Hydronic Systems Balance

Balancing Is Misunderstood

- Balancing is application of fundamental hydronic system math
- "Balance"
  - Adjustment of friction loss location
  - Adjustment of pump to requirements
  - By definition: Achieve ±10% Flow rate or better for required heat transfer of 97.5%
- Balancing cannot make up for poor design and component choices

- Evaluation Method: System Curve Math
  - System and Component Flow Coefficients

$$q = C_V \sqrt{\Delta P} \quad \text{or} \quad C_V = \frac{q}{\sqrt{\Delta P}}$$

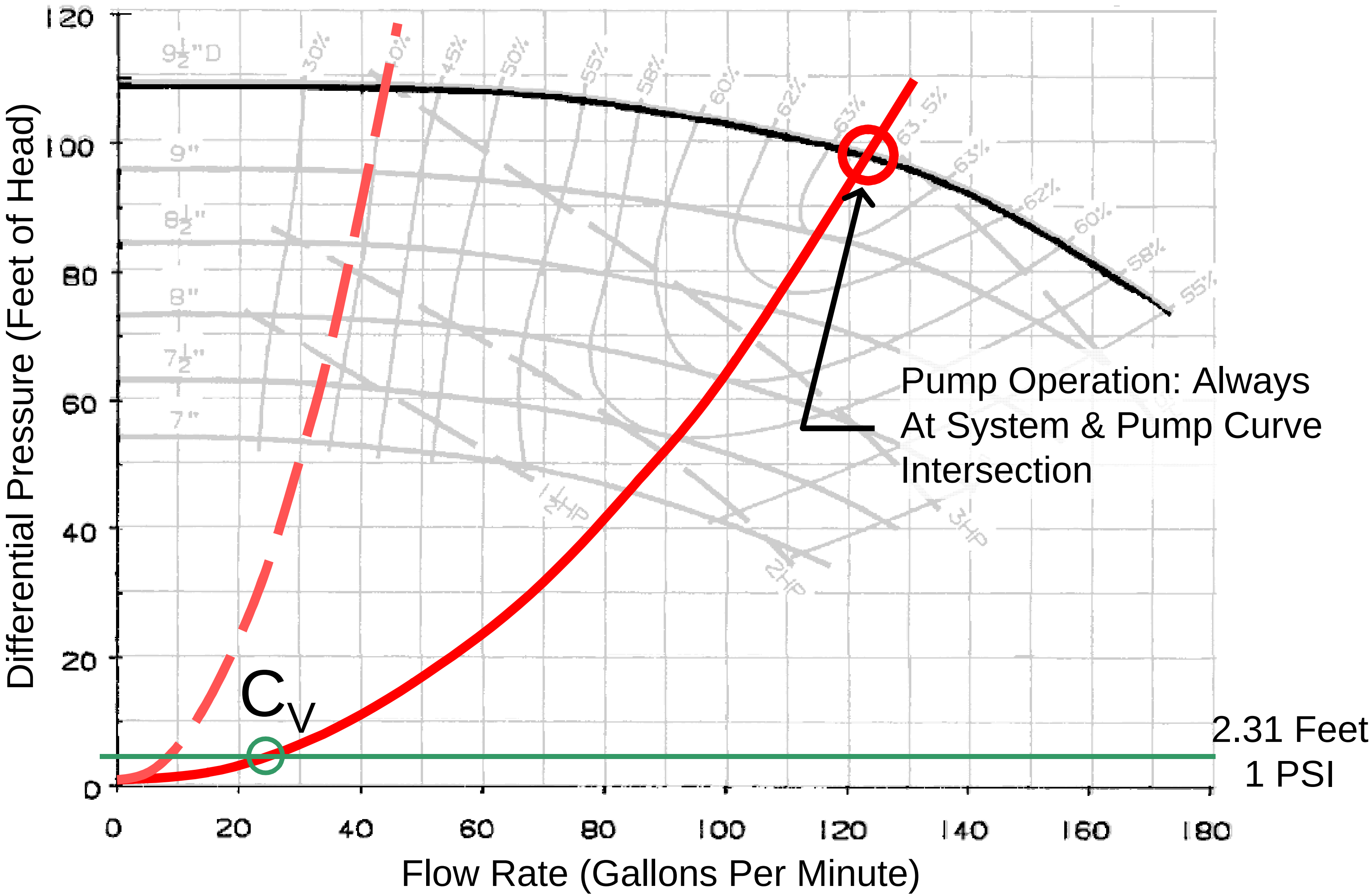
  - Components in series

$$\frac{1}{C_{VE}^2} = \frac{1}{C_{V1}^2} + \frac{1}{C_{V2}^2} + \frac{1}{C_{V3}^2} + \ldots + \frac{1}{C_{Vn}^2}$$

