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Let's Solve Water

ASHRAE® Boston Chapter

April 14th, 2026

Variable Speed Pumping Design Fundamentals

Presenter: Michael T. Licastro

Bell & Gossett
xylem

Summary of Topics for Discussion

- How to read and use a Pump Curve
- Applying the Darcy-Weisbach Equation to create the System Curve
- The Pump Affinity Laws and Pump Selection for Variable Speed
- Low or High Diversity System: Establishing the Control Area
- Which Control Strategy to use
- How much Control Head do you have
- Impeller Sizing for Variable Speed Operation

Calculating the Heating and Cooling Loads

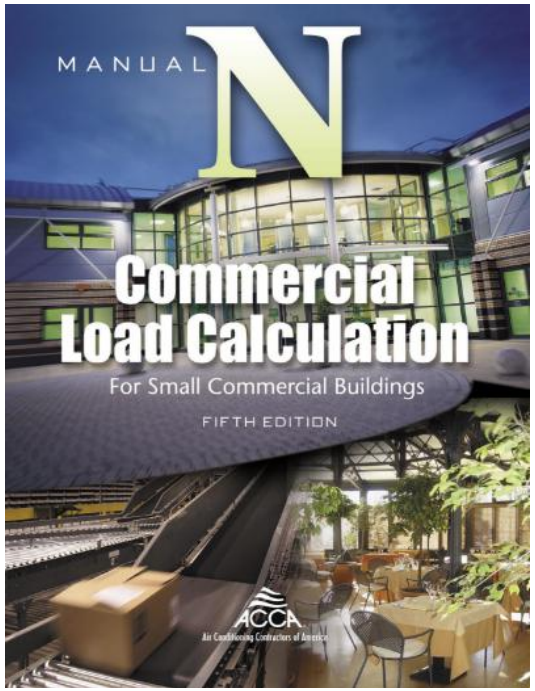
ASHRAE 90.1 Section 6.4 – Mandatory Provisions

6.4.2.1 Load Calculations

Heating and Cooling *system* design loads for the purpose of sizing *systems* and *equipment* shall be determined in accordance with ASHRAE/ACCA Standard 183*

Available resources:

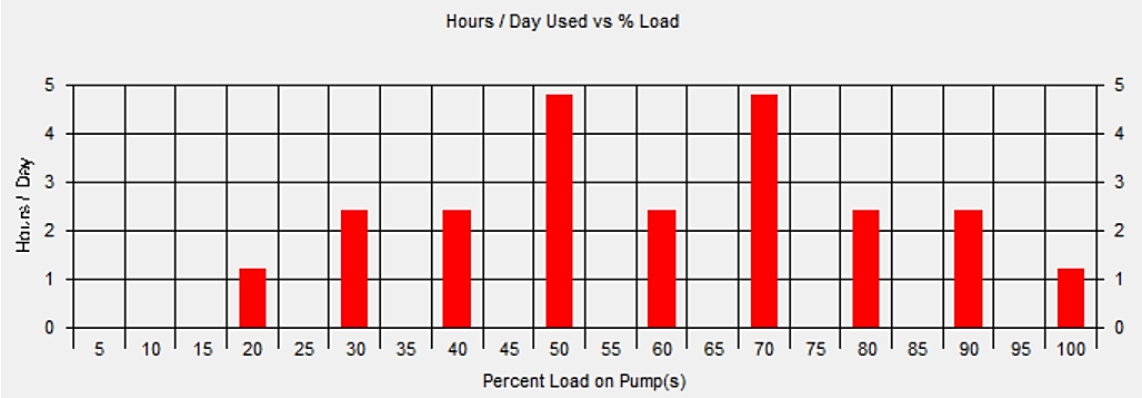
- **ASHRAE *Fundamentals Handbook* (Chapter 17 in the 2021 version)**
- **Air Conditioning Contractors of America (ACCA)**
  - **Manual J *(Residential Loads)***
  - **Manual N *(Commercial Loads)***
- **Third Party Manufacturers Software programs**



What does the building *“Load Profile”* look like?

Important reference document for selection of any major equipment

- Provides expected pattern of changes to building load, as a percentage of full “Design Day”, and the anticipated operating hours per day at each level



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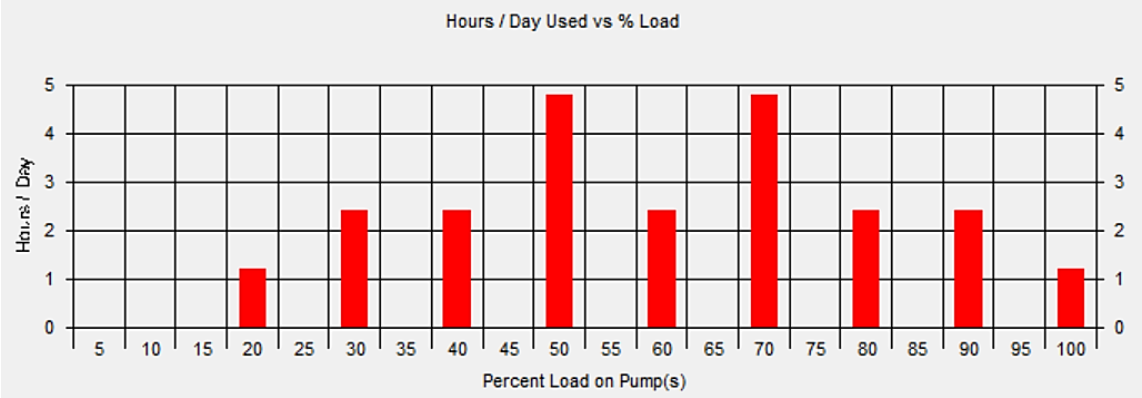

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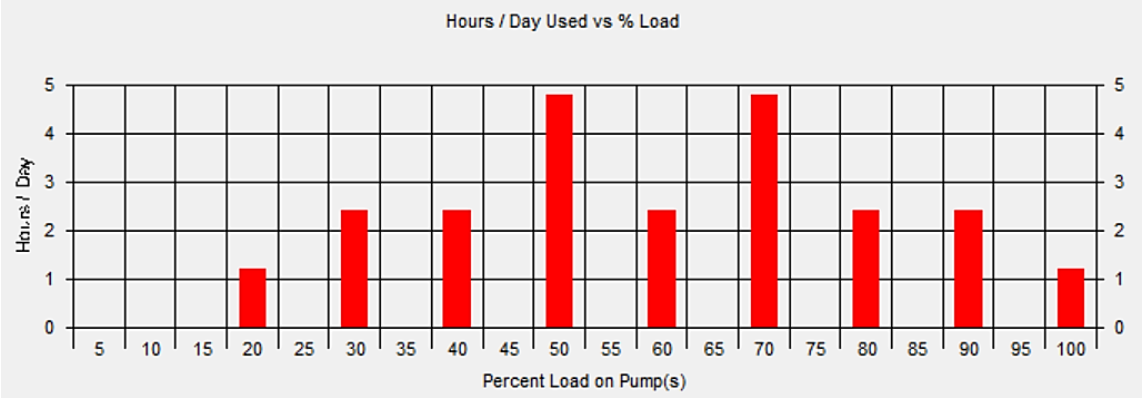
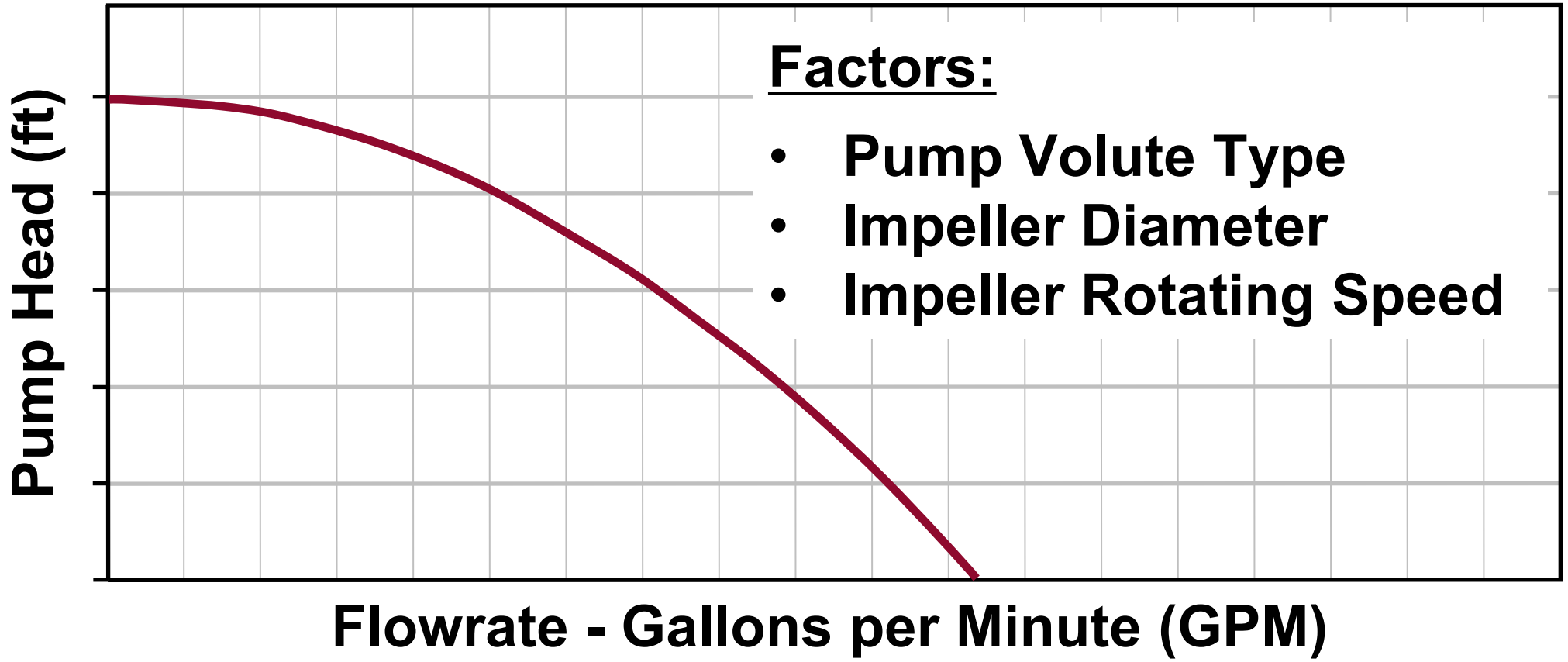
- For new construction, modeling software available using historical data based on building type and geographical location



Selecting a Pump:

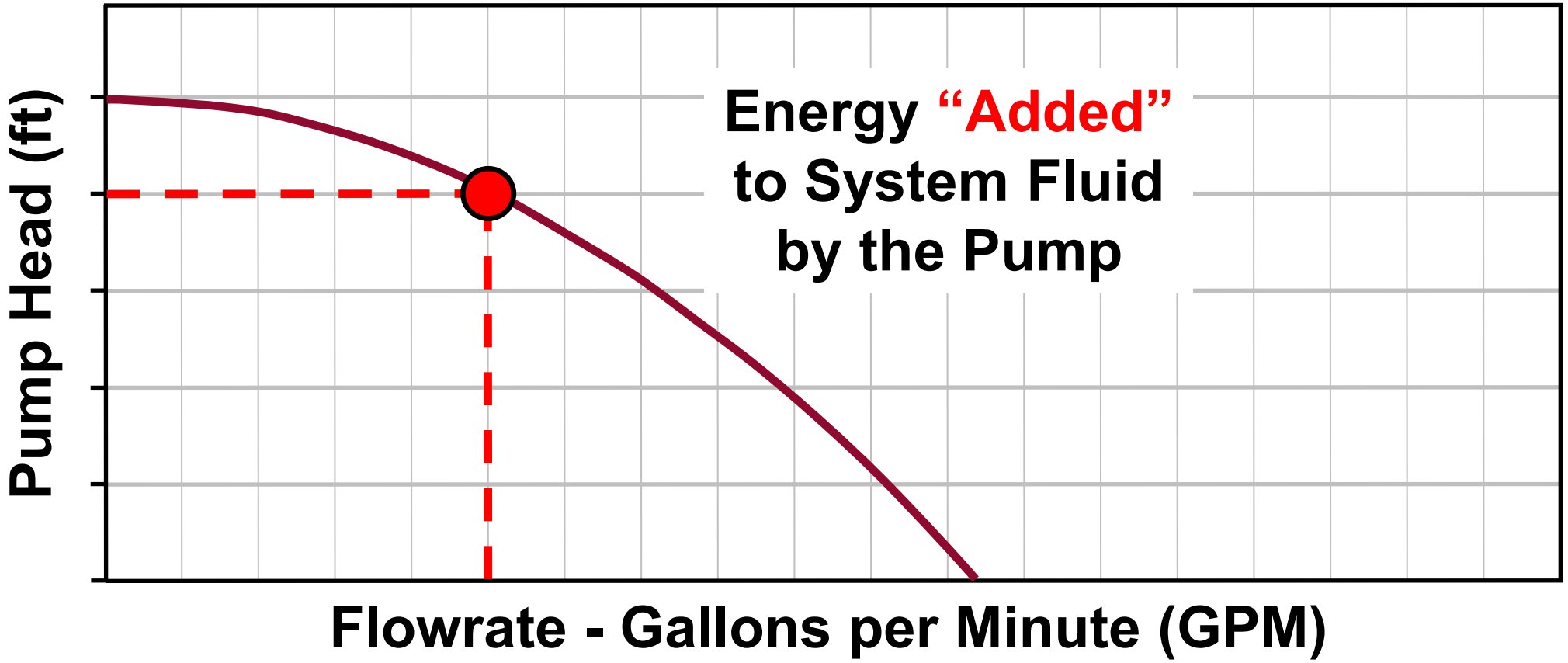
The Pump and System Performance Curves

Typical Pump Performance Curve Shape



More Flow produced, Less Pump Head developed

Pump Performance Curve – Impeller Diameter & Rotating Speed



Any combination of flow and head **must** intersect **on** the Pump Impeller Performance Curve

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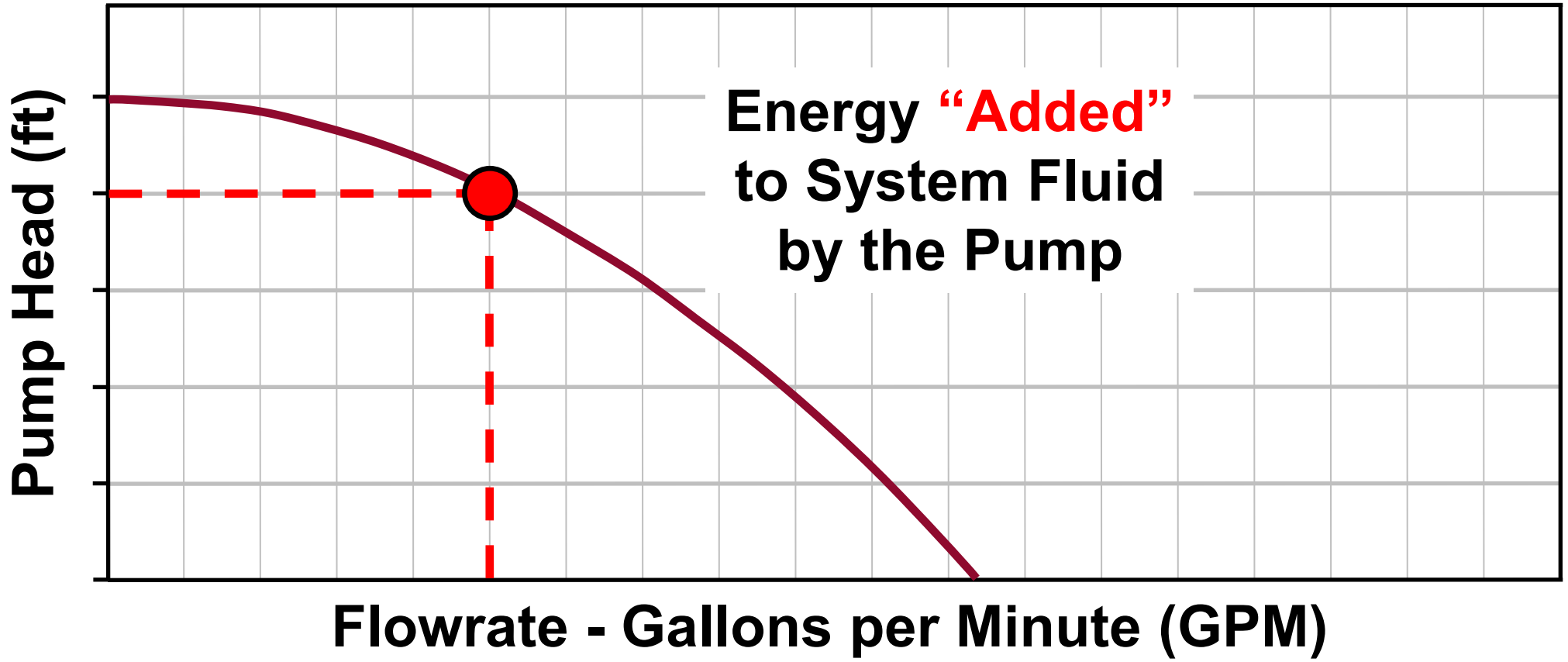

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Energy *(Pump Head)* (ft-lb/lb)

(Work Applied to the Fluid)

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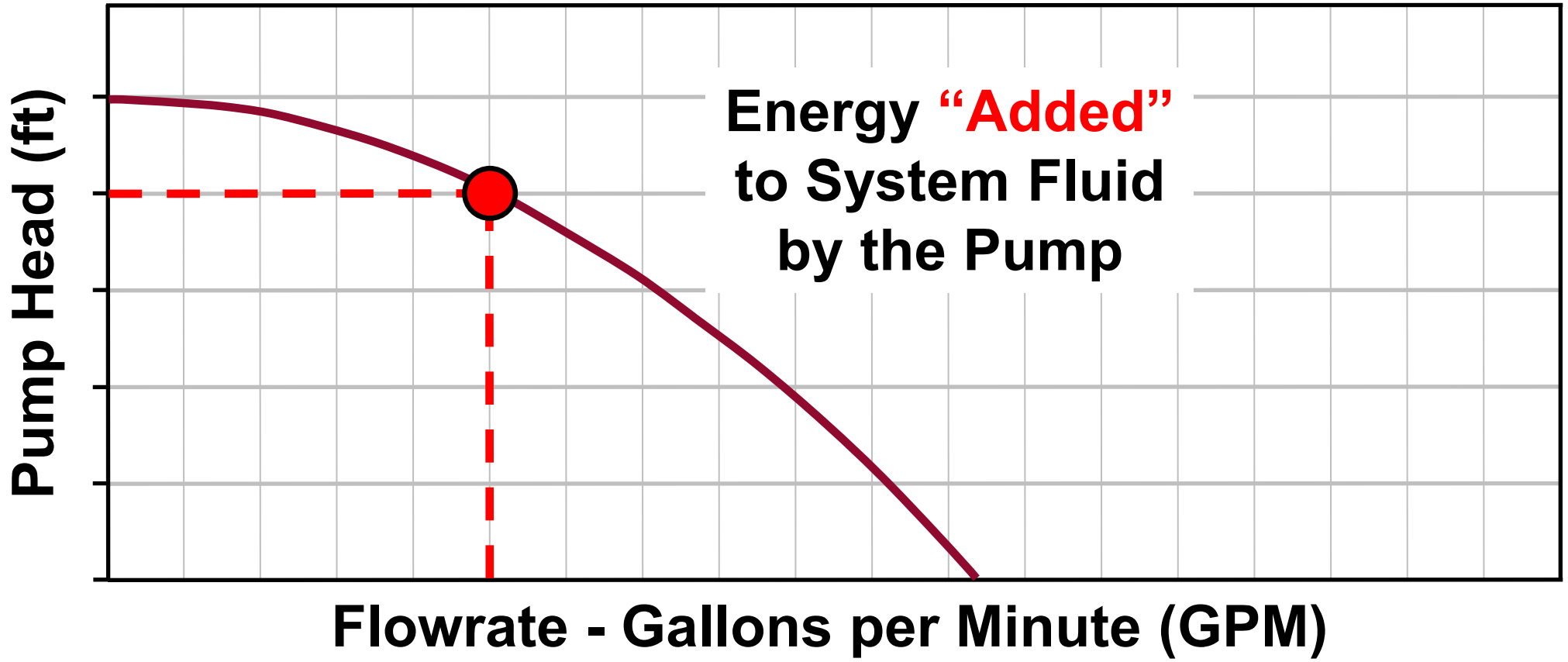

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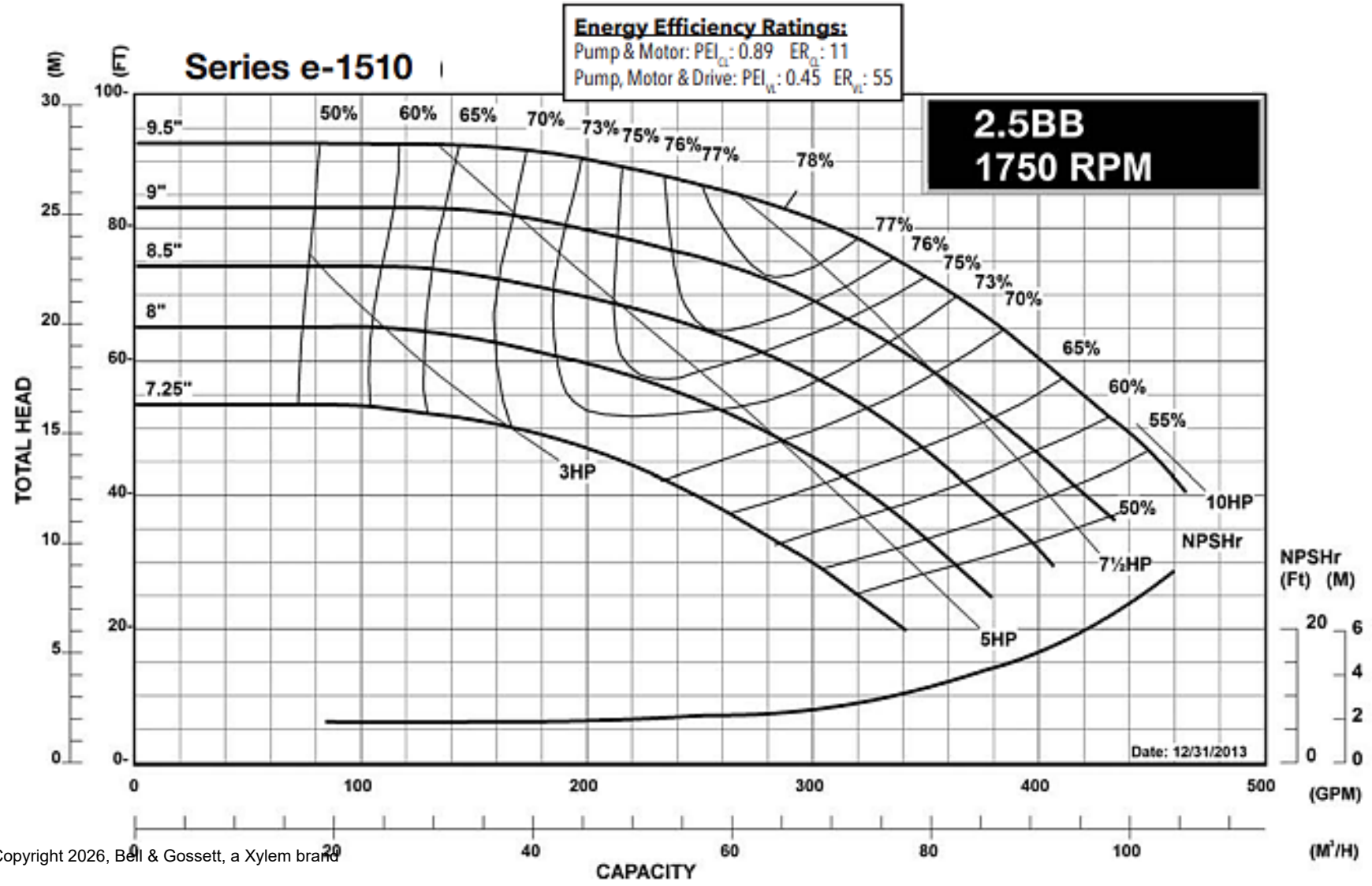
(Work Applied to the Fluid)

$$\text{Pump Head (ft)} = \text{PSI} \times \frac{2.31}{SG}$$

How to read a **Constant Speed** Pump Curve *(Old School!!)*



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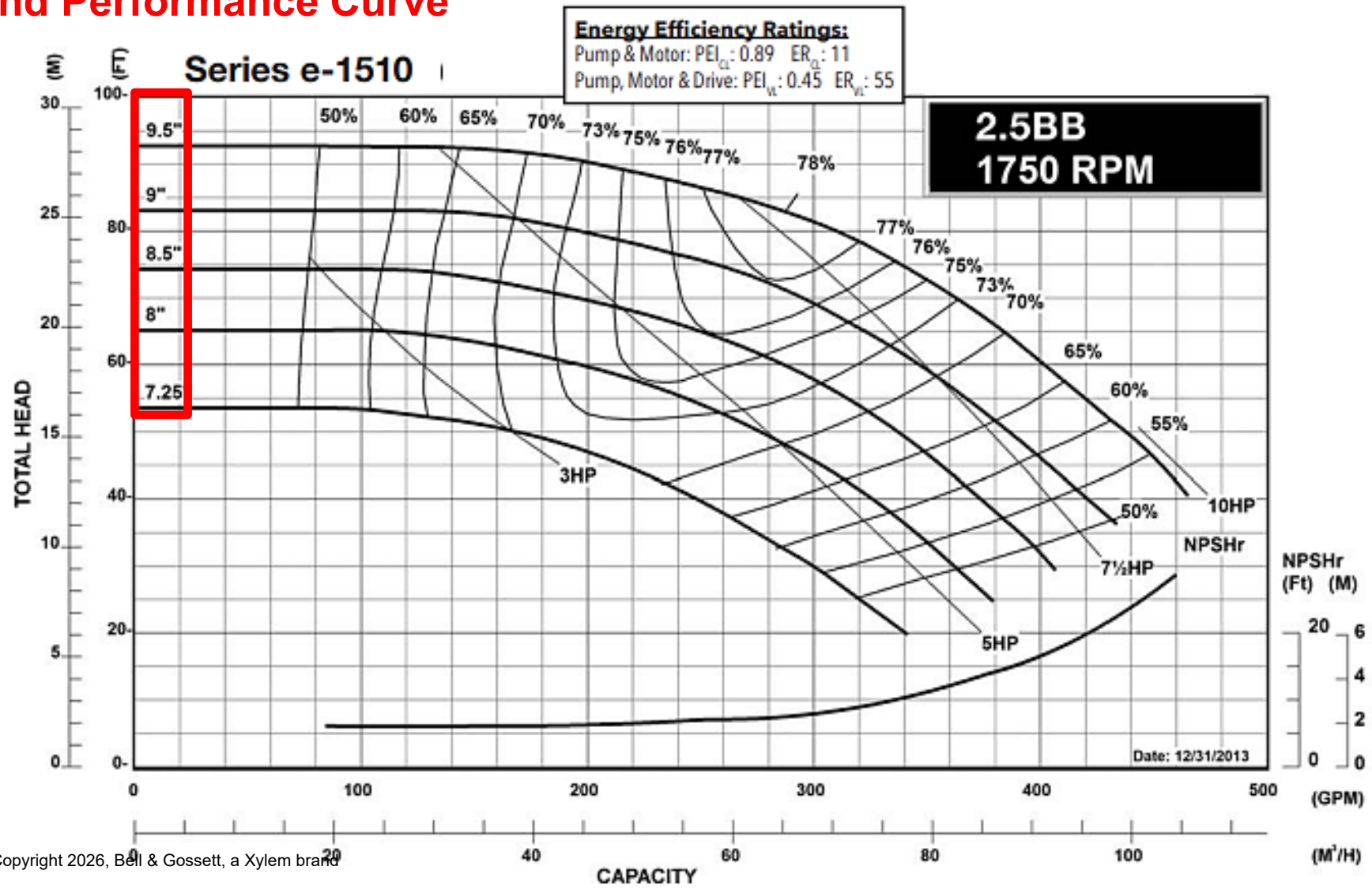
Impeller Diameter and Performance Curve



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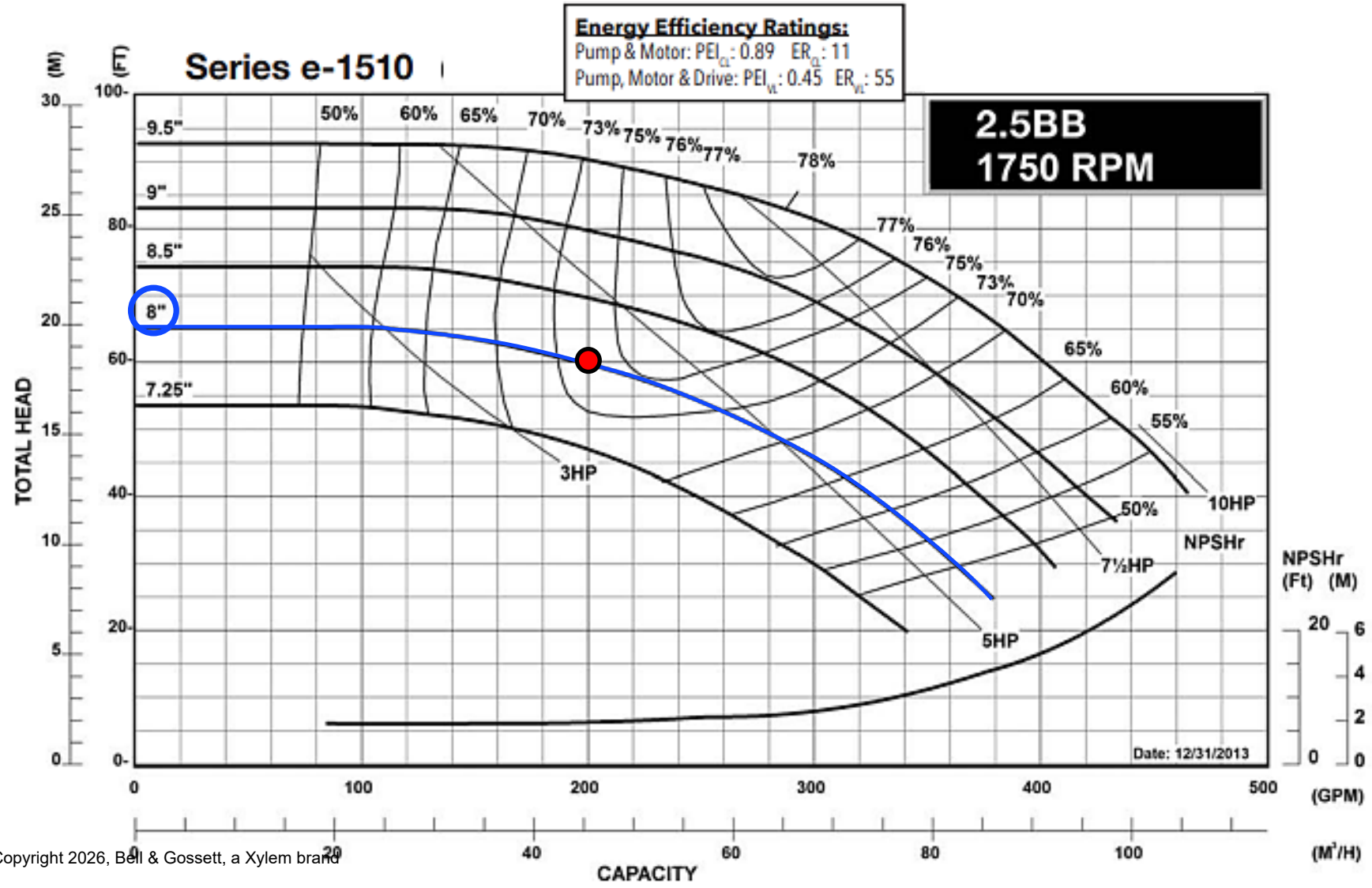

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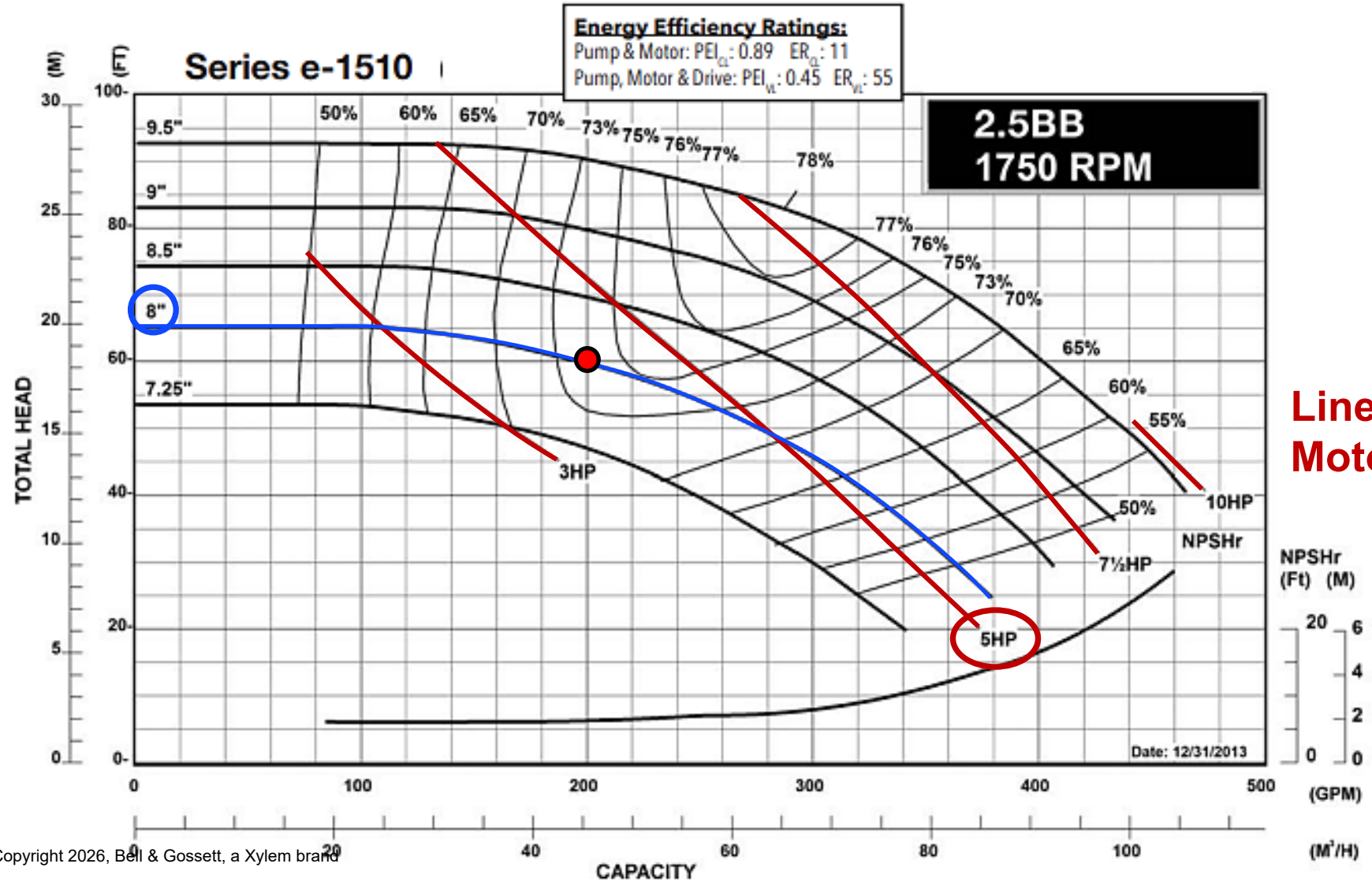

Lines of Constant Motor HP

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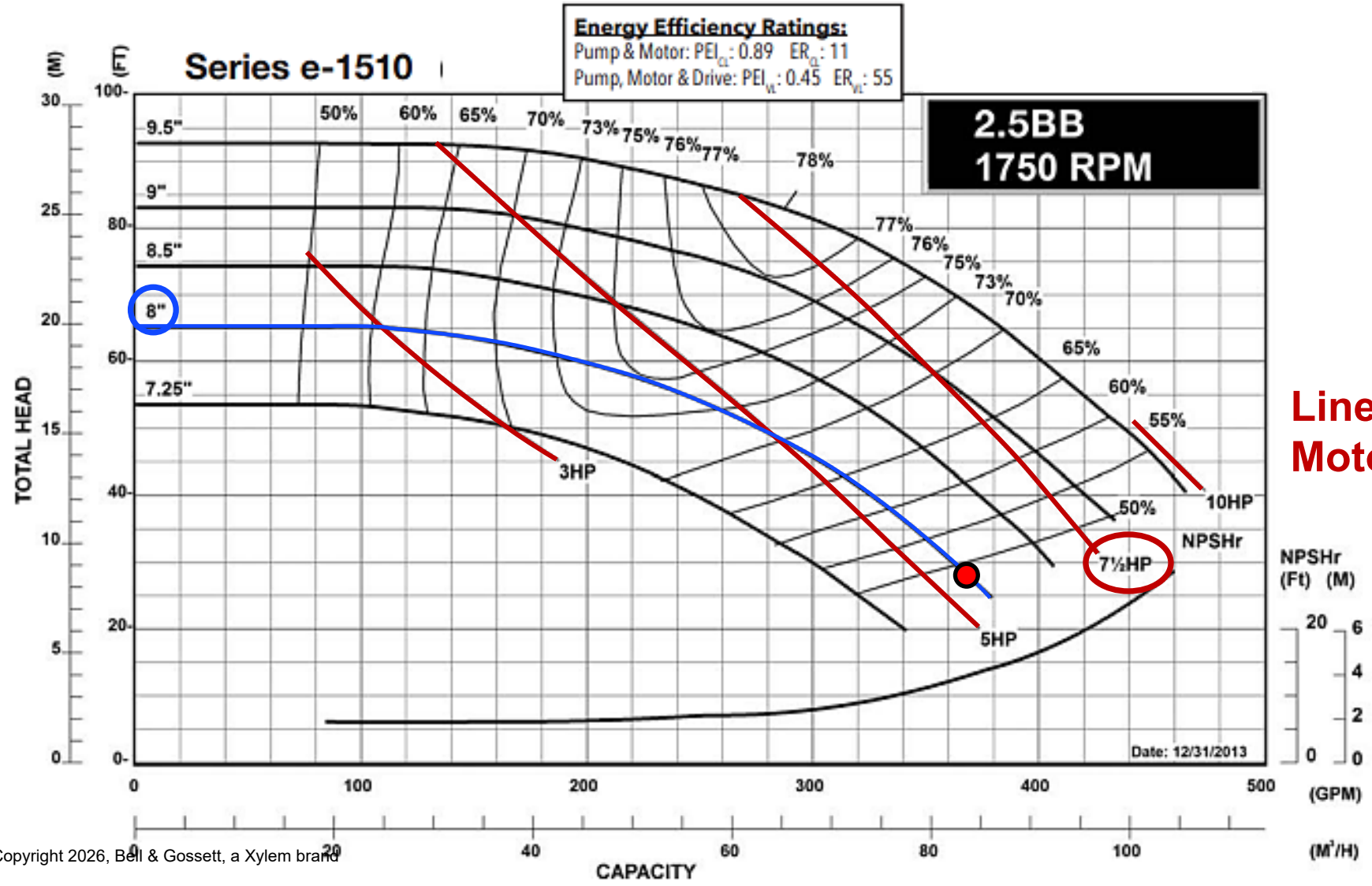

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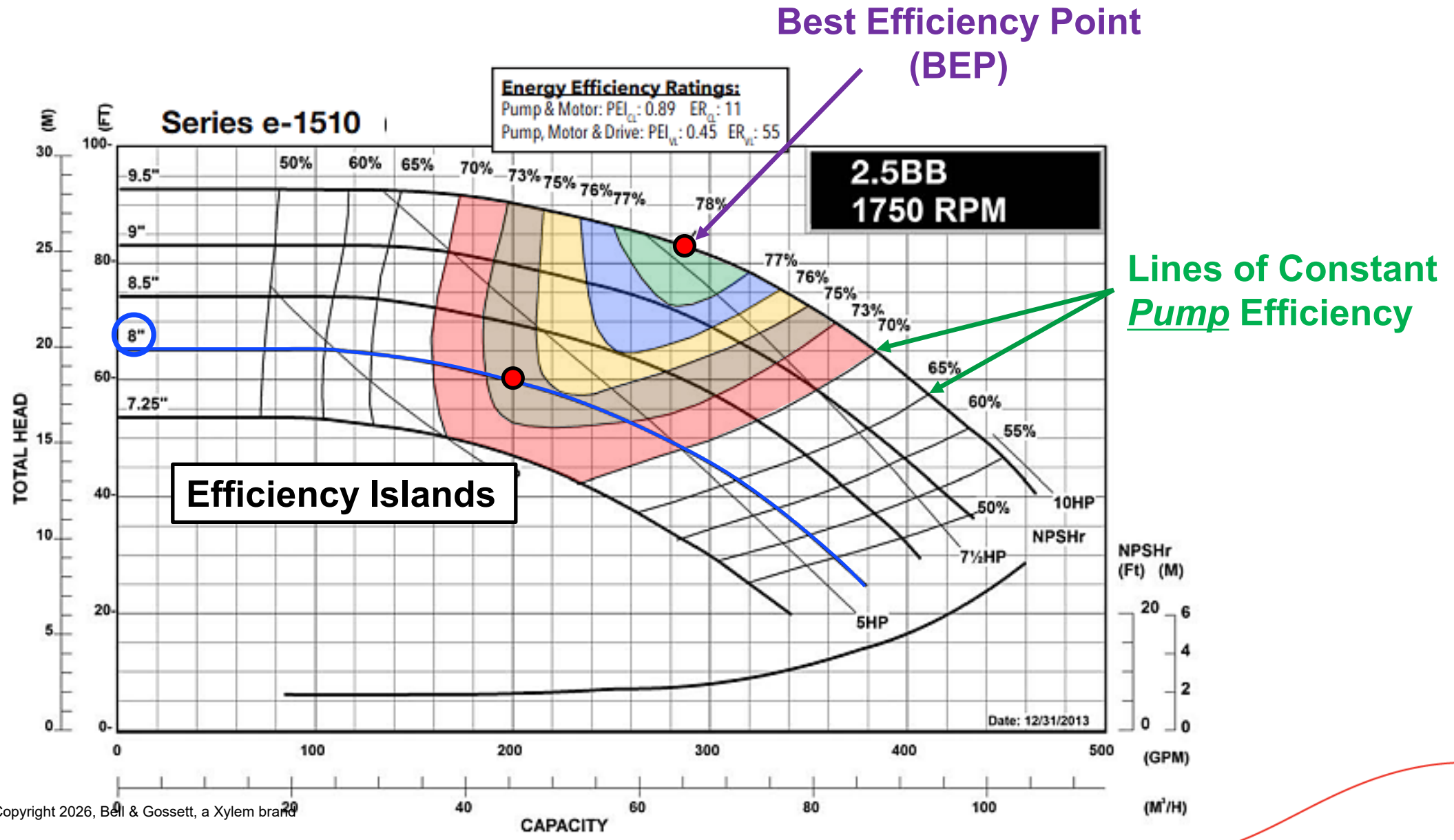

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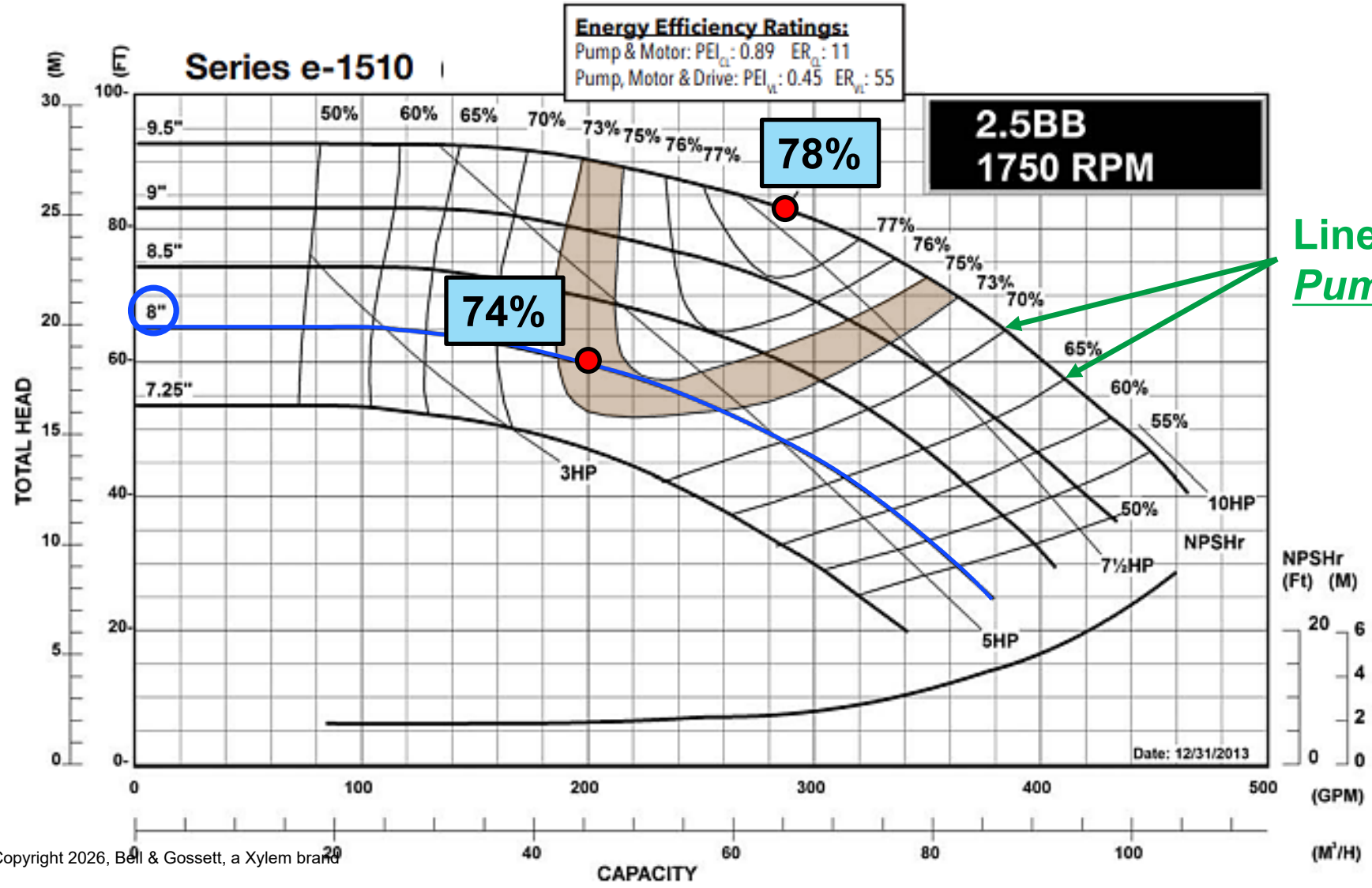
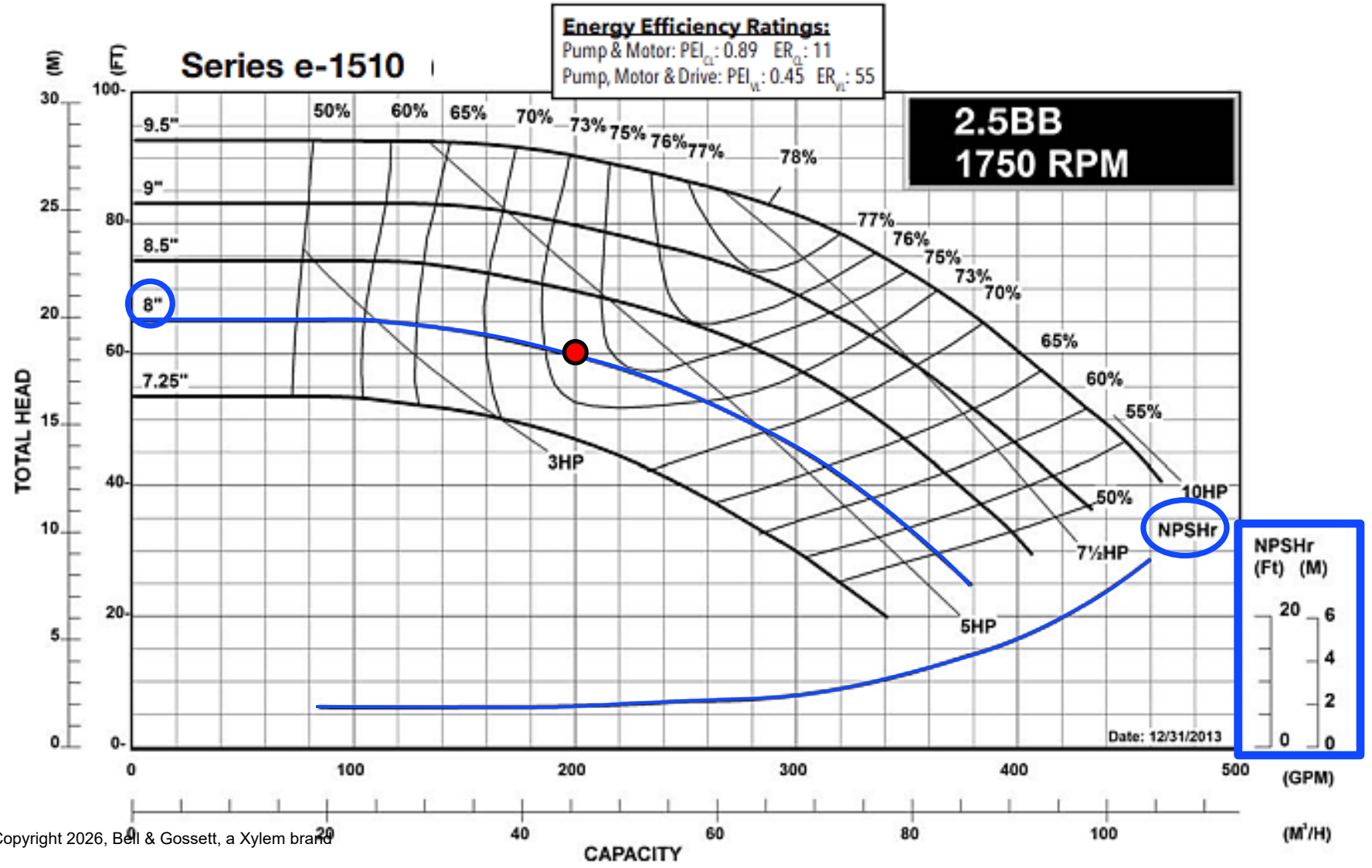


