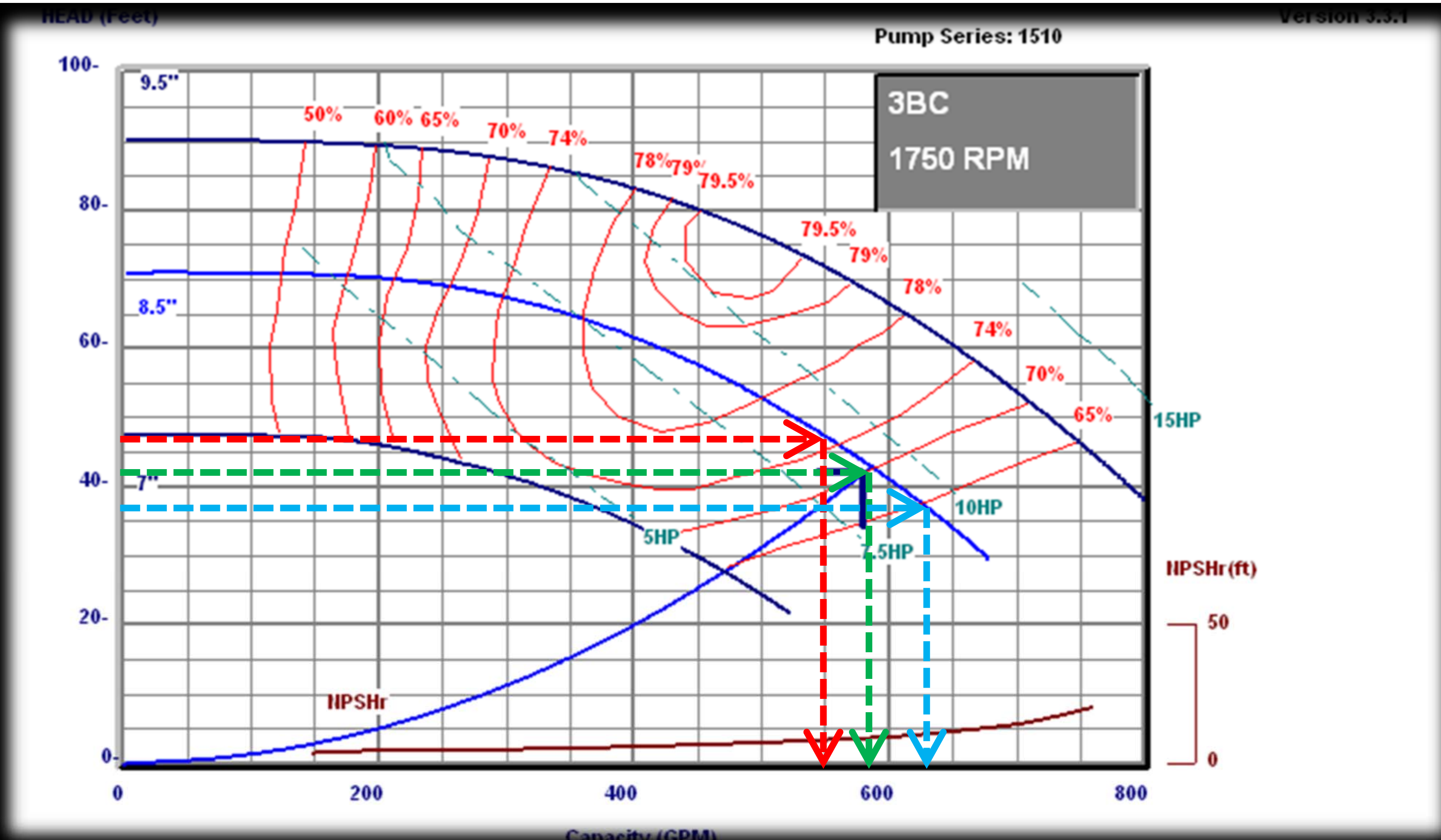


An Important Detail about Pump Tests

One gauge is better than two

- 2 Gauges
- Same make and model
- Same point of connection
- 2 different indications
  - 17 vs. 19 psi or 39 vs. 44 ft.w.c
  - 2 psi/5 ft.w.c. difference can be significant when reading a pump curve





Using 1 gauge to take both readings

Discharge 88 ft.w.c
Suction 46 ft.w.c.

Difference 42 ft.w.c.
Flow 580 gpm

Two gauges, discharge reads high

Discharge 93 ft.w.c
Suction 46 ft.w.c.

Difference 47 ft.w.c.
Flow 550 gpm

Two gauges, suction reads high

Discharge 88 ft.w.c
Suction 51 ft.w.c.