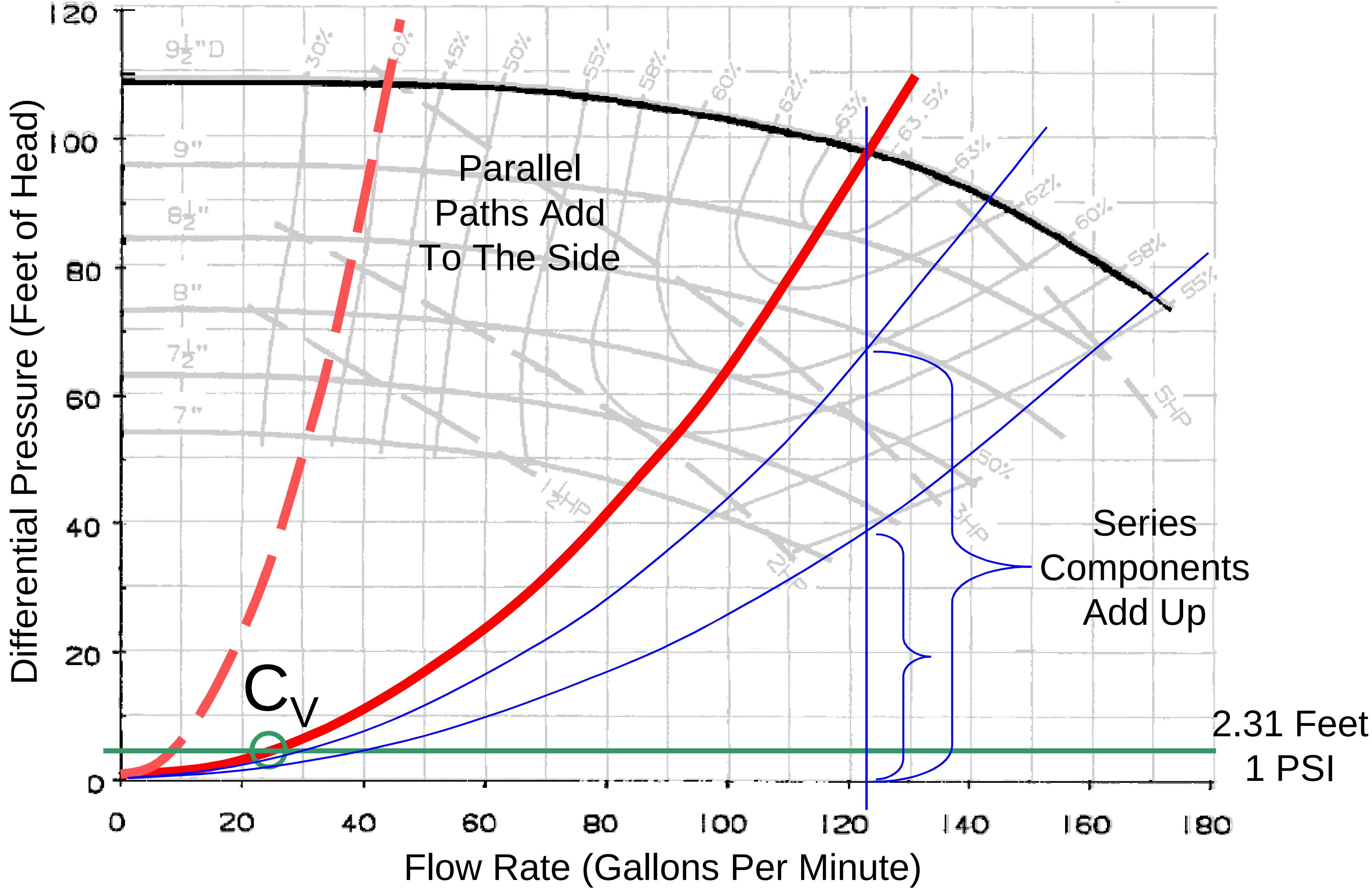
  - Paths in parallel

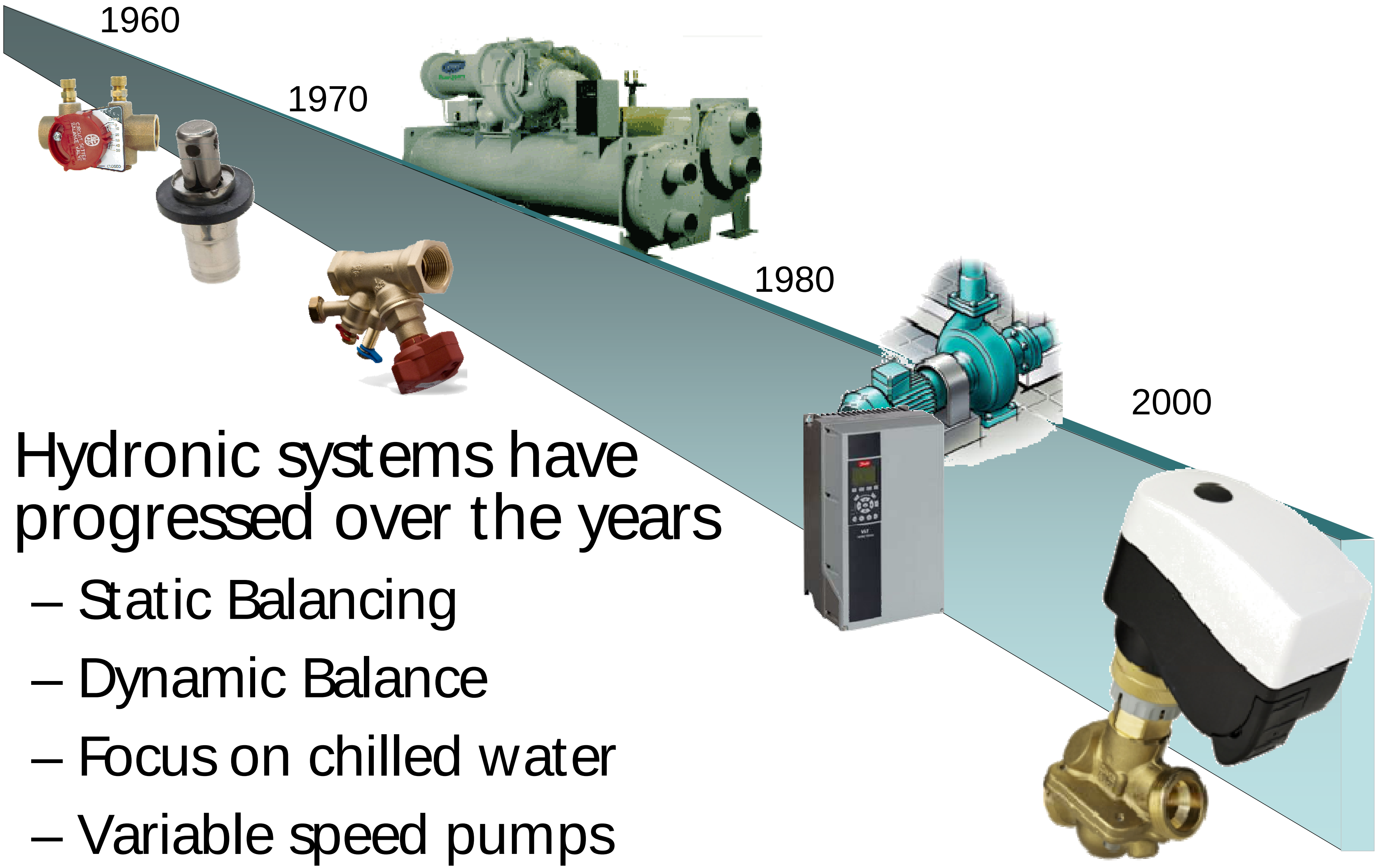
$$C_{VE} = C_{V1} + C_{V2} + C_{V3} + \ldots + C_{Vn}$$

- Evaluation Method: System Curve Math
  - Pump & System Curve & Spreadsheet



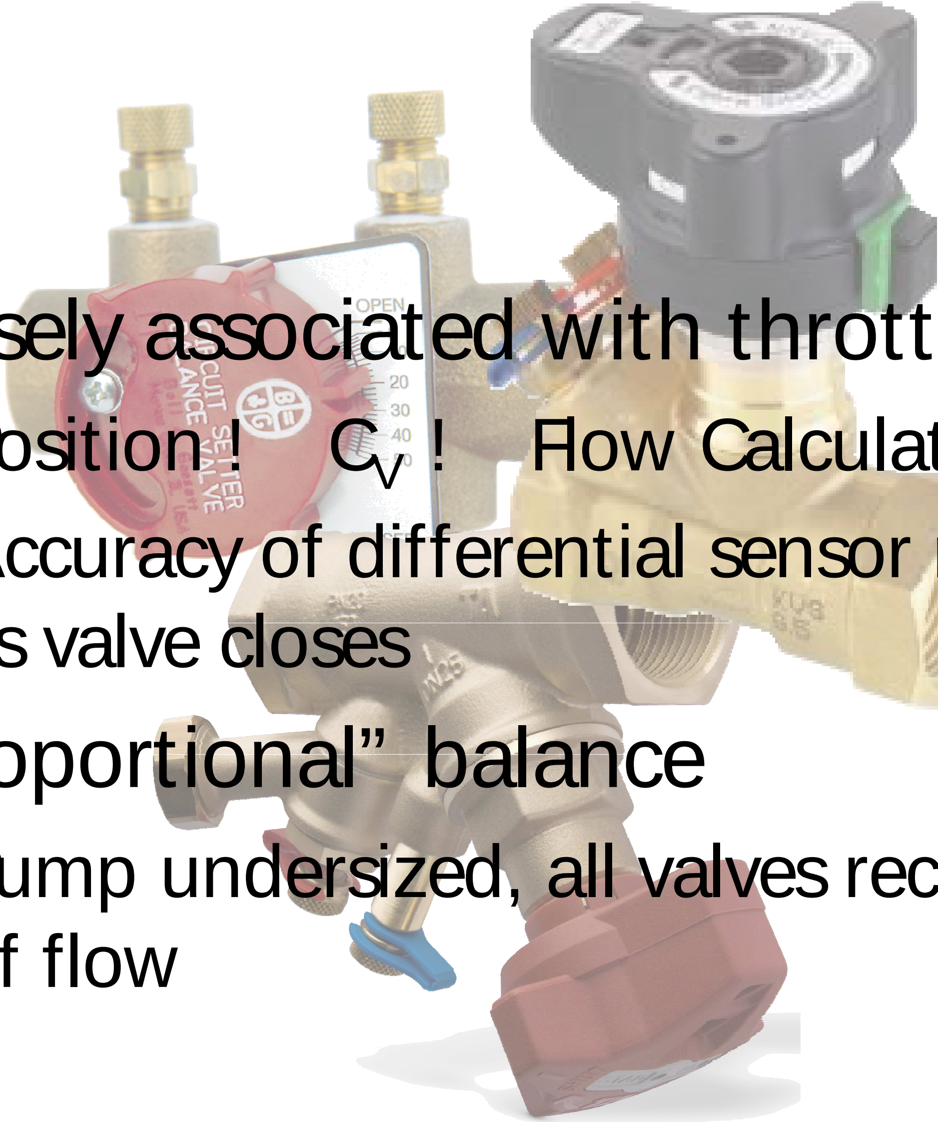
- Evaluation Method: System Curve Math
  - Pump & System Curve & Spreadsheet