Lines of Constant *Pump* Efficiency

How to read a **Constant Speed** Pump Curve *(Old School!!)*



Net Positive Suction Head *required*

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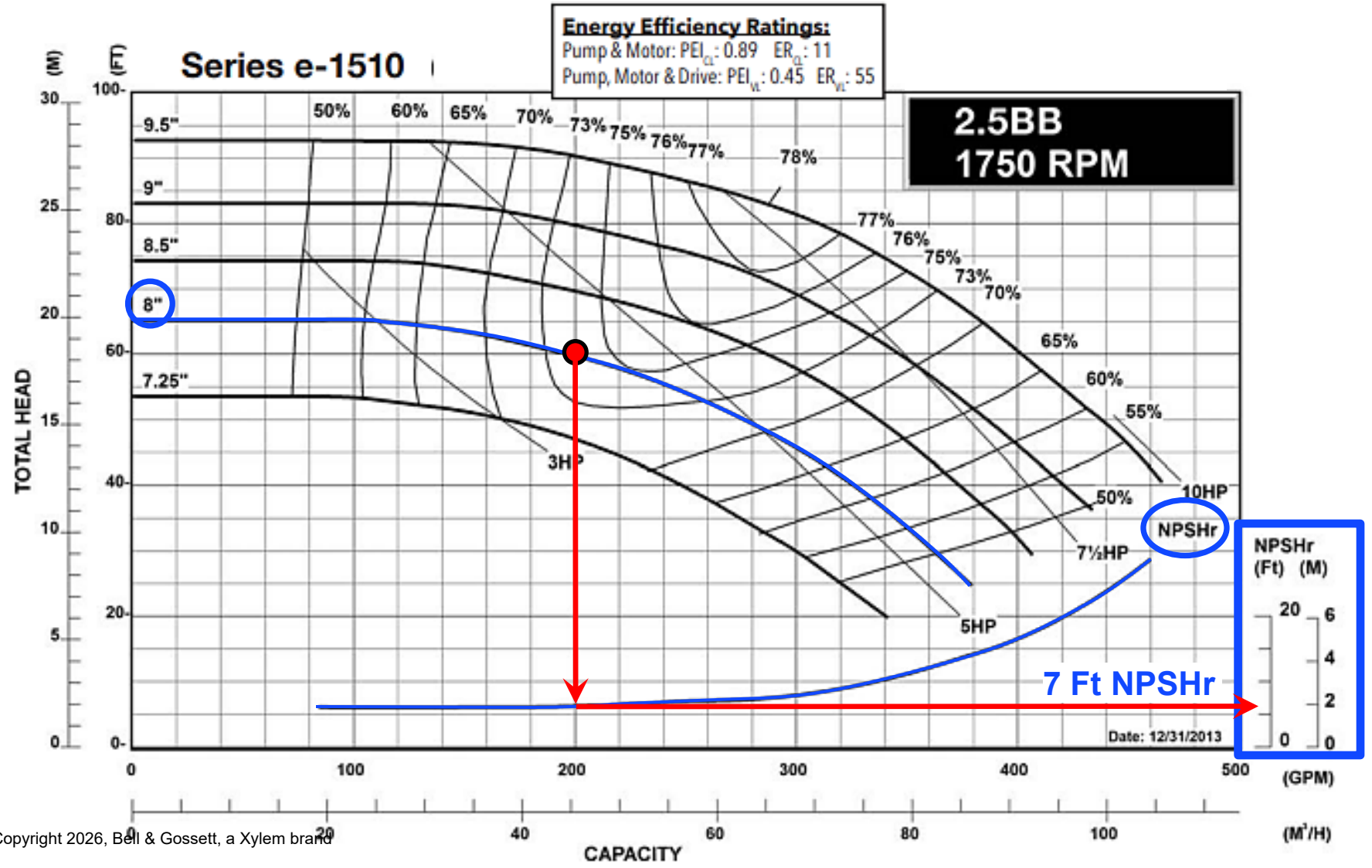

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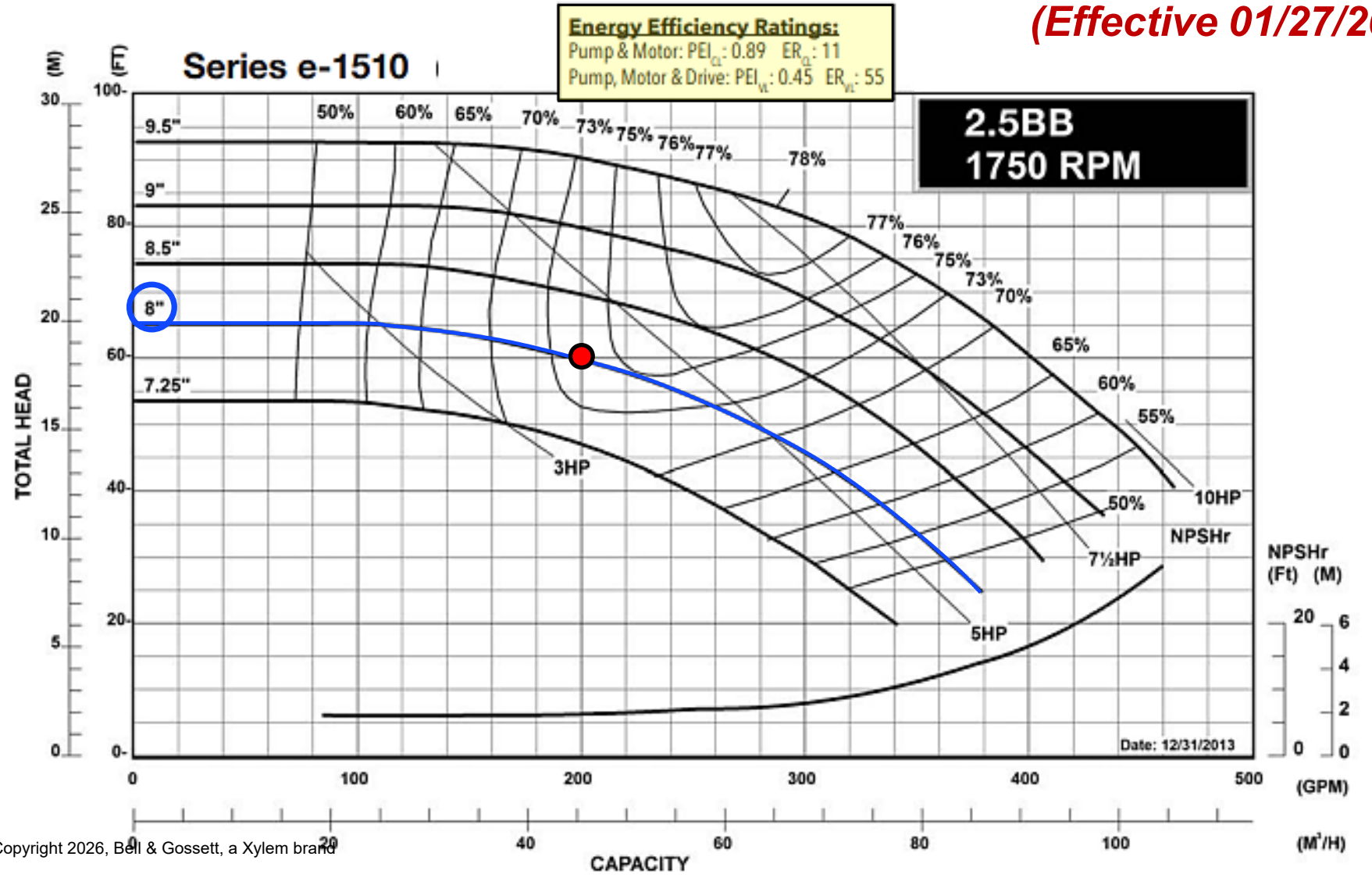
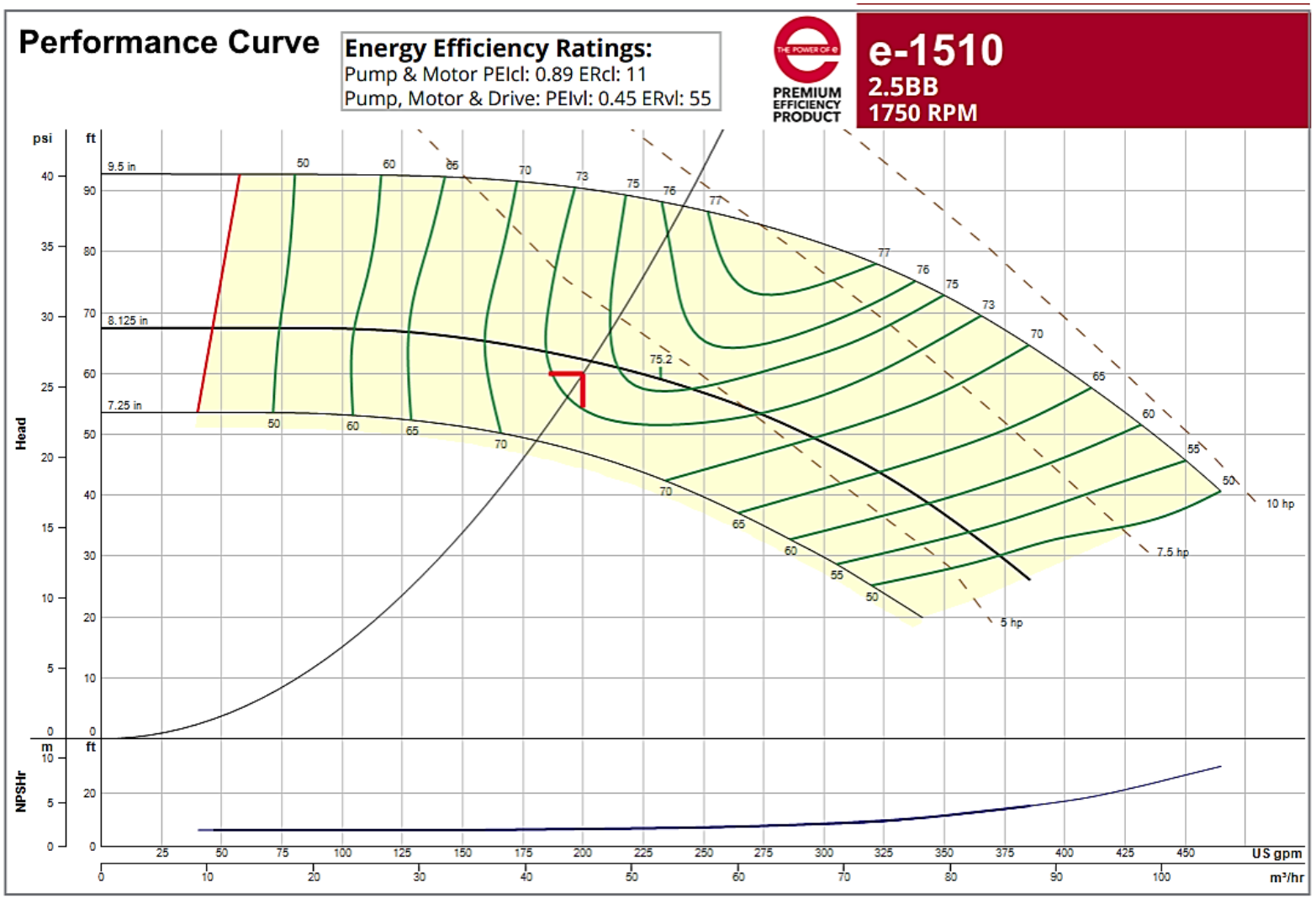
Department of Energy (DOE)
Energy Conservation Standards
(Effective 01/27/20)



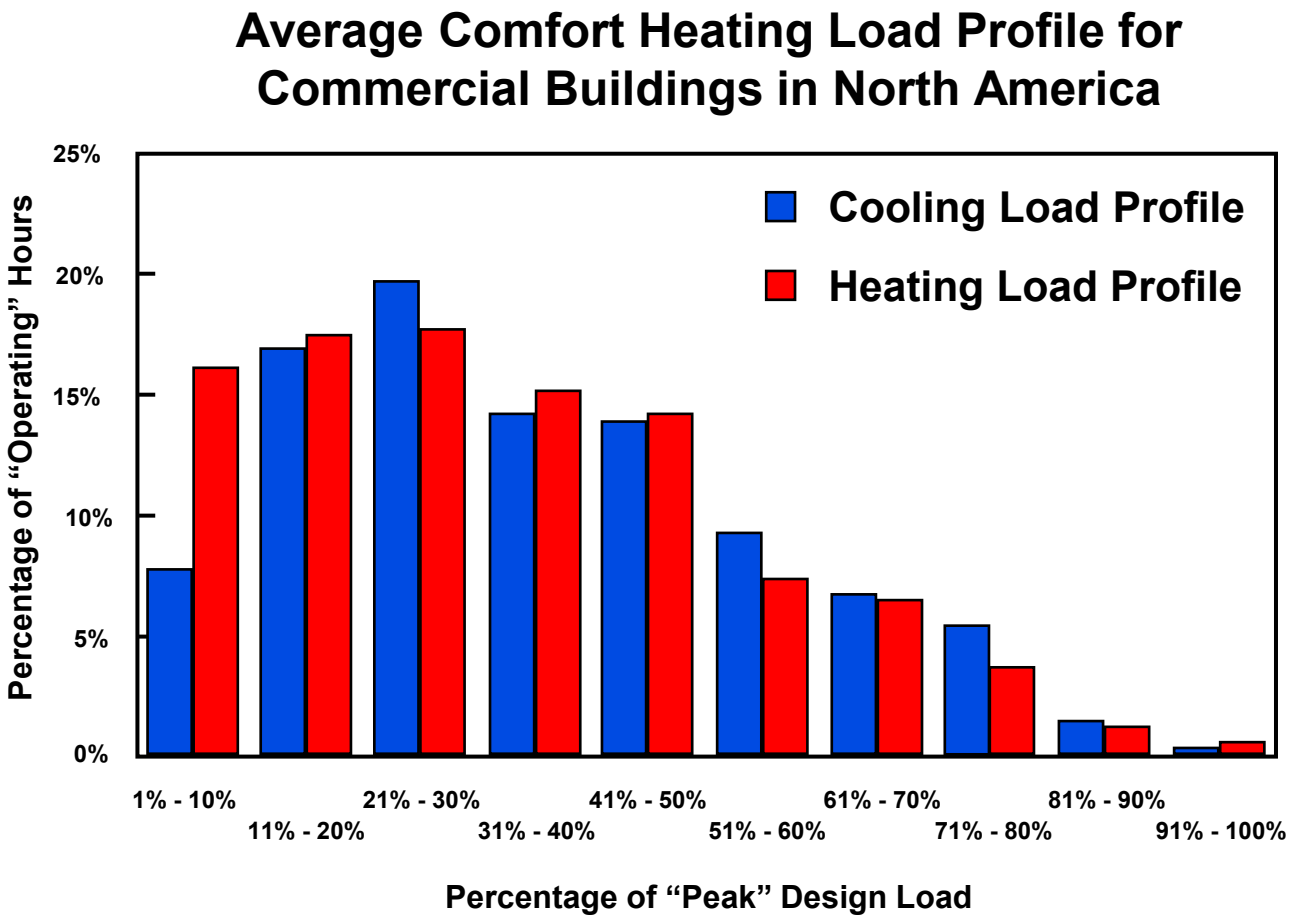
Constant Speed Pump Curve *(Pump Selection Tools)*



Pump Selection Summary

Duty Point Flow	200 US gpm
Duty Point Head	60 ft
Control Head	0 ft
Duty Point Pump Efficiency	74.2 %
Part Load Efficiency Value (PLEV)	0.0 %
Impeller Diameter	8.125 in
Motor Power	7.5 hp
Duty Point Power	4.27 bhp
Motor Speed	1800 rpm
RPM @ Duty Point	1750 rpm
NPSHr	6.6 ft
Minimum Shutoff Head	67.5 ft
Minimum Flow at RPM	46.4 US gpm
Flow @ BEP	232 US gpm
Fluid Temperature	68 °F
Fluid Type	Water
Weight *(approx. - consult rep for exact)*	260 lbs
Pump Floor Space Calculation	4.35 ft²

The Building Load Profile: A glimpse at reality



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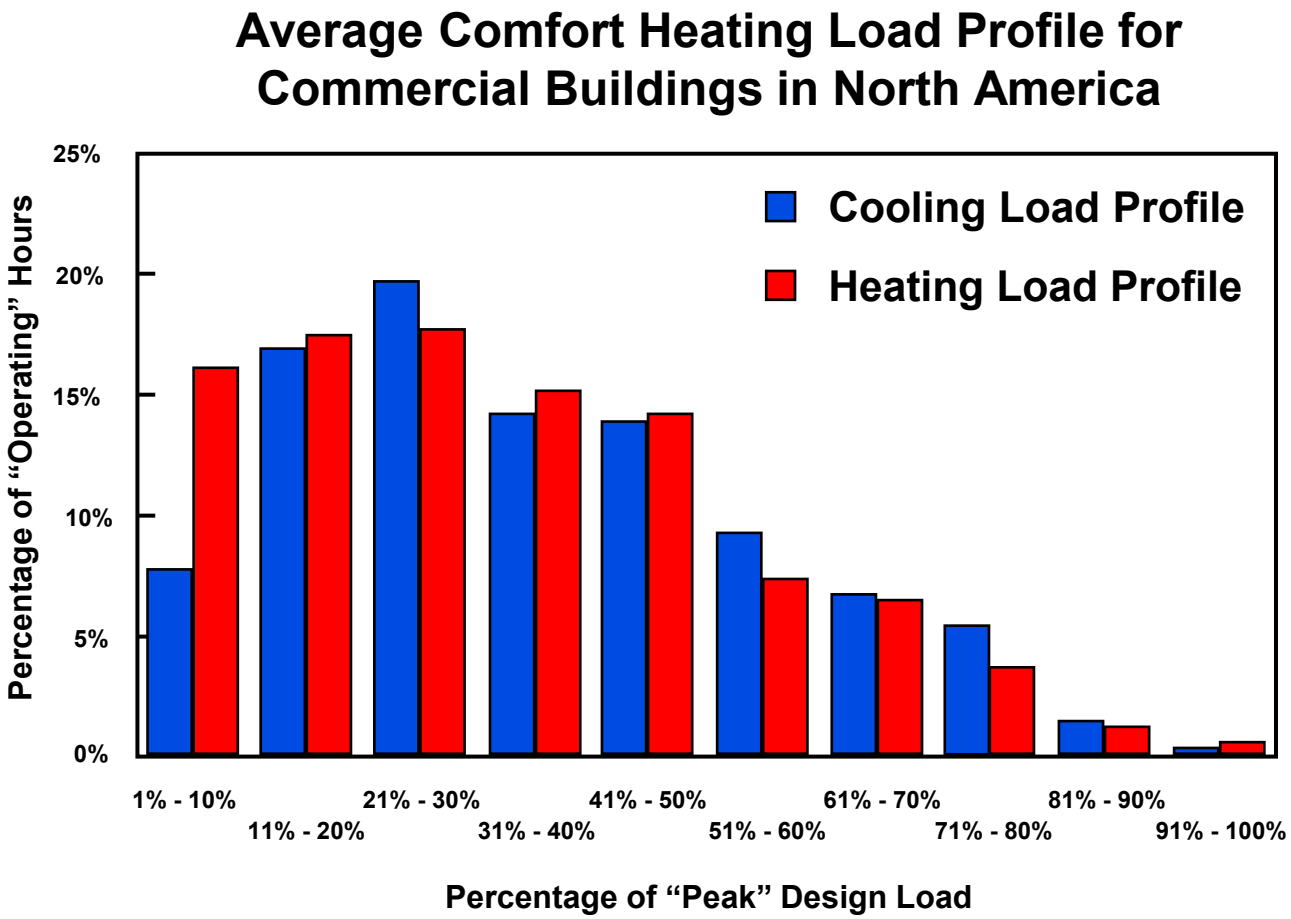
Typical System operates at 70% or less of Design Load over 90% of the time



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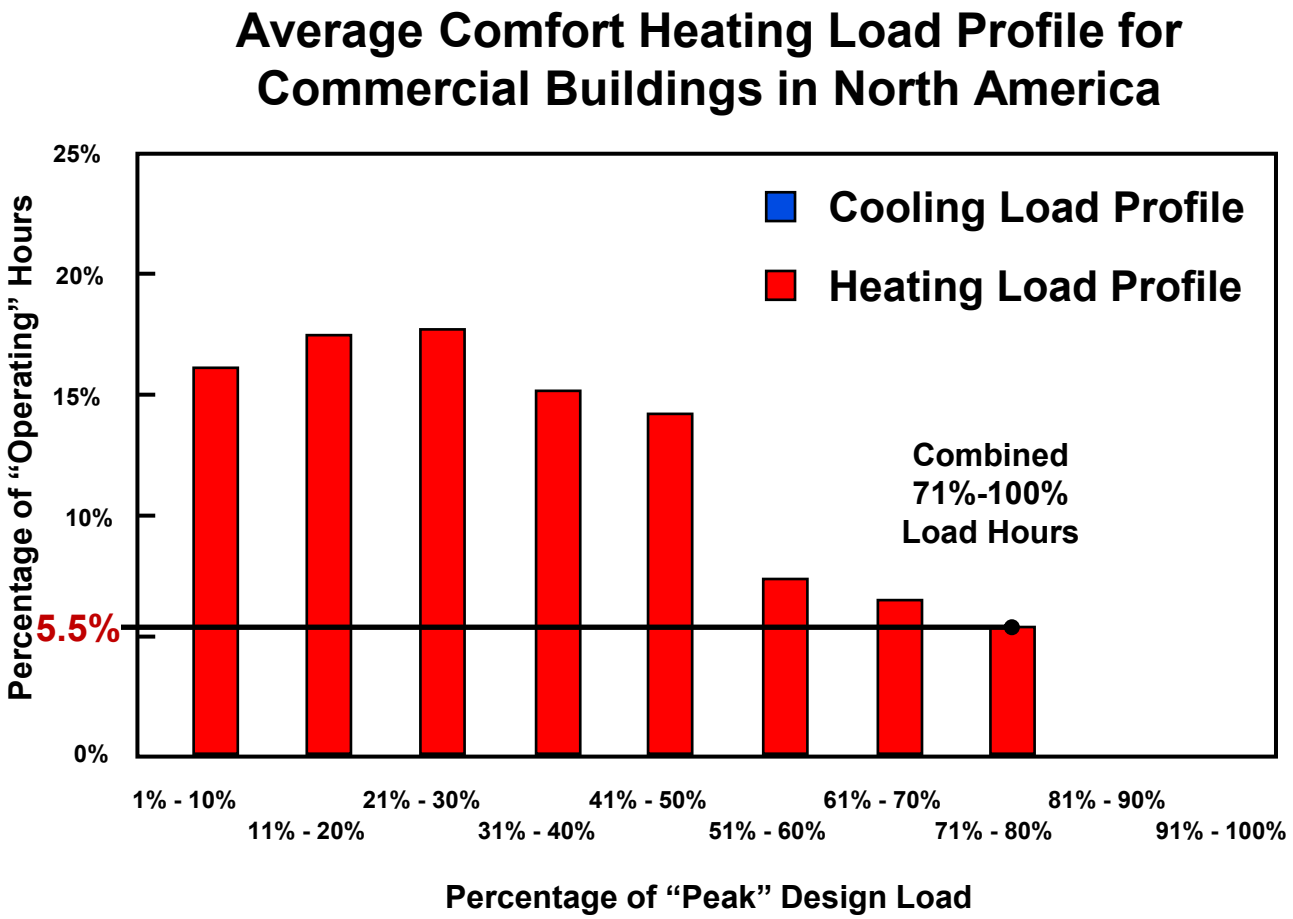

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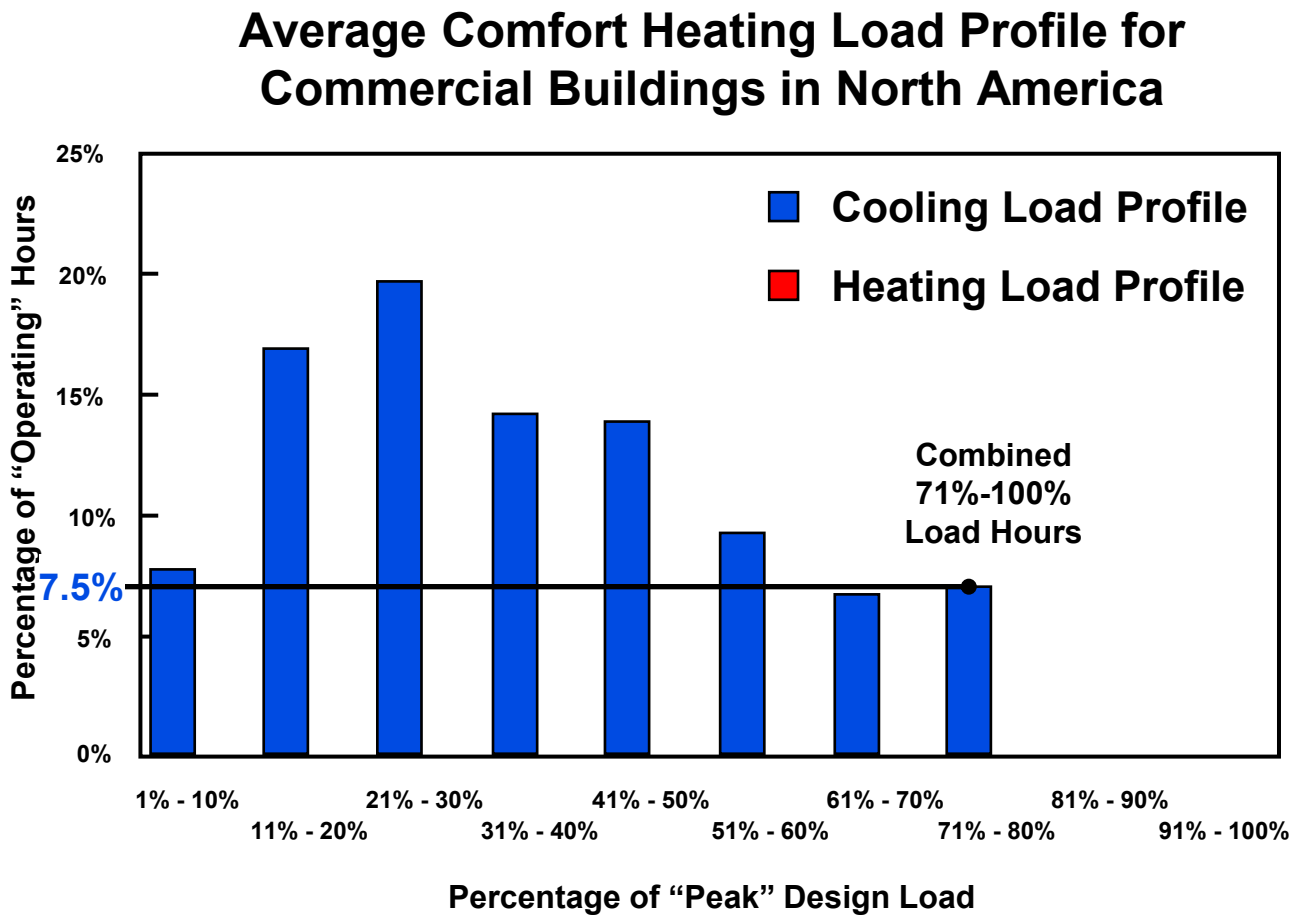


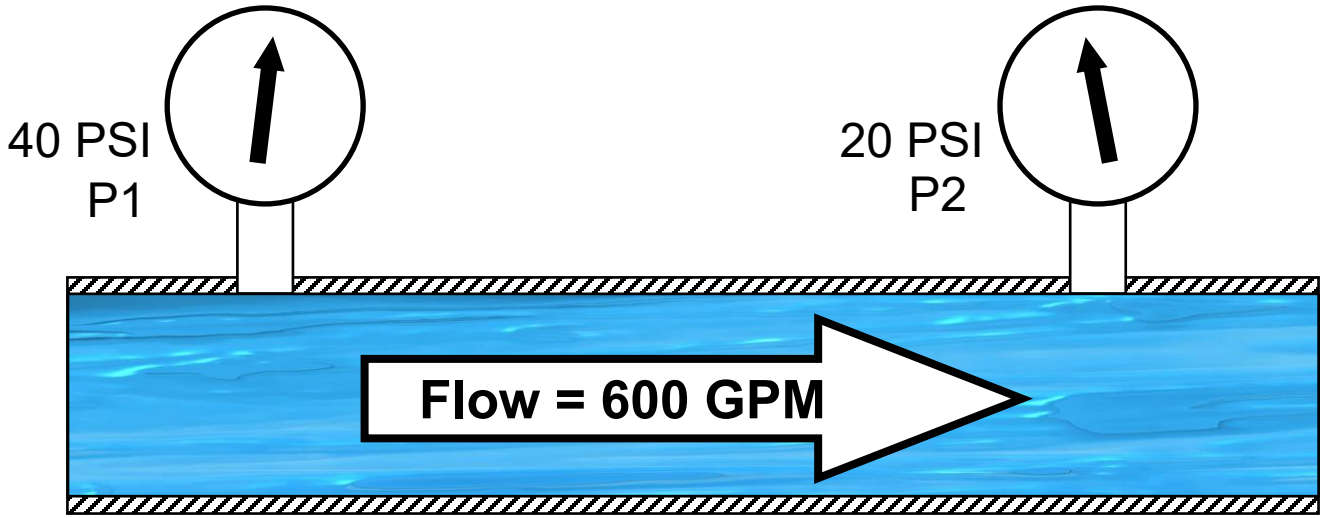
Where is highest pump efficiency most beneficial?

Pressure Drop (Friction Loss) and Flowrate Relationship

Simplified Darcy-Weisbach Equation: Head loss proportional to the Square of the Flow

$$\left(\frac{Q_2}{Q_1}\right)^2 = \left(\frac{h_2}{h_1}\right)$$

- Q_1 = Known (design) Flow
- Q_2 = Final Flow
- h_1 = Known (design) Head
- h_2 = Final Head



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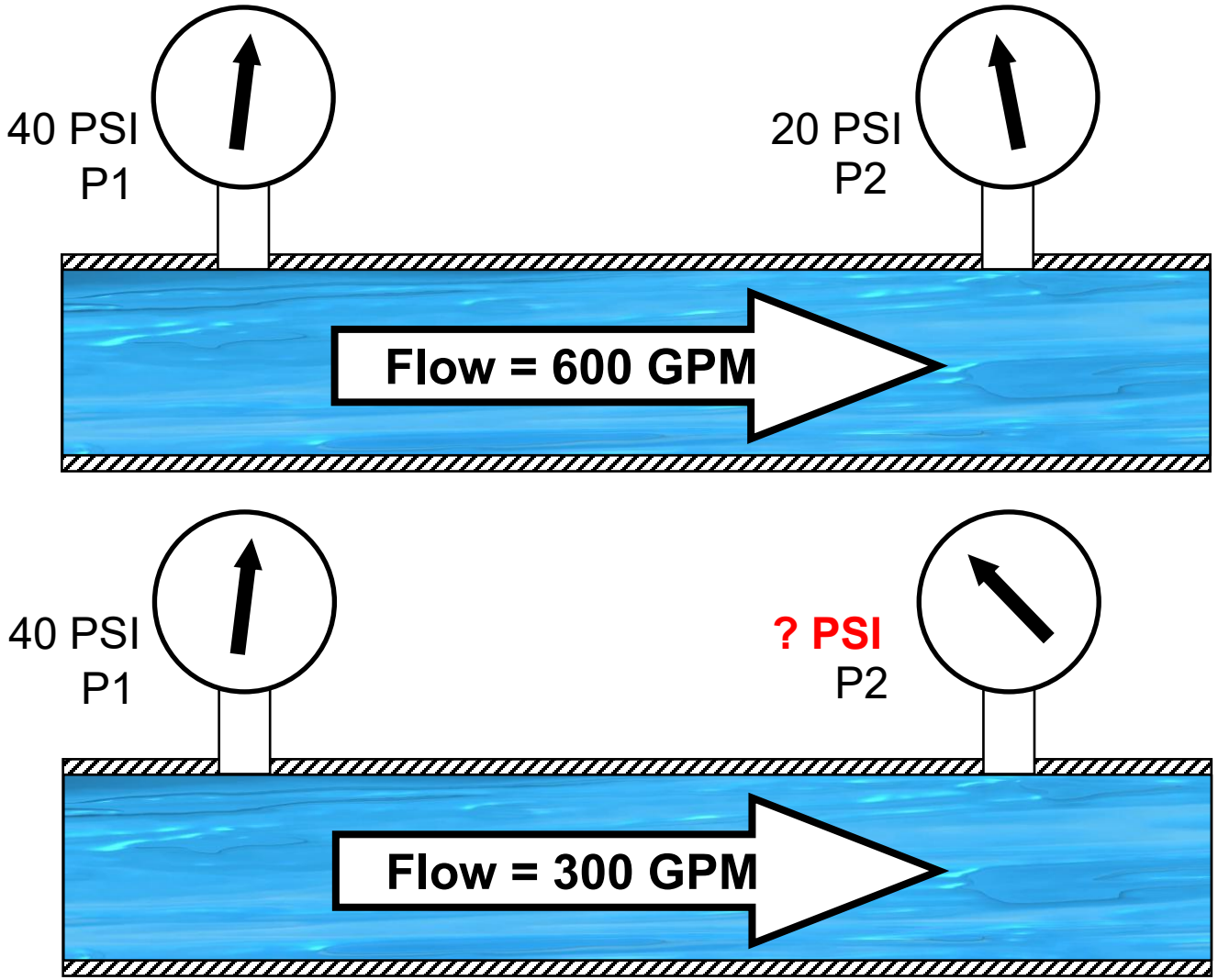

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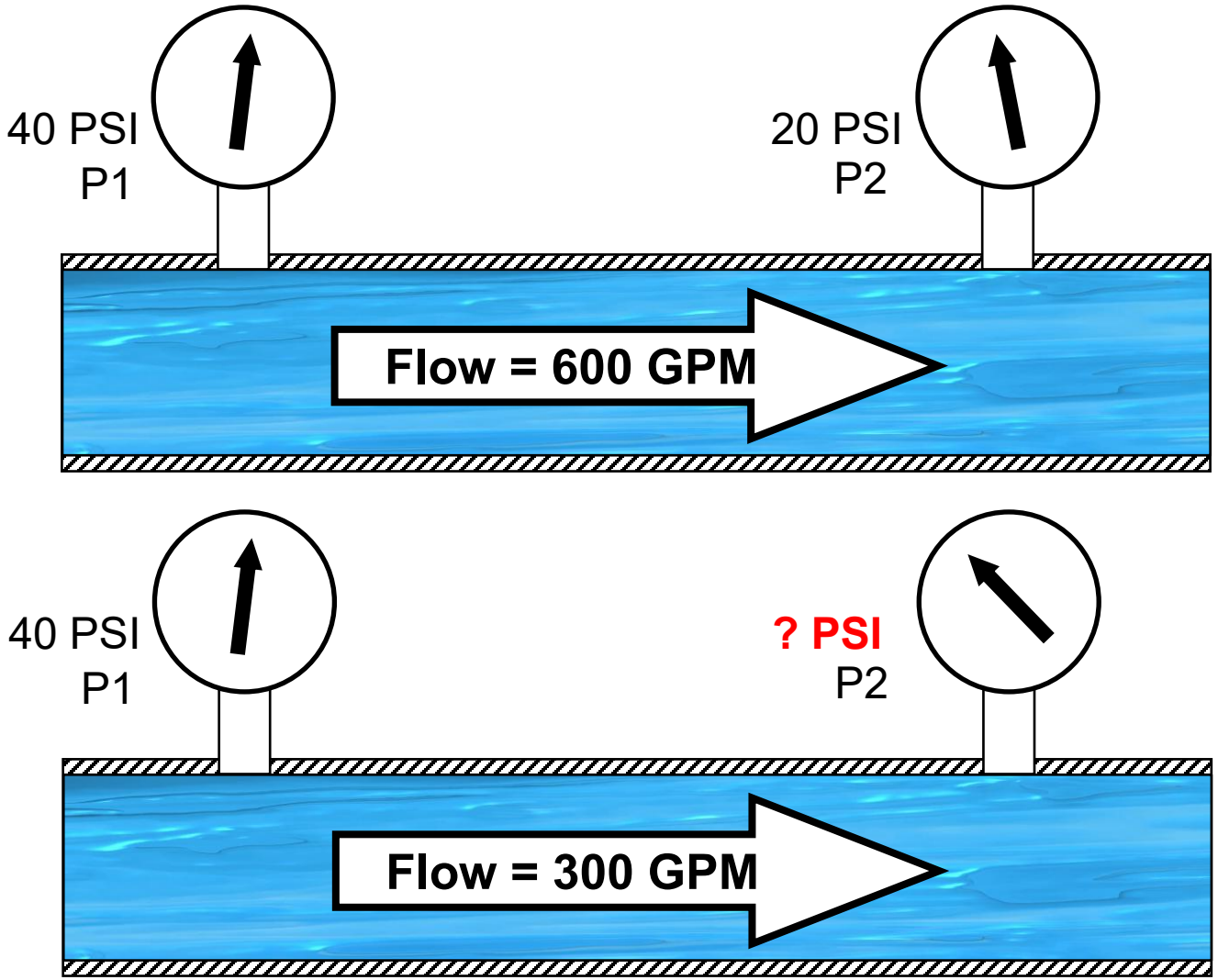

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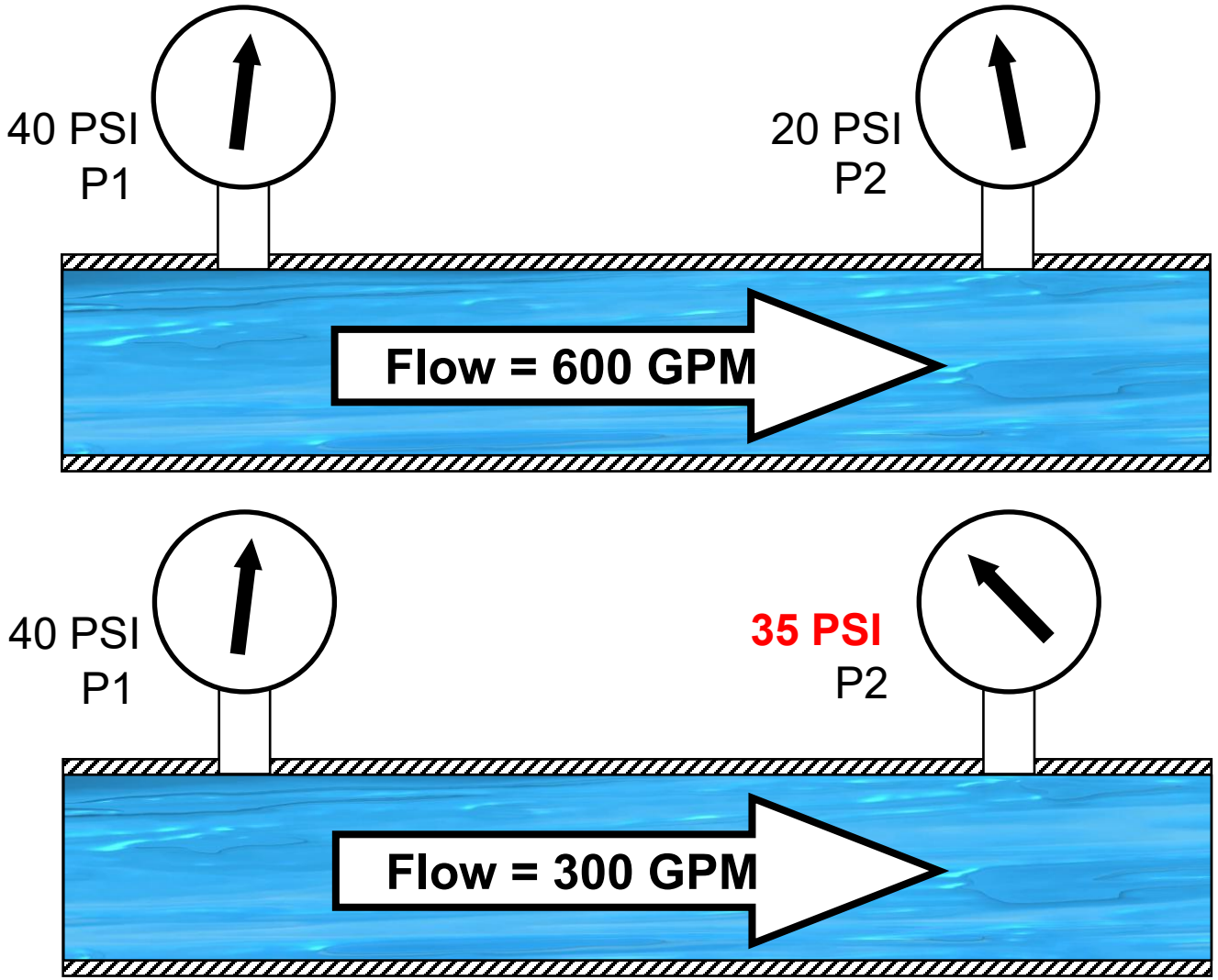
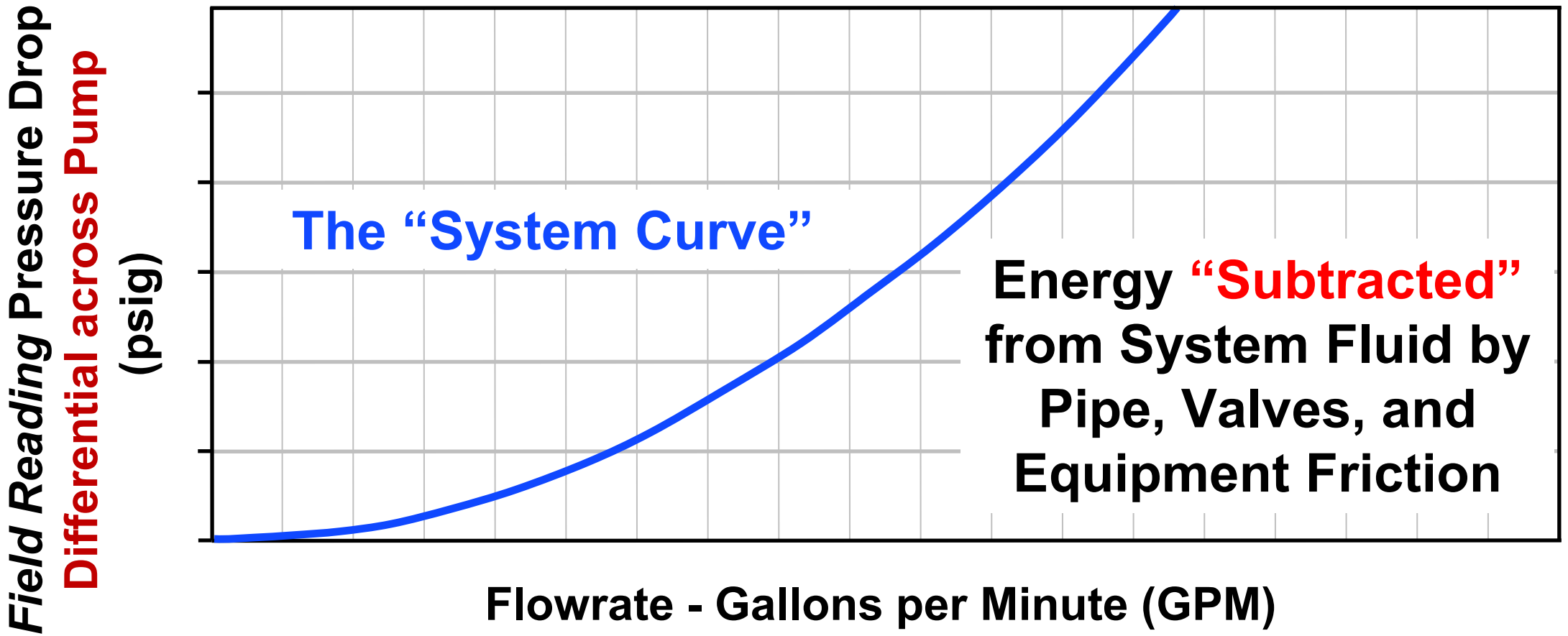
$$h_2 = \left[\frac{Q_2}{Q_1}\right]^2 \times h_1$$

$$5\ \text{PSI} = \left[\frac{300}{600}\right]^2 \times 20$$



What friction loss changes will the pump see at other flowrates?