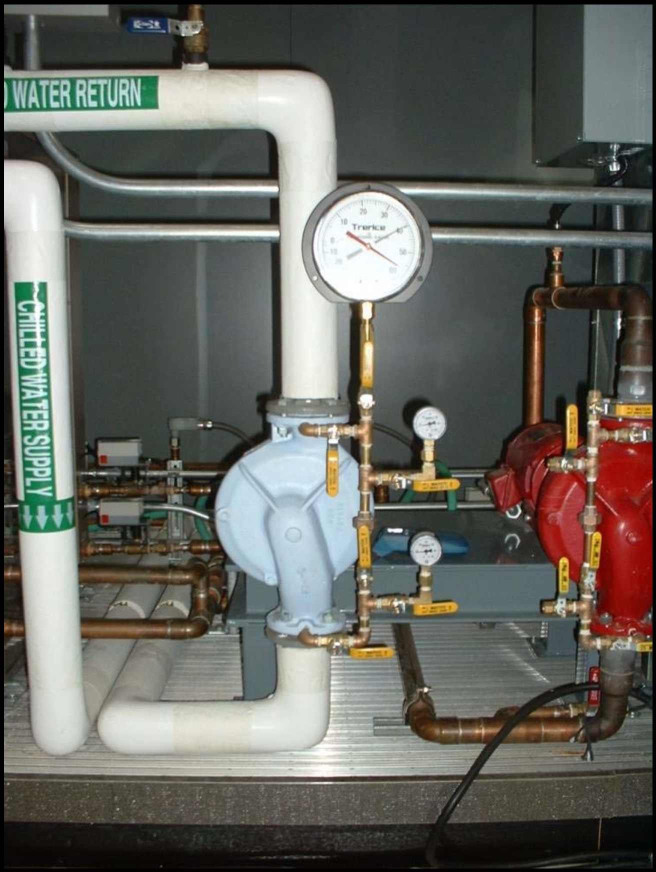
Difference 37 ft.w.c
Flow 630 gpm

Pressure Gauge Selection

- One gauge is better than two
  - Include “Max” indication feature

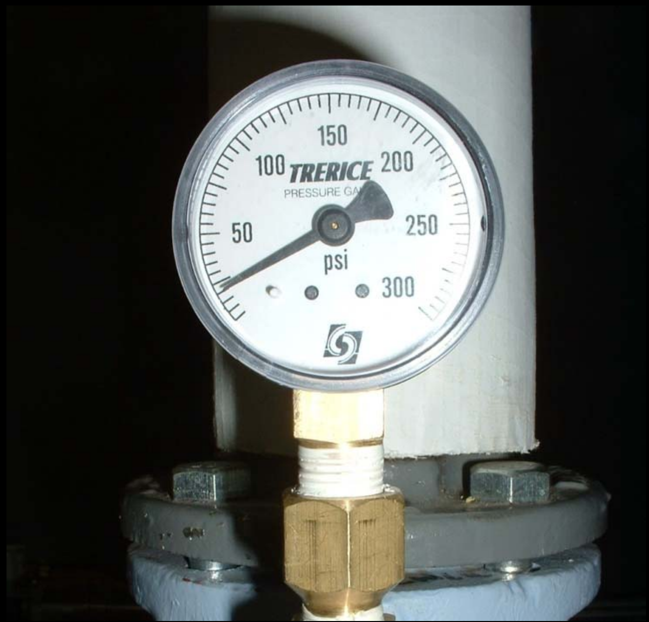
Pressure Gauge Selection

- One gauge is better than two
  - Include “Max” indication feature
  - Piped to read all pressures one at a time



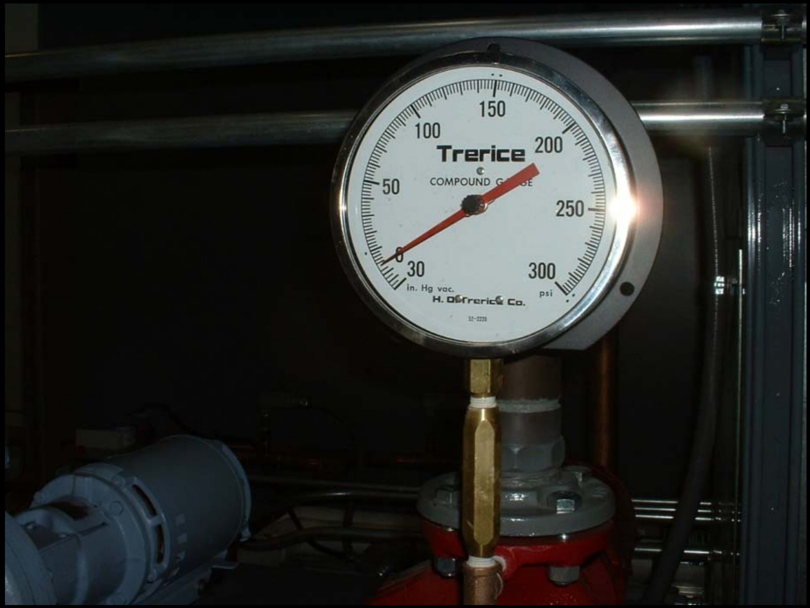
Pressure Gauge Selection

- One gauge is better than two
  - Piped to read all pressures one at a time
  - Include “Max” indication feature
  - Don’t skimp on accuracy
  - Don’t skimp on size
- Snubbers or impulse chambers are desirable
- Ball valves are better than gauge cocks