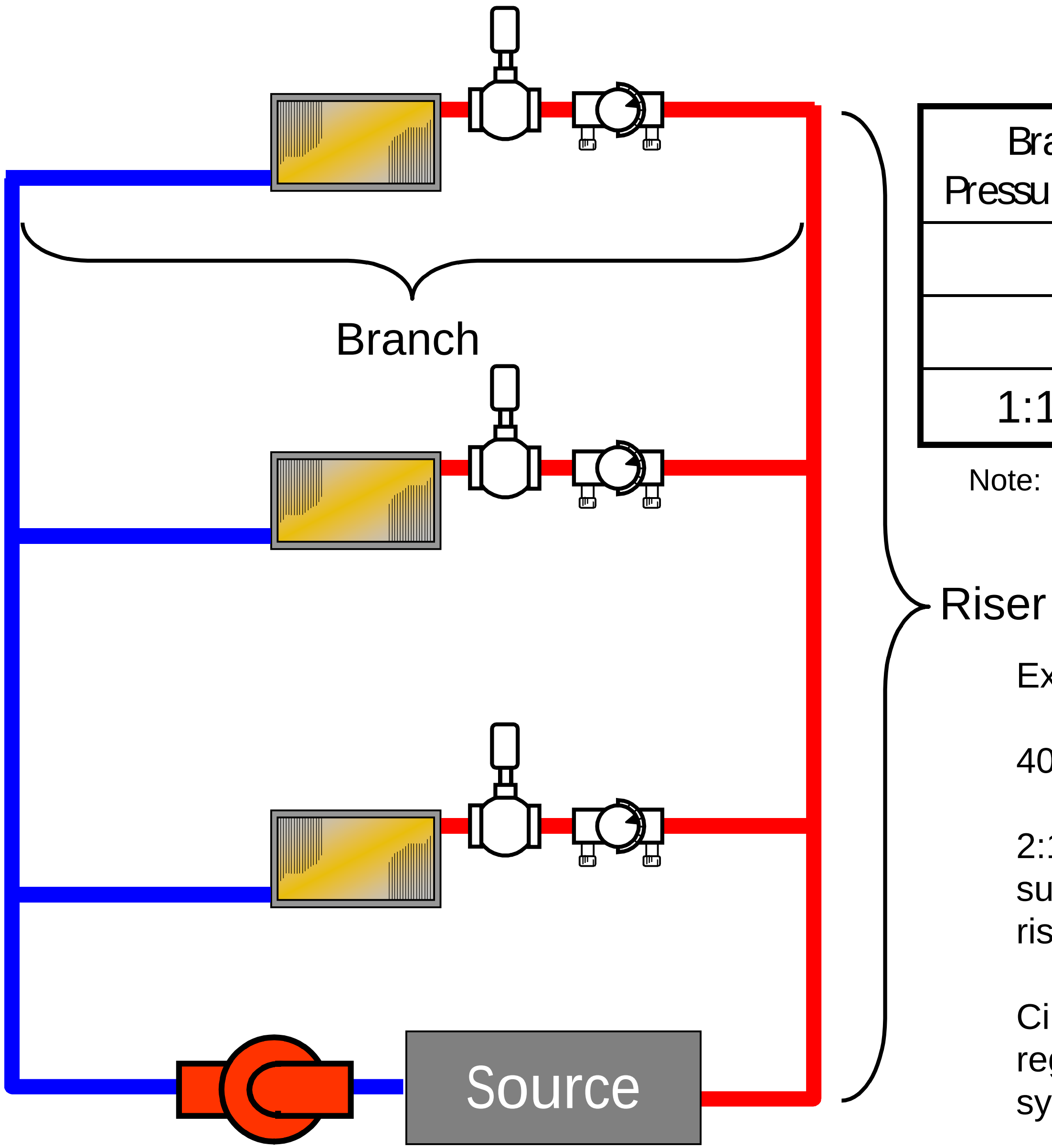


- Hydronic systems have progressed over the years
  - Static Balancing
  - Dynamic Balance
  - Focus on chilled water
  - Variable speed pumps
  - Pressure regulated control valves

Static Balance



- Closely associated with throttling valves
  - Position ! C_V ! Flow Calculation
  - Accuracy of differential sensor needs to adapt as valve closes
- "Proportional" balance
  - Pump undersized, all valves receive percentage of flow



Branch Riser Pressure Drop Ratio	Percent Design Flow All Circuits
4:1	95%
2:1	90%
1:1 and less	80% and less