The anticipated "Variable" Head Loss in a fixed piping circuit



ASHRAE Handbook: What the System Curve looks like

HVAC Systems and Equipment, Chapter 44, Centrifugal Pumps

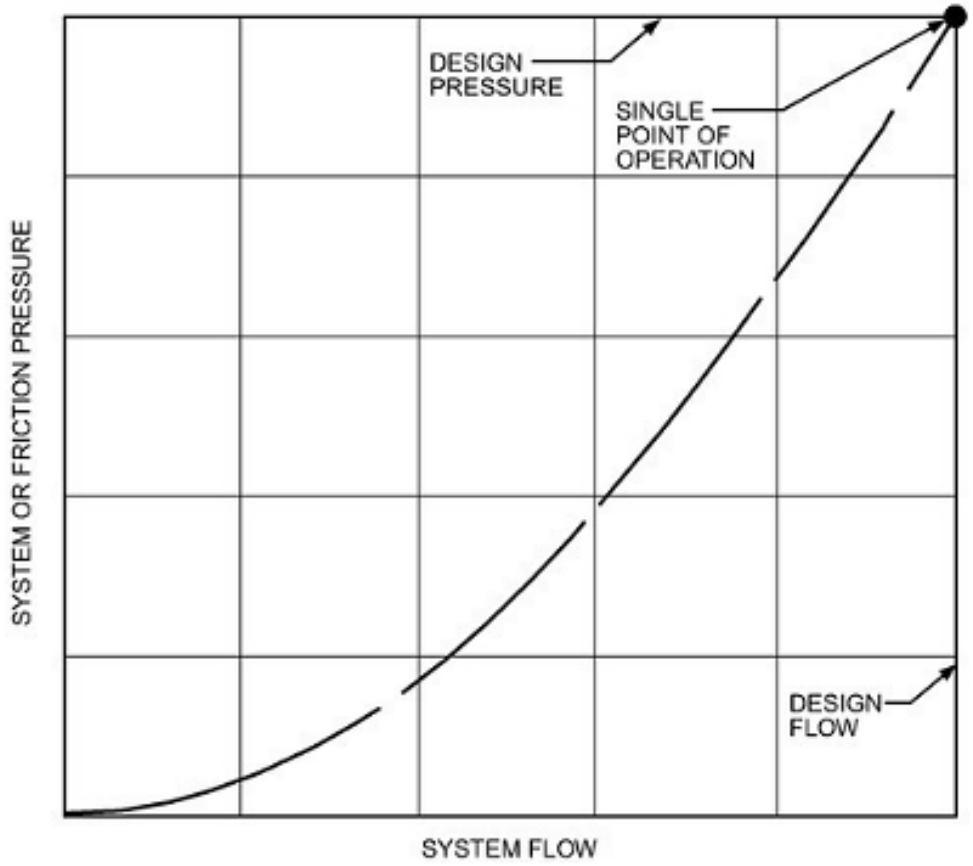
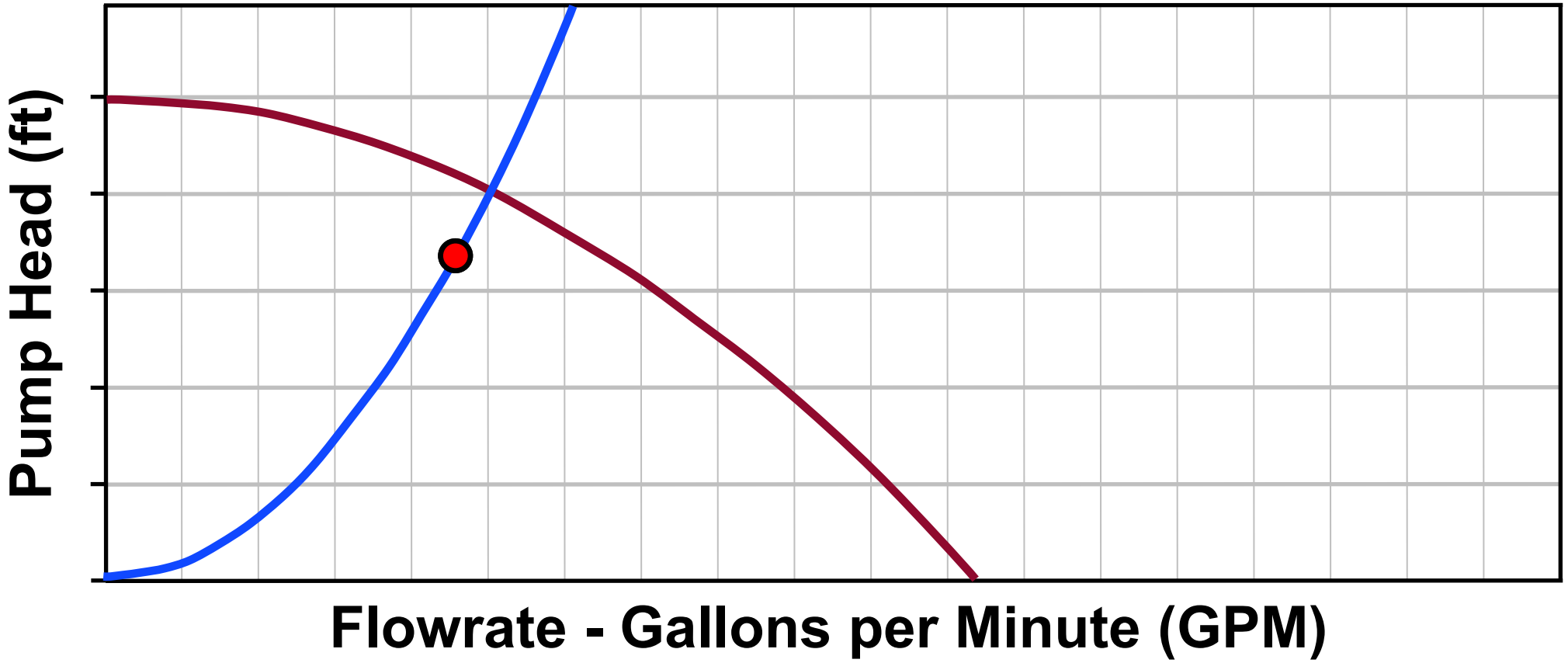


Figure 17. Typical System Curve

***Assumes all friction loss head is Variable in a Closed Loop System**

Where will the Pump Operate on its' Performance Curve?



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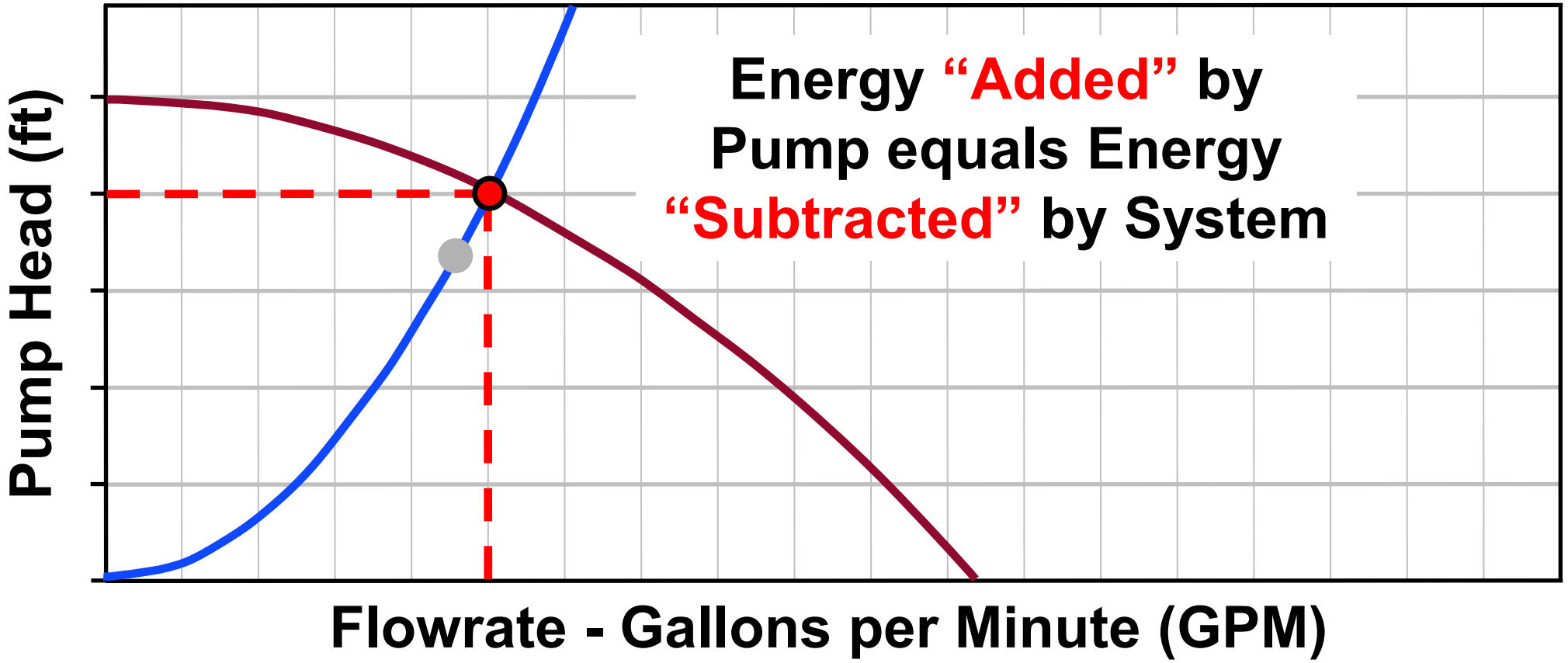
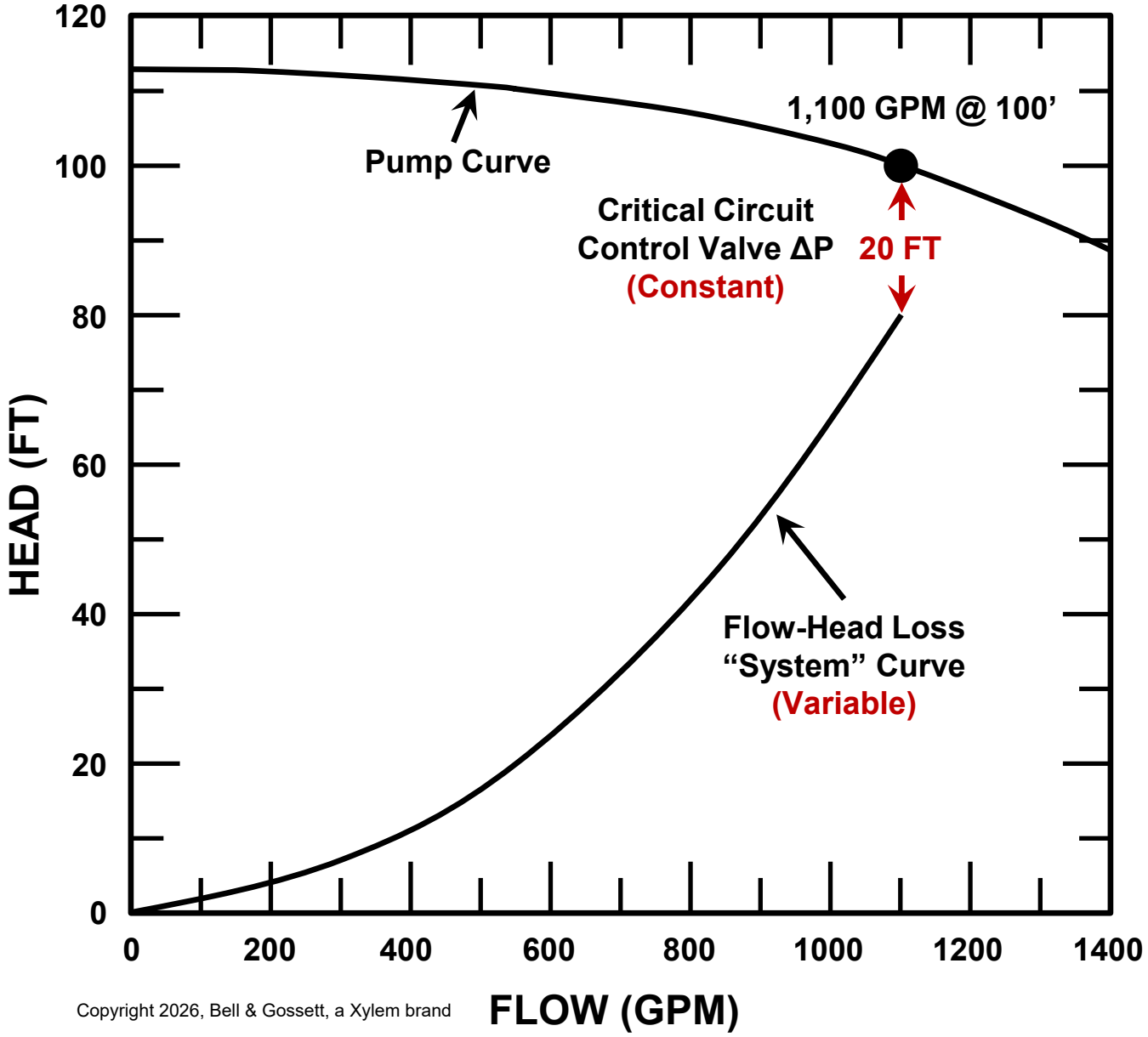


Intersection of **Pump** and **System** curve is always where the pump will operate.

Satisfies the Law of Conservation of Energy

Constant Speed Pumping: Control Valve Differential Head Increase



1,100 GPM @ 100'
Duty Point = 35.9 BHP
Motor Size = 40 HP

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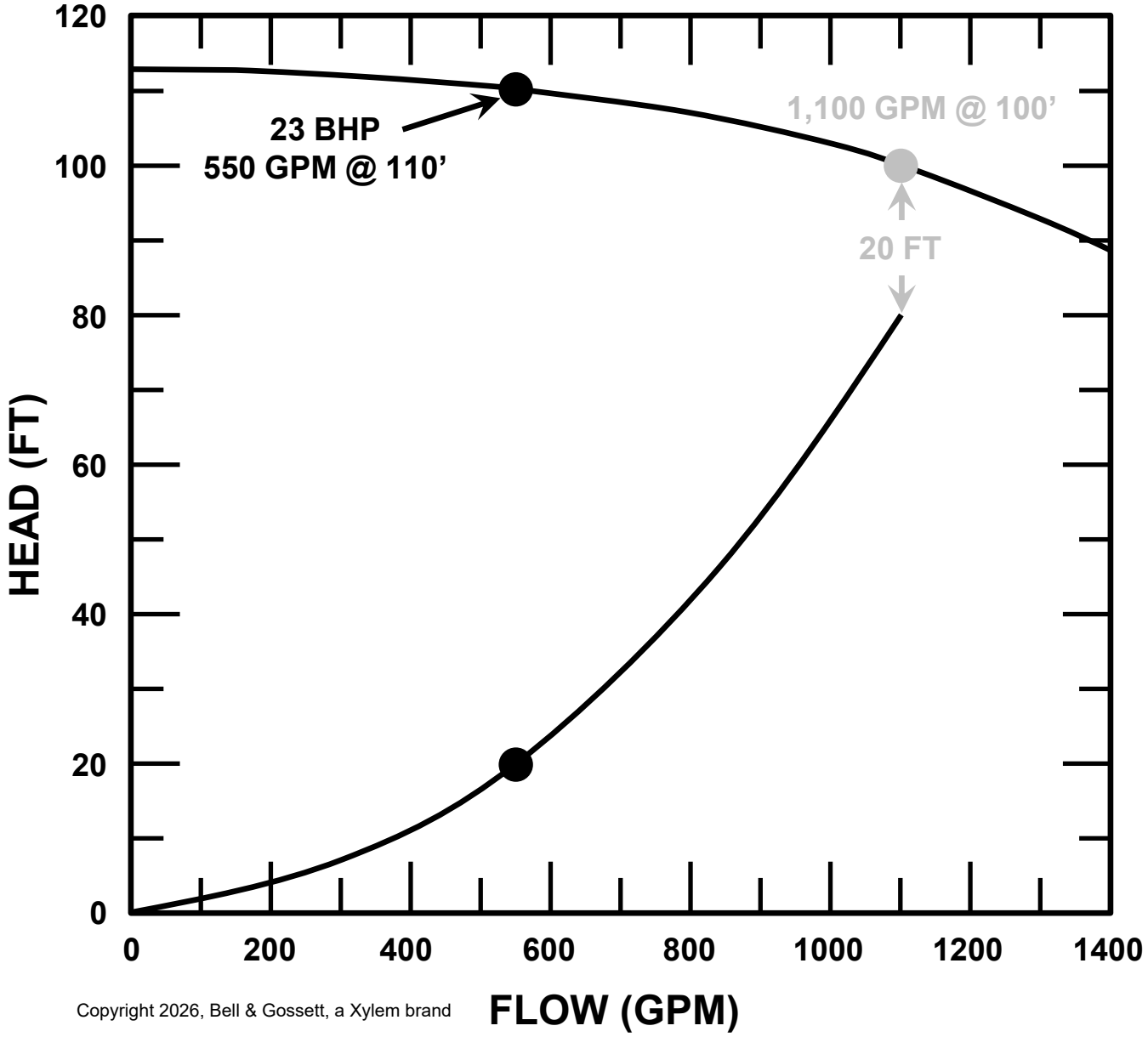

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Reduced Demand:
550 GPM @ 110'
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- **Pump Head increases with flow reduction**
- **Variable head loss decreases with flow reduction**

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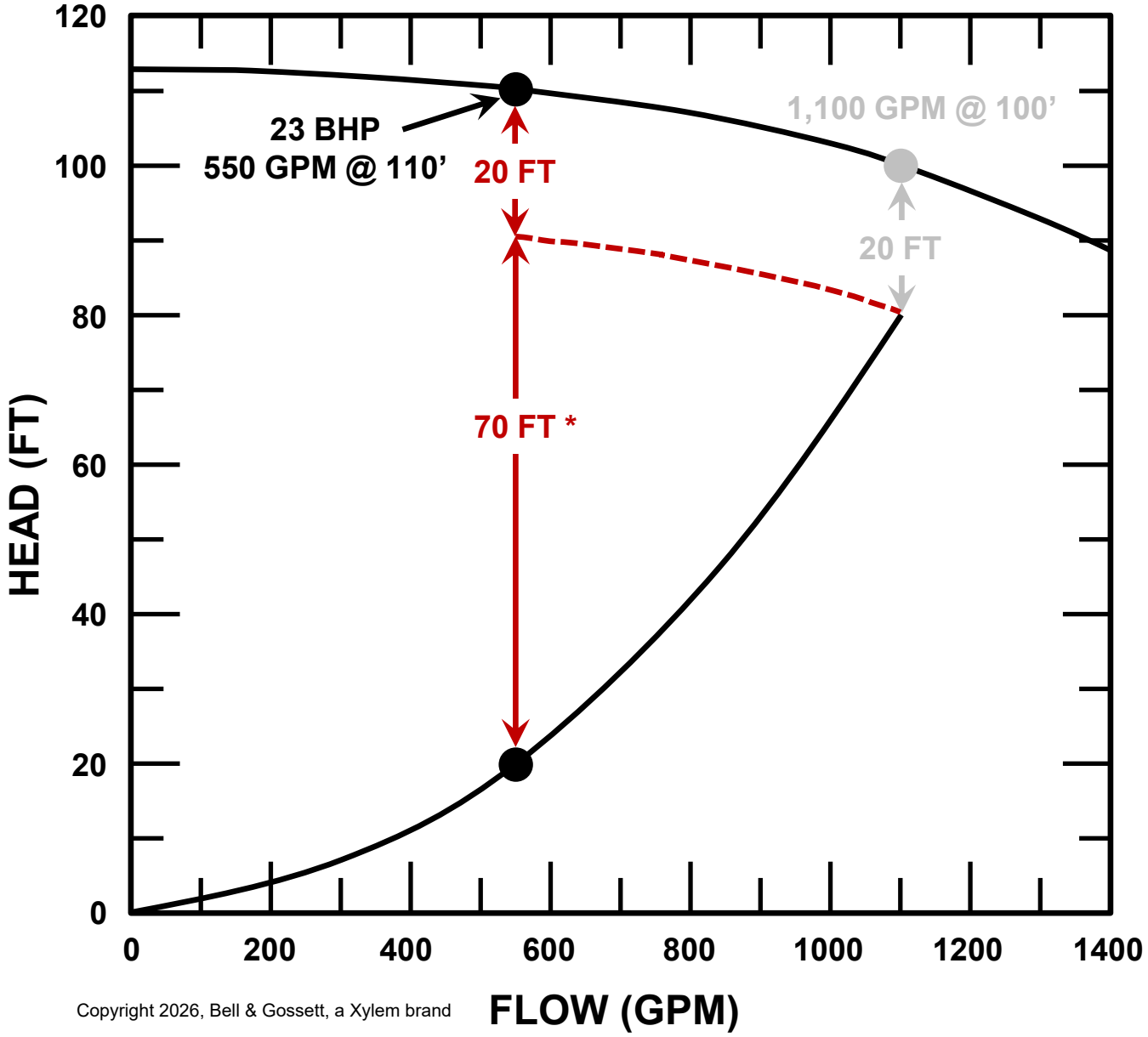

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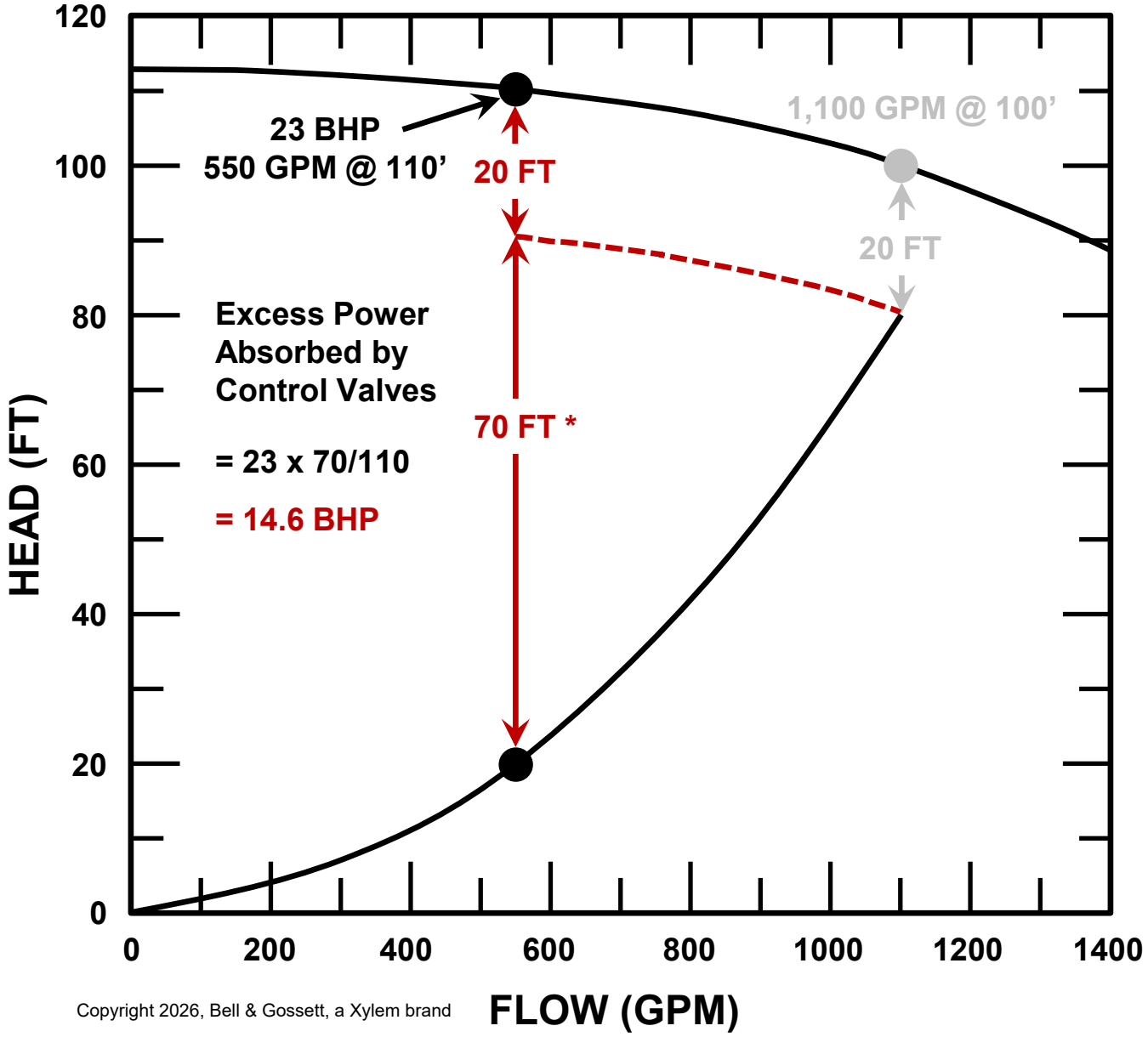

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Variable Speed Pumping:

Pump and Control Strategy Selection

ASHRAE 90.1 – Reduced power with Reduced flow

ASHRAE 90.1 Section 6.5 – Prescriptive Compliance Path

6.5.4.2 Hydronic Variable Flow Systems

Chilled- and – Hot Water *distribution systems* that include **three or more *control* valves** designed to modulate or step open and close as a function of load shall be designed for variable fluid flow and shall be capable of and configured to **reduce pump flow rates to no more than the larger of 25% of the design flow rate or the minimum flow required by the heating/cooling *equipment manufacturer*** for the proper operation of *equipment.*

…. Individual or parallel pumps serving variable-flow heating-water or chilled-water *systems*, where the *nameplate horsepower* of the motor or combined parallel motors is at least **2 HP or greater**, shall have *controls* or devices that will result in pump motor *demand* of **no more than 30% of design wattage at 50% of the design water flow.**

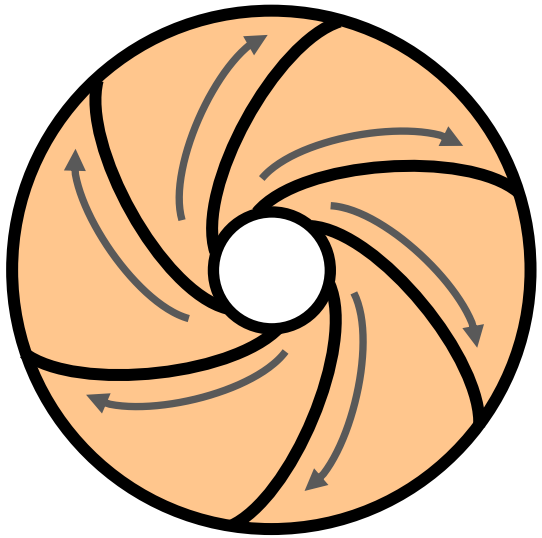
The **Pump Affinity Laws** *applied to Variable Speed Pumps*

- Flow
  - $Q_2 = Q_1 (N_2/N_1)$
- Head
  - $h_2 = h_1 (N_2/N_1)^2$
- Power
  - $bhp_2 = bhp_1 (N_2/N_1)^3$

Q = Flow
N = Speed
h = head
bhp = Horsepower

Subscript 2 indicates “new condition”

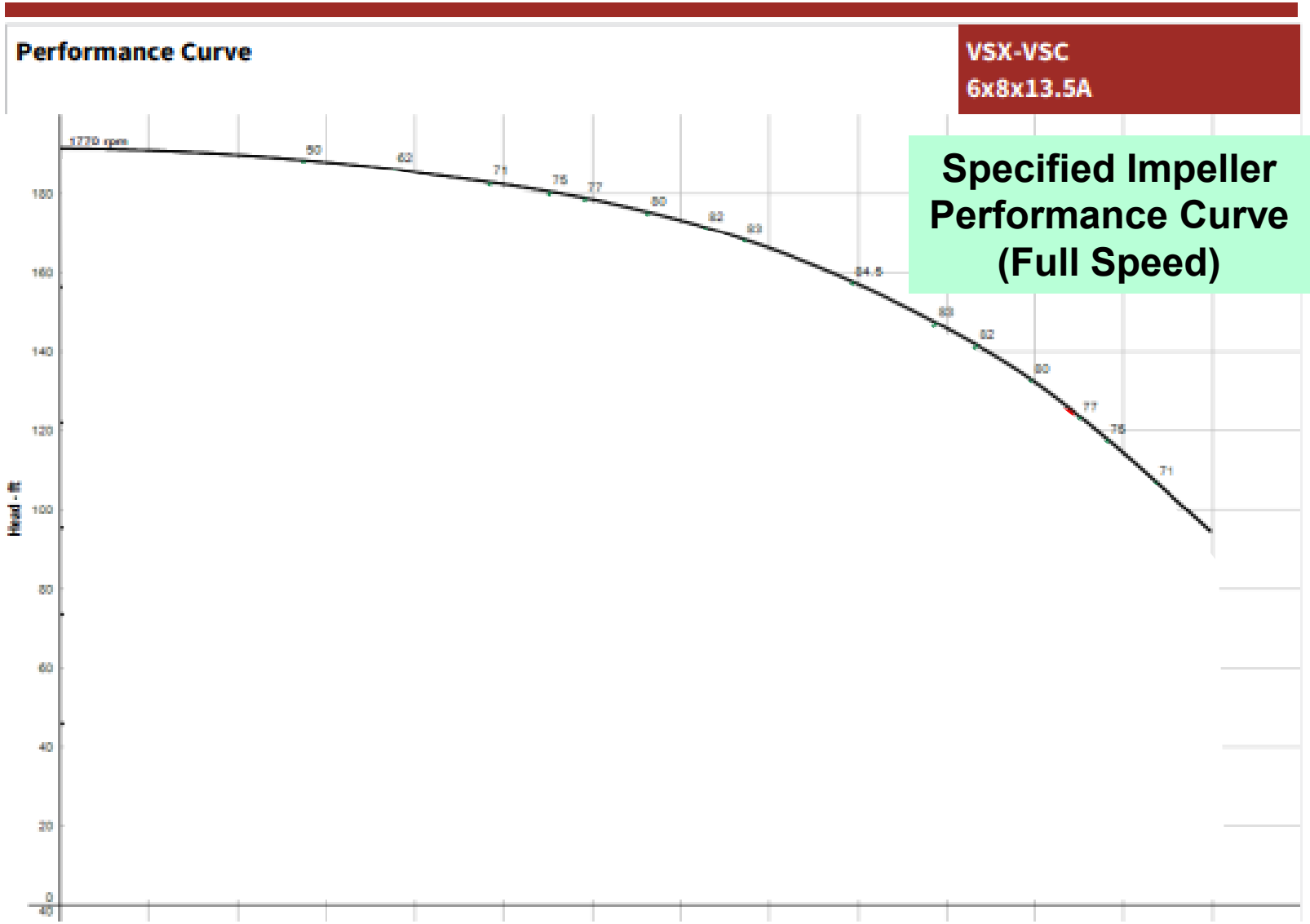
Subscript 1 indicates “old condition”



Speed	Flow/ Volume	Head	Horsepower Required
100%	100%	100%	100%
90%	90%	81%	73%
80%	80%	64%	51%
70%	70%	49%	34%
60%	60%	36%	22%
50%	50%	25%	13%
40%	40%	16%	6%
30%	30%	9%	3%
20%	20%	4%	-
10%	10%	1%	-
0%	0%	0%	-

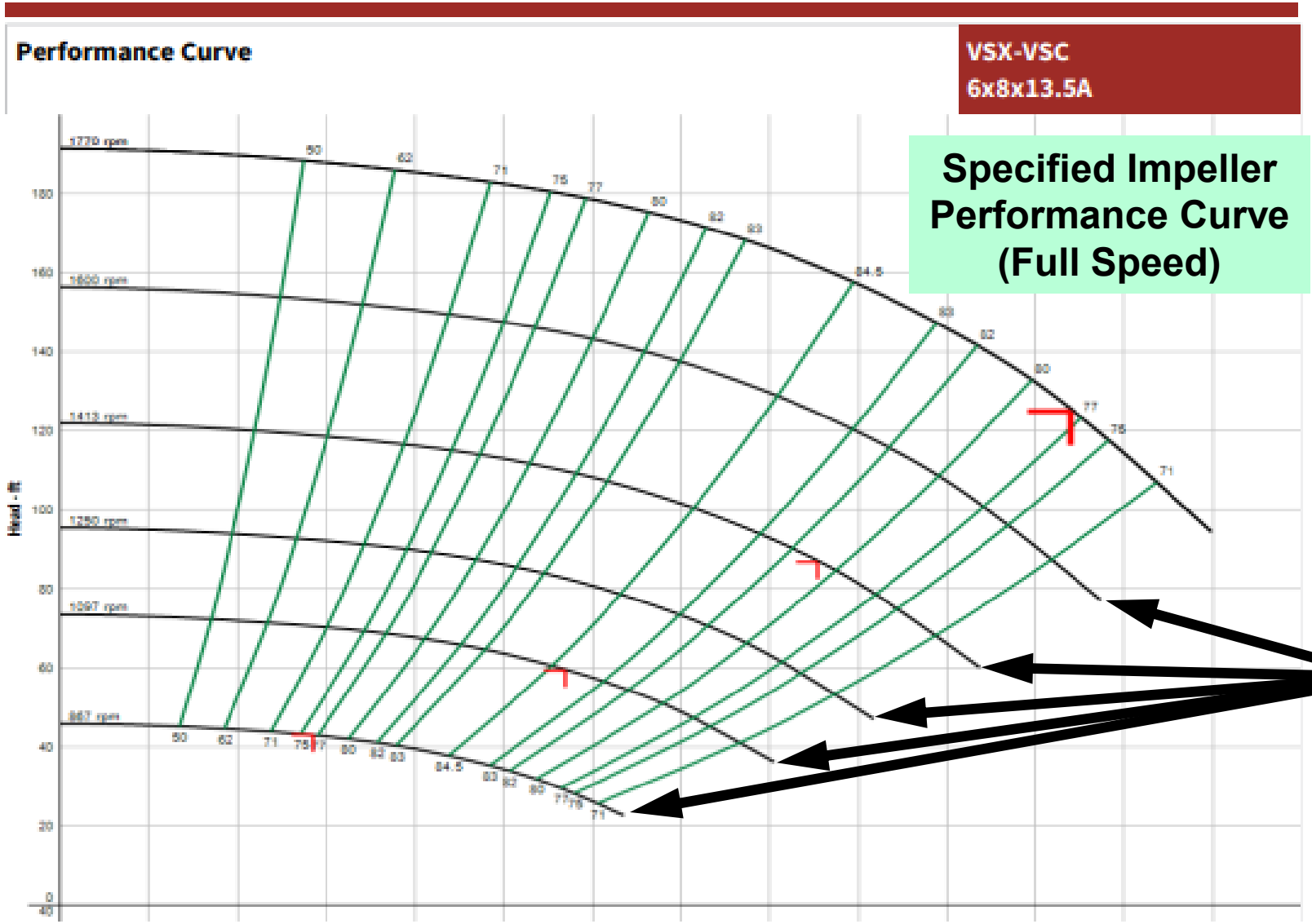
- **Assumes all Head is “Variable”**
- **Efficiency will remain relatively constant**

Applying Variable Speed – Altering the Pump Curve Shape



Specified Impeller Performance Curve (Full Speed)

Applying Variable Speed – Altering the Pump Curve Shape

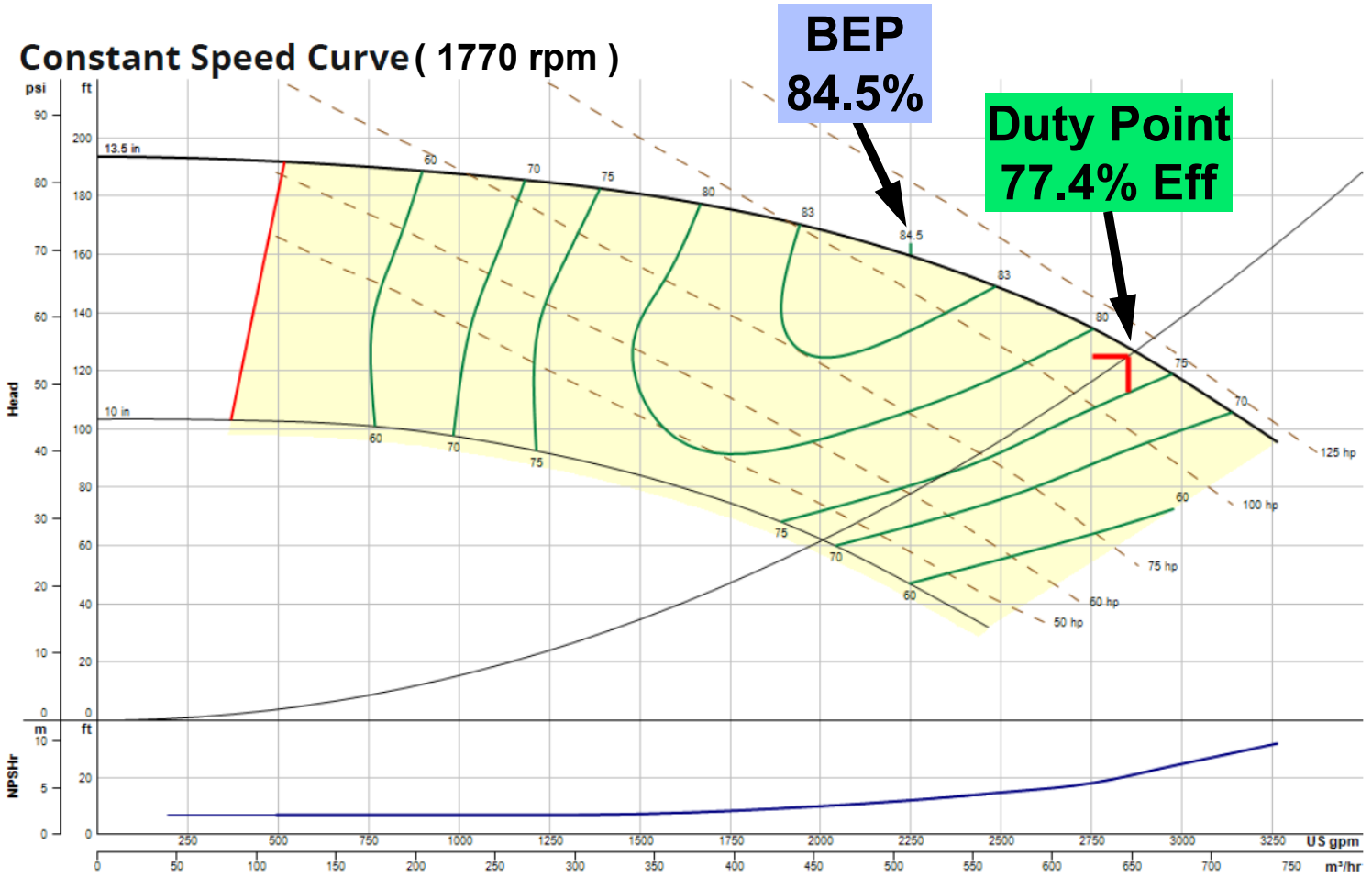


Specified Impeller Performance Curve (Full Speed)

Specified Impeller Performance Curves (Varying Speeds)

Variable Speed Pumping: Select Duty Point **to the Right of BEP**

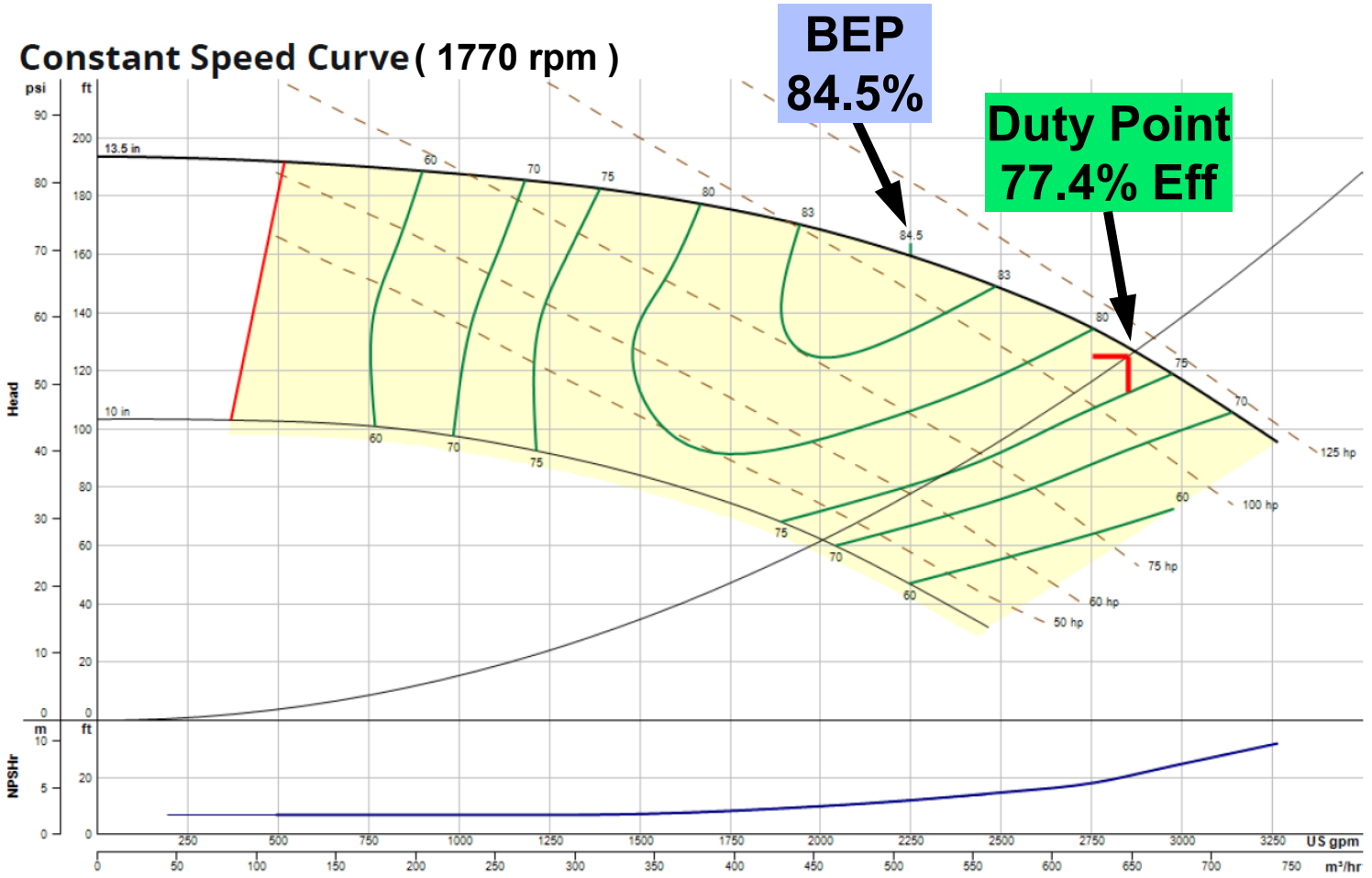
Considering Part Load Efficiency Value (PLEV)



Duty Point: 2,850 GPM @ 125’
116 BHP (Motor Size: 125 HP)

Variable Speed Pumping: Select Duty Point to the Right of BEP

Considering Part Load Efficiency Value (PLEV)



Double Suction Split Case Pump

Series: VSX-VSC

Model: 6x8x13.5A

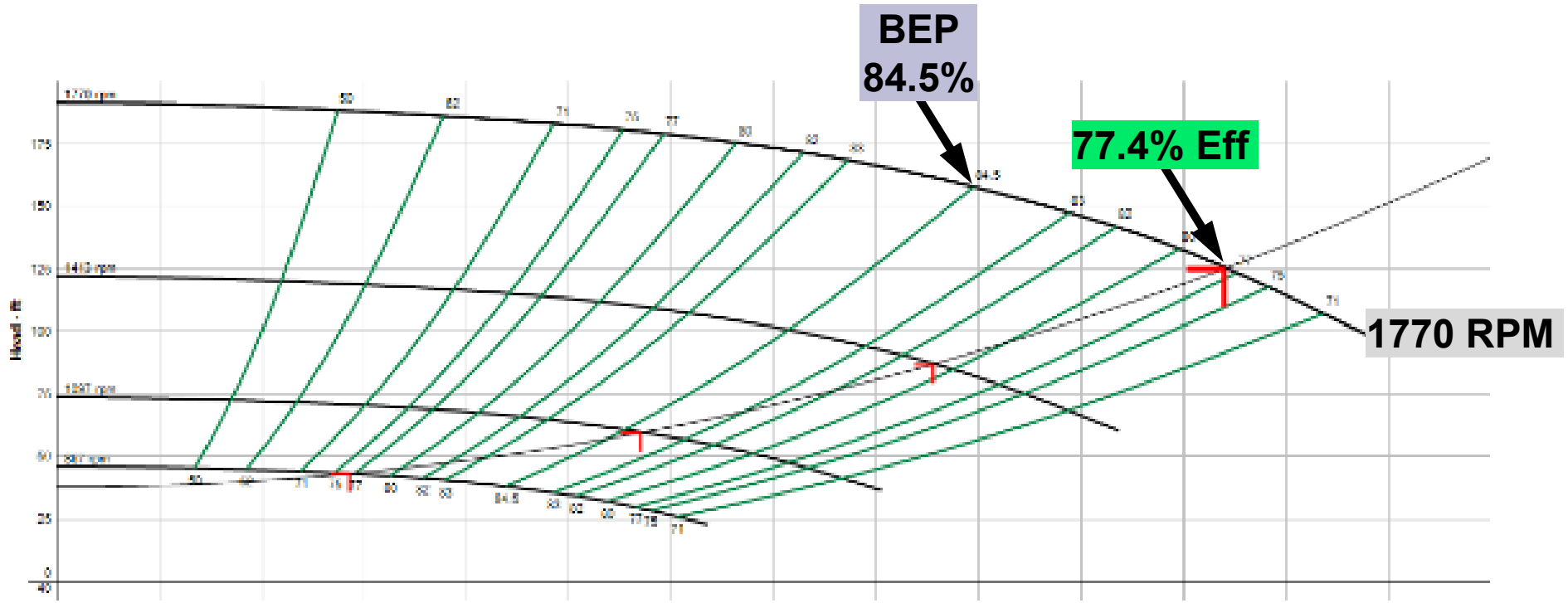
Features & Design
Space saving footprint
Multiple suction and discharge flange orientations
Maintenance-free bearings
Alignment-friendly coupling

Pump Selection Summary	
Duty Point Flow	2850 US gpm
Duty Point Head	125 ft
Control Head	37.5 ft
Duty Point Pump Efficiency	77.4 %
Part Load Efficiency Value (PLEV)	81.6 %
Impeller Diameter	13.5 in
Motor Power	125 hp
Duty Point Power	116 bhp
Motor Speed	1800 rpm
RPM @ Duty Point	1770 rpm
NPSHr	20.9 ft
Minimum Shutoff Head	191 ft
Minimum Flow at RPM	514 US gpm
Flow @ BEP	2236 US gpm
Fluid Temperature	45 °F
Fluid Type	Water
Weight *(approx. - consult rep for exact)*	3137 lbs
Pump Floor Space Calculation	14.11 ft²

Duty Point: 2,850 GPM @ 125’
116 BHP (Motor Size: 125 HP)

Why Right of BEP? Meeting ASHRAE 90.1

Increasing **Efficiency with** ***Decreasing*** **Flow Demand**



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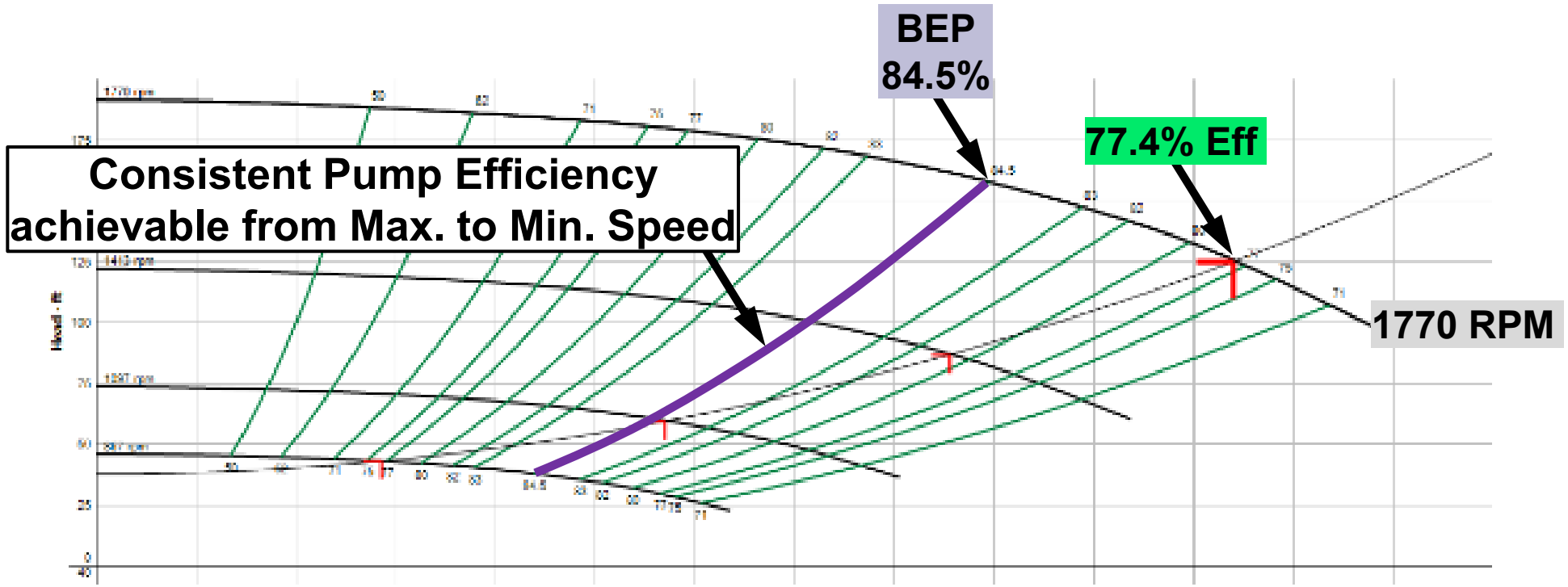

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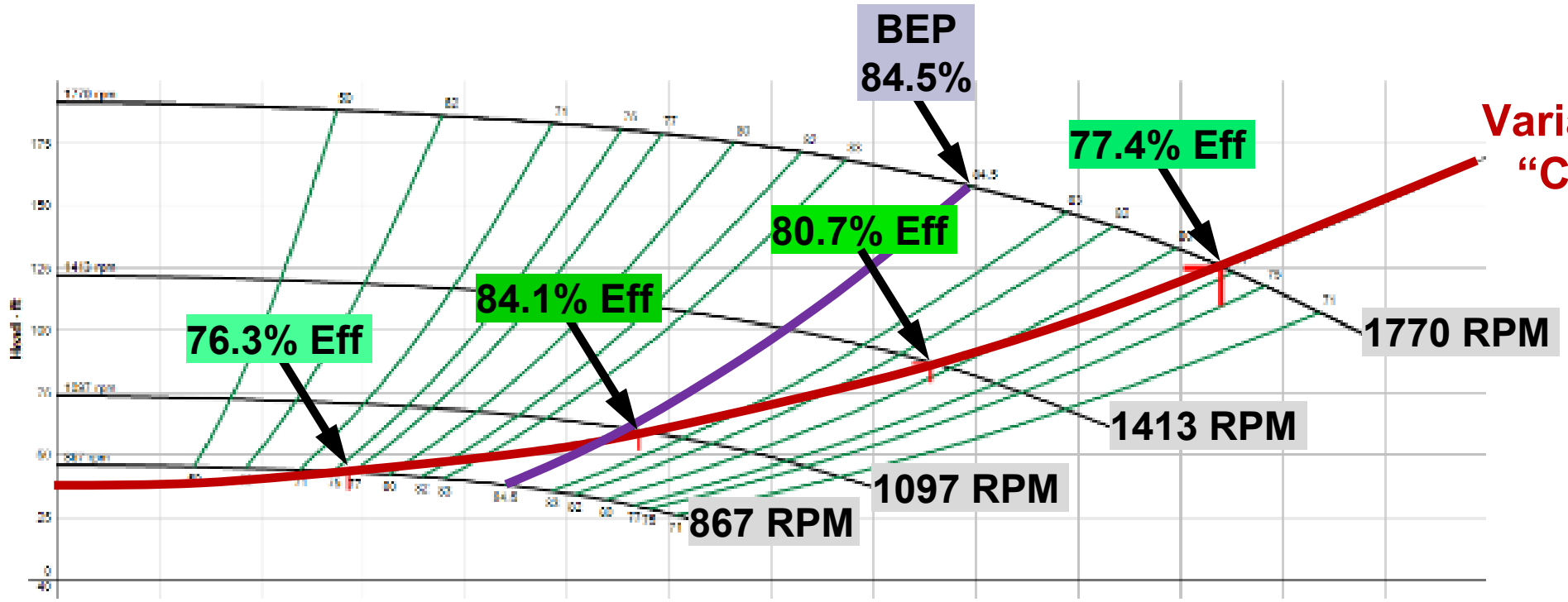
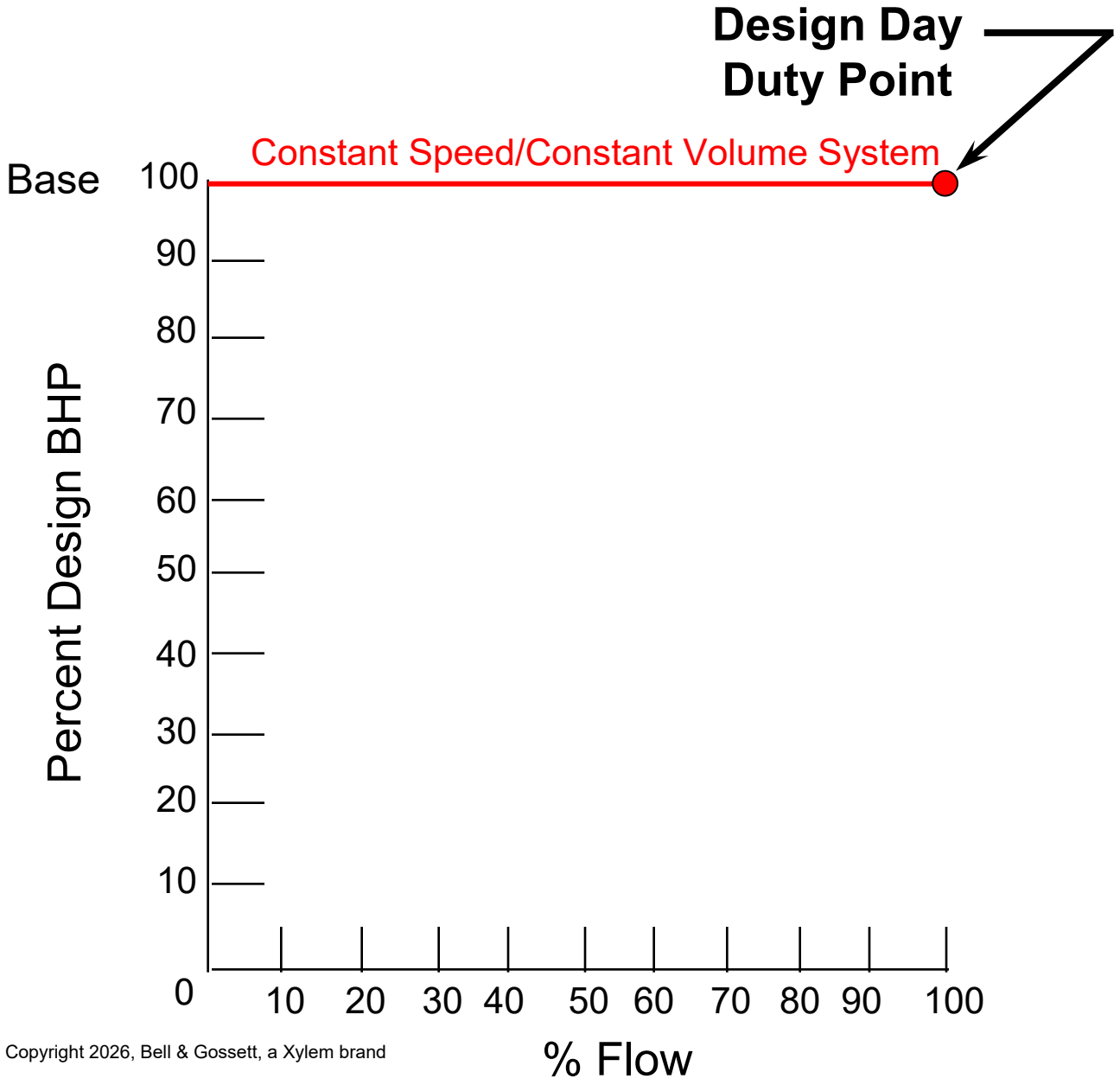
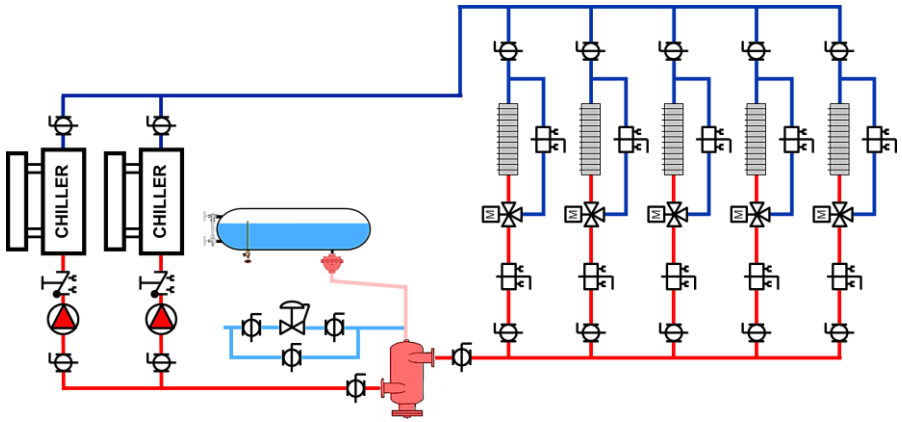


Applying Variable Speed – What's the Variable Head Loss Ratio?