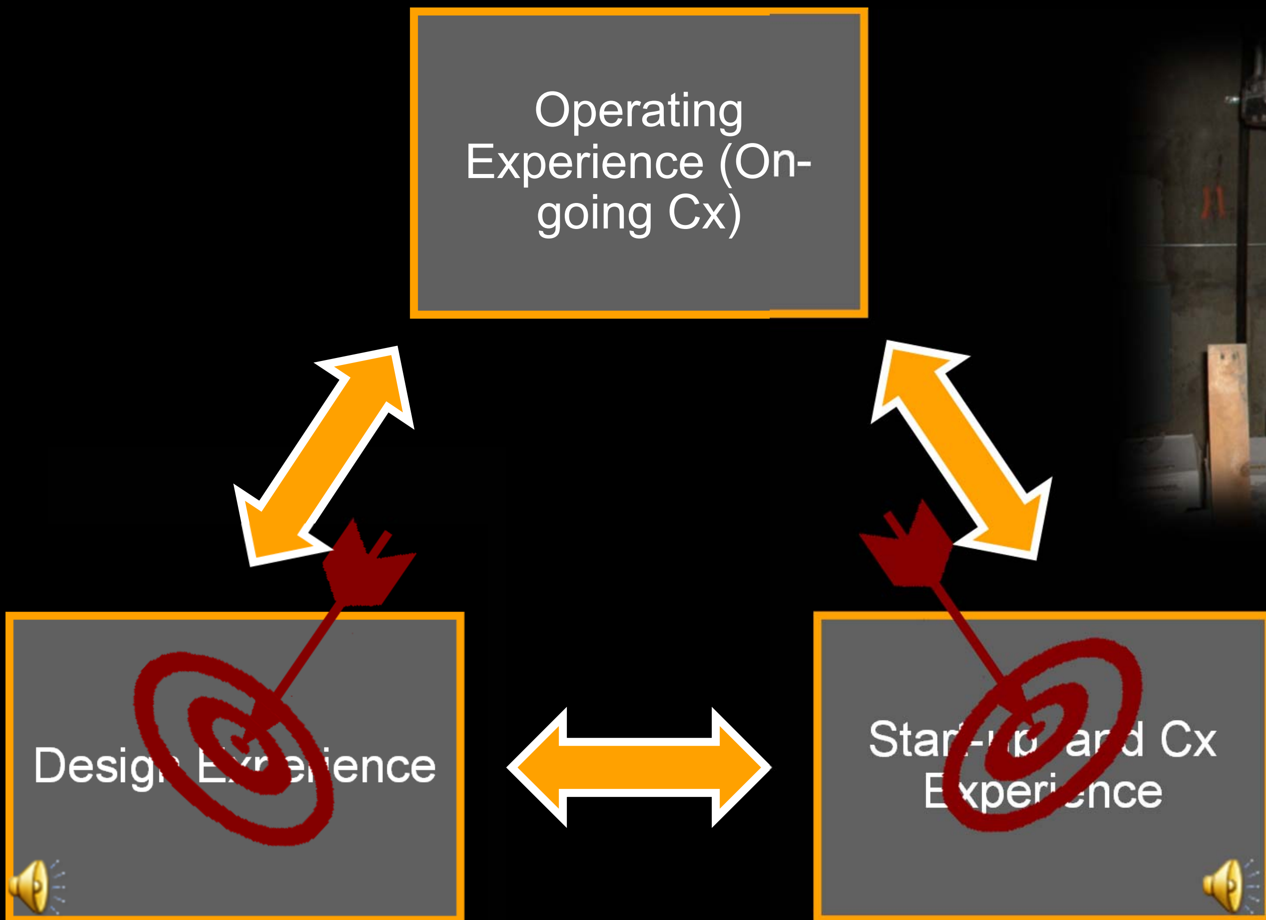
Pressure Gauge Selection

- Range
  - Selected so anticipated reading is mid-scale
  - Anticipate negative suction pressures
  - Accommodate high static pressures



Pressure Gauge Selection

- Range
  - Selected so anticipated reading is mid-scale
  - Anticipate negative suction pressures
  - Accommodate high static pressures
- Viewing angle can make a difference
- Orientation can make a difference



Specify “optional” gauge taps!

… and verify the requirement in review cycles

Make sure the gauges are connected to the gauge taps …

… and train the operating team on their use