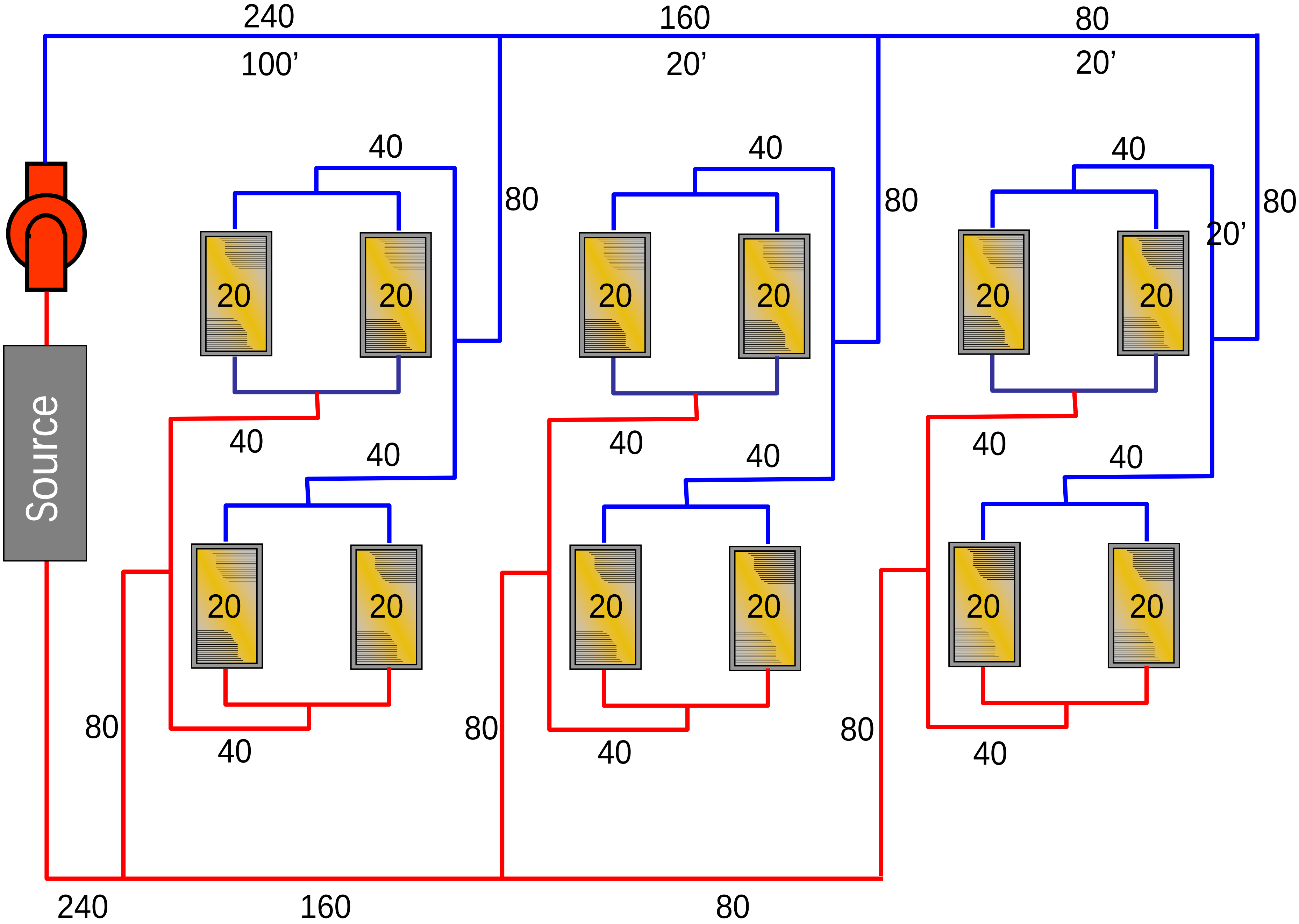
Note: Based on constant speed pumps

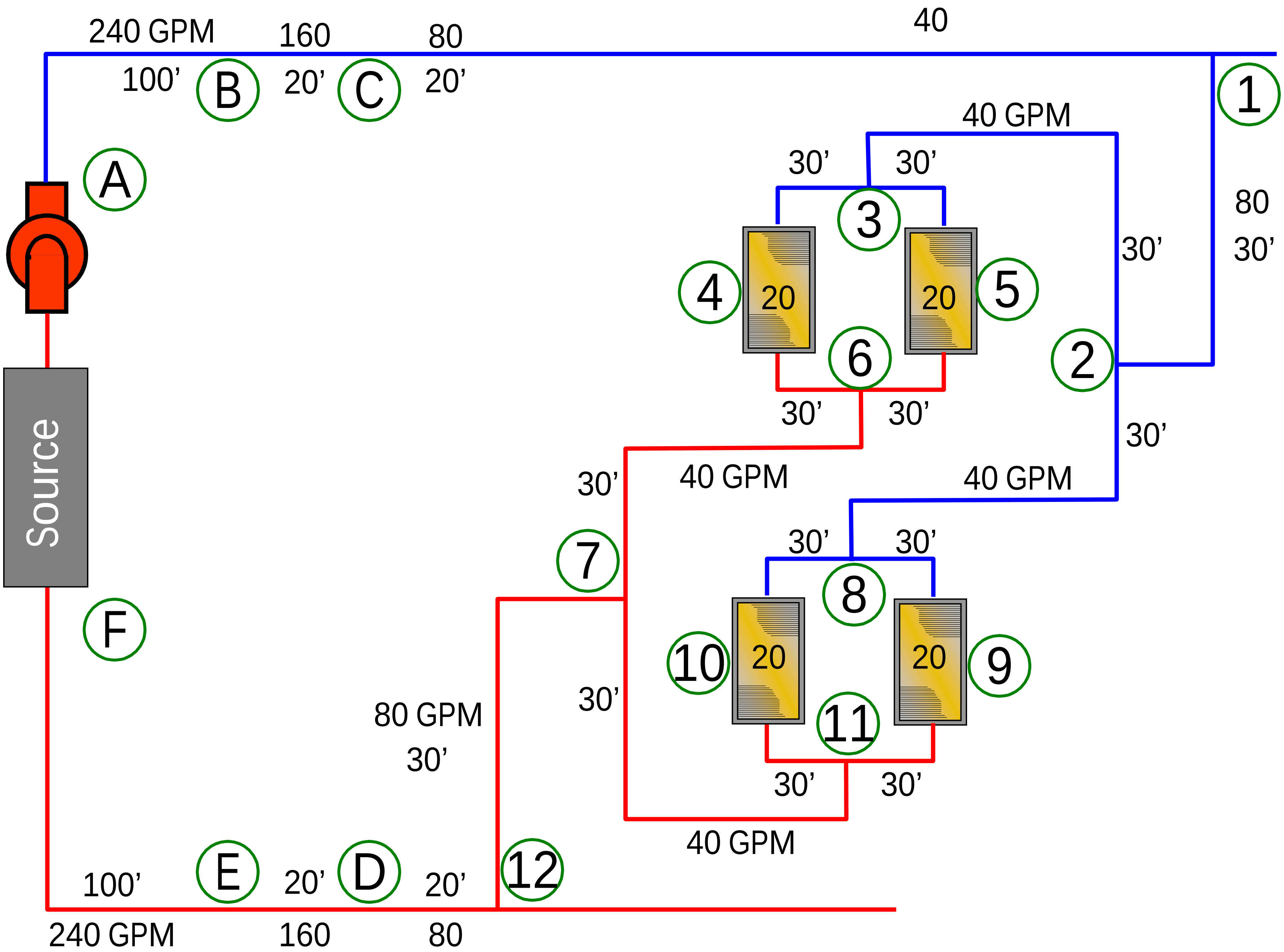
Example:

40 Ft Head loss in branch

2:1 Ratio equals 20 feet allowed in supply and return piping, or 10’ per riser.

Circuits can receive 90% design flow regardless of what other valves do in system


240
100'
160
20'
80
20'
40
80
40
80
40
80
20'
20
20
20
20
20
20
Source
40
40
40
40
40
40
20
20
20
20
20
20
80
40
80
40
80
40
240
160
80


240 GPM
160
80
40
100’
B
20’
C
20’
1
40 GPM
30’
30’
A
3
80
30’
30’
4
20
20
5
6
2
30’
30’
Source
30’
30’
40 GPM
40 GPM
30’
30’
7
8
F
10
20
20
9
80 GPM
30’
30’
11
30’
30’
40 GPM
100’
E
20’
D
20’
12
240 GPM
160
80

Friction Loss Charts

- Published by ASHRAE & Hydraulic Institute
- D/W Eqn.