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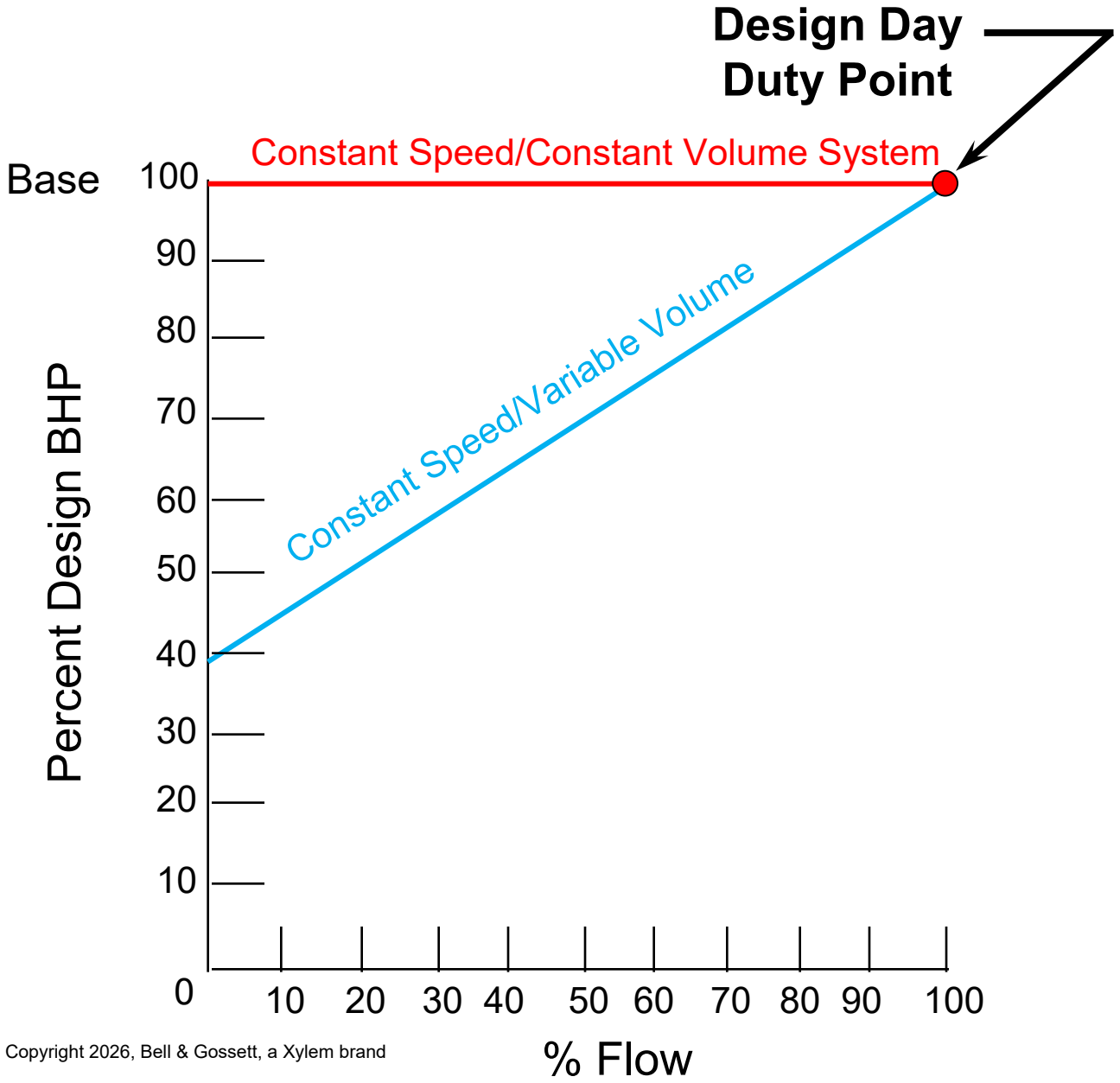

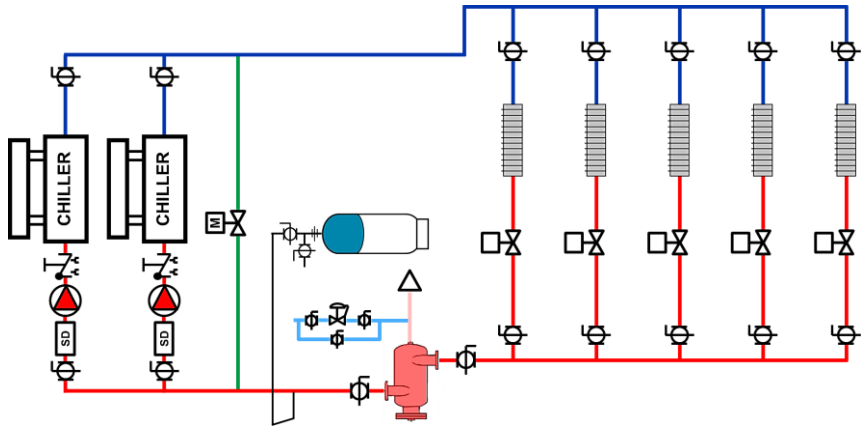

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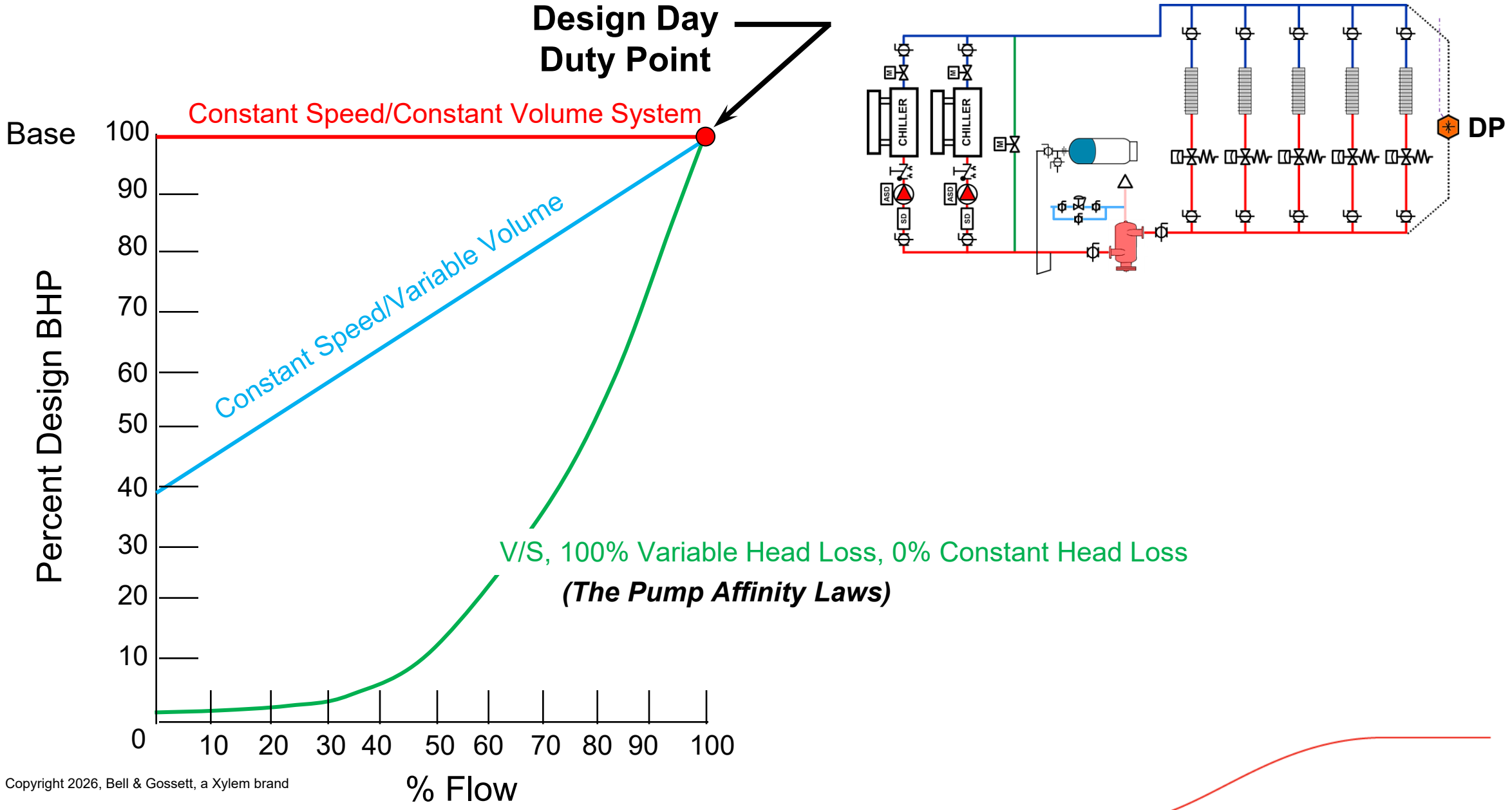

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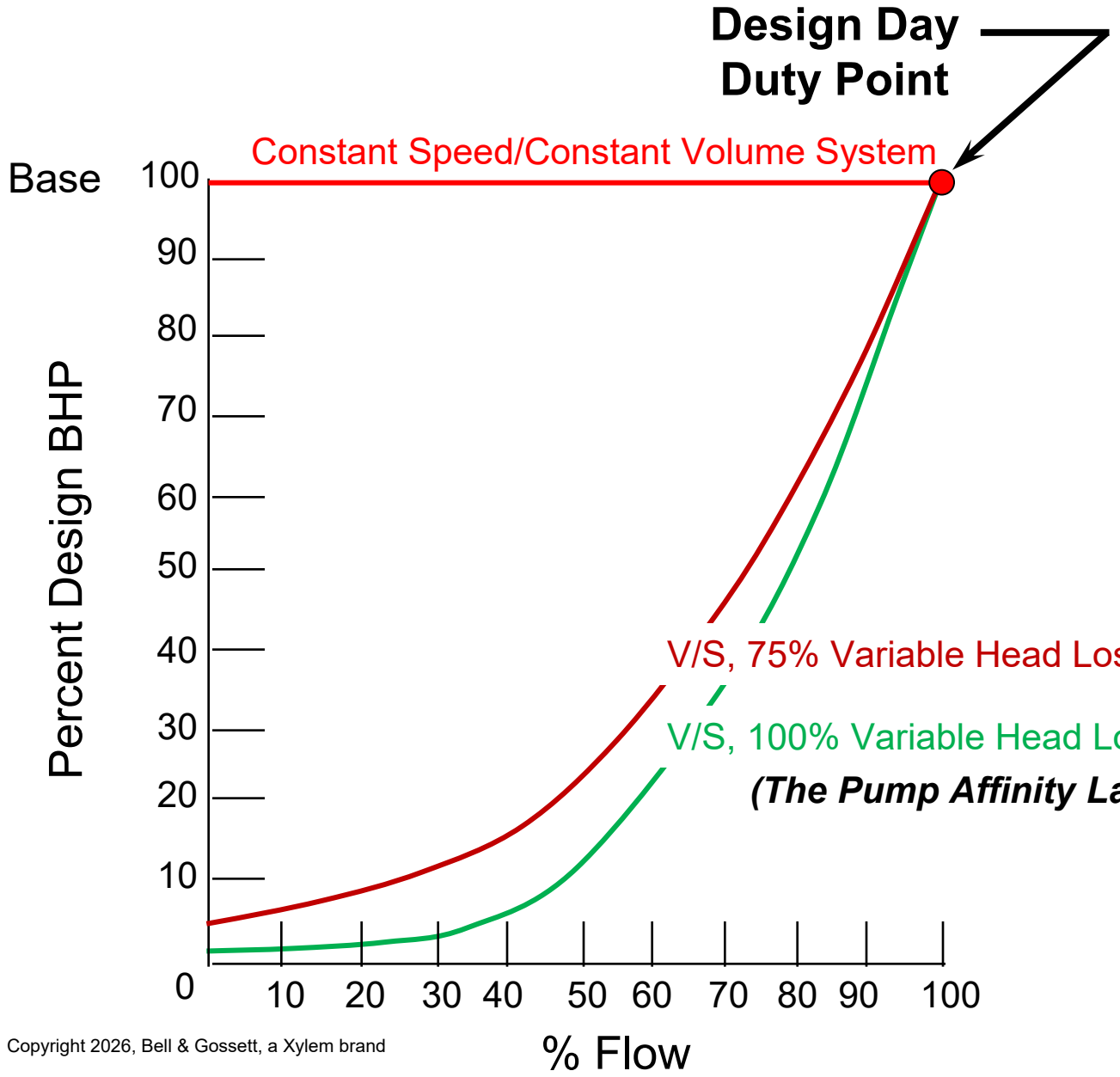

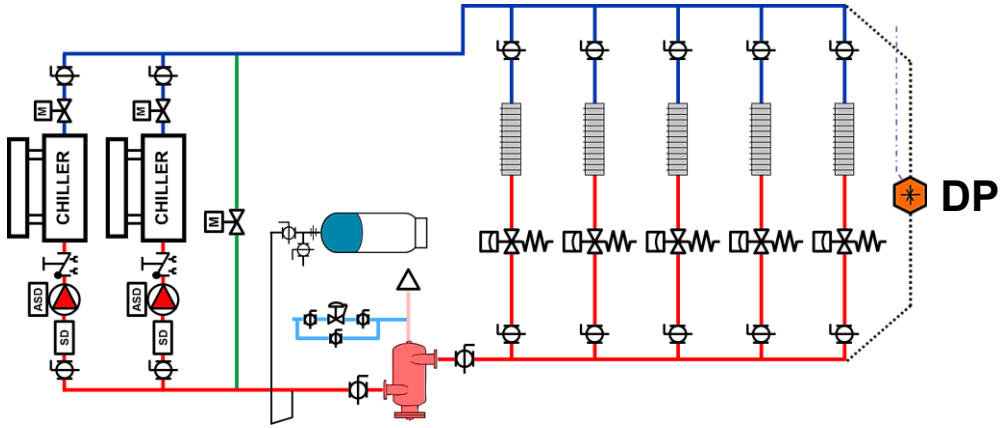

V/S, 75% Variable Head Loss, 25% Constant Head Loss

V/S, 100% Variable Head Loss, 0% Constant Head Loss

(The Pump Affinity Laws)

ASHRAE Handbook: System Curve Starting Point w/Static Head

HVAC Systems and Equipment, Chapter 44, Centrifugal Pumps

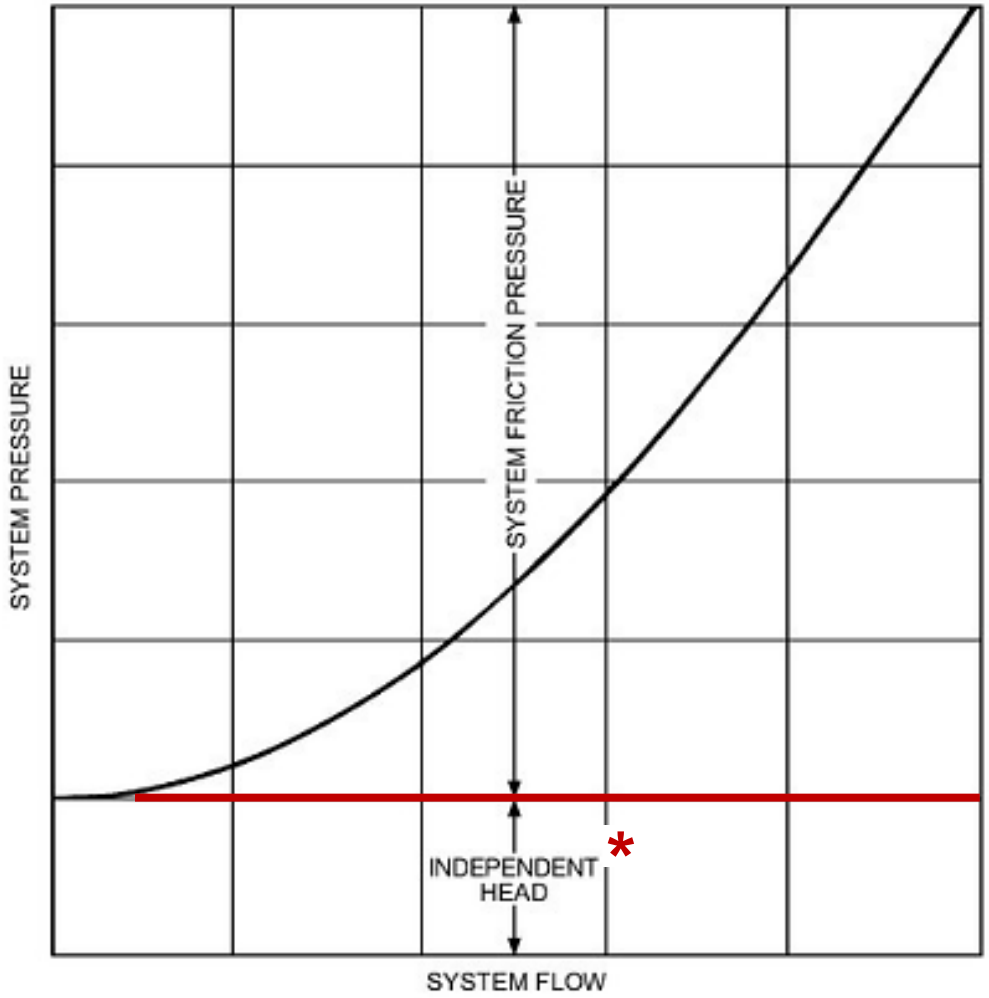

Figure 18. Typical System Curve with Independent Head

ASHRAE Handbook: System Curve Starting Point w/Static Head

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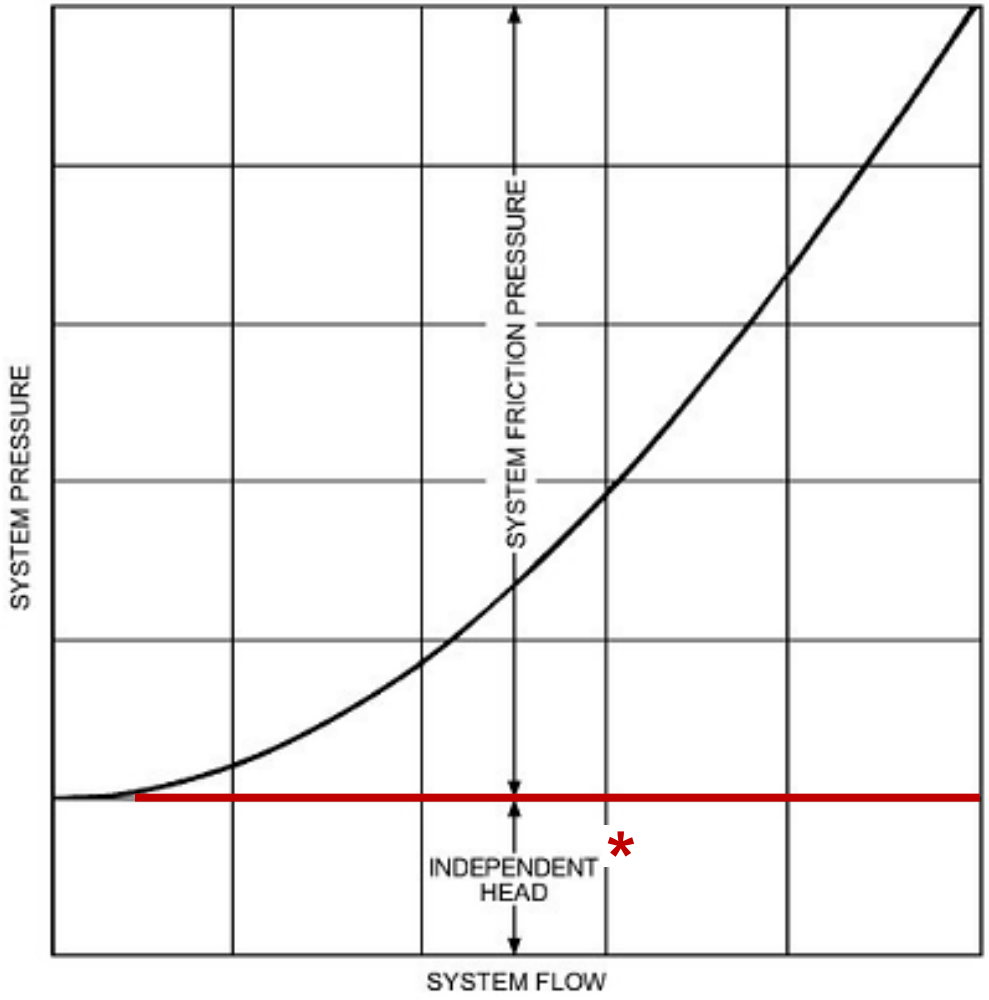

Figure 18. Typical System Curve with Independent Head

For Open Loop Systems:

Where there is a static difference in height between the liquid source and it's final delivery point

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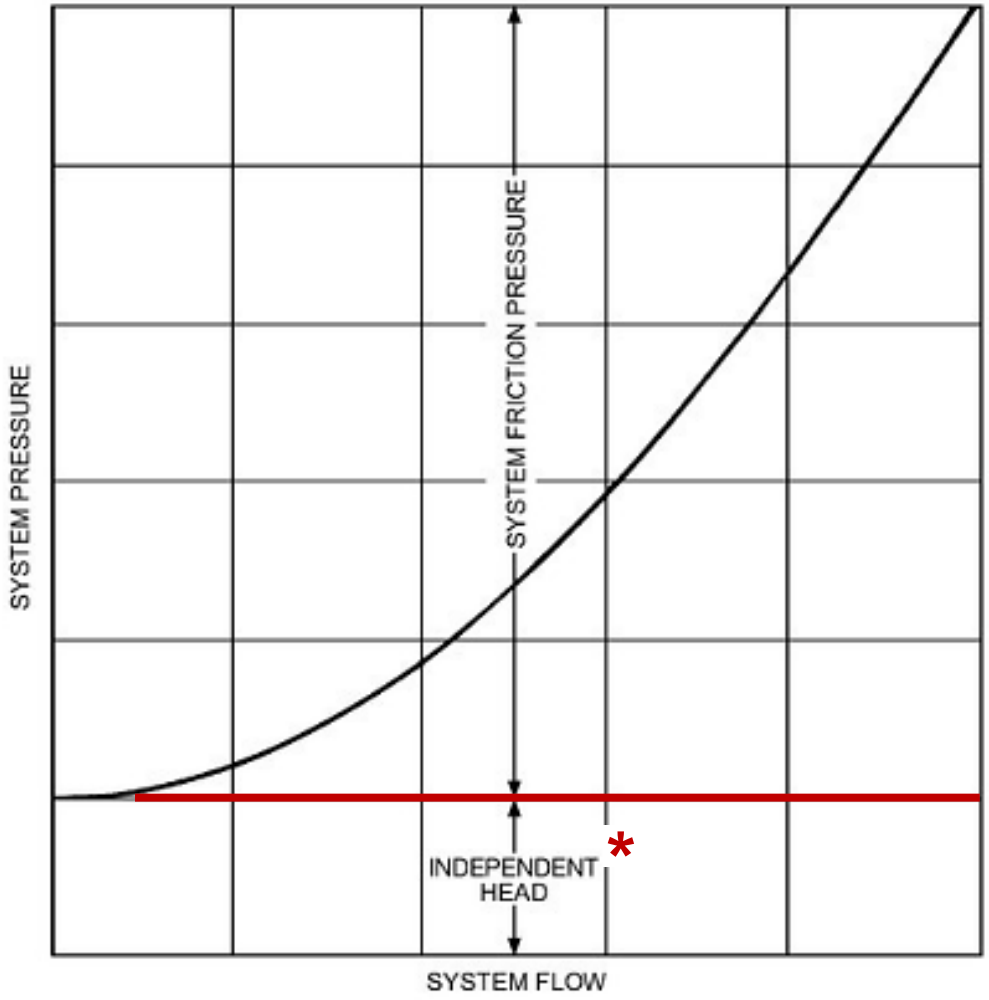

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For Open Loop Systems:

Where there is a static difference in height between the liquid source and it's final delivery point

- OR -

For Closed Loop Systems:

The *Critical Circuit* "Branch" Head Loss is now treated as Static *Control* Head for all possible system flow rates.

ASHRAE Handbook: System Curve in Variable Flow Systems

HVAC Systems and Equipment, Chapter 44, Centrifugal Pumps

Defining your system: Low or High Diversity?

- Amount of system distribution piping
- Control valve count
- How are the terminal units loaded or unloaded
  - Frequency and magnitude of changes
  - Valve “open” or “closed” locations

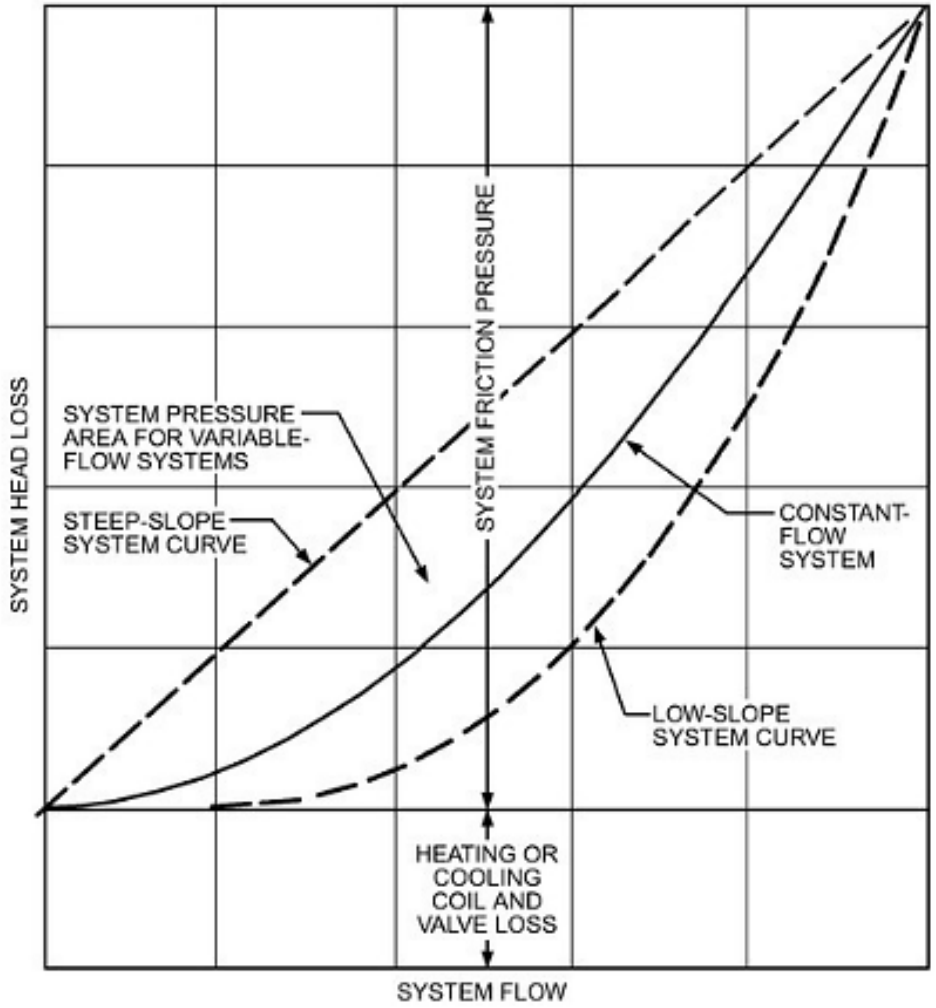

Figure 22. System Curve, Constant and Variable Head Loss

ASHRAE Handbook: System Curve in Variable Flow Systems

HVAC Systems and Equipment, Chapter 44, Centrifugal Pumps

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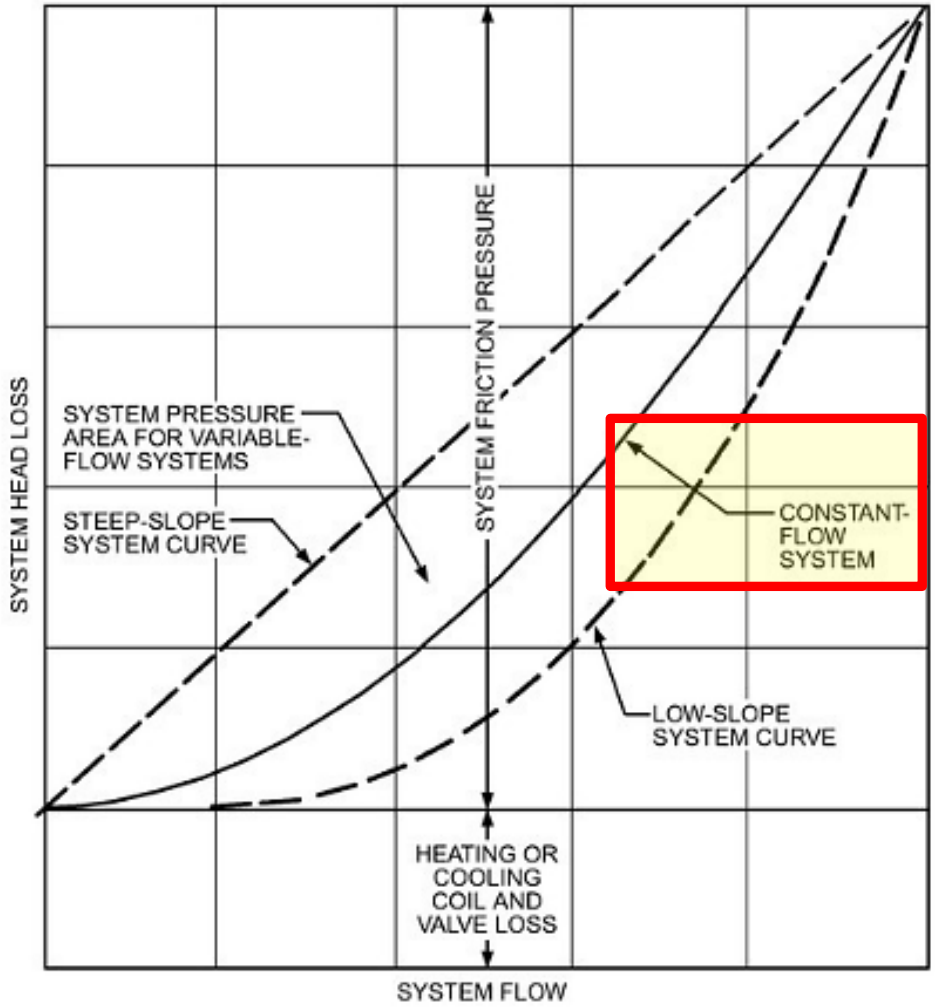

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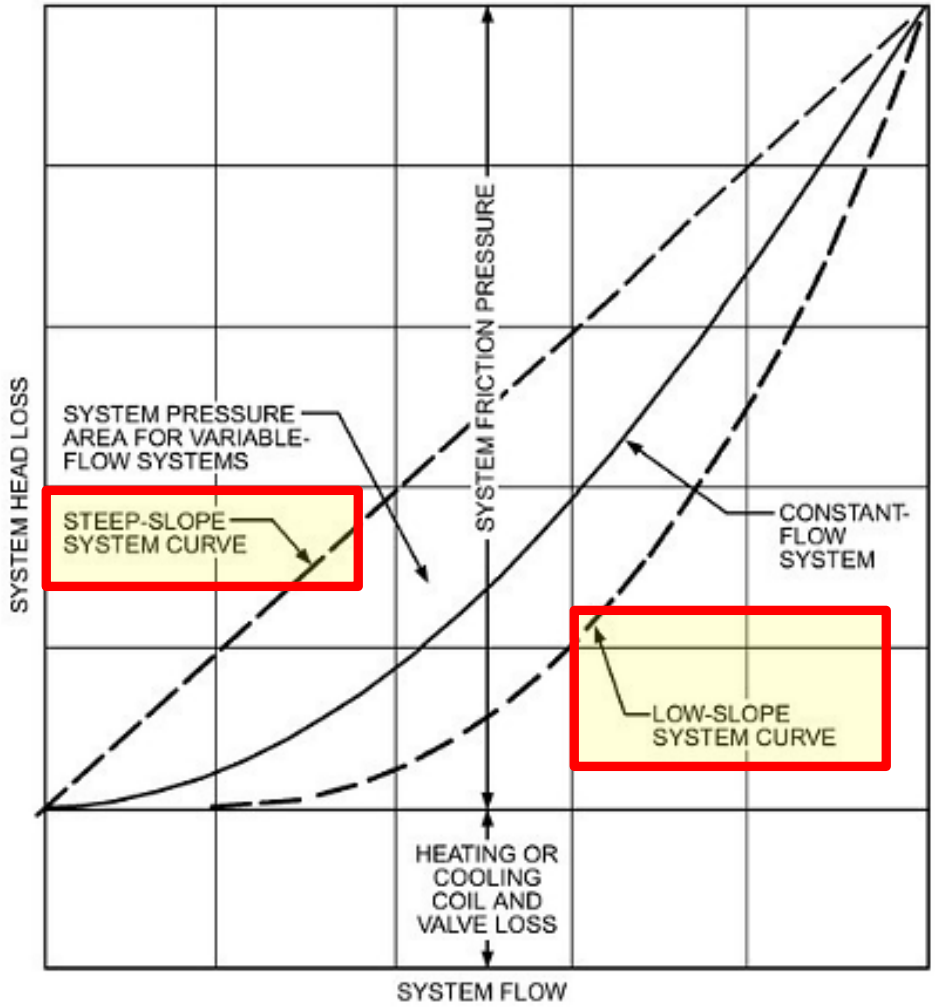

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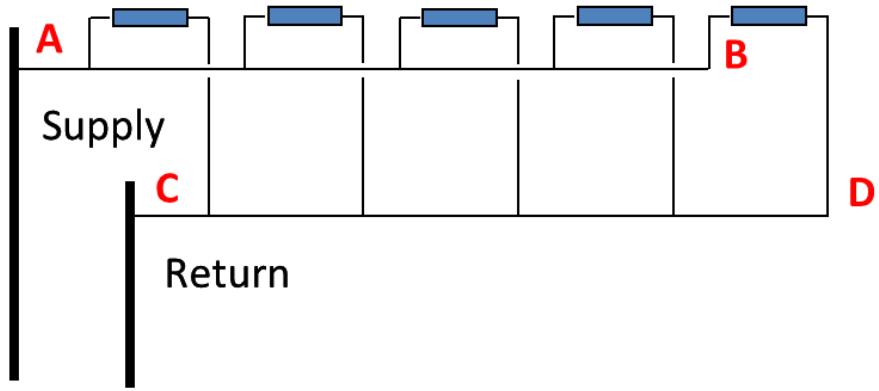


- Application of incorrect variable speed control strategy can lead to many **Under** or **Over** pumping situations during load changes

- The Steep & Low slope system curves represent the extremes for required pump head at a given system flow in Variable Volume (Flow) systems.

- The shape and distance between the curves is influenced by the piping ***Branch to Riser Pressure Drop Ratio***

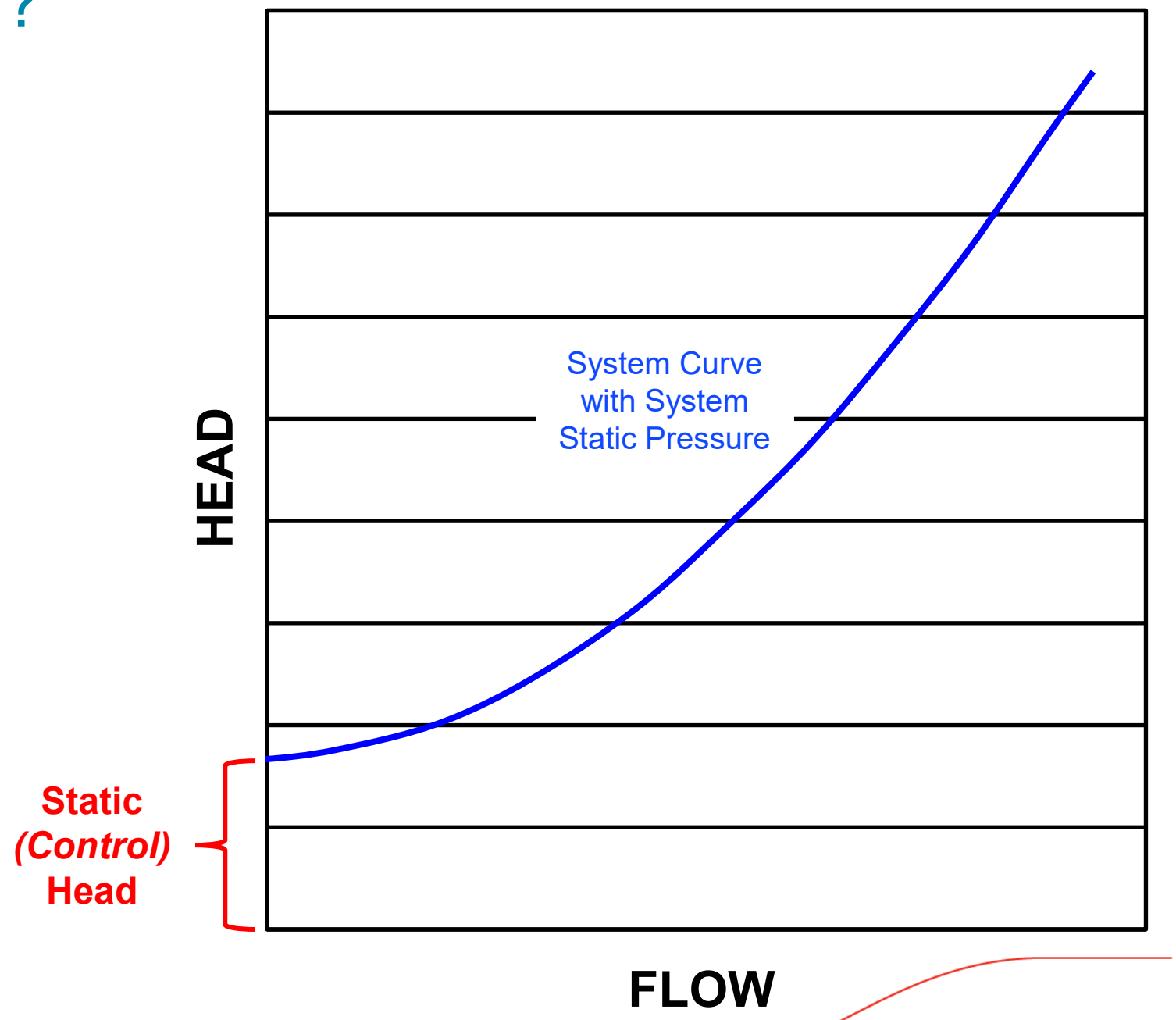
$$BRPDR = \frac{BD}{AB + CD}$$

BD – The “Branch”

AB – Supply Riser

CD – Return Riser

What is the “Control Area”?



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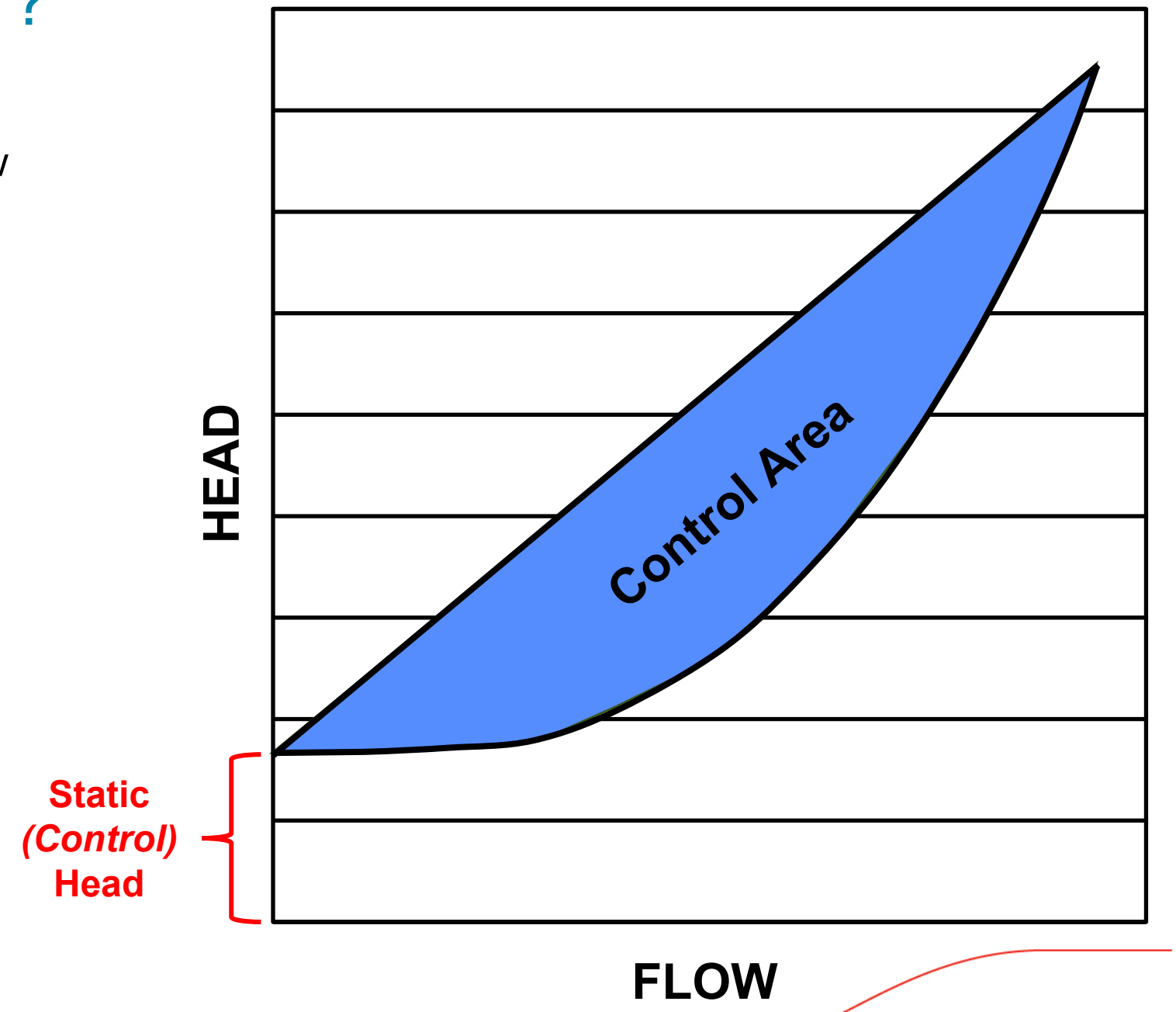
- The region between the Steep & Low slopes is called the **“Control Area”**



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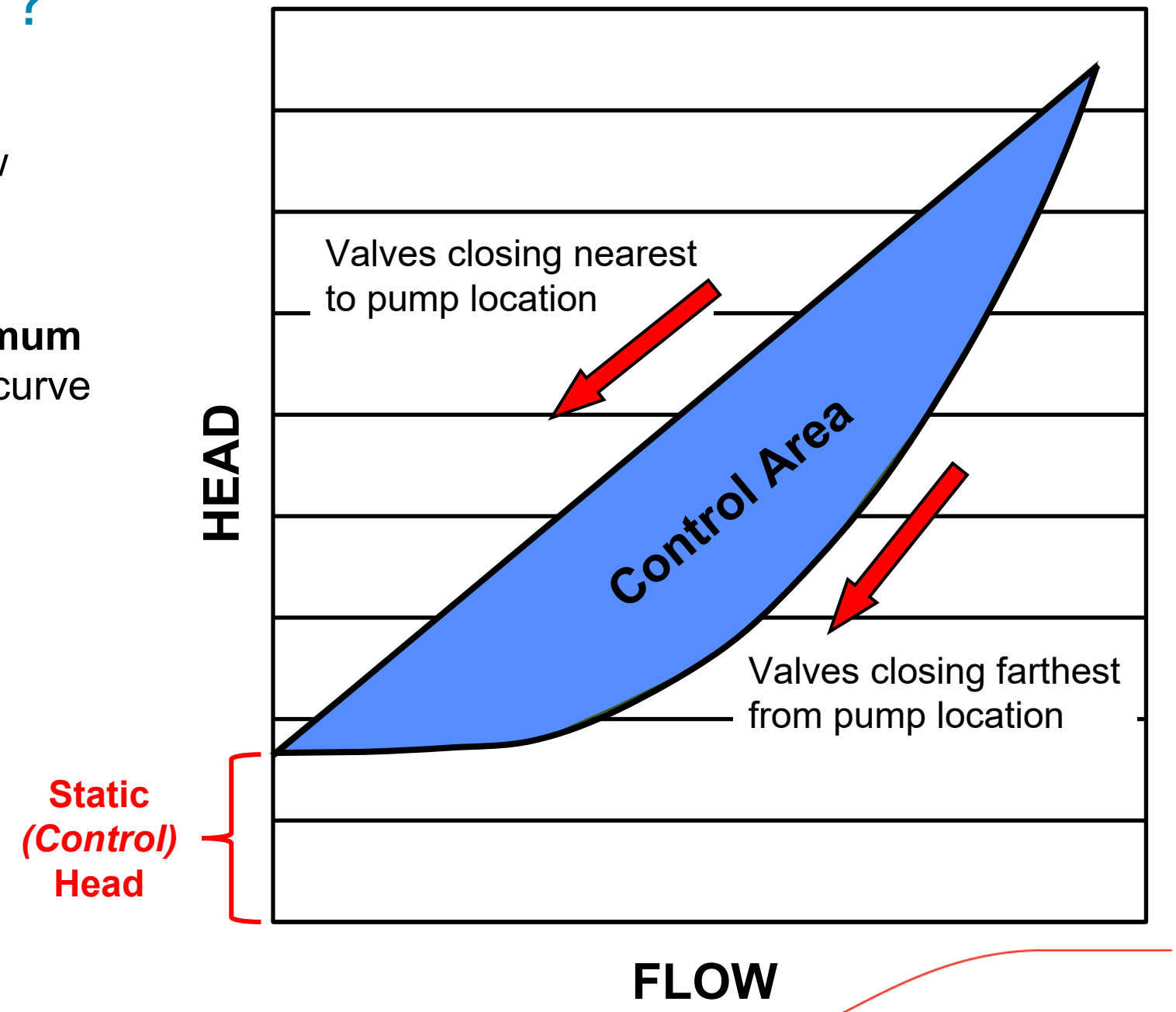

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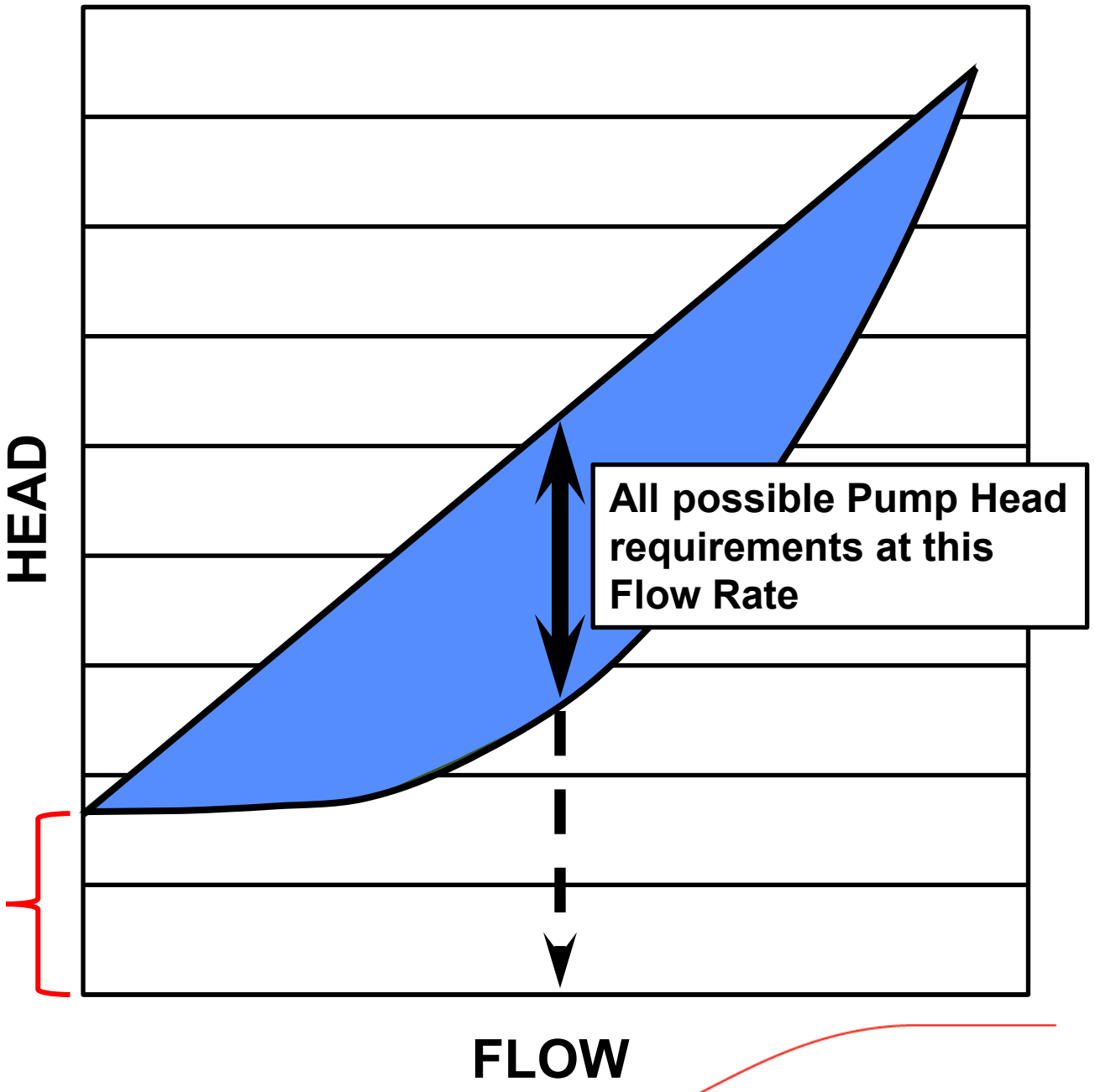

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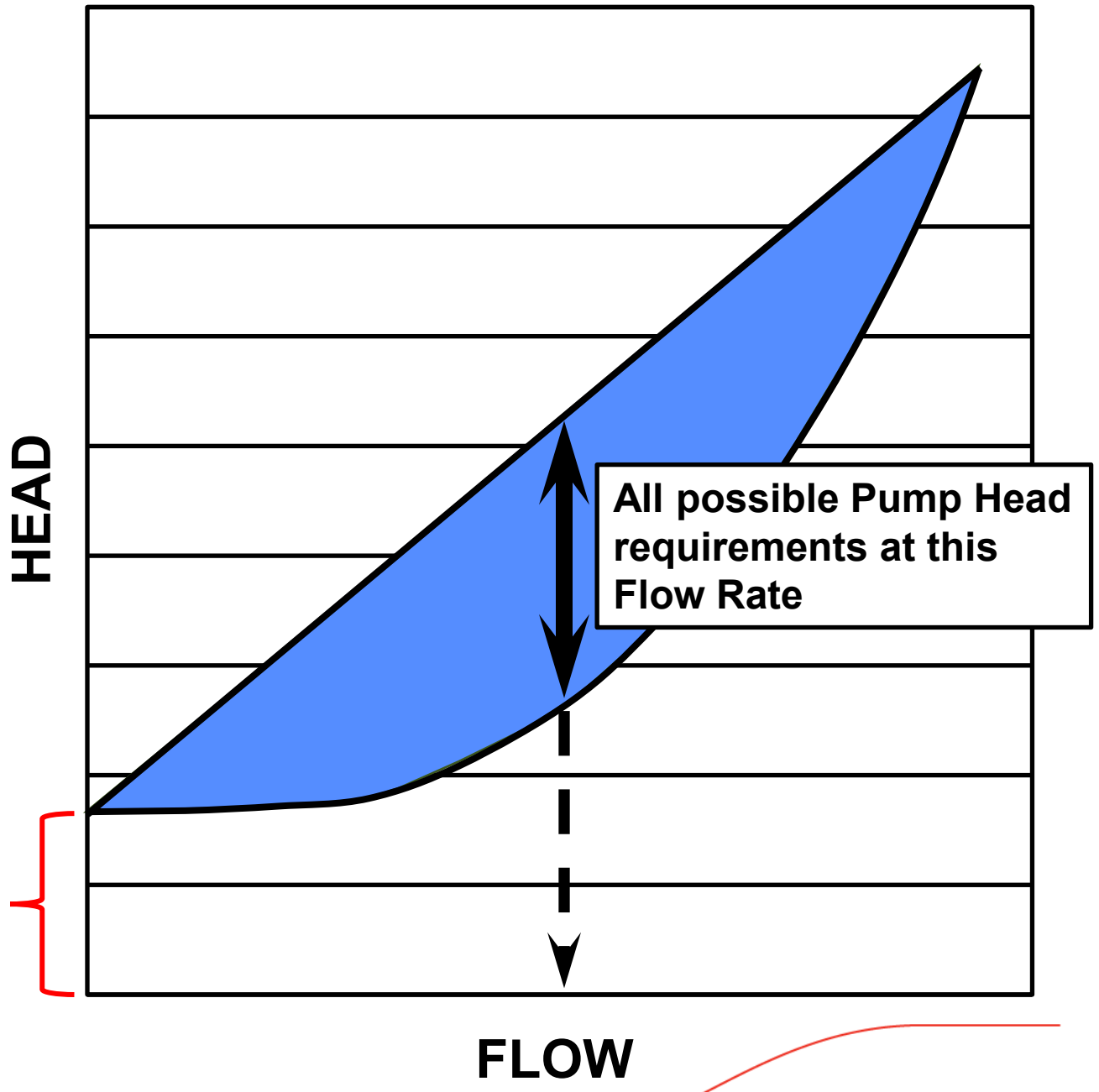
- The size & shape of **Control Area** is used for selecting applicable Variable Speed Control Strategy

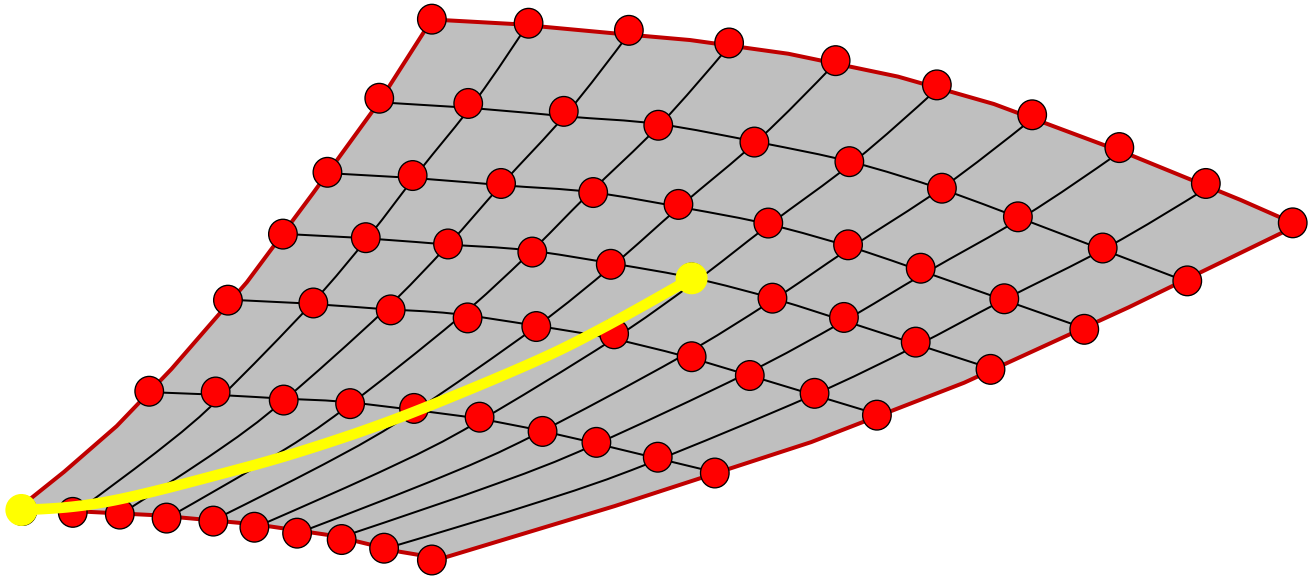


Applying Variable Speed – Which Control Strategy to Use?

Curve Control

- Factory generated Pump Performance Map
  - Flow
  - Head
  - Power
  - Speed
  - Torque

7 Speeds
10 Data Pts. Each



- **The Control Curve is generated within the Pre-Loaded Performance Map**
- **Provides a path for pump speed adjustment with changing flow demand**
- **Uses Control Head input to establish starting point**
- **Uses Design flow & head to create end point**

System Curve and Control Area: Low Diversity Systems

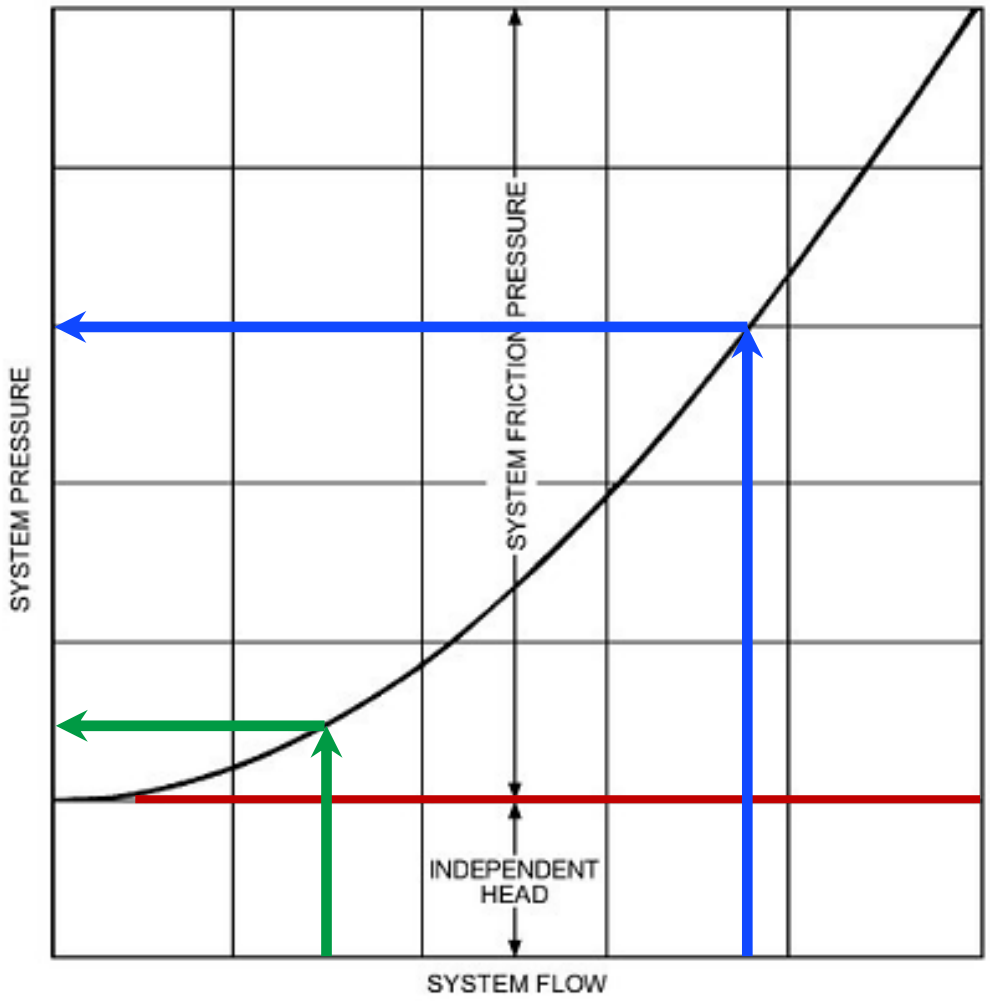


Figure 18. Typical System Curve with Independent Head

* **Using "Curve Control" assumes there is only 1 pump head amount required for each possible flow rate. Pump speed will be adjusted to follow the slope of this curve**

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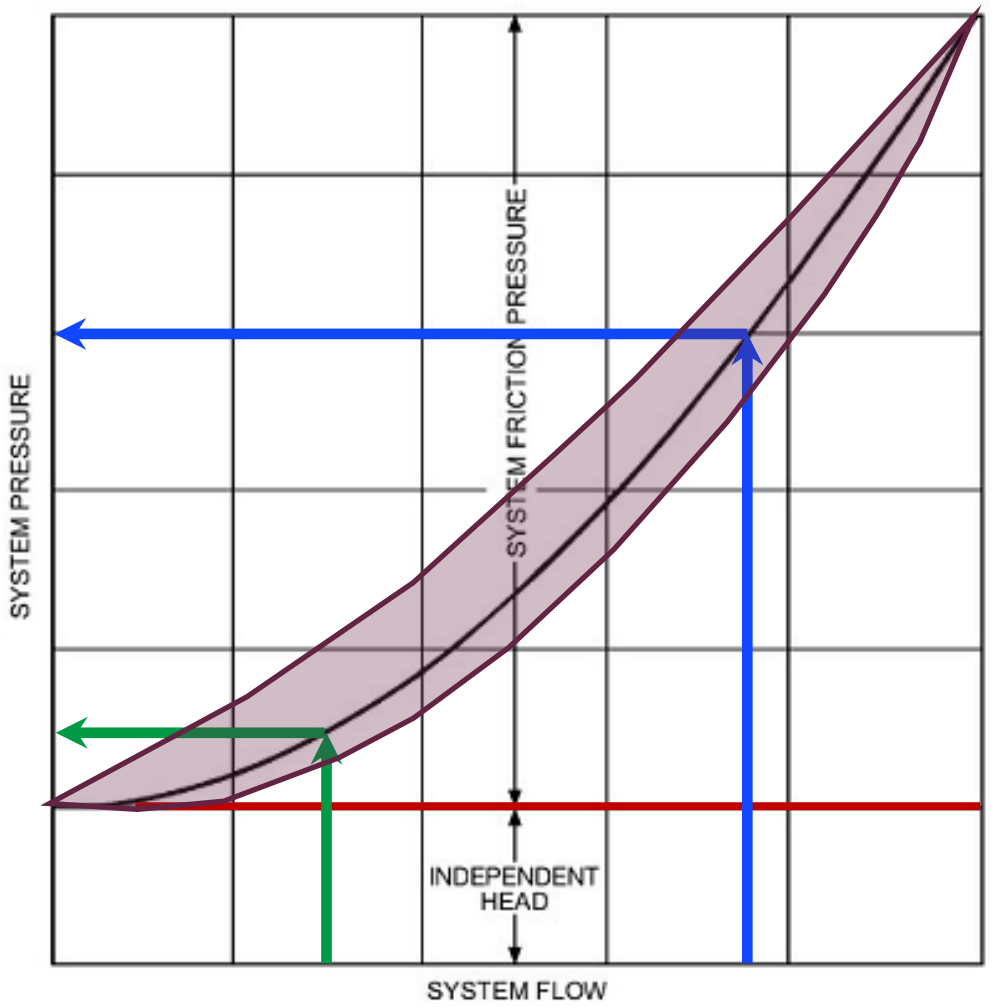

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* Using "Curve Control" assumes there is only 1 pump head amount required for each possible flow rate. Pump speed will be adjusted to follow the slope of this curve

Suggested "Curve Control" Applications:

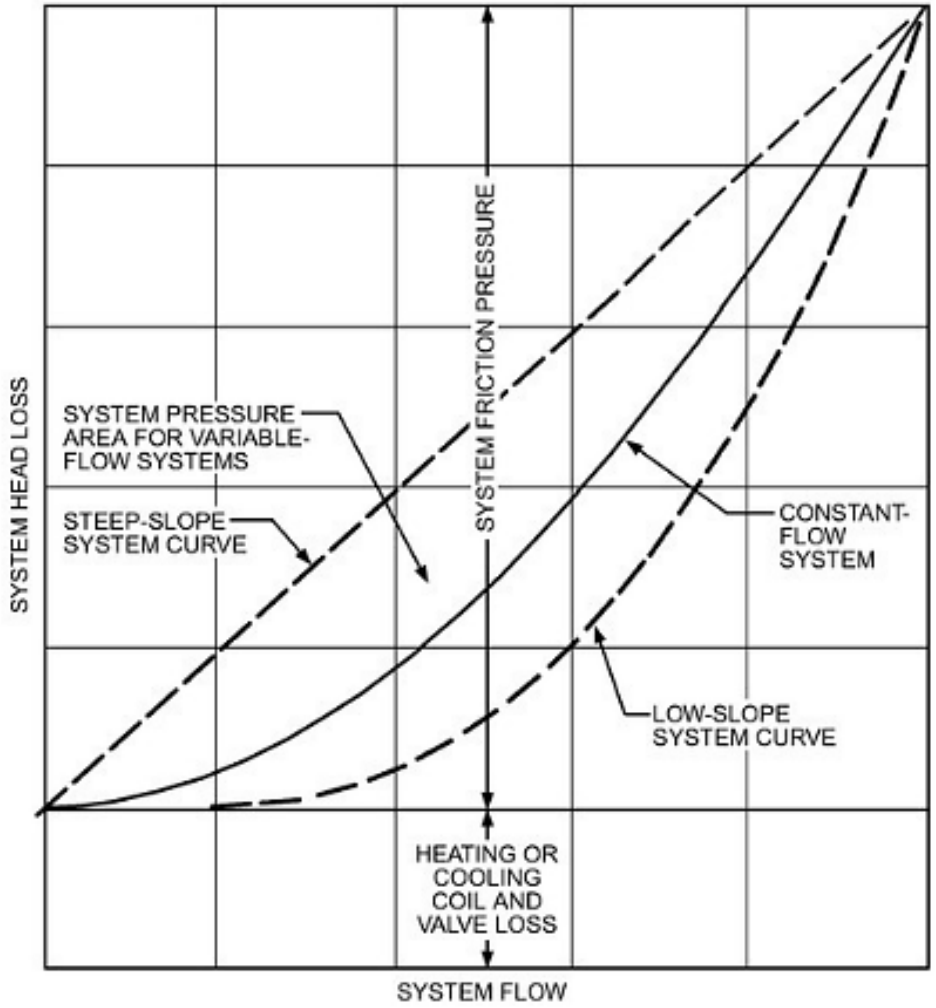
- **Small systems with similar flow and pressure drop across all branches**
- **Systems where loads increase or decrease uniformly in all zones**
- **Systems where Branch to Riser Pressure Drop Ratio is High (Smaller Control Area)**

ASHRAE Handbook: System Curve in Variable Flow Systems

HVAC Systems and Equipment, Chapter 44, Centrifugal Pumps

A **High Diversity System** can be defined as:

- System distribution piping is significant
- Control valve count is high
- Loading & Unloading of terminal units is extremely random from zero to full load



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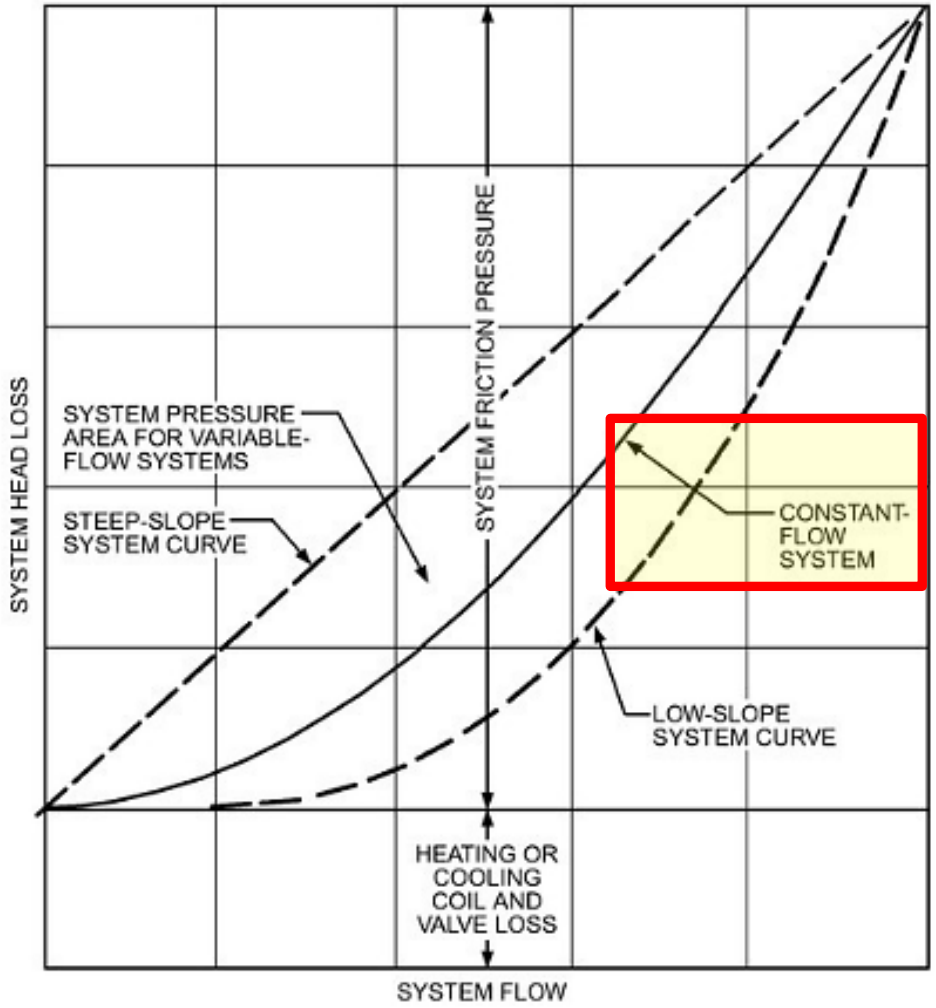

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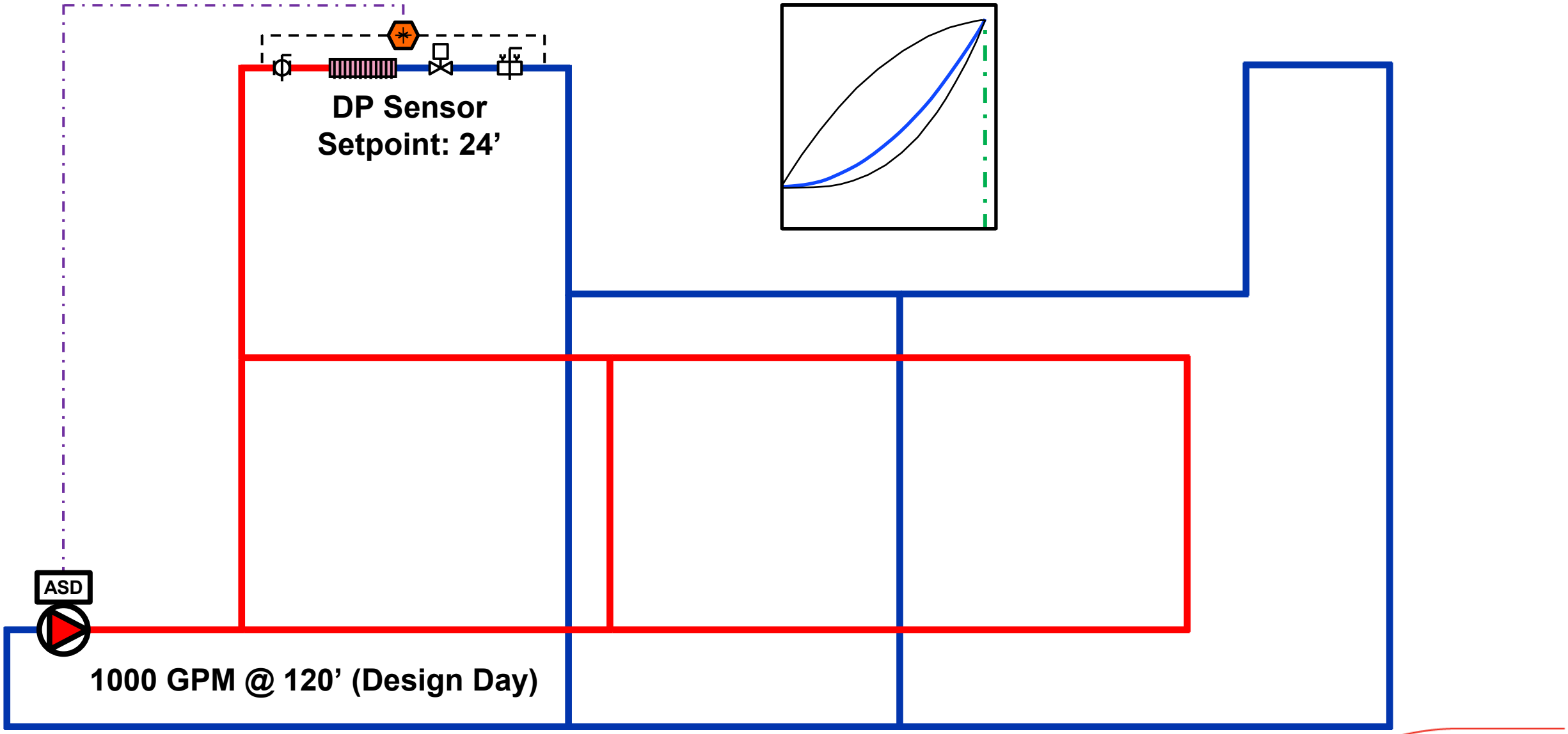
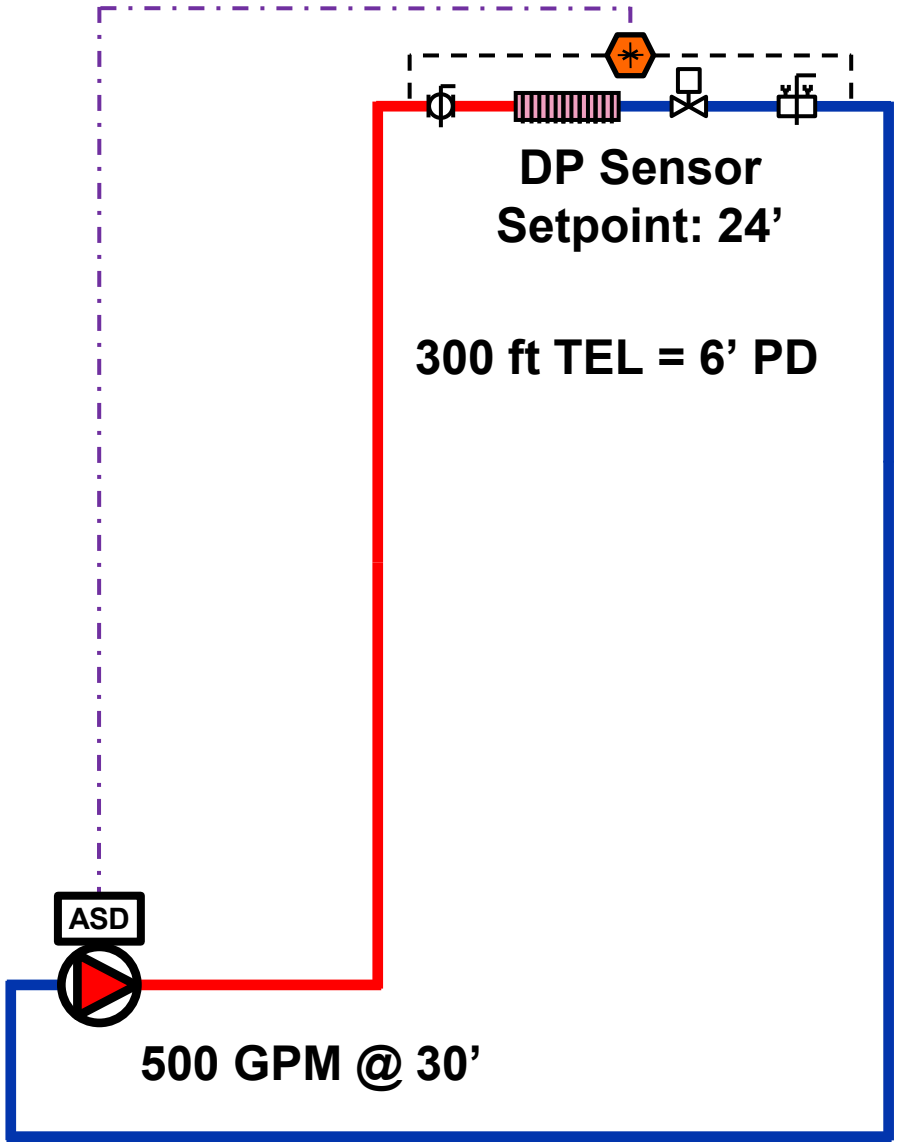
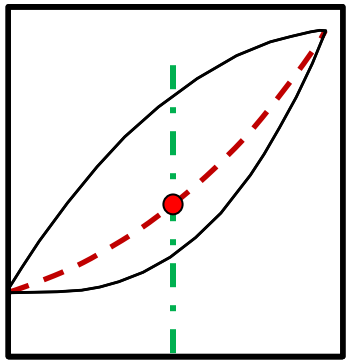
Ex: High Diversity System using Feedback Sensor (Full Load)



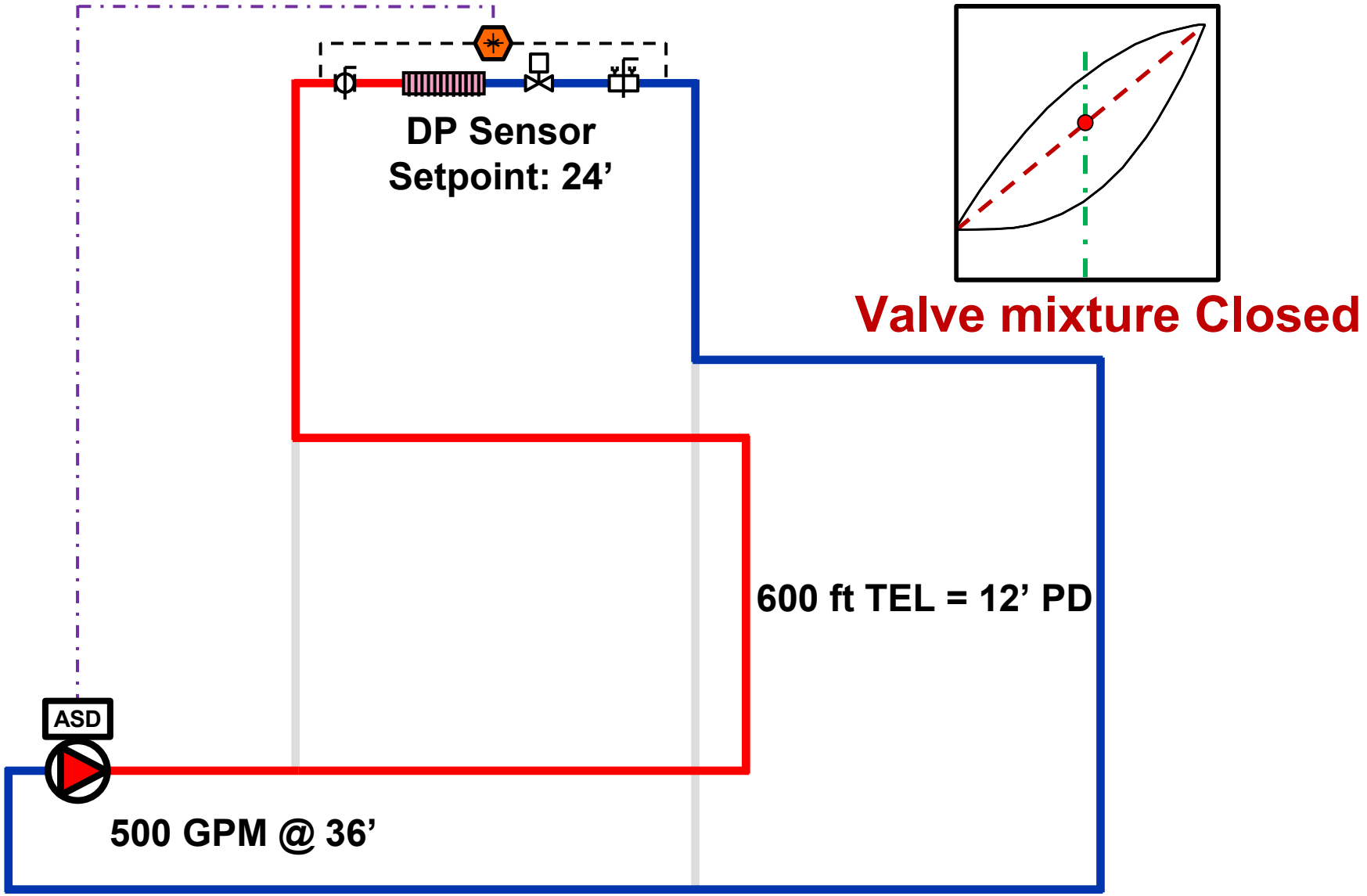
Ex: High Diversity System using Feedback Sensor (Part Load)





Valves farthest Closed

Ex: High Diversity System using Feedback Sensor (Part Load)



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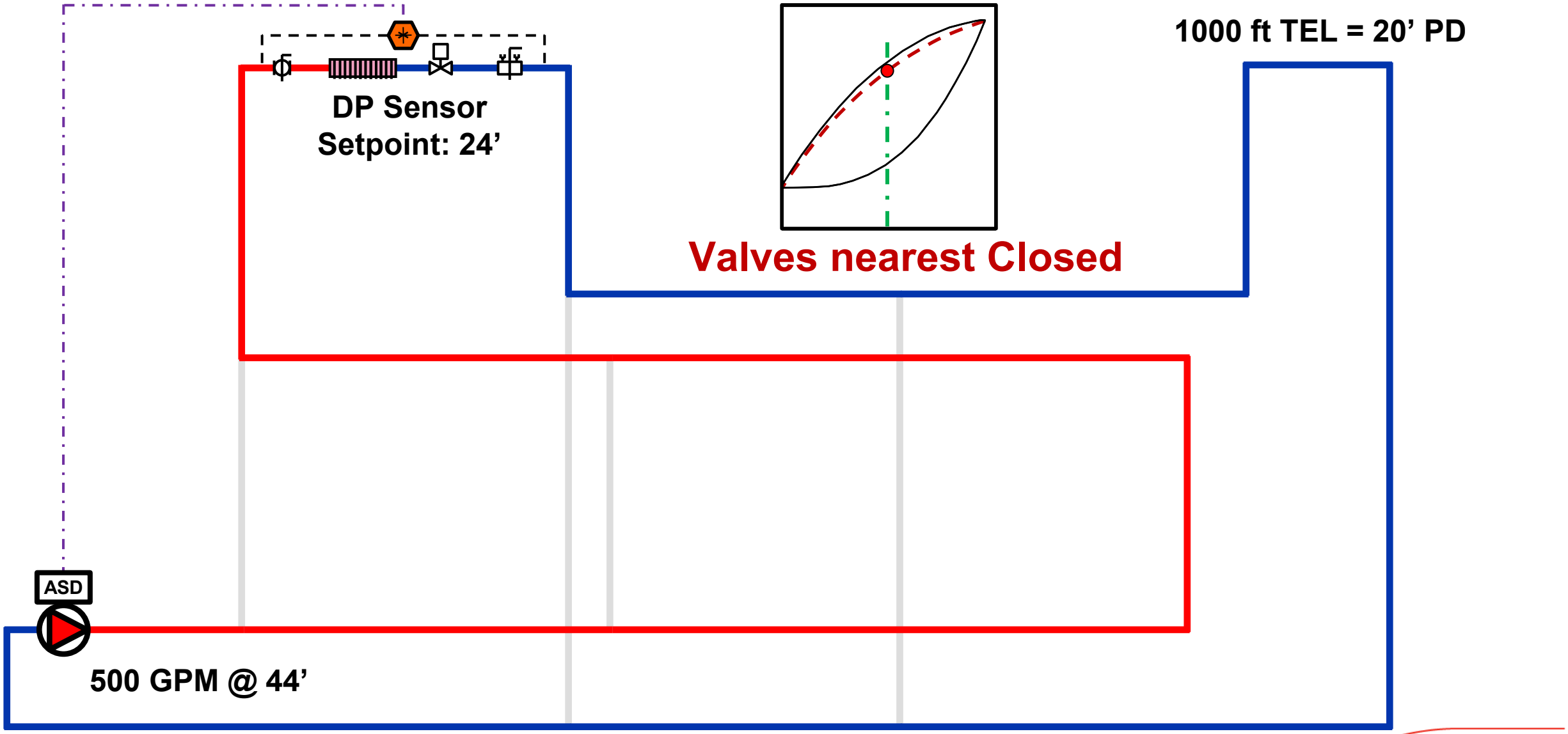


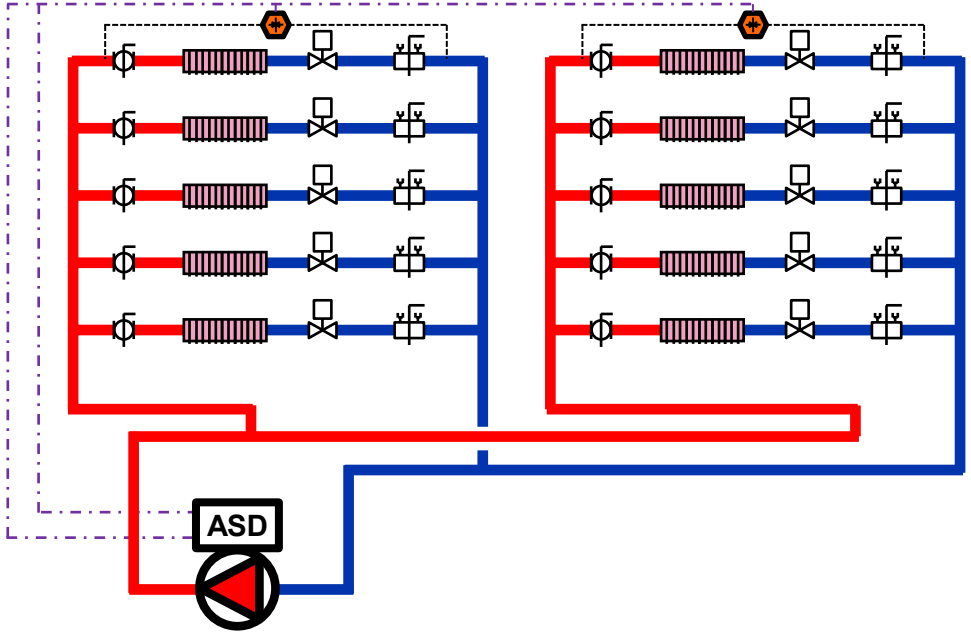
Applying Variable Speed – Which Control Strategy to Use?

Area Control

- **Feedback Sensor(s) located in the System**
  - Wired directly to ASD
  - Wired to a BMS

Applications

- **High Diversity** Hot & Chilled Water Systems
- Large Control Area *(Low BRPDR)*



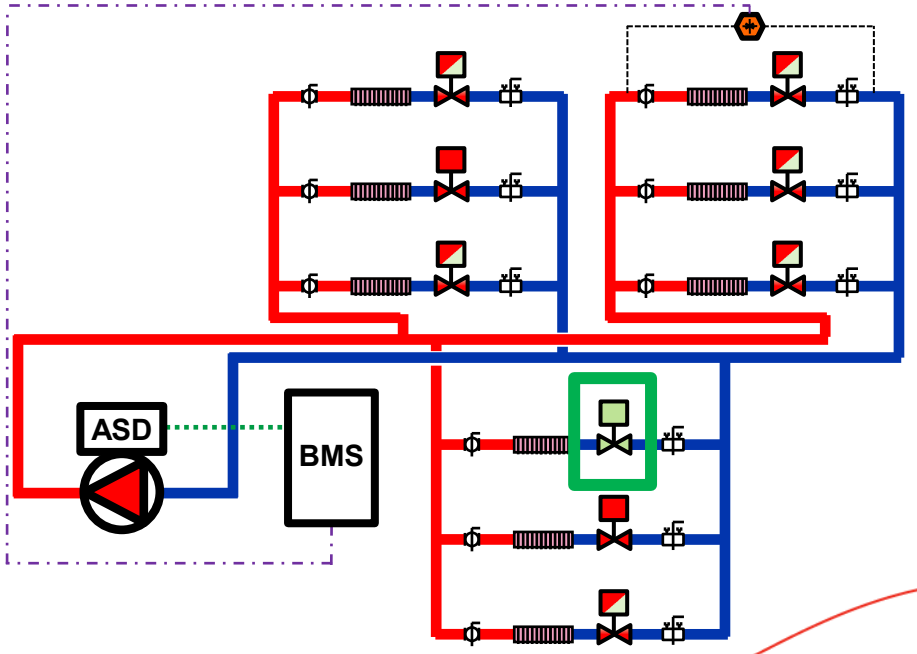
Applying Variable Speed – Which Control Strategy to Use?