STANDARDS OF THE HYDRAULIC INSTITUTE

TABLE ET-1

SCHEDULE 40 STEEL PIPE—FRICTION LOSS FOR WATER IN FEET PER 100 FEET

U. S. Gallons per Minute	¼ In.		⅜ In.		½ In.		¾ In.		U. S. Gallons per Minute	1 In.		1¼ In.		1½ In.	
	V Ft /Sec	h_f Frict.	V Ft /Sec	h_f Frict.	V Ft /Sec	h_f Frict.	V Ft /Sec	h_f Frict.		V Ft /Sec	h_f Frict.	V Ft /Sec	h_f Frict.	V Ft /Sec	h_f Frict.
0.8	2.47	12.7	......	......	......	......	......	......	6	2.23	2.68	......	......	......	......
1.0	3.08	19.1	......	......	......	......	......	......	8	2.97	4.54	......	......	......	......
1.2	3.70	26.7	......	......	......	......	......	......	10	3.71	6.86	......	......	......	......
1.4	4.32	35.3	2.35	7.85	......	......	......	......	12	4.45	9.62	2.57	2.48	......	......
120	11.5	24.7	8.04	10.0	5.21	3.37	3.02	0.877	600	9.62	5.88	6.66	2.34	3.85	0.597
140	13.4	33.2	9.38	13.5	6.08	4.51	3.53	1.17	700	11.2	7.93	7.77	3.13	4.49	0.797
160	15.3	43.0	10.7	17.4	6.94	5.81	4.03	1.49	800	12.8	10.22	8.88	4.03	5.13	1.02
180	......	......	12.1	21.9	7.81	7.28	4.54	1.86	900	14.4	12.9	9.99	5.05	5.77	1.27
200	......	......	13.4	26.7	8.68	8.90	5.04	2.27	1000	16.0	15.8	11.1	6.17	6.41	1.56
220	......	......	14.7	32.2	9.55	10.7	5.54	2.72	1100	......	......	12.2	7.41	7.05	1.87
240	......	......	16.1	38.1	10.4	12.6	6.05	3.21	1200	......	......	13.3	8.76	7.70	2.20
260	......	......	......	......	11.3	14.7	6.55	3.74	1300	......	......	14.4	10.2	8.34	2.56
280	......	......	......	......	12.2	16.9	7.06	4.30	1400	......	......	15.5	11.8	8.98	2.95
300	......	......	......	......	13.0	19.2	7.56	4.89	1500	......	......	......	......	9.62	3.37
350	......	......	......	......	15.2	26.1	8.82	6.55	1600	......					3.82
400	......	......	......	......	......	......	10.10	8.47	1700	......					4.29
450	......	......	......	......	......	......	11.4	10.65	1800	......					4.79
500	......	......	......	......	......	......	12.6	13.0	1900	......					5.31
550	......	......	......	......	......	......	13.9	15.7	2000	......					5.86
600	......	......	......	......	......	......	15.1	18.6	2100	......					6.43
									2200	......					

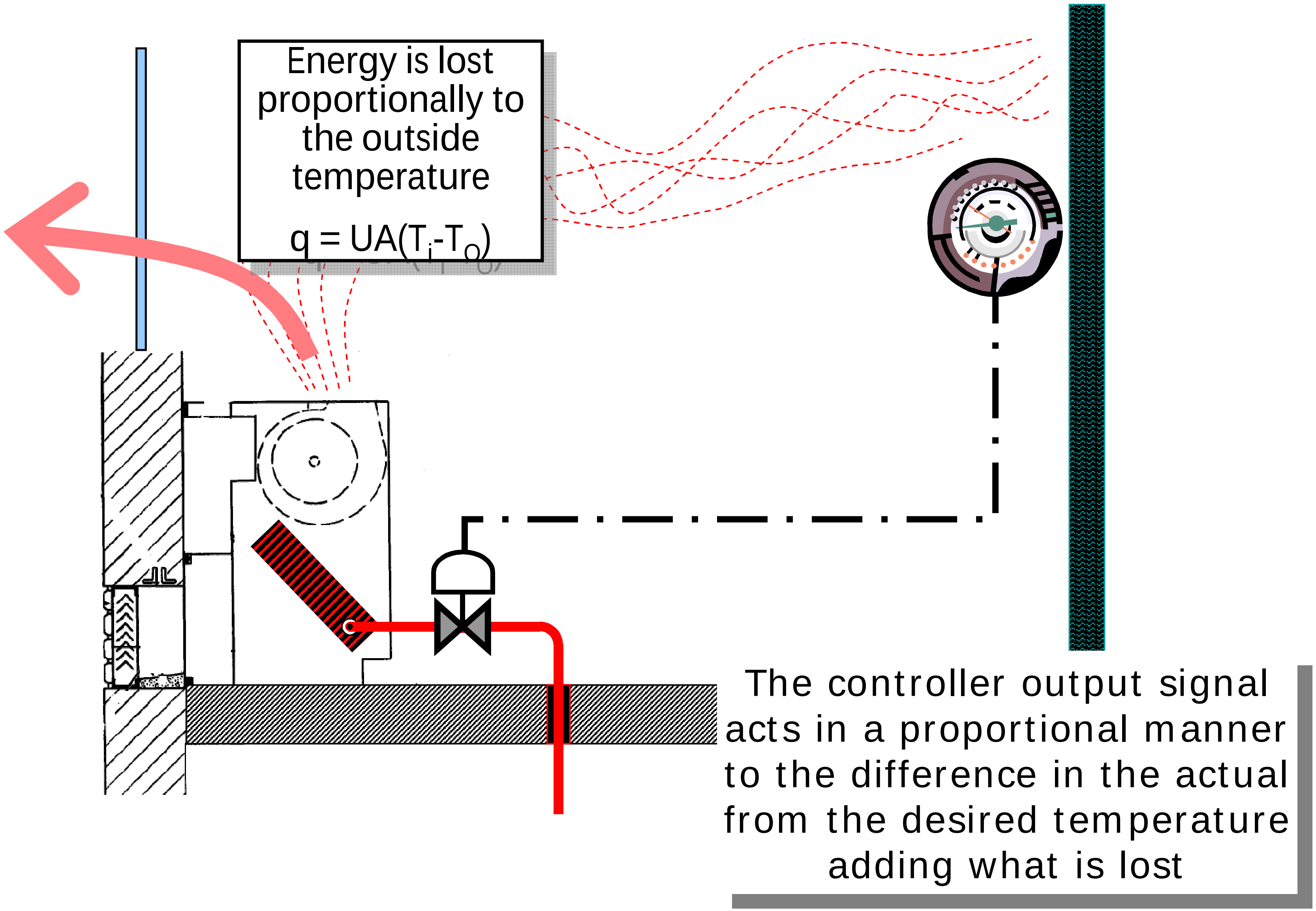
Add 15%!

NOTE: The above table shows average values of pipe friction for new pipe. For commercial installations it is recommended that 15% be added to the above values. No allowance for aging of pipe is included.