Area Control

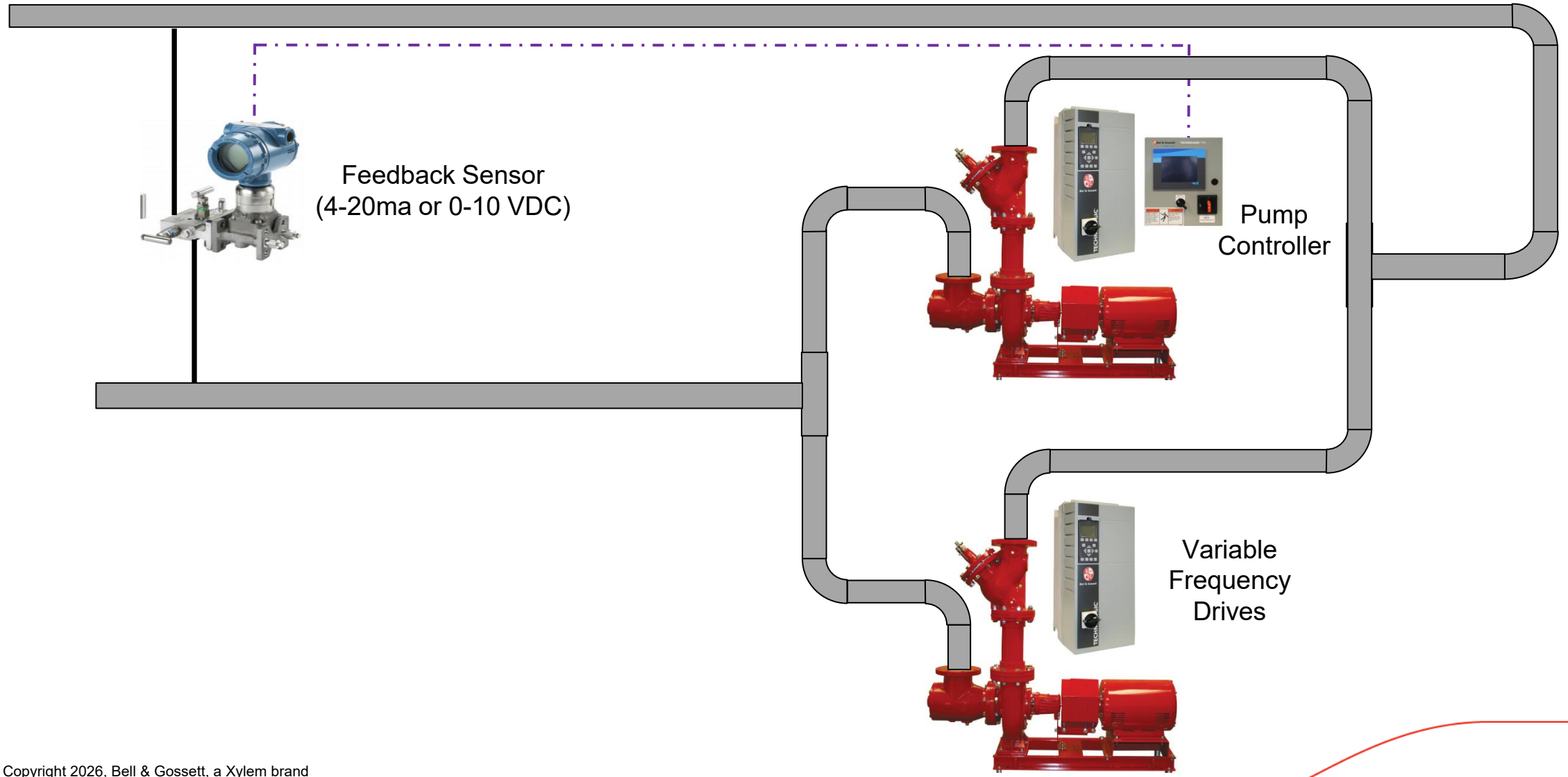
- **Control Valve Position *(ASHRAE 90.1 "Reset")***
  - Use Valve Actuator Feedback Signal Only
  - Add Differential Pressure Sensor, modify setpoint

Applications

- Where BMS can monitor valve position
- *Not recommended when PICV's are used*



Area Control: Feedback Sensors for **Large** *Control Area* Systems



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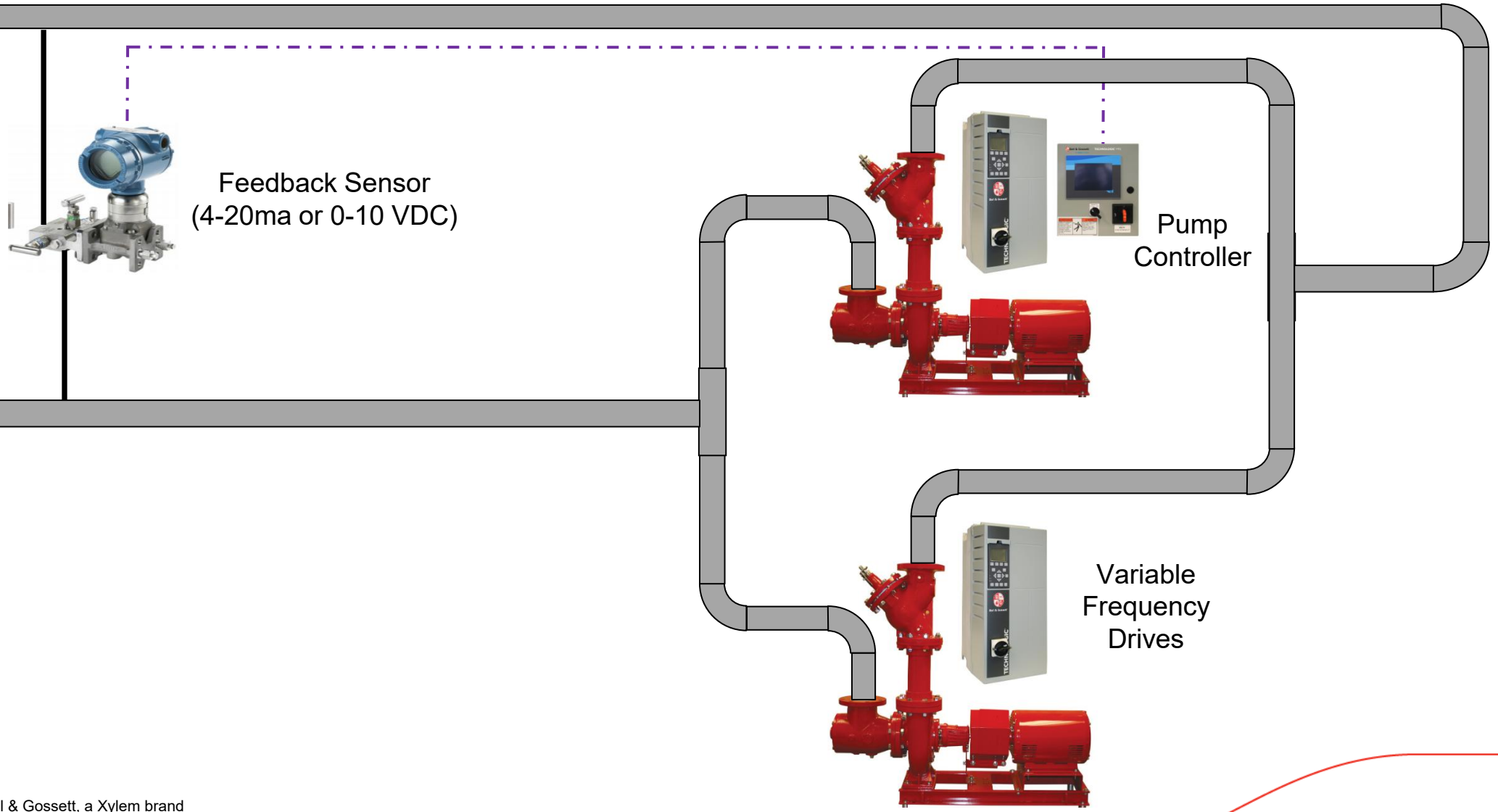

- **Questions:**

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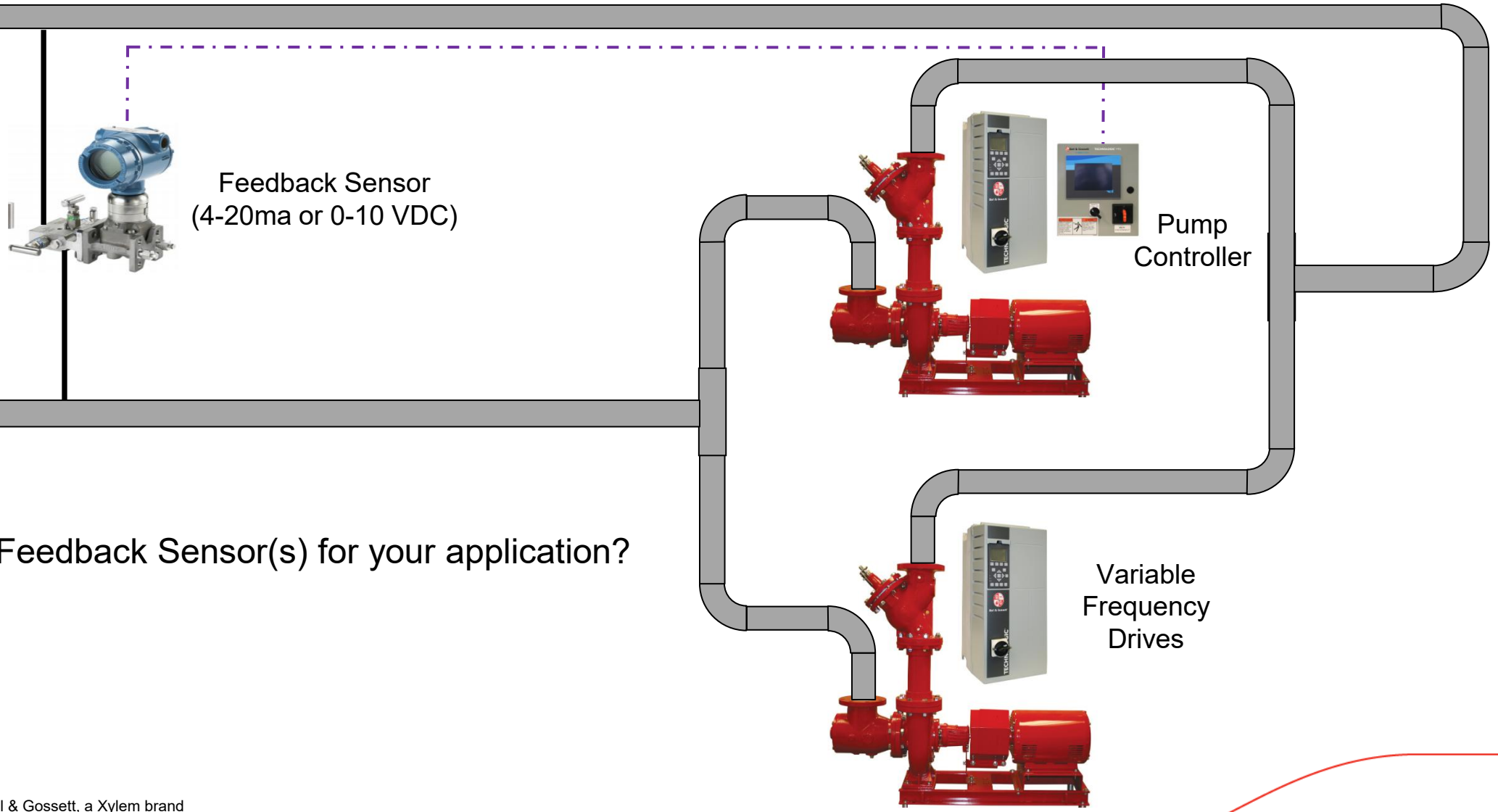

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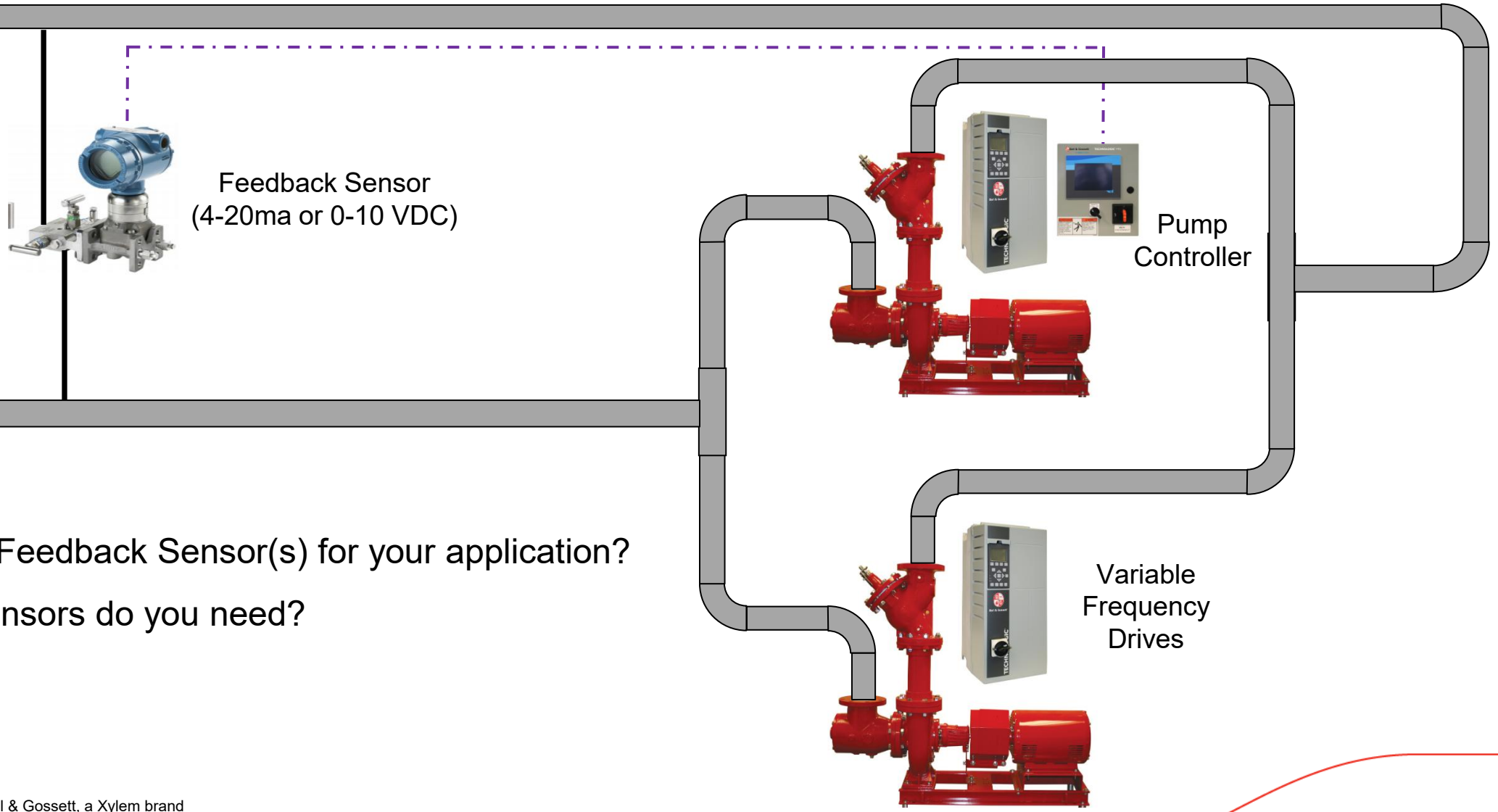

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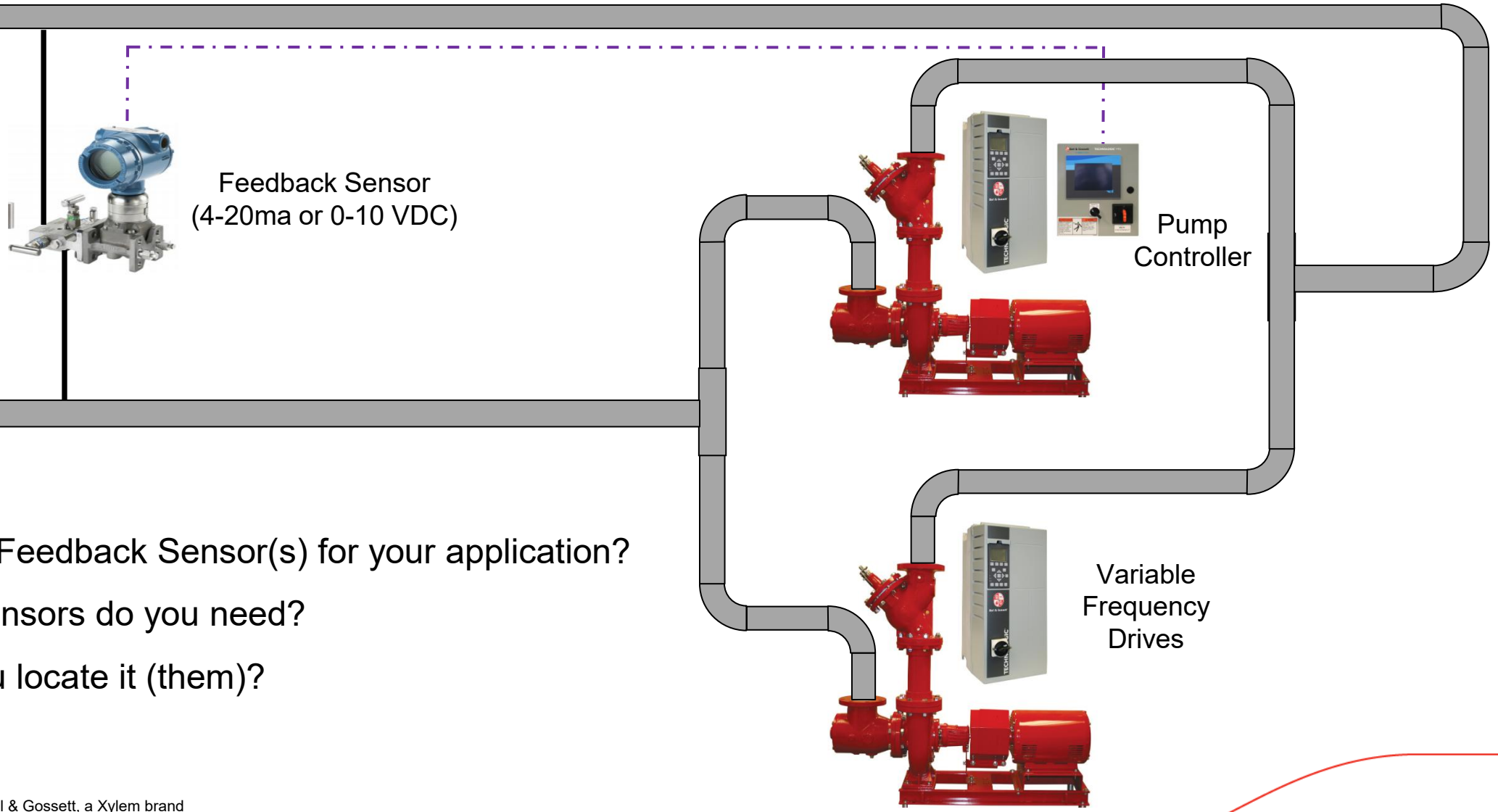

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- Where do you locate it (them)?

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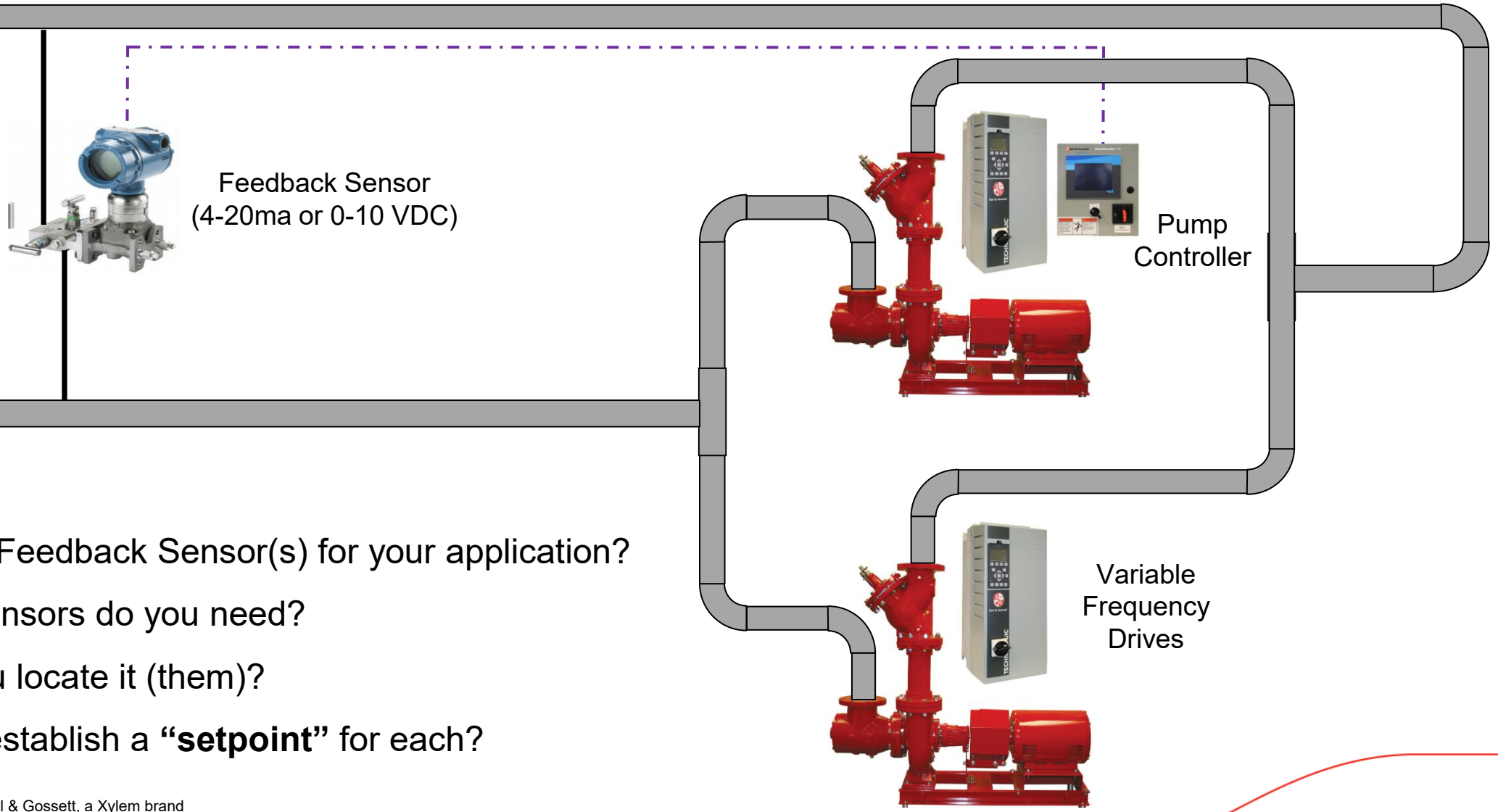
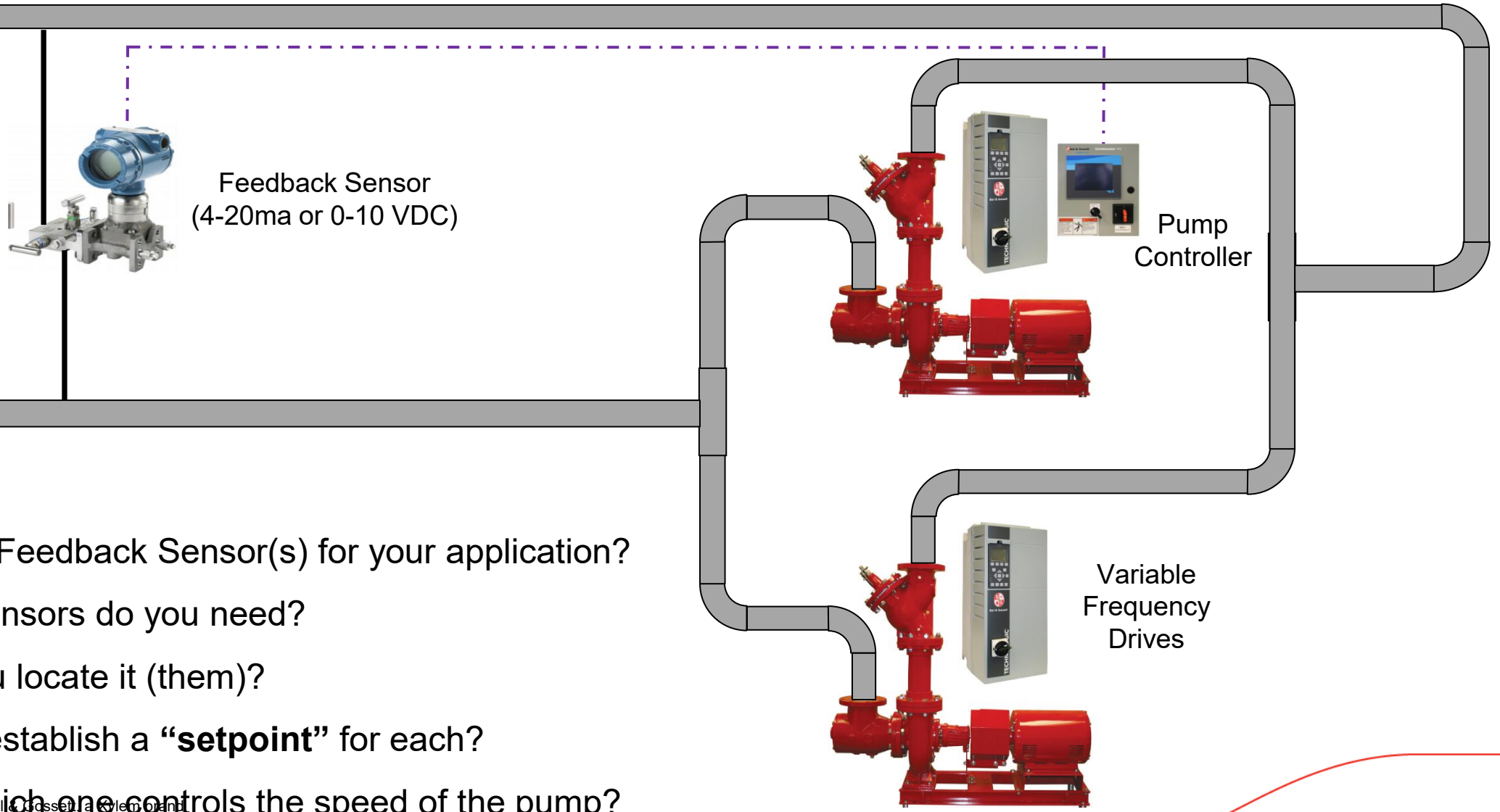


- **<u>Questions:</u>**
- What type of Feedback Sensor(s) for your application?
- How many sensors do you need?
- Where do you locate it (them)?
- How do you establish a **“setpoint”** for each?

Area Control: Feedback Sensors for **Large** *Control Area* Systems



- **<u>Questions:</u>**
- What type of Feedback Sensor(s) for your application?
- How many sensors do you need?
- Where do you locate it (them)?
- How do you establish a **"setpoint"** for each?
- If multiple, which one controls the speed of the pump?

What Type of Feedback Sensor to use? Where do you locate it?

- **Common Feedback Sensor Options:**
- **Pressure** – Change in pressure at single point *(Potable Water Pressure Boosting)*
- **Differential Pressure** – Change in pressure between two points *(HVAC Heating and Cooling)*
- **Temperature** – Change in temperature at single point *(Batch Process Tank)*
- **Differential Temperature** – Change in temperature between two points *(Air or Water side of HVAC Coils)*
- **Flow Meter** – Change in flowrate in pipe or equipment *(Pump Staging, Backup to other Feedback Sensors)*
- **Discharge Air Temperature** – Air Temperature on discharge side of a water coil *(VFD Zone Pumping)*

What Type of Feedback Sensor to use? Where do you locate it?

- **Differential Pressure** – Change in pressure between two points *(HVAC Heating and Cooling)*

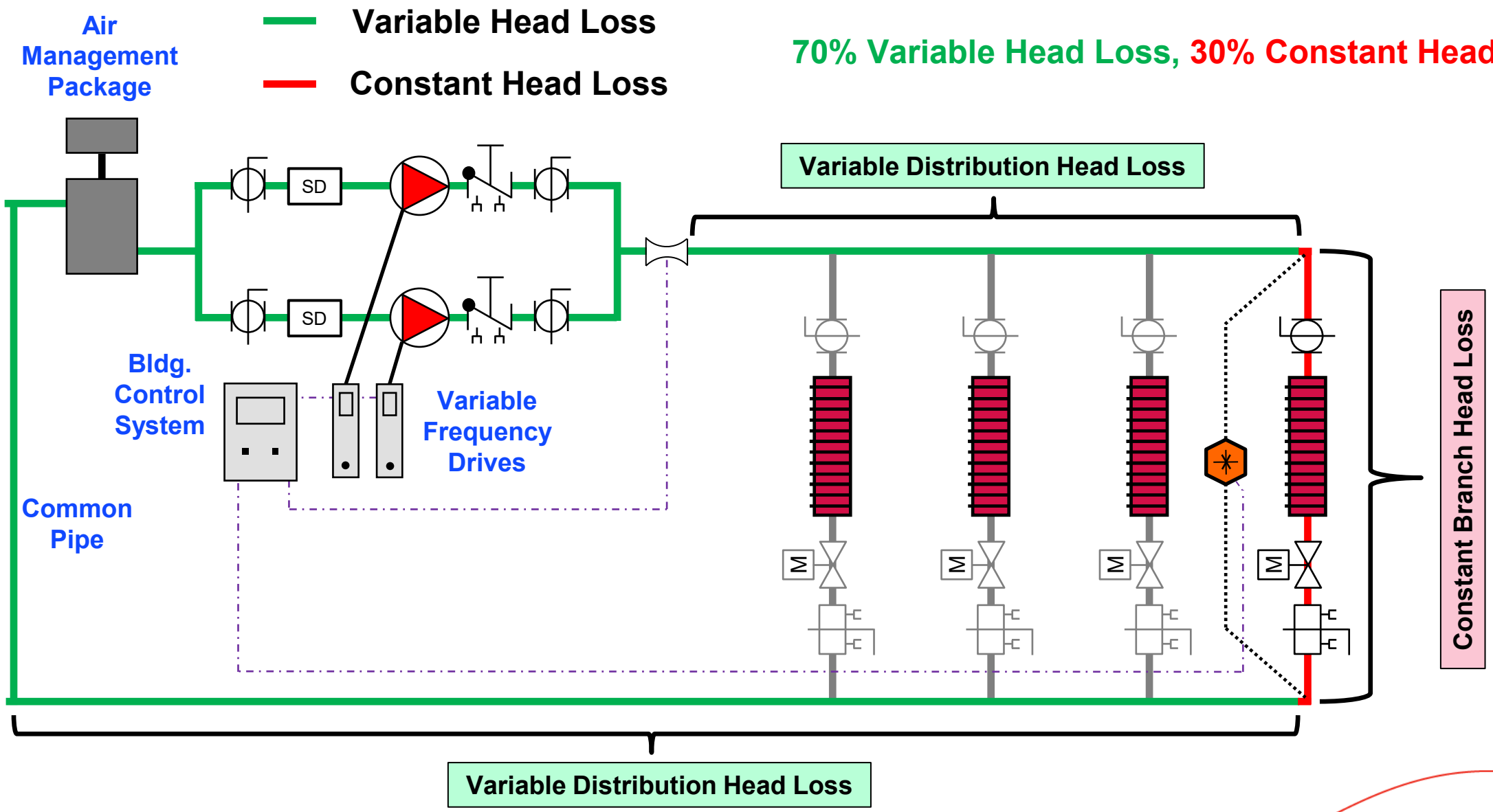
- **<u>Differential Pressure Feedback Sensor Locations:</u>**

What Type of Feedback Sensor to use? Where do you locate it?

- **Differential Pressure** – Change in pressure between two points *(HVAC Heating and Cooling)*

- **<u>Differential Pressure Feedback Sensor Locations:</u>**
- Mechanical Room
- 2/3 the system piping distance from the Mechanical Room
- Most remote hydraulic head loss circuit pump will serve ***(The "Critical Circuit")***
- **It doesn't matter (???)**

Direct Return – Where do you locate the Feedback Sensor?



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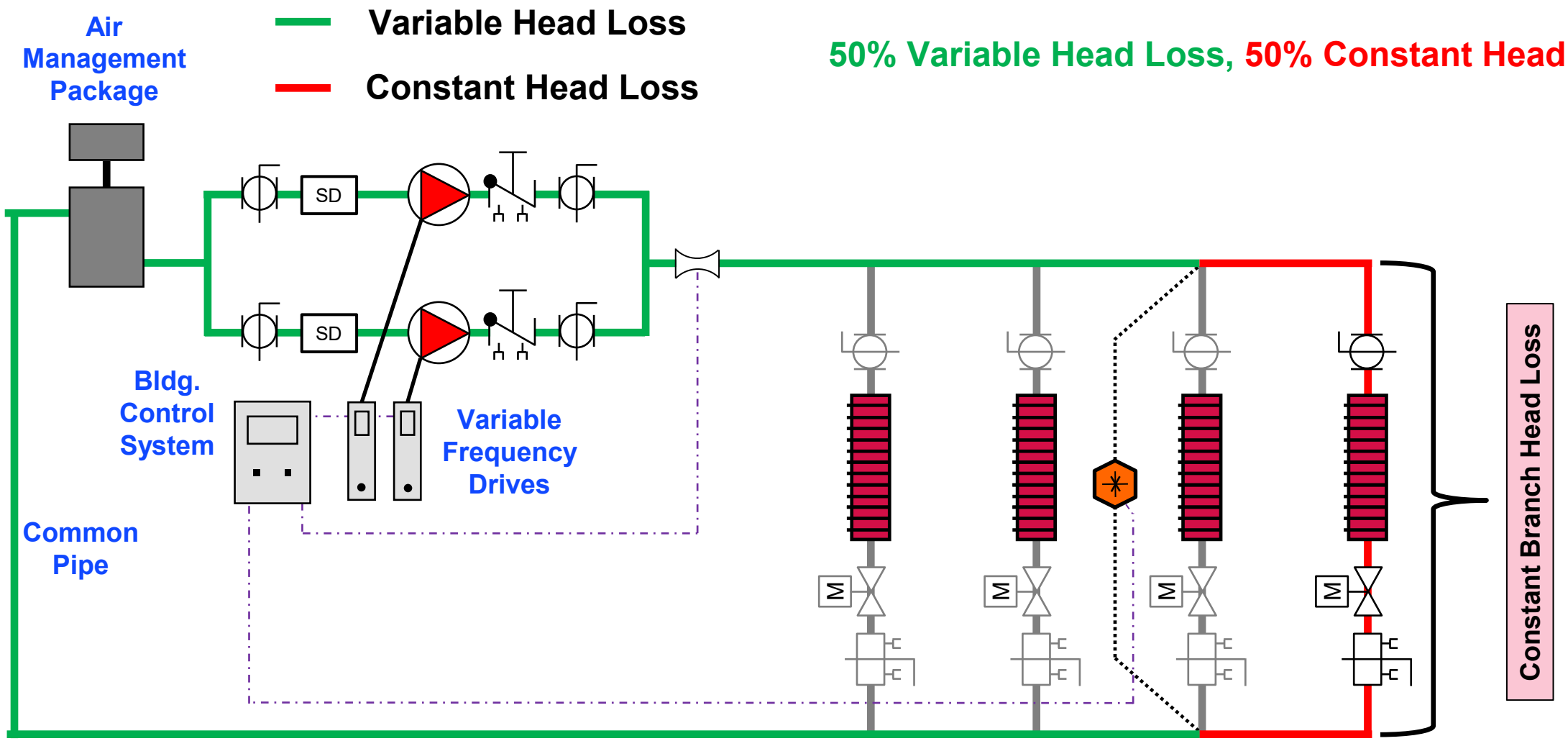
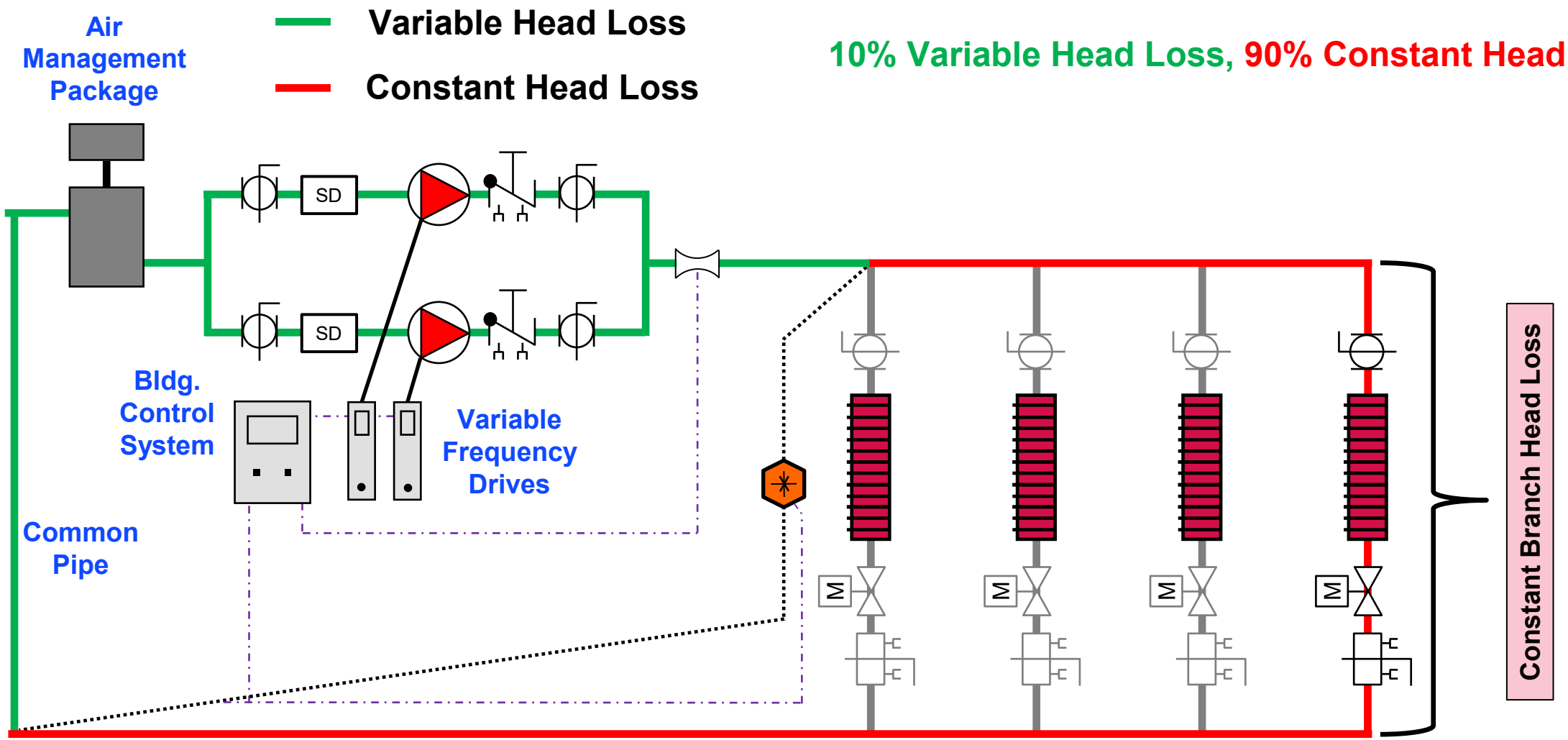


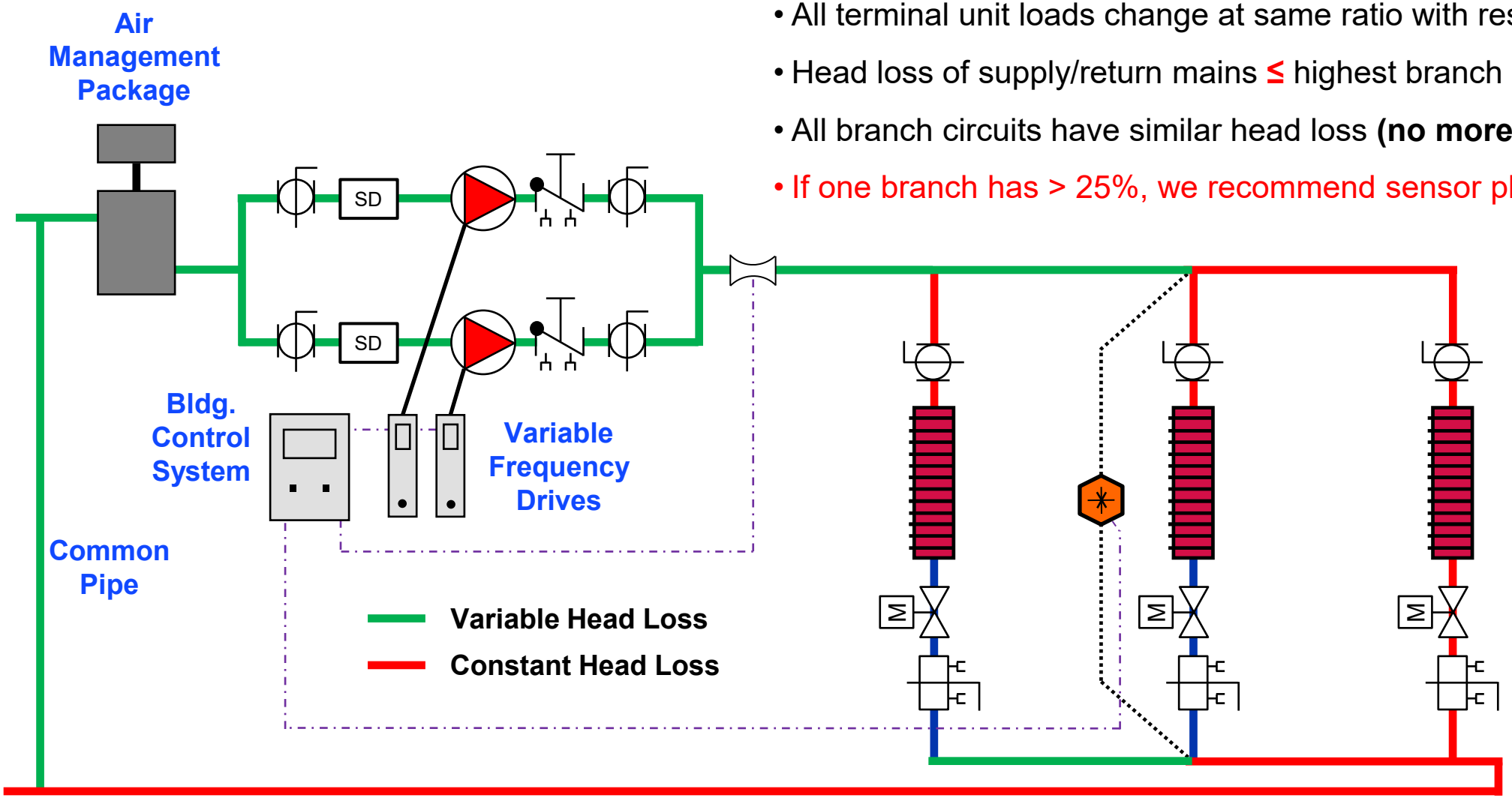
Direct Return – Where do you locate the Feedback Sensor?



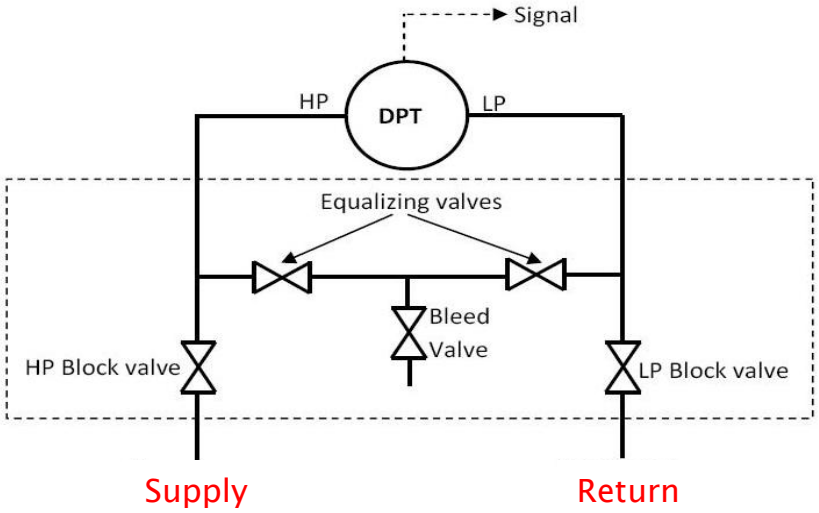
Reverse Return – Where do you locate the Feedback Sensor?

Suggested Sensor Location Assumptions:

- All terminal unit loads change at same ratio with respect to time
- Head loss of supply/return mains ≤ highest branch circuit head loss
- All branch circuits have similar head loss **(no more than 25% difference)**
- If one branch has > 25%, we recommend sensor placement at that location.

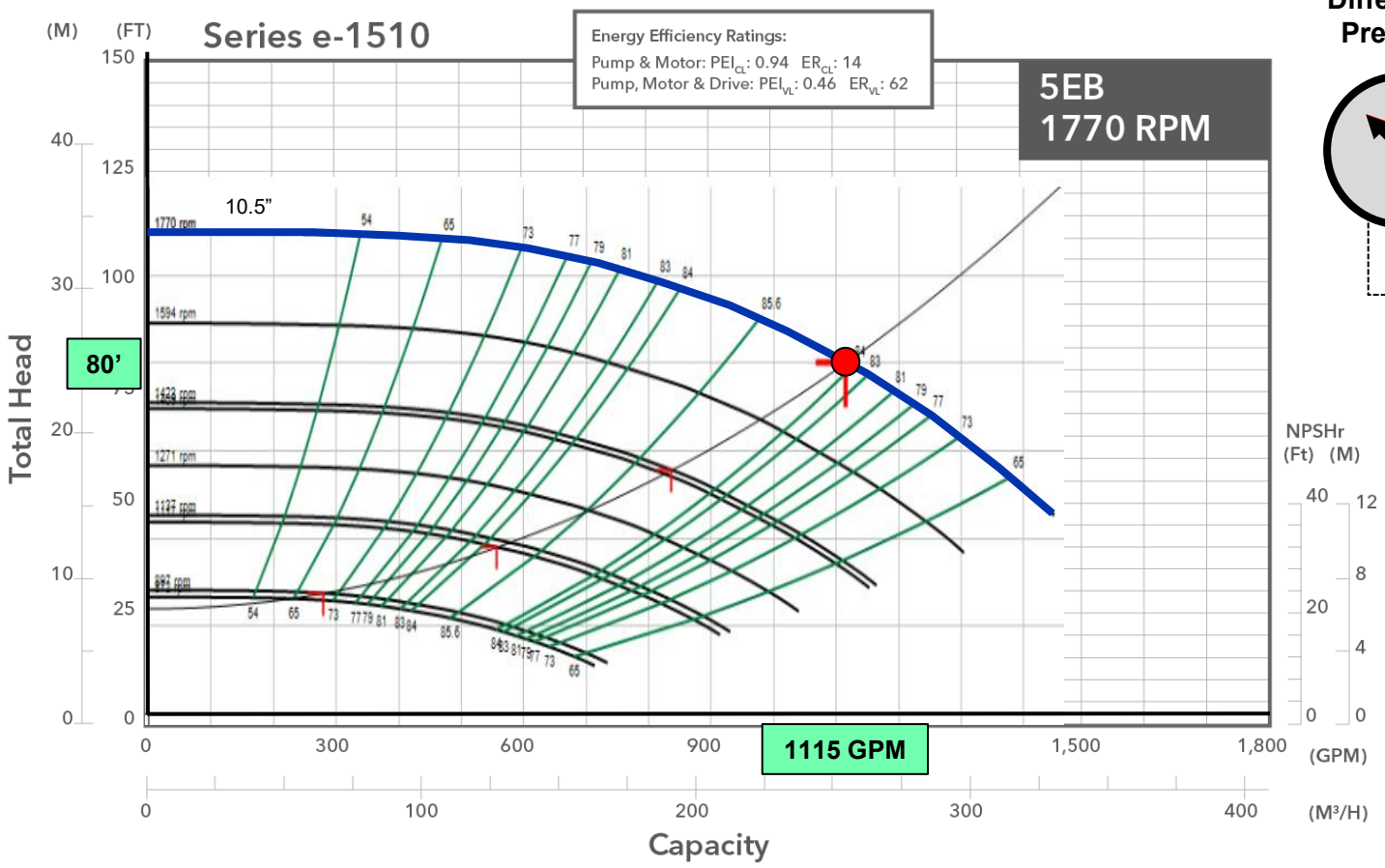


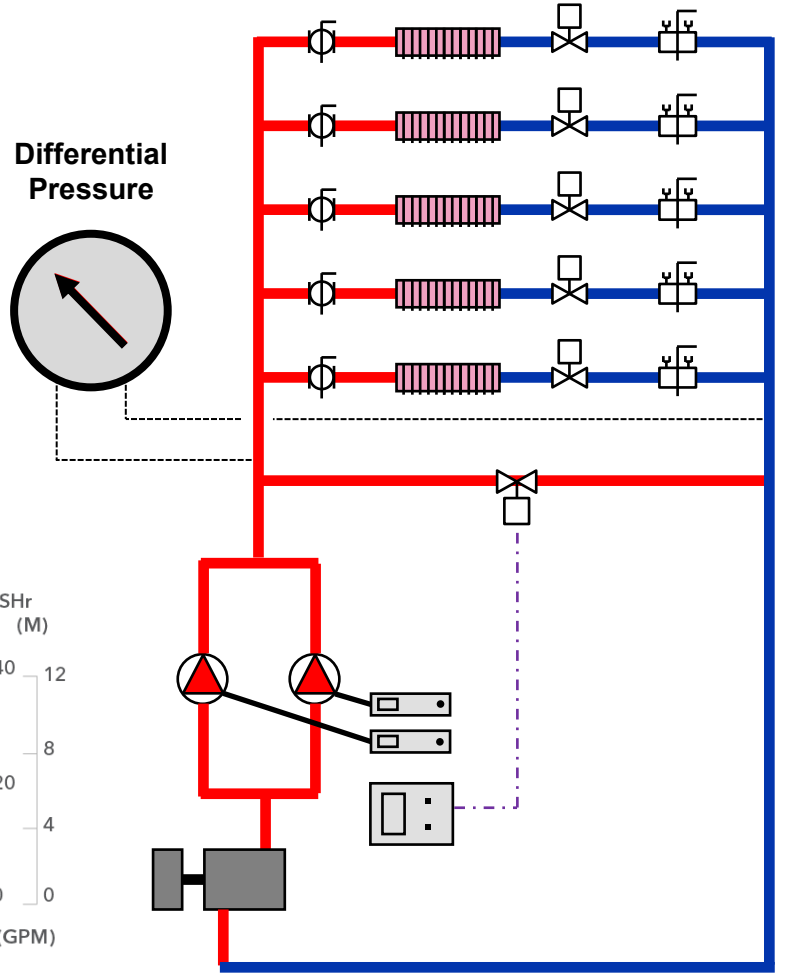
Establishing the Differential Feedback Sensor Setpoint



- Measure Pressures at Supply and Return to obtain differential
- Must be done under **"Design Day"** simulation **after final hydronic system balance has been completed**
- Data must be recorded independently for **each** sensor's location
- Establish sensor signal range values in pump controller ***(i.e. 4ma = 18Hz., 20ma = 60Hz.)***

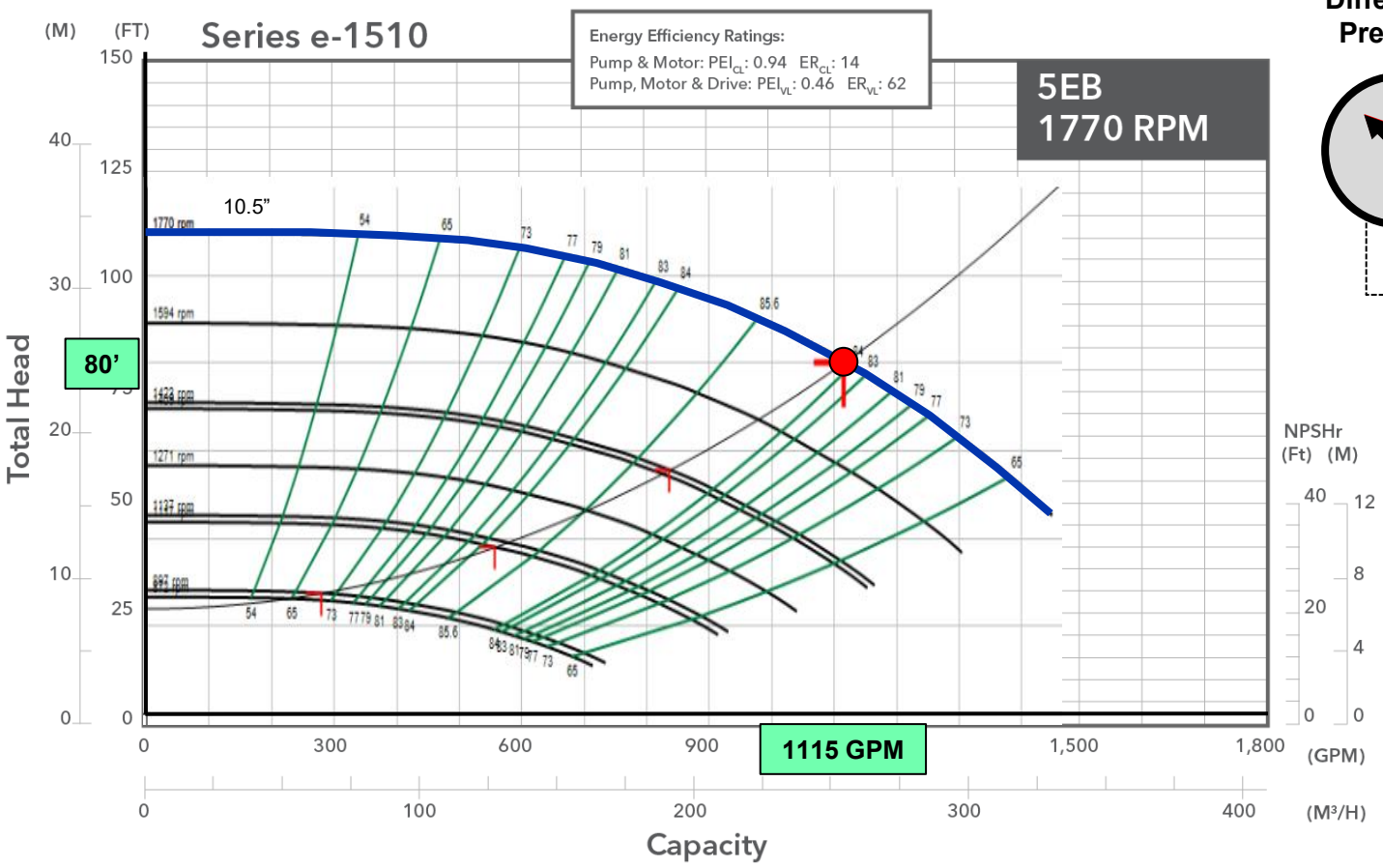
Setting the *Control Head* using the Critical Circuit

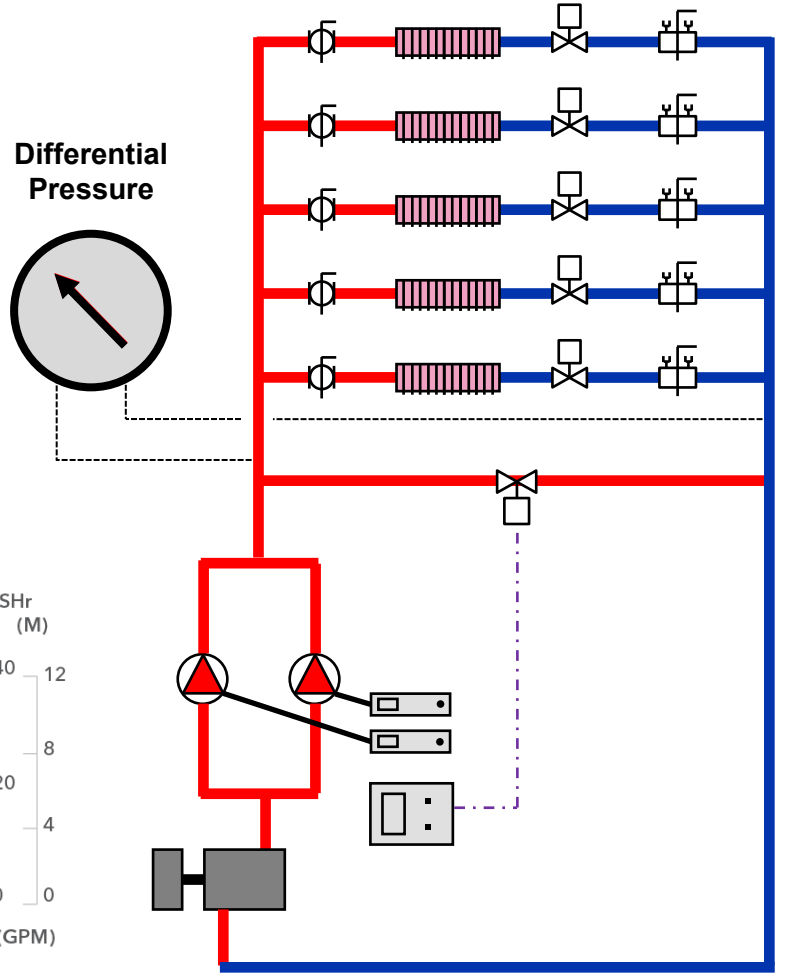




Setting the *Control Head* using the Critical Circuit

70% Variable Head Loss, 30% Constant Head Loss





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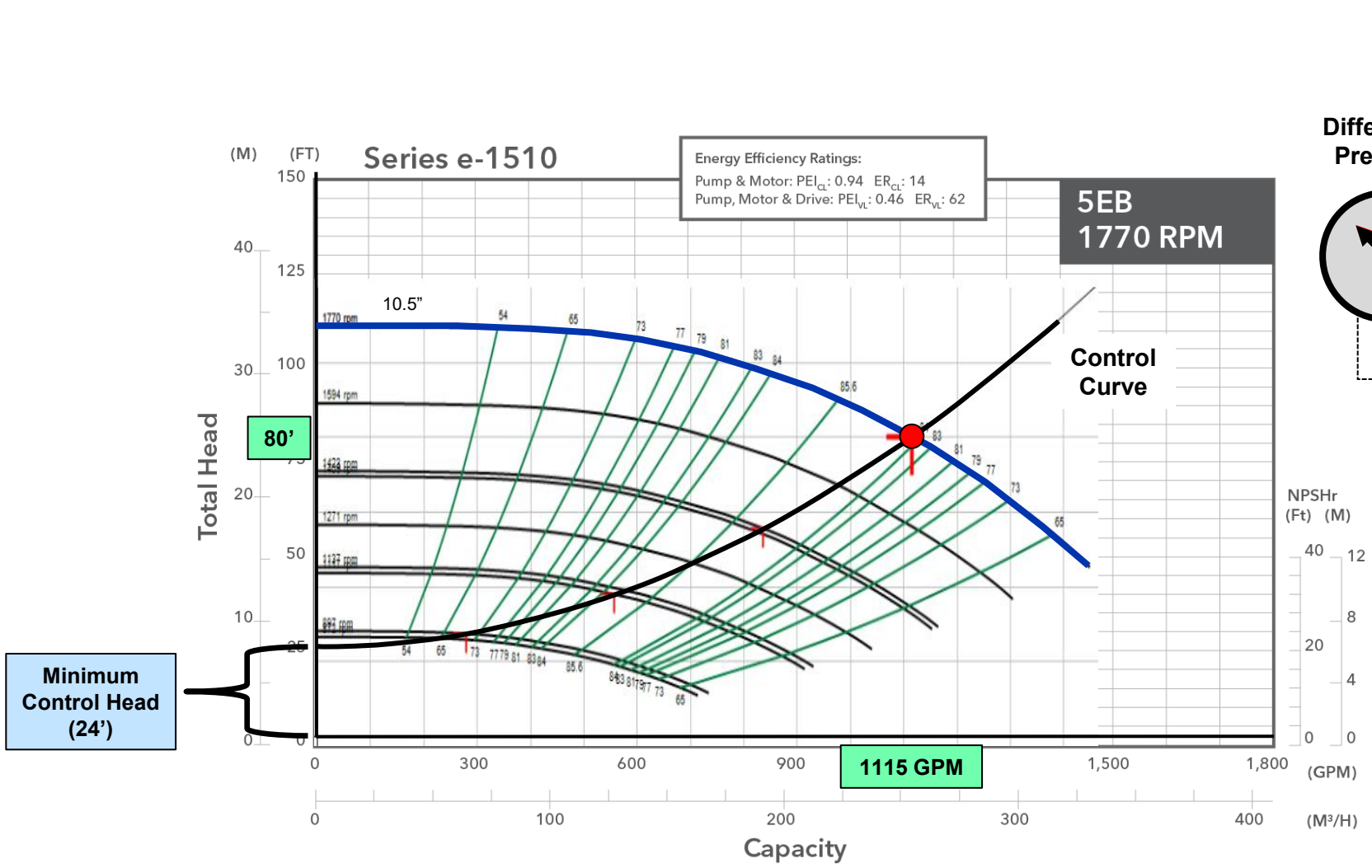

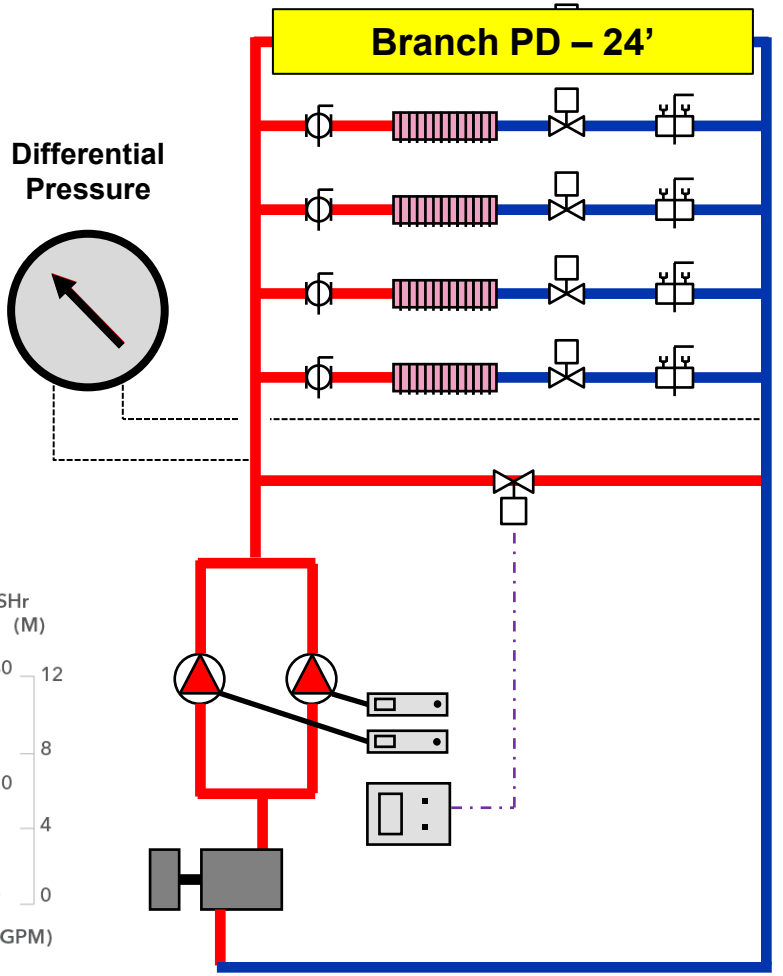

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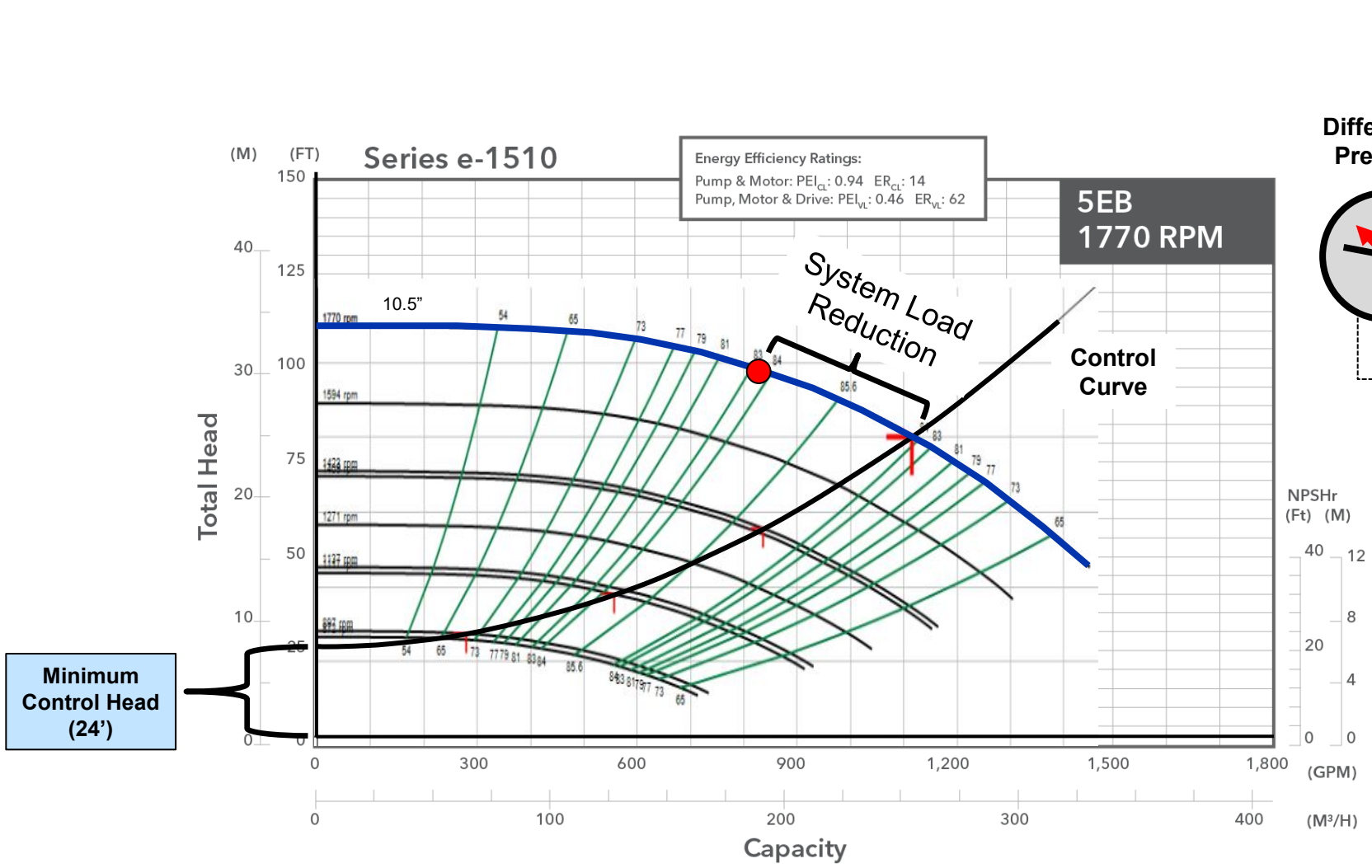

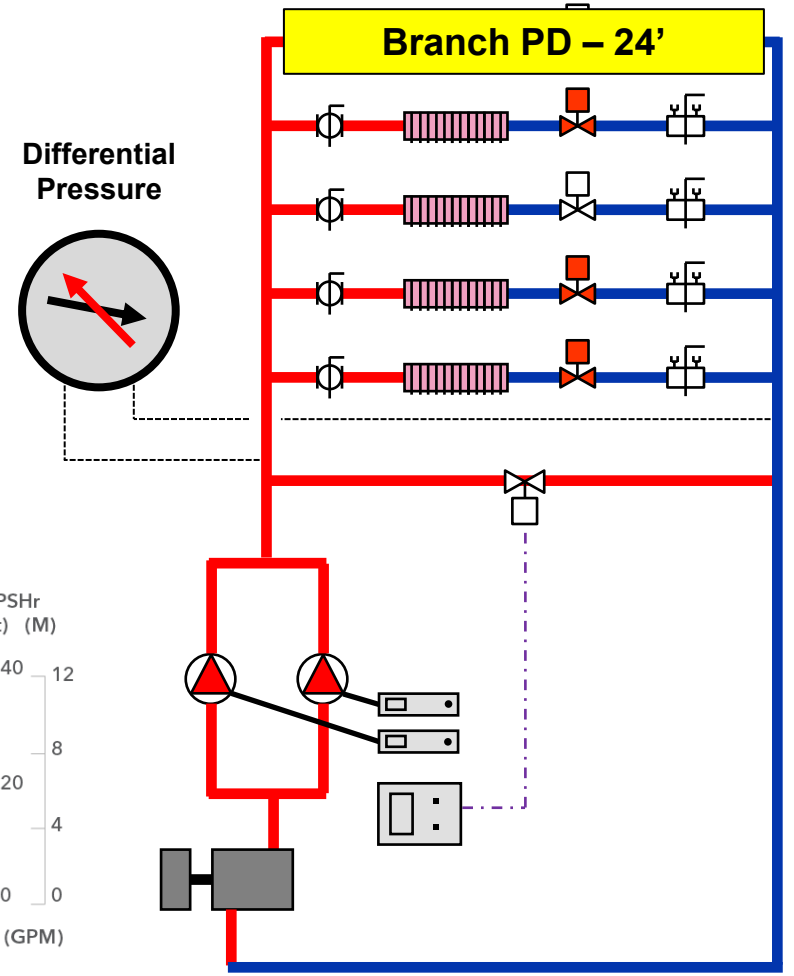

Setting the *Control Head* using the Critical Circuit

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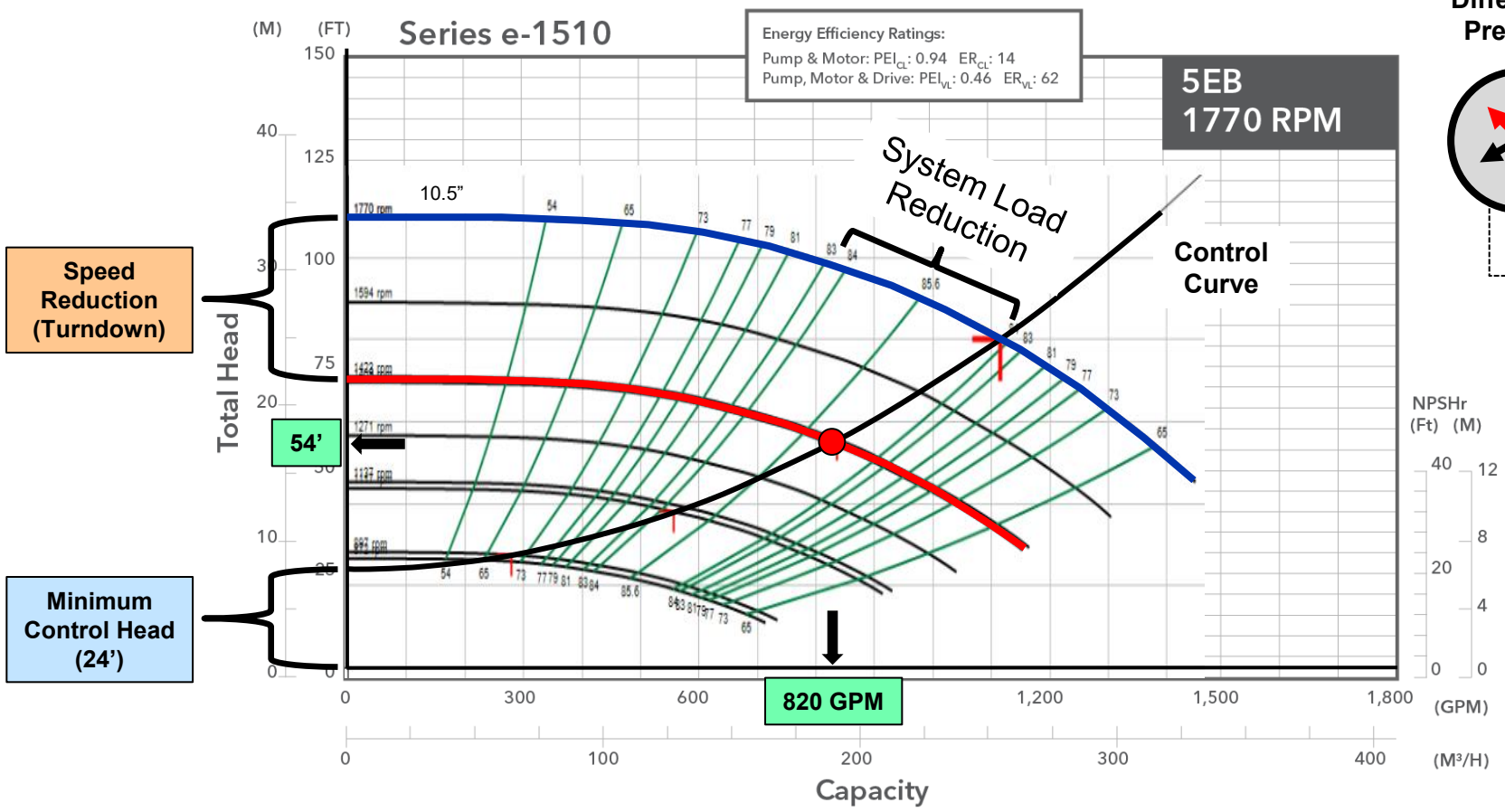
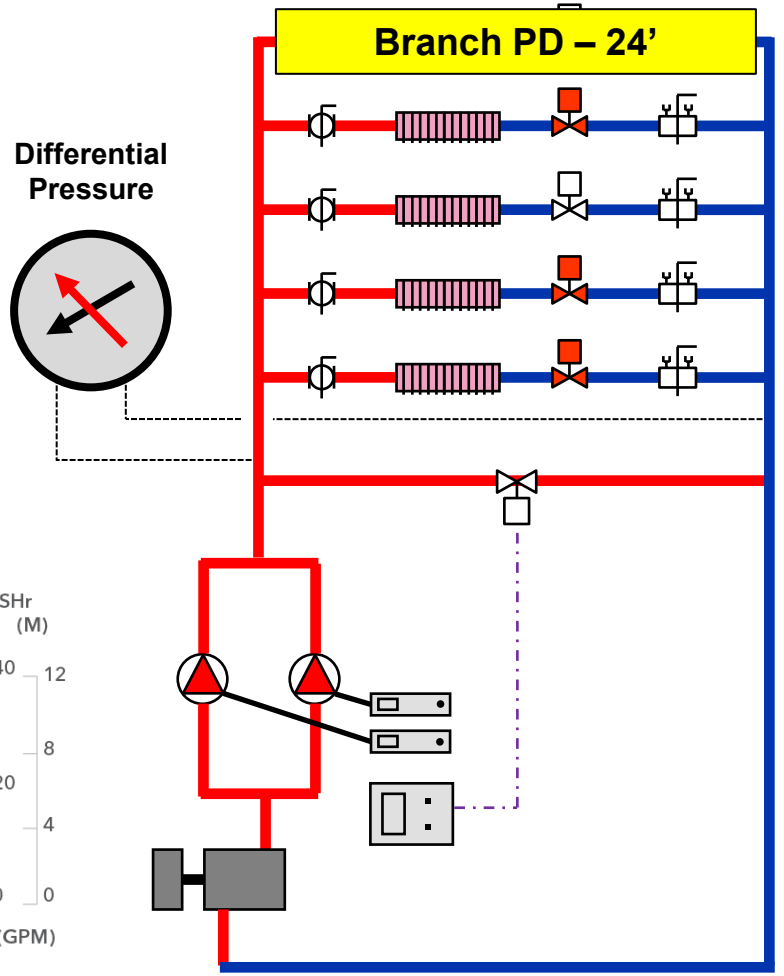
(1) e-1510 5EB with 10.5" Impeller
820 GPM @ 54' [1404 RPM]

- 13.1 BHP (30HP Mtr. NOL)





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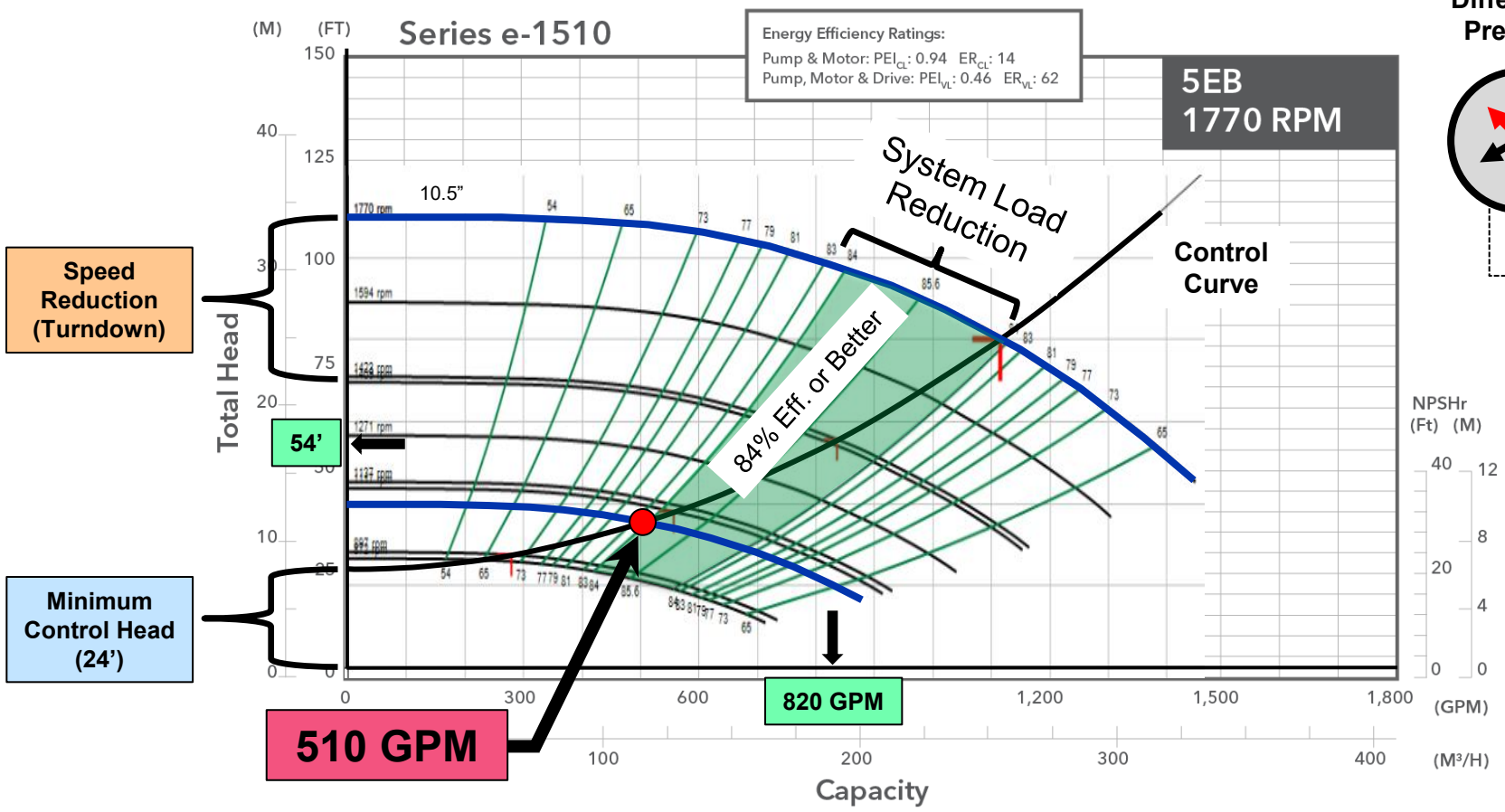
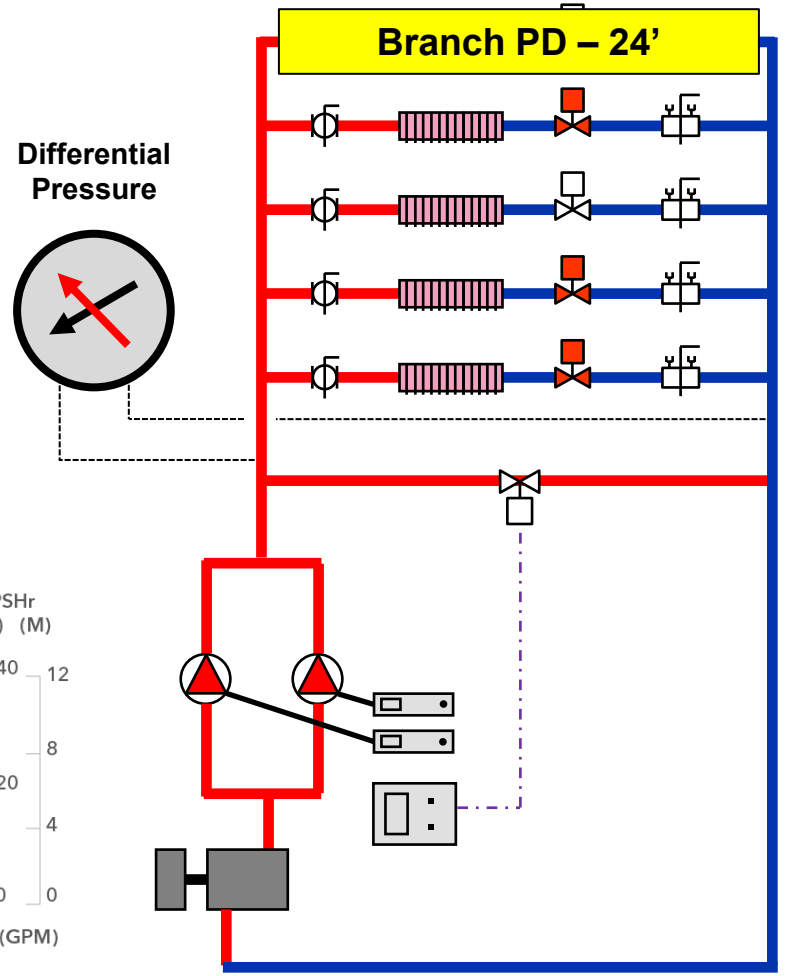
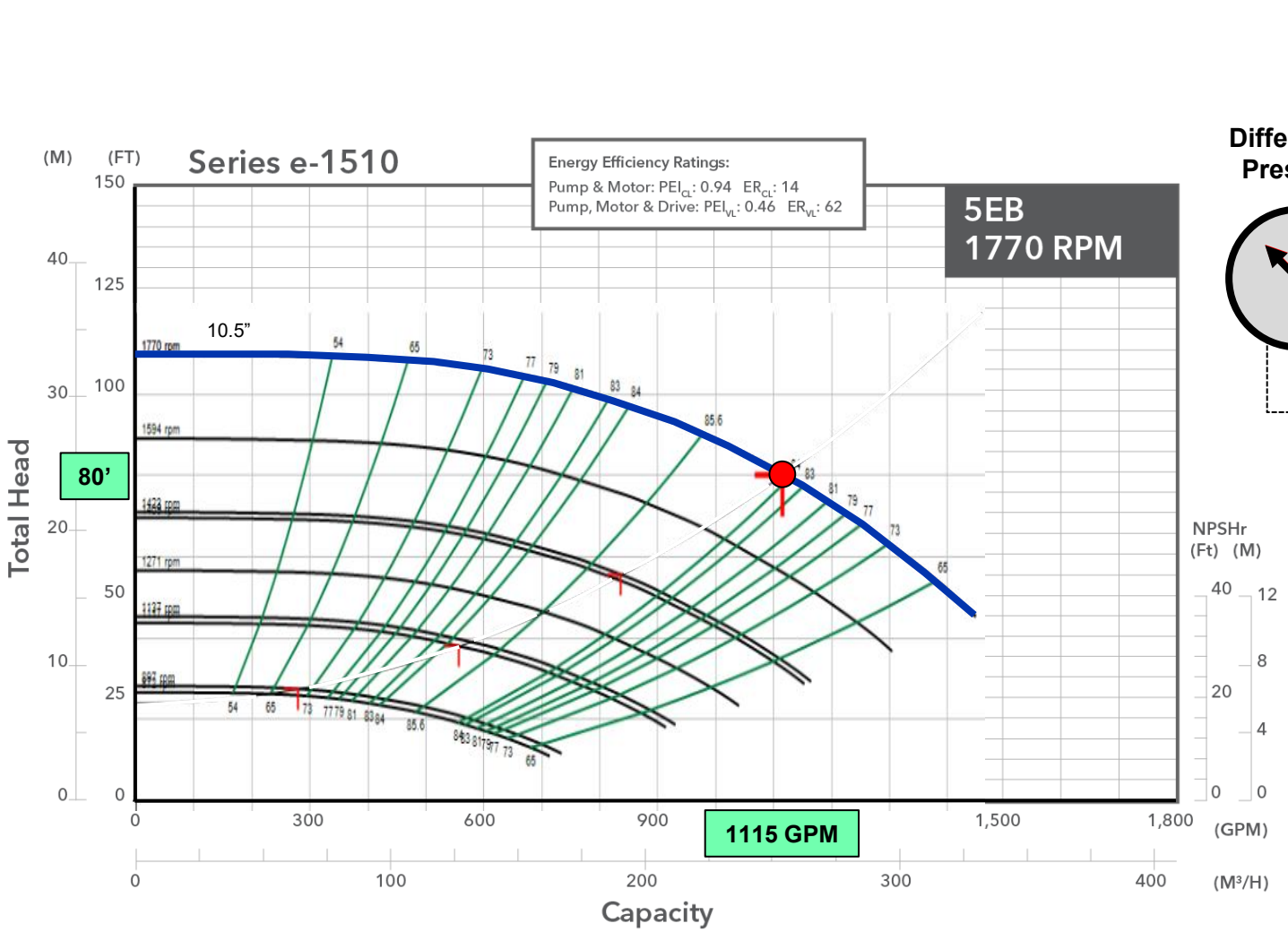
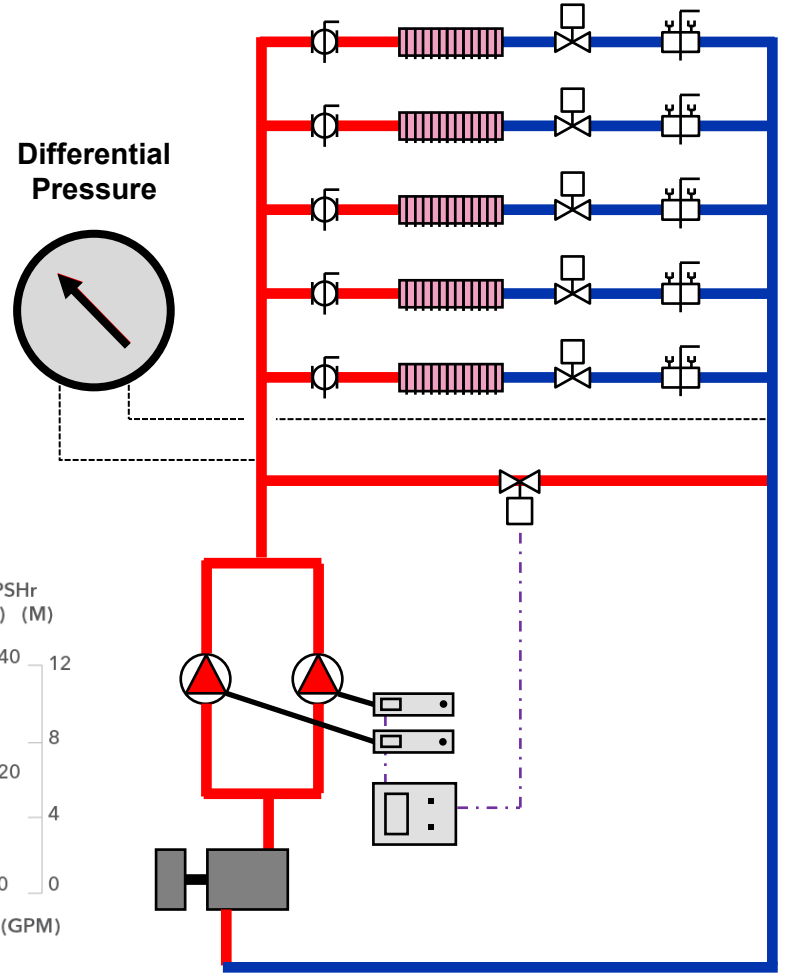




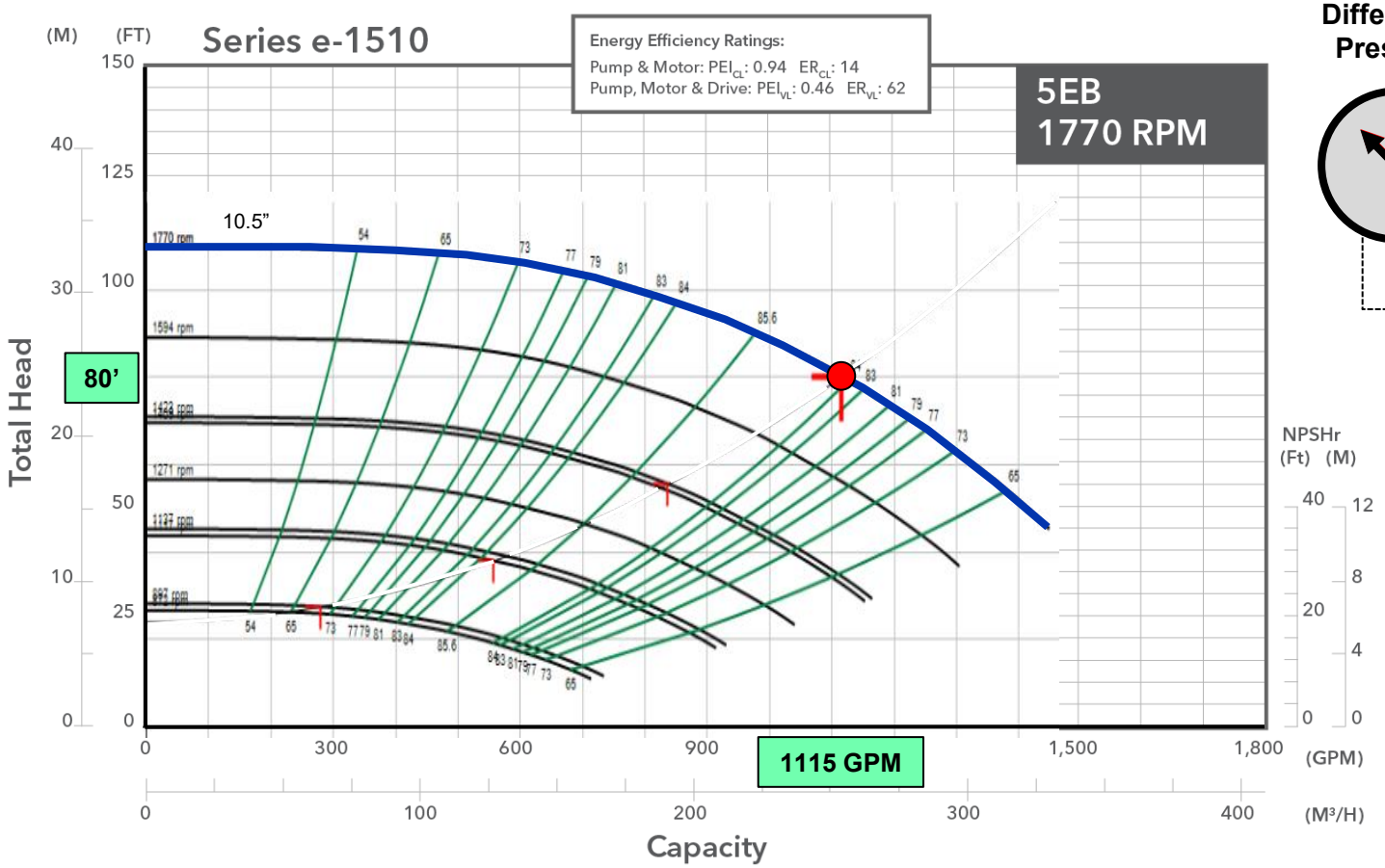
Setting the *Control Head* using the Mechanical Room

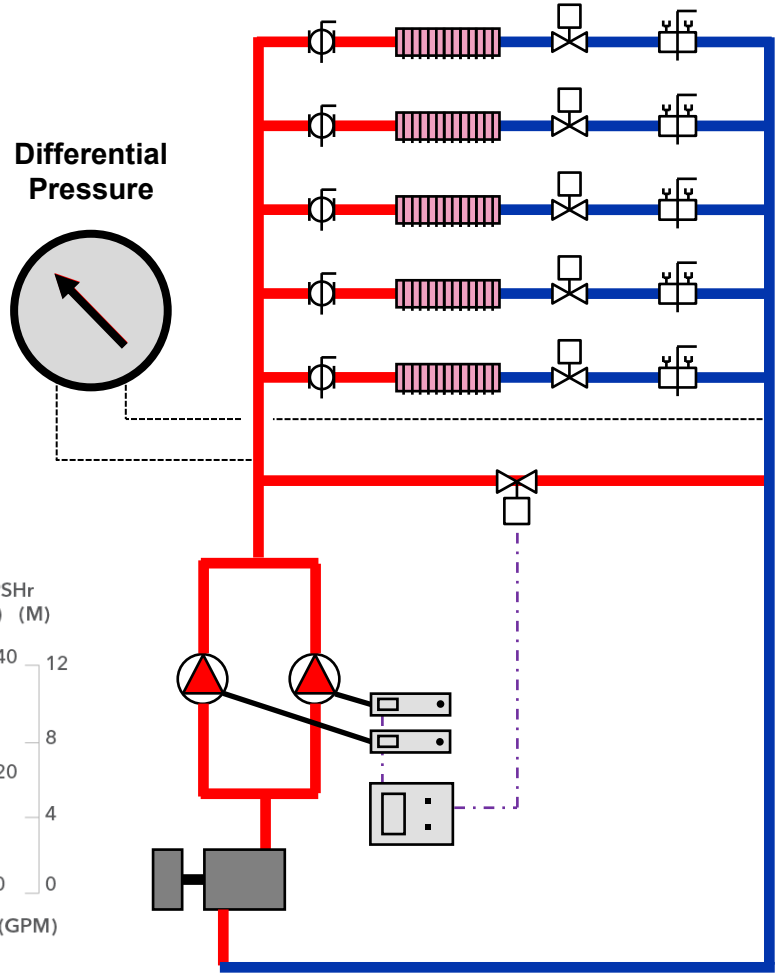




Setting the *Control Head* using the Mechanical Room

10% Variable Head Loss, 90% Constant Head Loss





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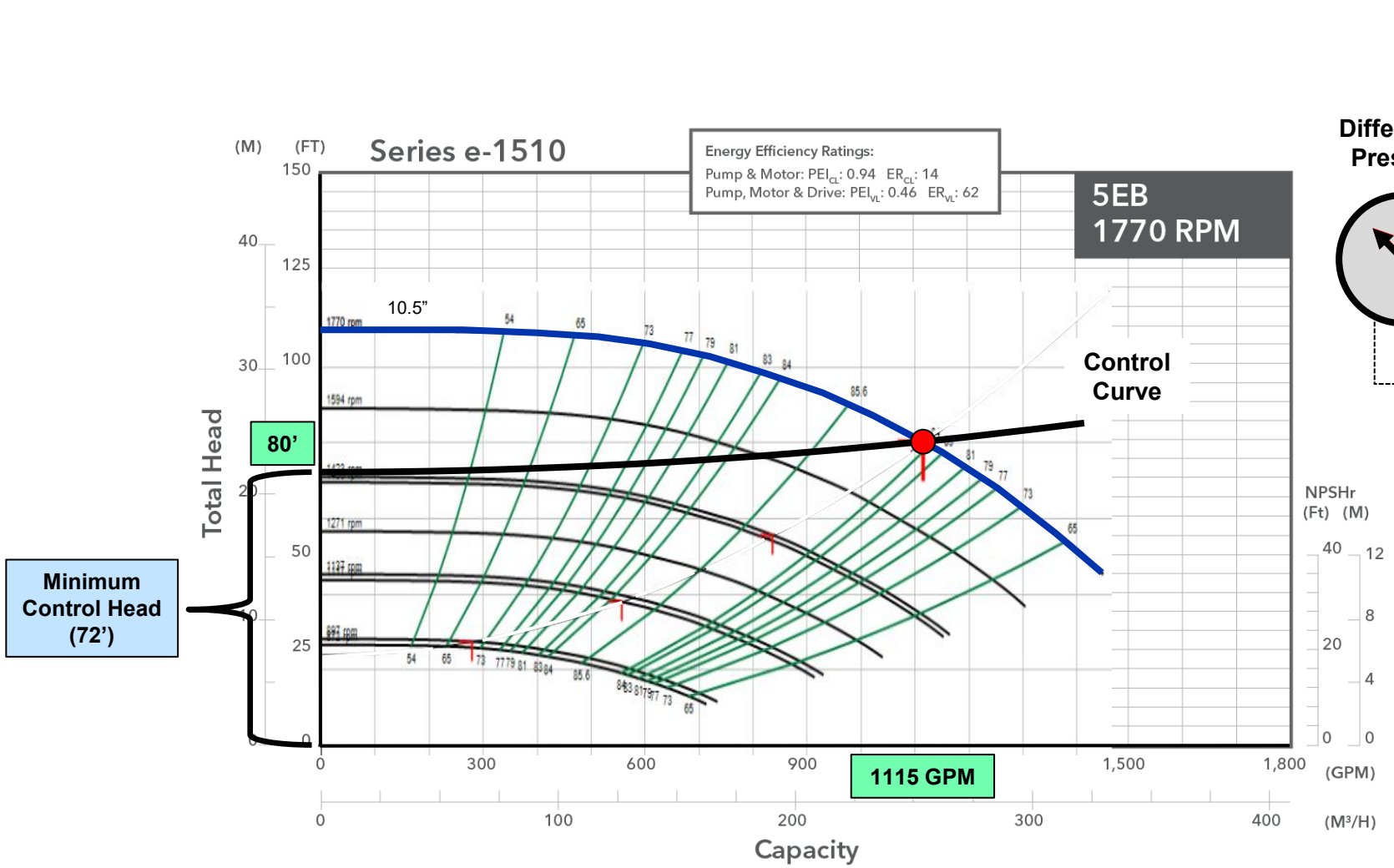