Calculate Head Loss & Flow Requirement

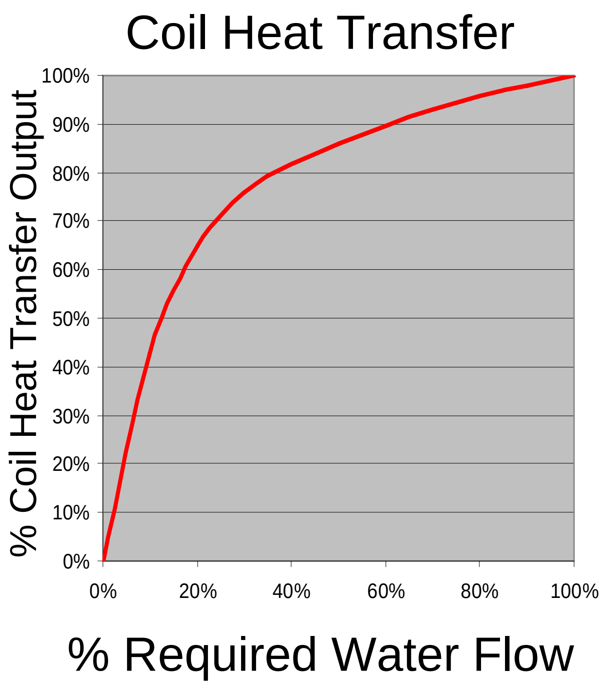
SEGMENT	A	B	C	1-2	2-3	3-4-6	3-5-6	6-7	2-8	8-10-11	8-9-11	11-7	7-12	D	E	F	
Flow	240	160	80	80	40	20	20	40	40	20	20	40	80	80	160	240	
Size	4"	3"	2.5"	2.5	1.5	1.25	1.25	1.5	1.5	1.25	1.25	1.5	2.5	2.5"	3"	4"	
Length	100'	20'	20'	30	30	60	60	30	30	60	60	30	30	20'	20'	100'	
H_F Rate	3	5.5	4.5	4.5	12.5	9	9	12.5	12.5	9	9	12.5	4.5	4.5	5.5	3	
Friction Loss	3	1.1	0.9	1.35	3.75	5.4	5.4	3.75	3.75	5.4	5.4	3.75	1.35	0.9	1.1	3	
Fittings					2	2	2	2	2	2	2	2	2	2	2	2	
Service Valves	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
Coil						17	17			17	17						
Control Valve																	
Balance Valve																	
Source																30	
Total	5	3.1	2.9	3.35	7.75	26.4	26.4	7.75	7.75	26.4	26.4	7.75	5.35	4.9	5.1	37	
																	PATH TOTAL
A-1-2-3-4-6-7-12-F	5			3.35	7.75	26.4		7.75					5.35			37	92.6
A-1-2-3-5-6-7-12-F	5			3.35	7.75		26.4	7.75					5.35			37	92.6
A-1-2-8-10-11-7-12-F	5			3.35					7.75	26.4		7.75	5.35			37	92.6
A-1-2-8-9-11-7-12-F	5			3.35					7.75		26.4	7.75	5.35			37	92.6
A-B-1-2-3-4-6-7-12-E-F	5	3.1		3.35	7.75	26.4		7.75					5.35		5.1	37	100.8
A-B-1-2-3-5-6-7-12-E-F	5	3.1		3.35	7.75		26.4	7.75					5.35		5.1	37	100.8
A-B-1-2-8-10-11-7-12-E-F	5	3.1		3.35					7.75	26.4		7.75	5.35		5.1	37	100.8
A-B-1-2-8-9-11-7-12-E-F	5	3.1		3.35					7.75		26.4	7.75	5.35		5.1	37	100.8
A-B-C-1-2-3-4-6-7-12-D-E-F	5	3.1	2.9	3.35	7.75	26.4		7.75					5.35	4.9	5.1	37	108.6
A-B-C-1-2-3-5-6-7-12-D-E-F	5	3.1	2.9	3.35	7.75		26.4	7.75					5.35	4.9	5.1	37	108.6
A-B-C-1-2-8-10-11-7-12-D-E-F	5	3.1	2.9	3.35					7.75	26.4		7.75	5.35	4.9	5.1	37	108.6
A-B-C-1-2-8-9-11-7-12-D-E-F	5	3.1	2.9	3.35					7.75		26.4	7.75	5.35	4.9	5.1	37	108.6