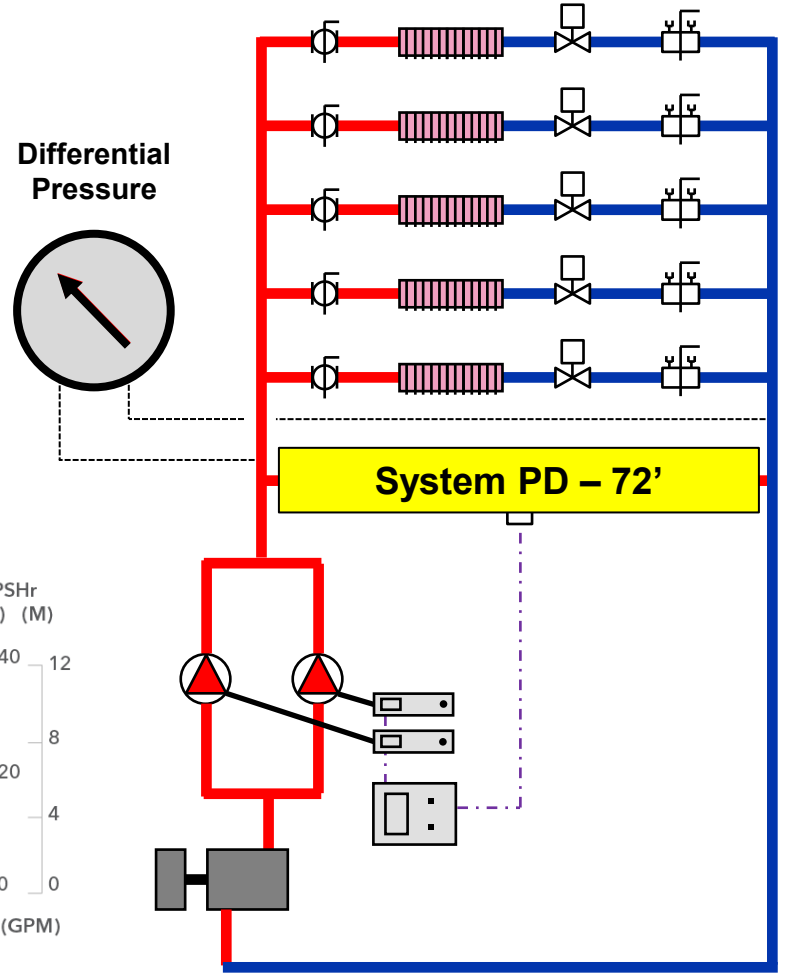

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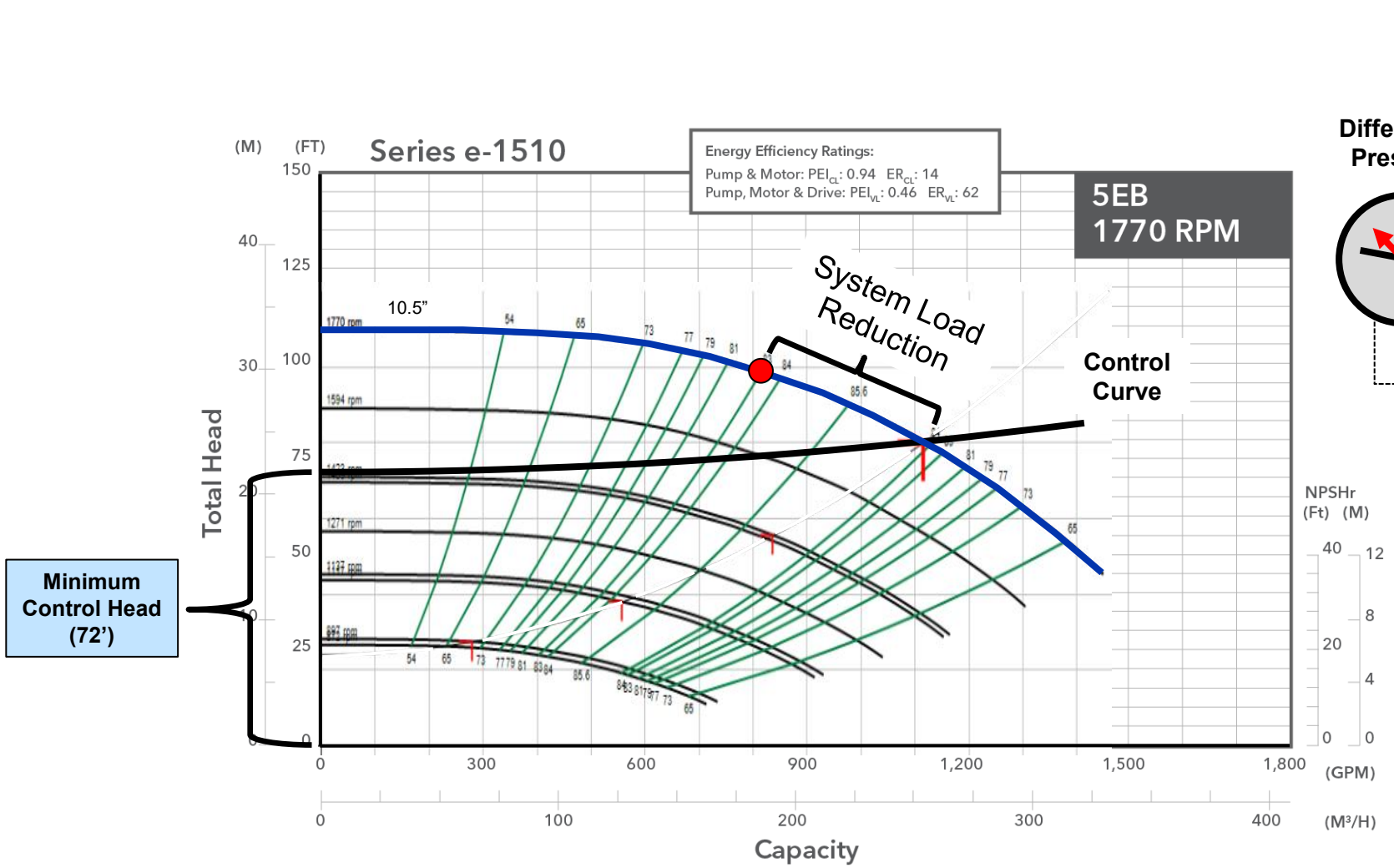

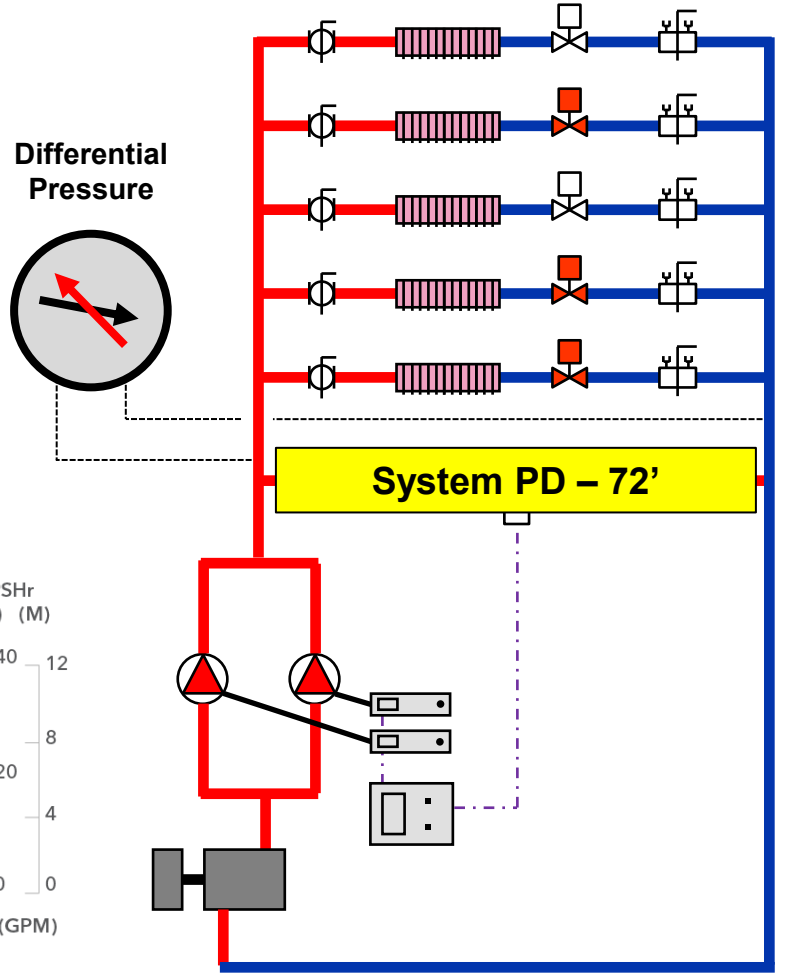

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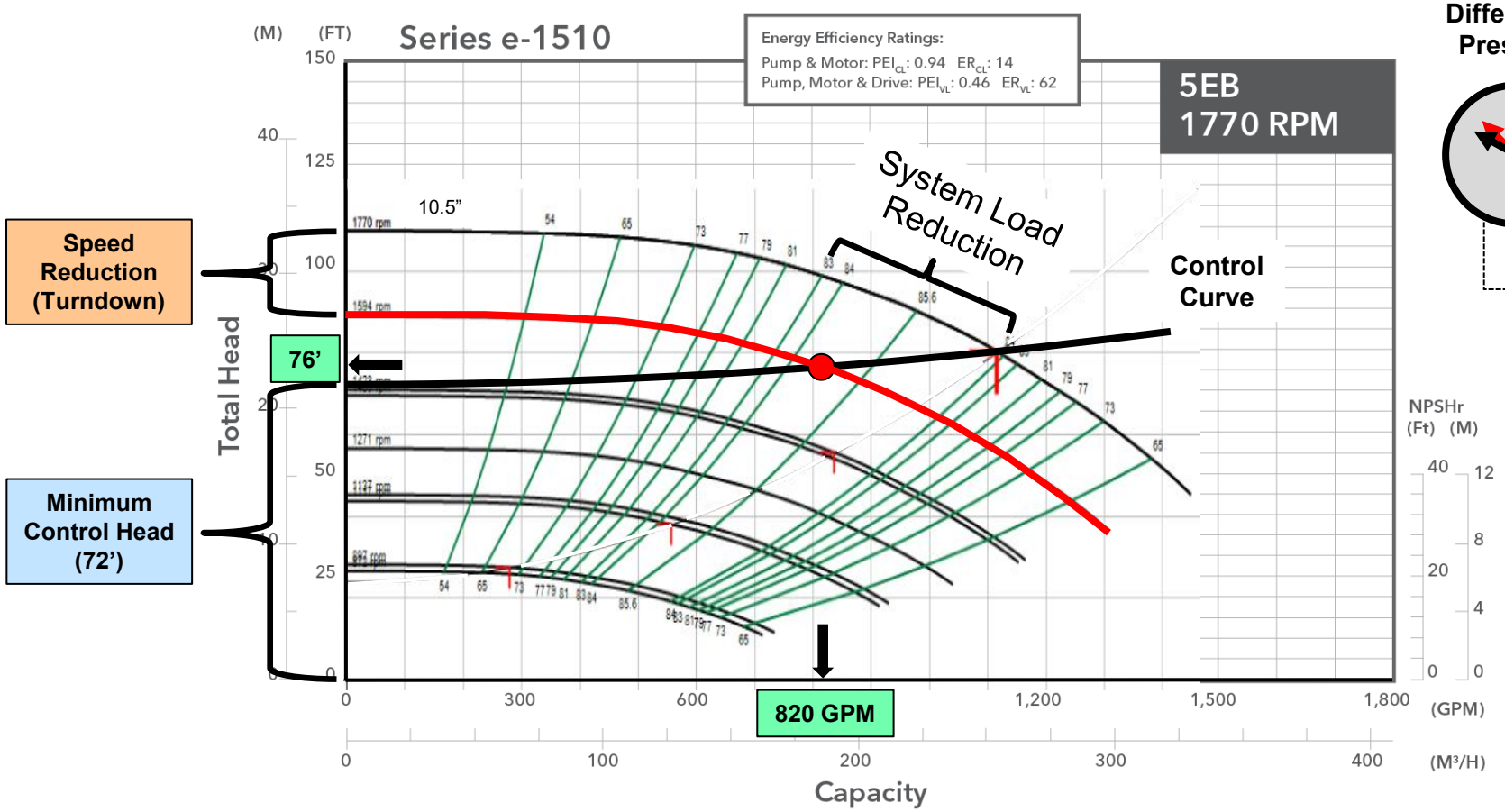

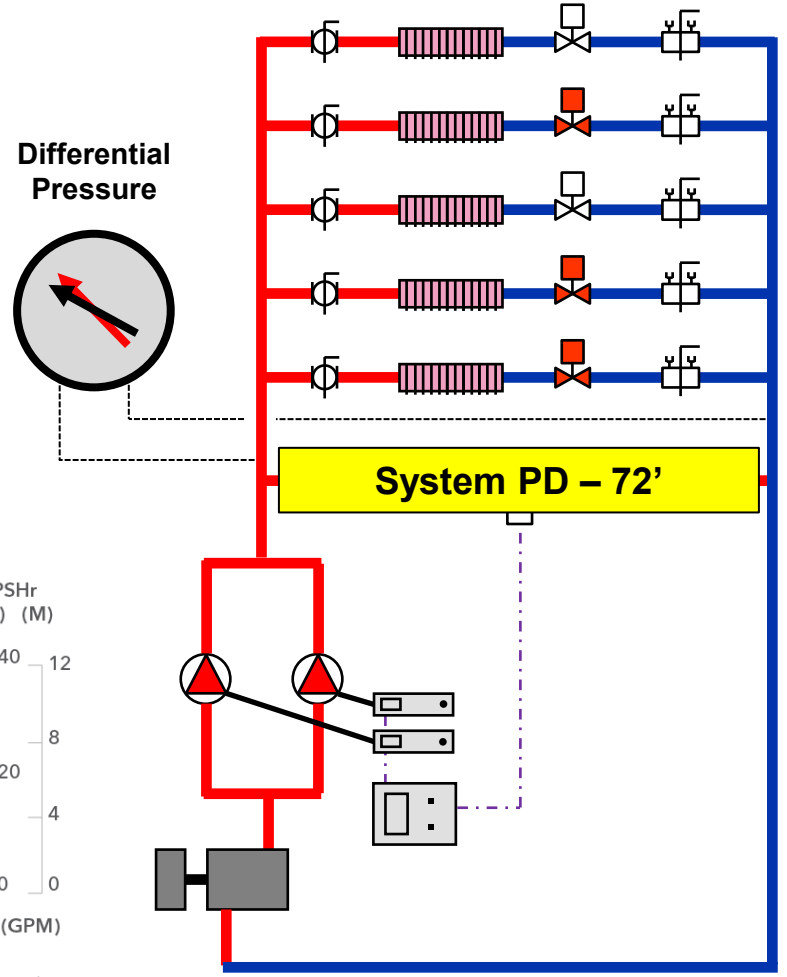

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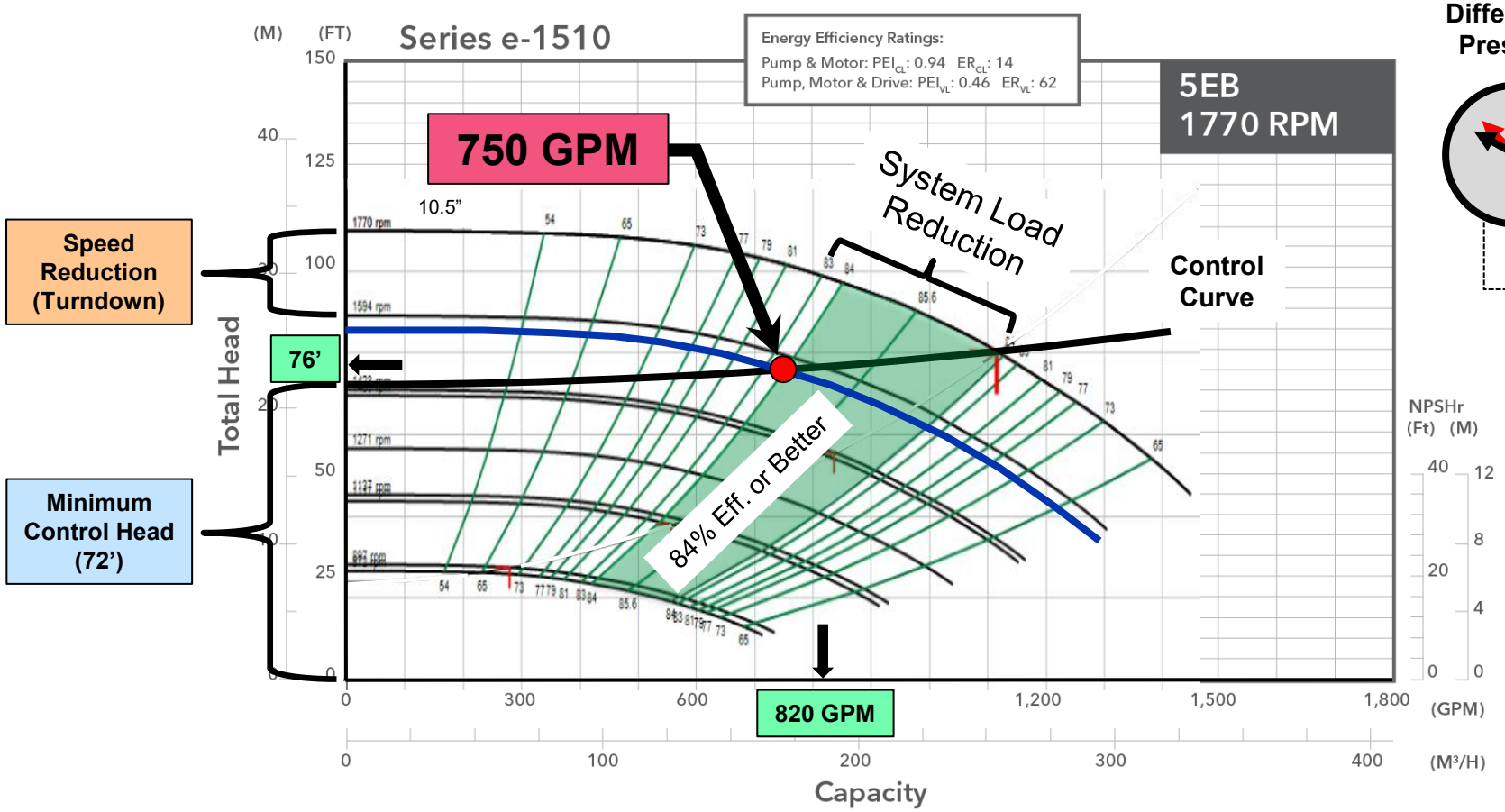
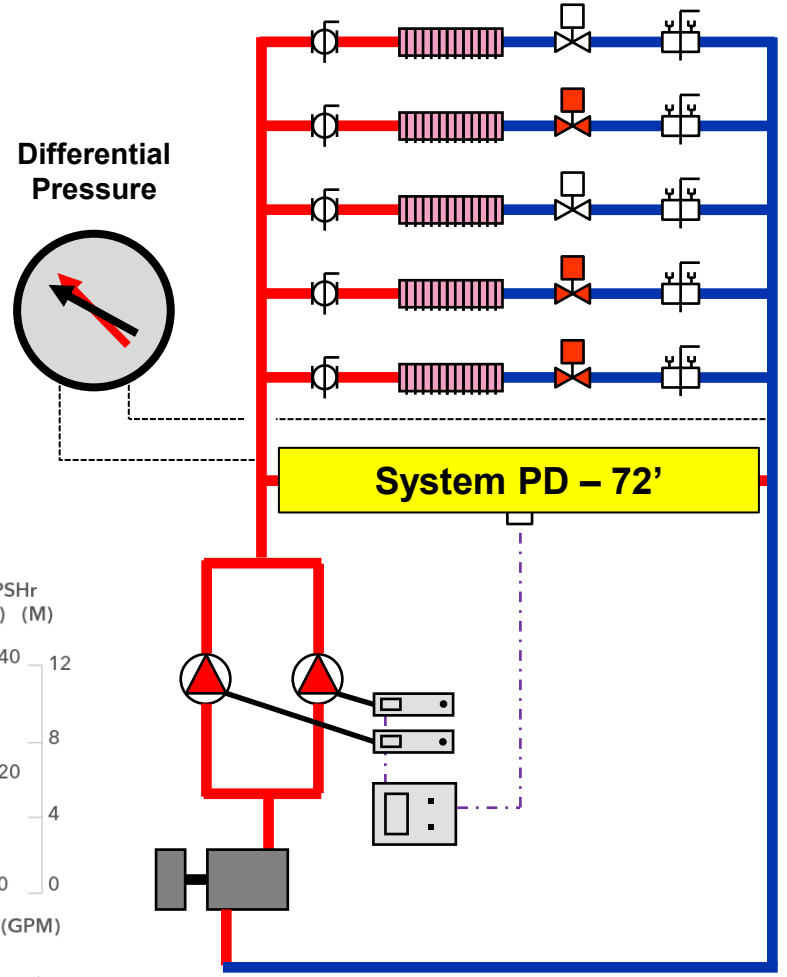
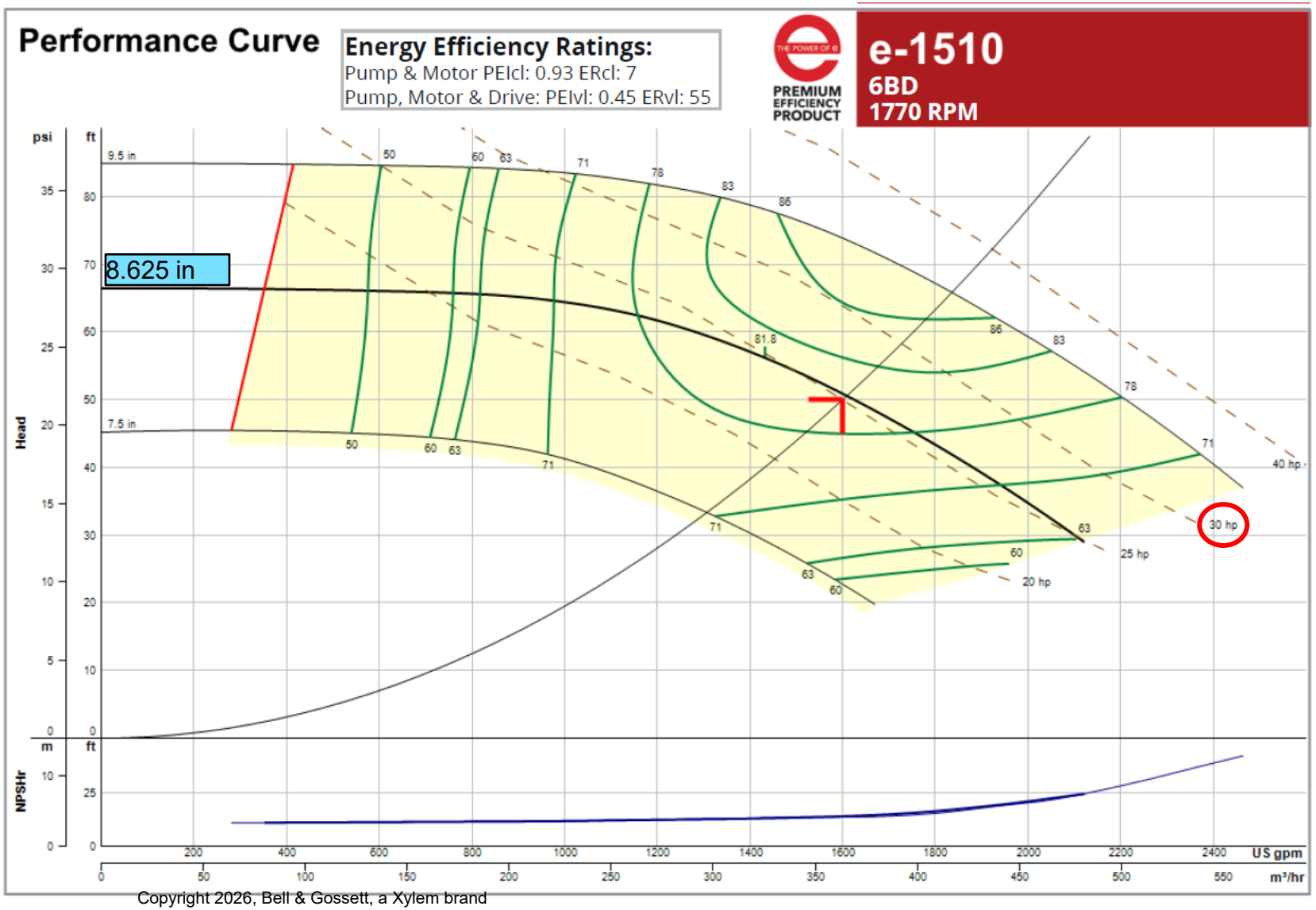




Closing "Tip" - Impeller Sizing for Maximum Efficiency

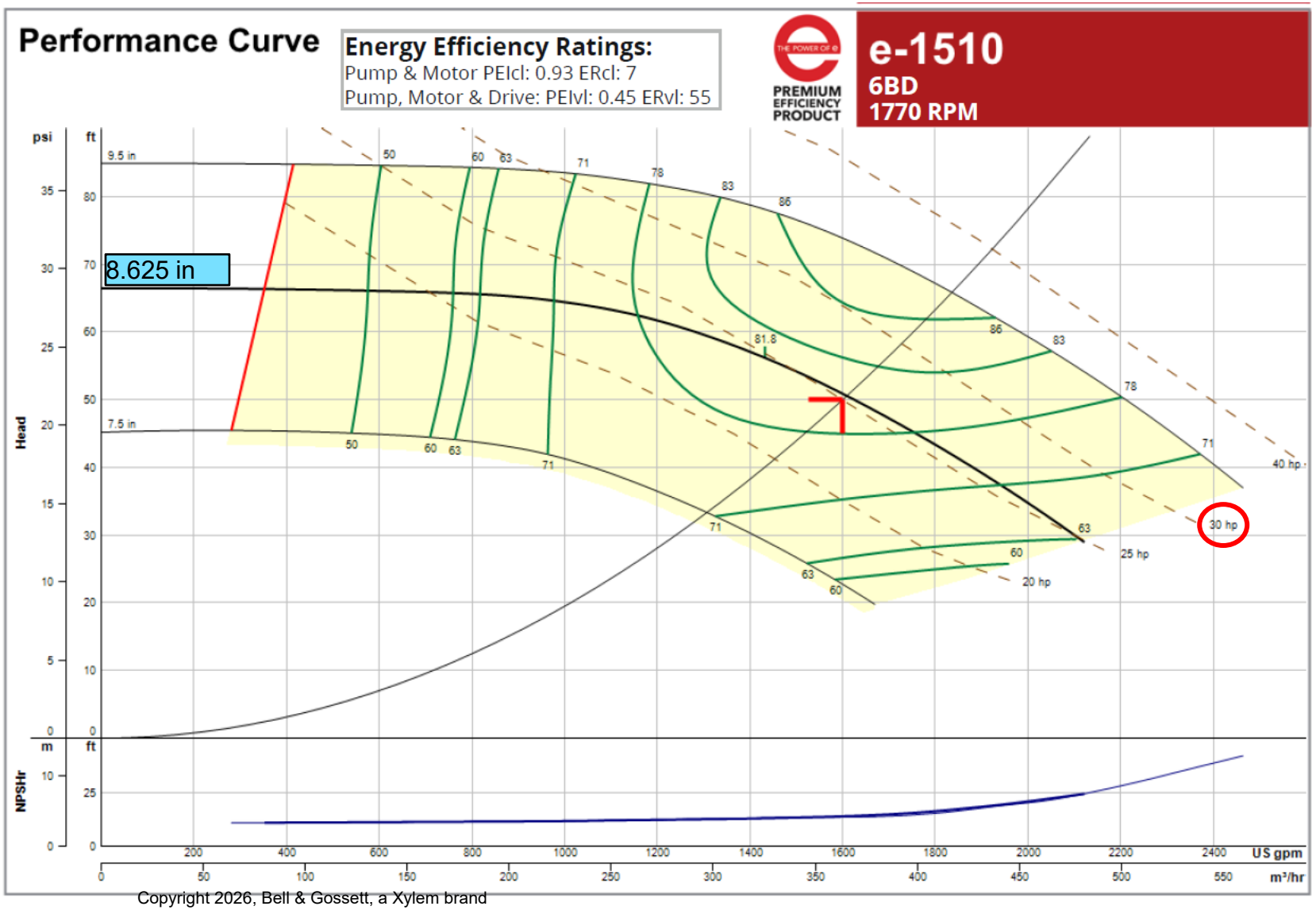
Trimmed to Duty Point



Pump Selection Summary	
Duty Point Flow	1600 US gpm
Duty Point Head	50 ft
Control Head	0 ft
Duty Point Pump Efficiency	79.7 %
Part Load Efficiency Value (PLEV)	0.0 %
Impeller Diameter	8.625 in
Motor Power	30 hp
Duty Point Power	25.3 bhp
Motor Speed	1800 rpm
RPM @ Duty Point	1770 rpm
NPSHr	14.3 ft
Minimum Shutoff Head	66.4 ft
Minimum Flow at RPM	329 US gpm
Flow @ BEP	1432 US gpm
Fluid Temperature	68 °F
Fluid Type	Water
Weight *(approx. - consult rep for exact)*	928 lbs
Pump Floor Space Calculation	8.74 ft²

Closing "Tip" - Impeller Sizing for Maximum Efficiency

Trimmed to Duty Point



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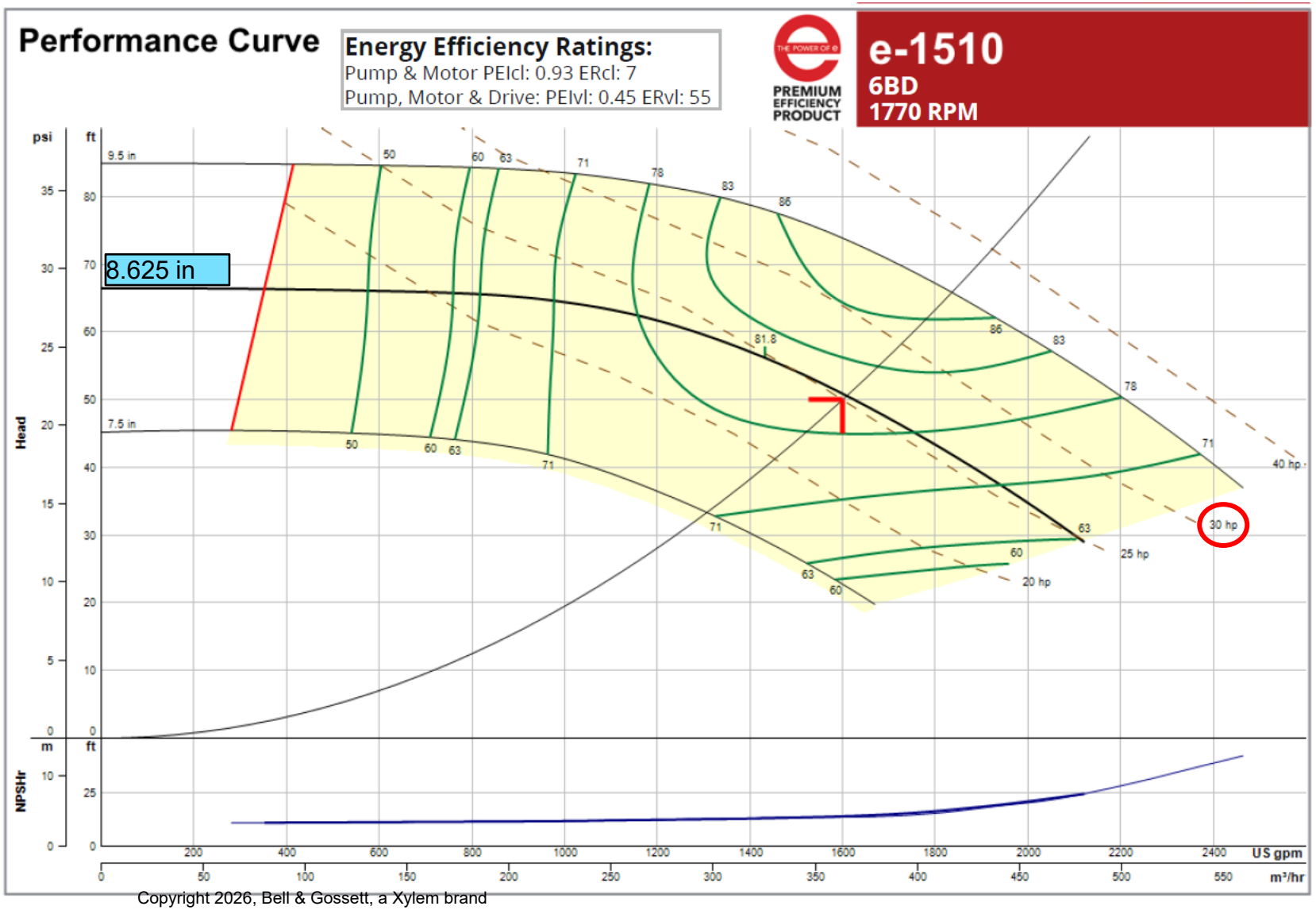

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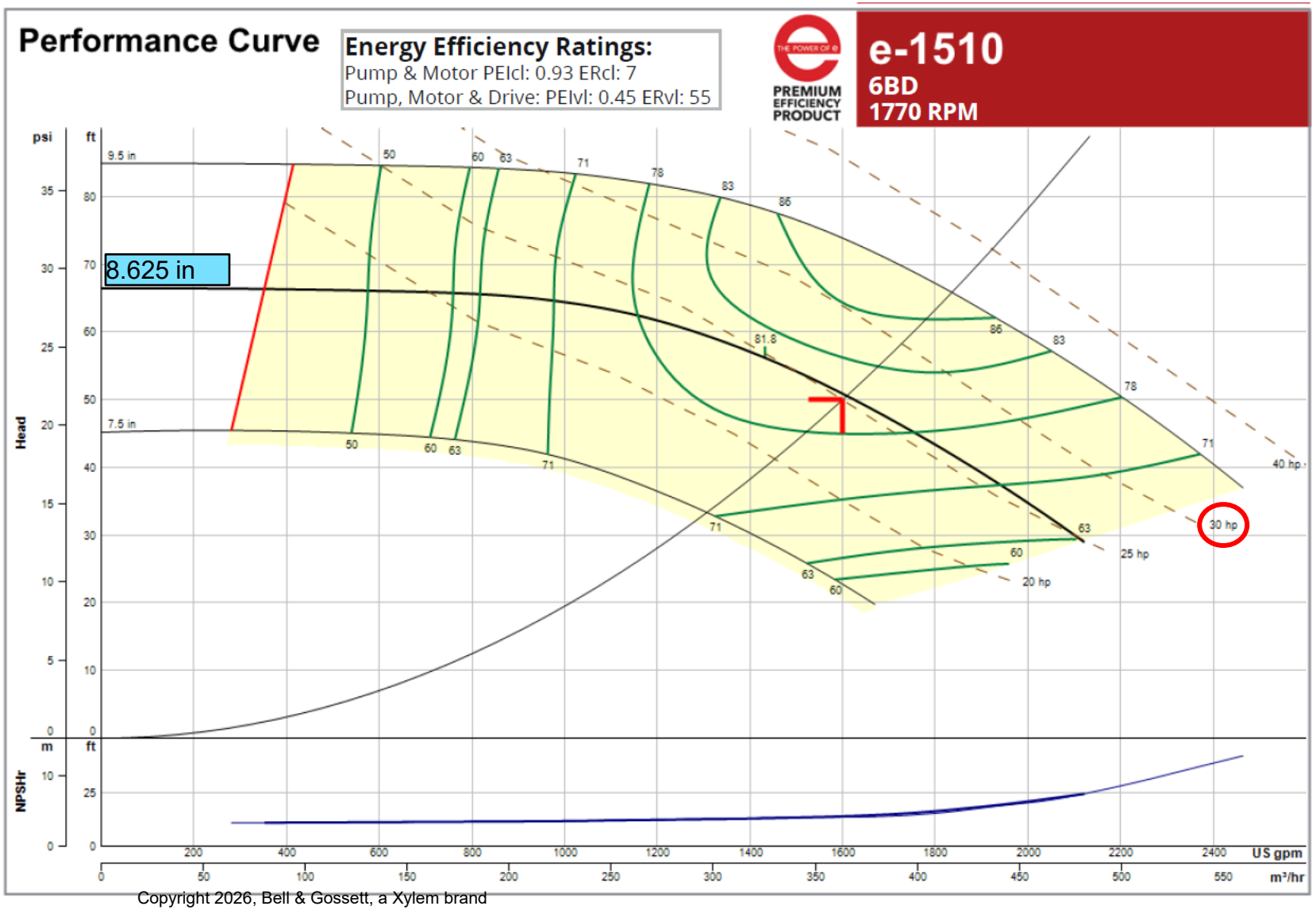

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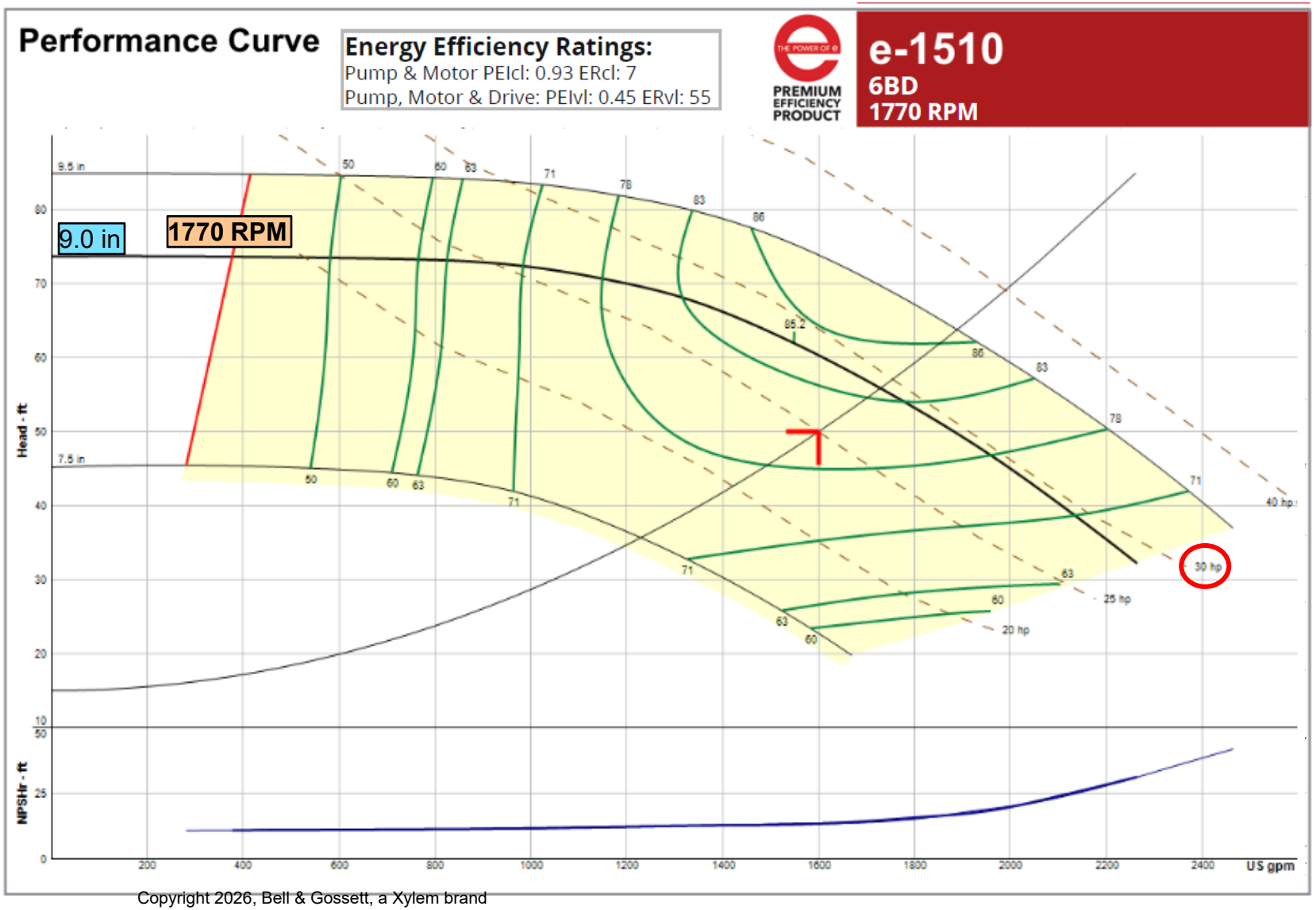
Closing "Tip" - Impeller Sizing for Maximum Efficiency

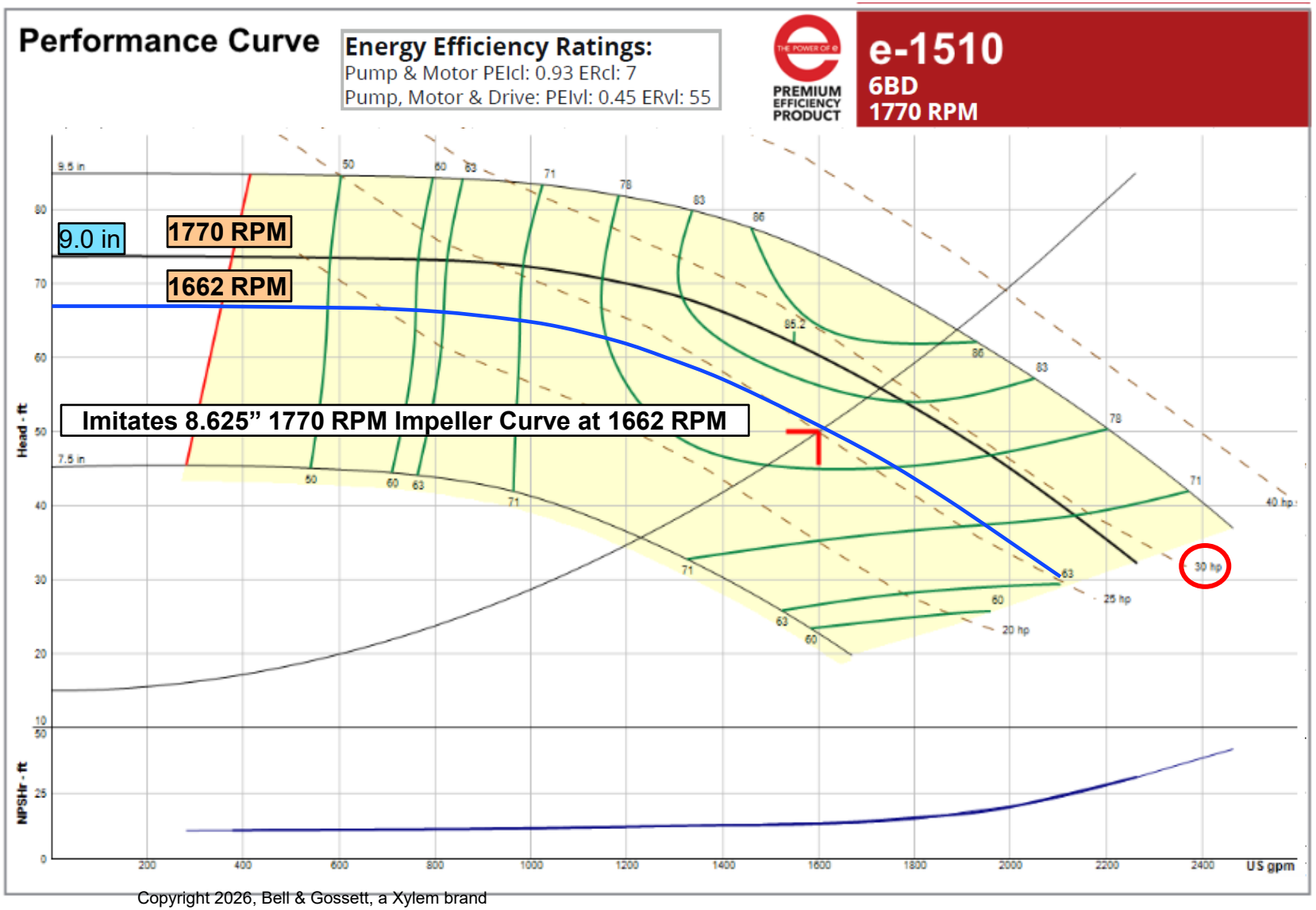
Trimmed to Largest Diameter for Motor Size



Pump Selection Summary	
Duty Point Flow	1600 US gpm
Duty Point Head	50 ft
Control Head	15 ft
Duty Point Pump Efficiency	84 %
Part Load Efficiency Value (PLEV)	80.9 %
Impeller Diameter	9 in
Motor Power	30 hp
Duty Point Power	24 bhp
Motor Speed	1800 rpm
RPM @ Duty Point	1662 rpm
NPSHr	12.8 ft
Minimum Shutoff Head	65 ft
Minimum Flow at RPM	334 US gpm
Flow @ BEP	1454 US gpm
Fluid Temperature	68 °F
Fluid Type	Water
Weight *(approx. - consult rep for exact)*	928 lbs
Pump Floor Space Calculation	8.74 ft²

Closing "Tip" - Impeller Sizing for Maximum Efficiency

Trimmed to Largest Diameter for Motor Size



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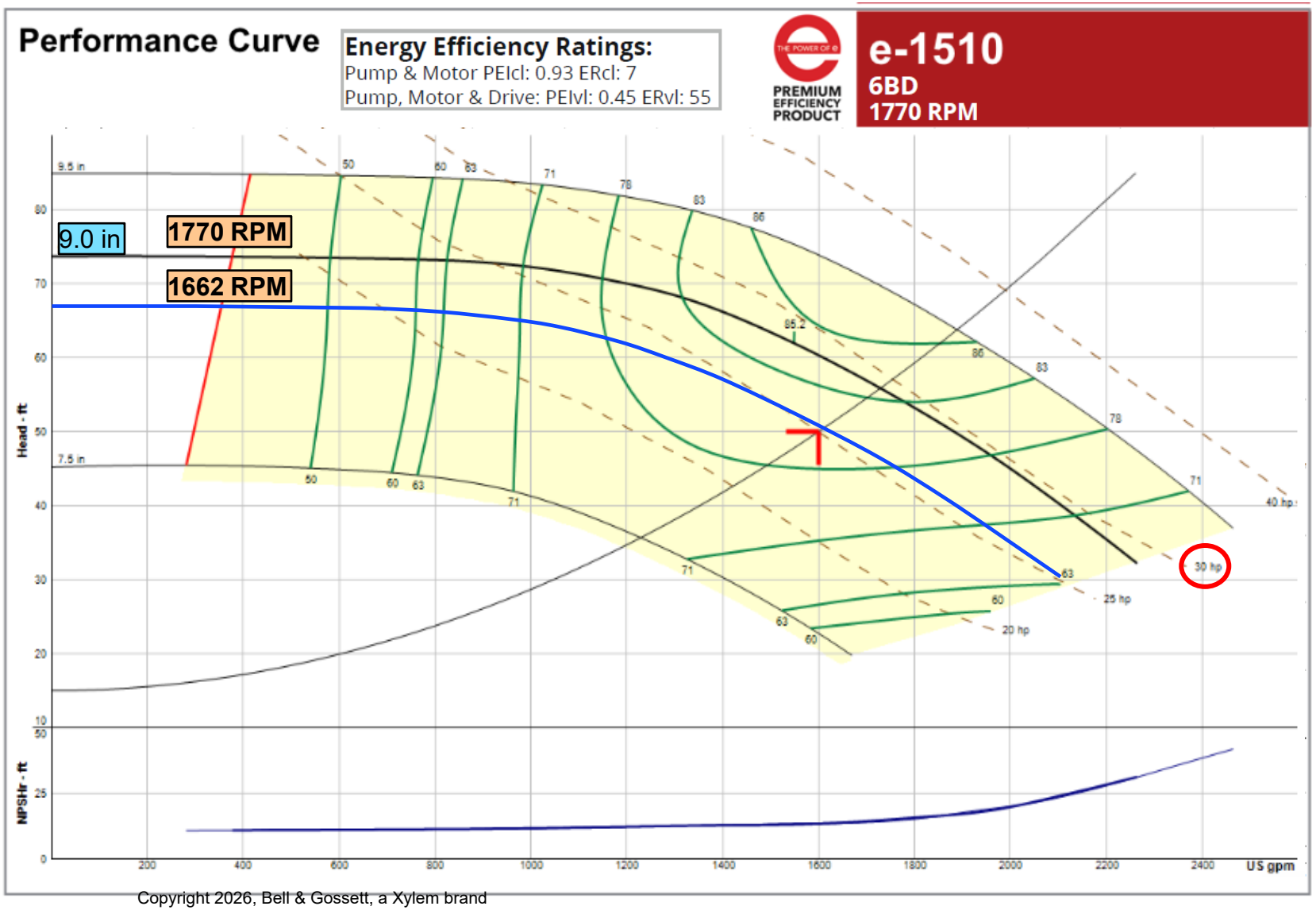
Closing "Tip" - Impeller Sizing for Maximum Efficiency

Largest Diameter at Reduced Speed to meet Duty Point



Efficiency Gain:

84% - 79.7% = 4.3%

BHP Reduction:

25.3 – 24.0 = 1.3 BHP