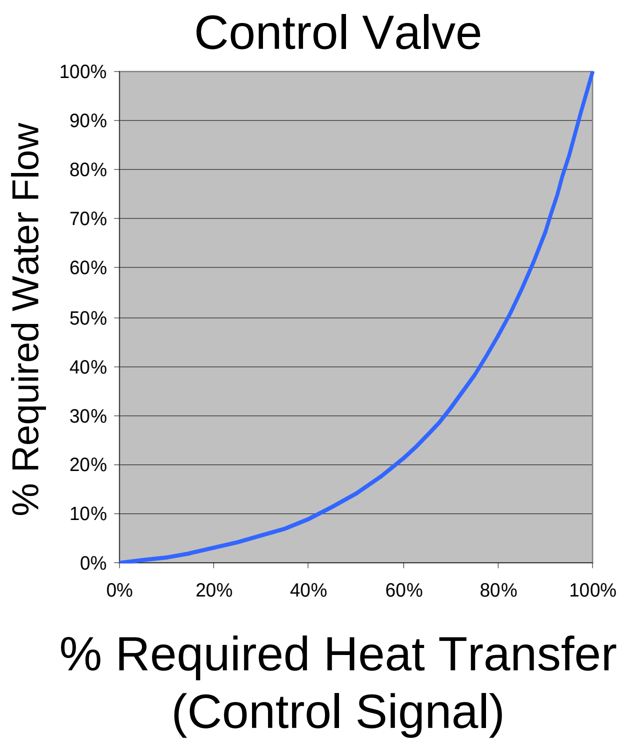
Automated Control

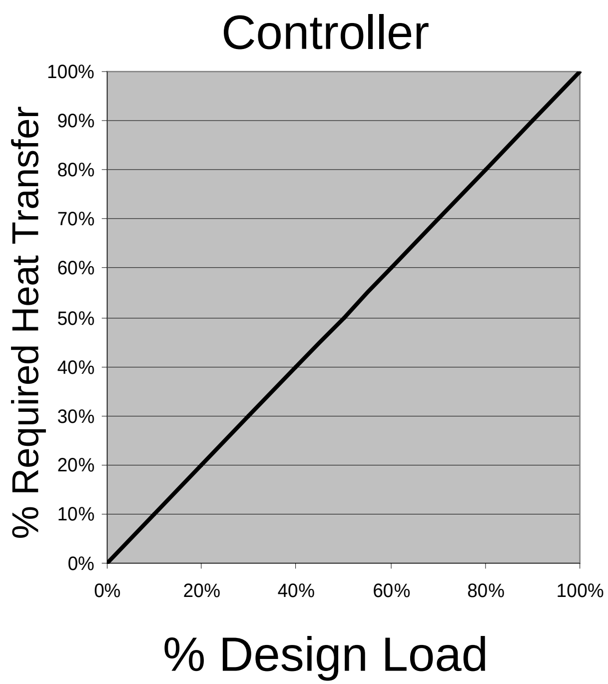


Engineering Practice: Valve Authority

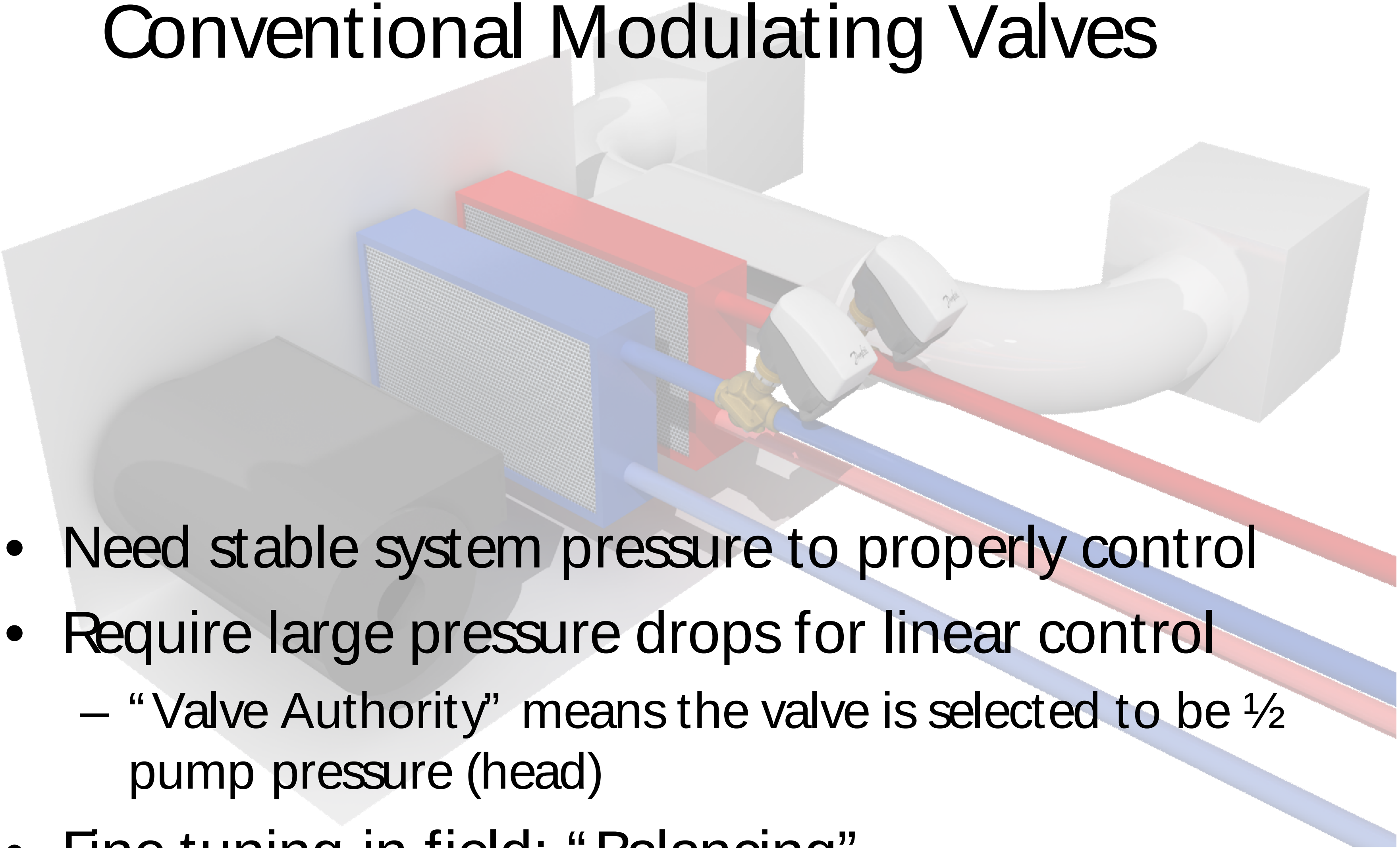
- Control relies on predictable linear control
  - – Coil and valve look like a straight line
  - – The weather changes, we add or subtract flow proportionally to the worst case day





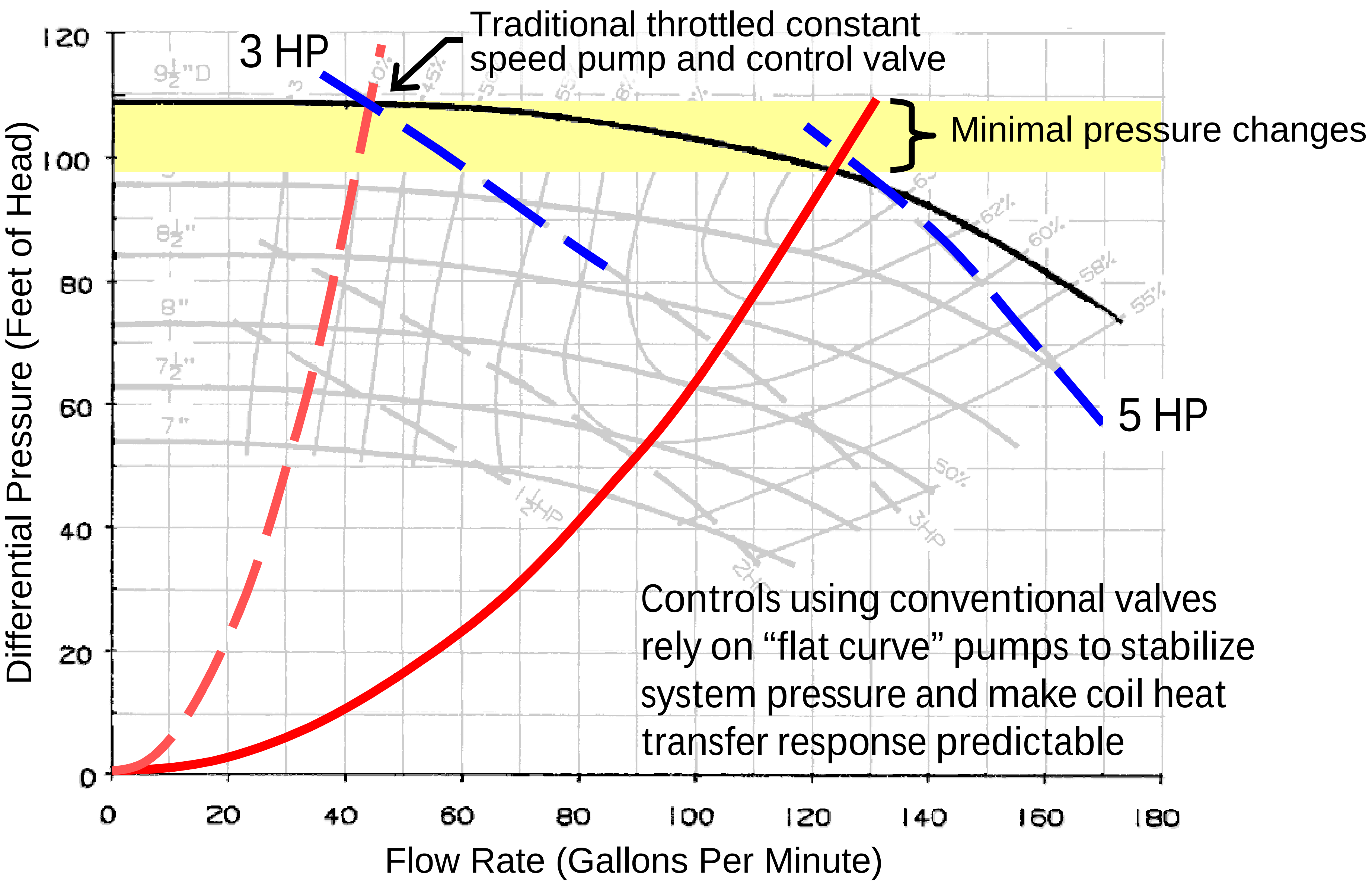


Conventional Modulating Valves



- Need stable system pressure to properly control
- Require large pressure drops for linear control
  - "Valve Authority" means the valve is selected to be ½ pump pressure (head)
- Fine tuning in field; "Balancing"
- Extra design calculations

Traditional Valve Application



SEGMENT	A	B	C	1-2	2-3	3-4-6	3-5-6	6-7	2-8	8-10-11	8-9-11	11-7	7-12	D	E	F	
Flow	240	160	80	80	40	20	20	40	40	20	20	40	80	80	160	240	
Size	4"	3"	2.5"	2.5	2	1.5	1.5	2	2	1.5	1.5	2	2.5	2.5"	3"	4"	
Length	100'	20'	20'	30	30	60	60	30	30	60	60	30	30	20'	20'	100'	
H_F Rate	3	5.5	4.5	4.5	3.25	3.75	3.75	3.25	3.25	3.75	3.75	3.25	4.5	4.5	5.5	3	
Friction Loss	3	1.1	0.9	1.35	0.98	2.25	2.25	0.98	0.98	2.25	2.25	0.98	1.35	0.9	1.1	3	
Fittings																	
Service Valves																	
Coil						17	17			17	17						
Control Valve						43.7	43.7			43.667	43.67						
Balance Valve																	
Source																30	
Total	3	1.1	0.9	1.35	0.98	62.9	62.9	0.98	0.98	62.917	62.92	0.98	1.35	0.9	1.1	33	
																	PATH TOTAL
A-1-2-3-4-6-7-12-F	3			1.35	0.98	62.9		0.98					1.35			33	103.567
A-1-2-3-5-6-7-12-F	3			1.35	0.98		62.9	0.98					1.35			33	103.567
A-1-2-8-10-11-7-12-F	3			1.35					0.98	62.917		0.98	1.35			33	103.567
A-1-2-8-9-11-7-12-F	3			1.35					0.98		62.92	0.98	1.35			33	103.567
A-B-1-2-3-4-6-7-12-E-F	3	1.1		1.35	0.98	62.9		0.98					1.35		1.1	33	105.767
A-B-1-2-3-5-6-7-12-E-F	3	1.1		1.35	0.98		62.9	0.98					1.35		1.1	33	105.767
A-B-1-2-8-10-11-7-12-E-F	3	1.1		1.35					0.98	62.917		0.98	1.35		1.1	33	105.767
A-B-1-2-8-9-11-7-12-E-F	3	1.1		1.35					0.98		62.92	0.98	1.35		1.1	33	105.767
A-B-C-1-2-3-4-6-7-12-D-E-F	3	1.1	0.9	1.35	0.98	62.9		0.98					1.35	0.9	1.1	33	107.567
A-B-C-1-2-3-5-6-7-12-D-E-F	3	1.1	0.9	1.35	0.98		62.9	0.98					1.35	0.9	1.1	33	107.567
A-B-C-1-2-8-10-11-7-12-D-E-F	3	1.1	0.9	1.35					0.98	62.917		0.98	1.35	0.9	1.1	33	107.567
A-B-C-1-2-8-9-11-7-12-D-E-F	3	1.1	0.9	1.35					0.98		62.92	0.98	1.35	0.9	1.1	33	107.567

Control Valve

- We reduced head loss to 66’
- We want 50% Authority, so size valve for _?_
  - 66’ (28.6 PSI)

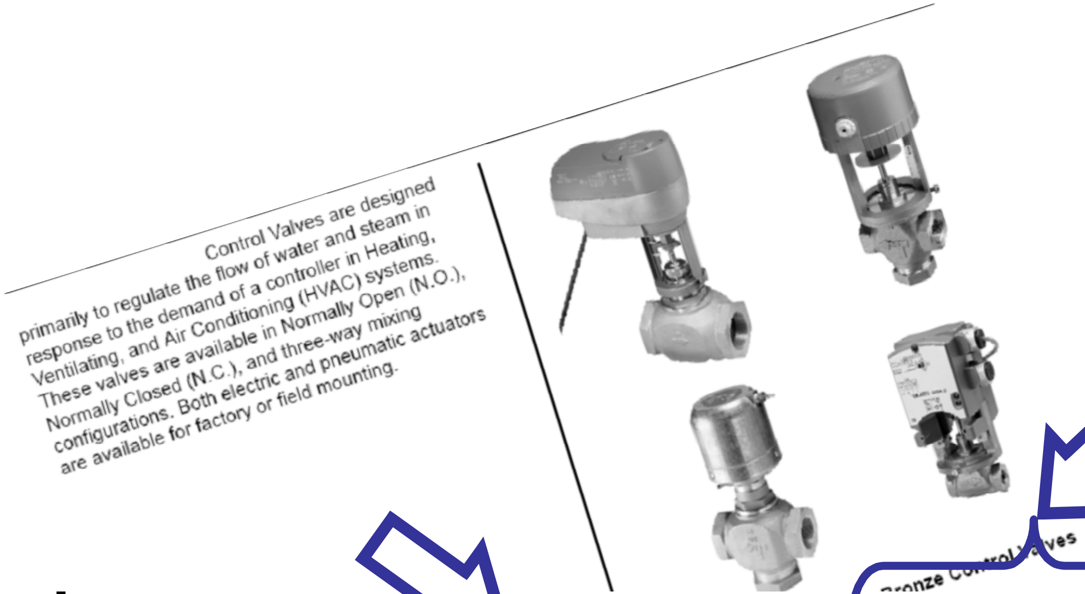
$$q = C_V \sqrt{\Delta P}$$

$$20\,\text{GPM} = C_V \sqrt{\frac{66}{2.31}}$$

$$\frac{20}{\sqrt{\frac{66}{2.31}}} = C_V = 3.74$$

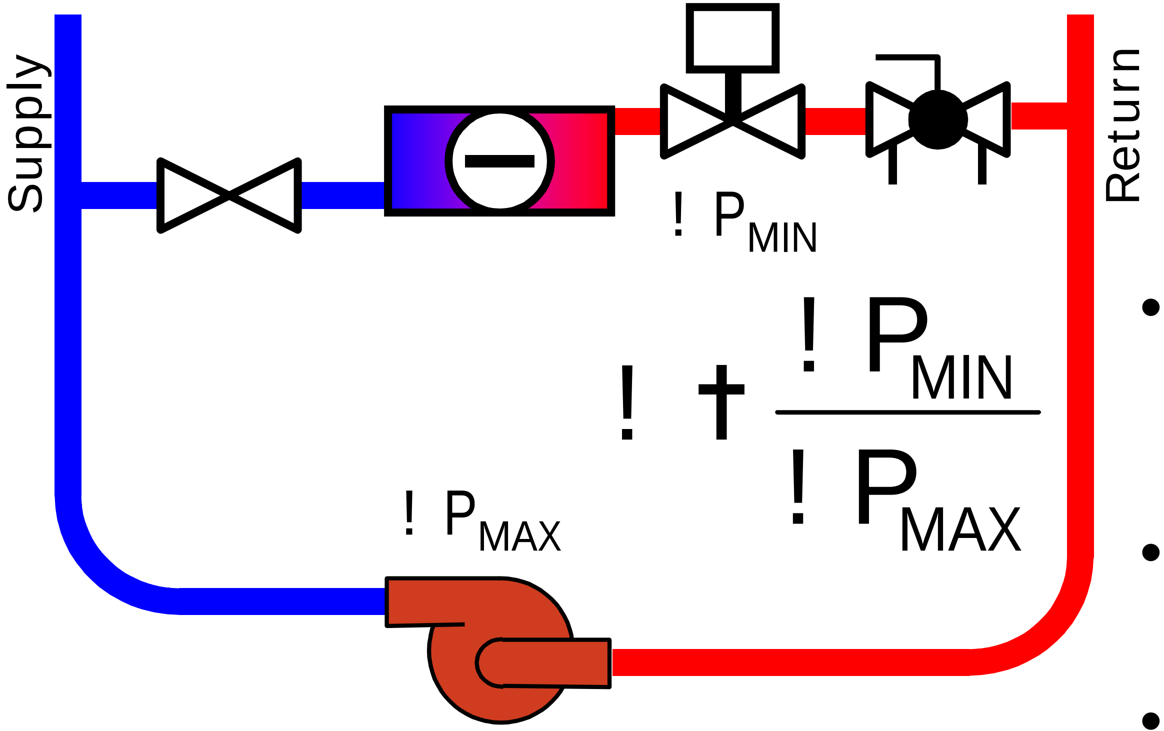
Control Valve Selection

- Required C_V = 3.75
- Pipe Size = 1½"
- Rules of Thumb
  - One pipe size smaller
  - 5 PSI; C_V = 9



Valve Size, in. (DN)	1/2 (DN15)			3/4 (DN20)	1 (DN25)	1-1/4 (DN32)	1-1/2 (DN40)	2 (DN50)
Maximum Cv (Kv) Factor	0.73 (0.63)	1.8 (1.6)	4.6 (4.0)	7.3 (6.3)	11.6 (10.0)	18.5 (16.0)	28.9 (25.0)	46.2 (40.0)

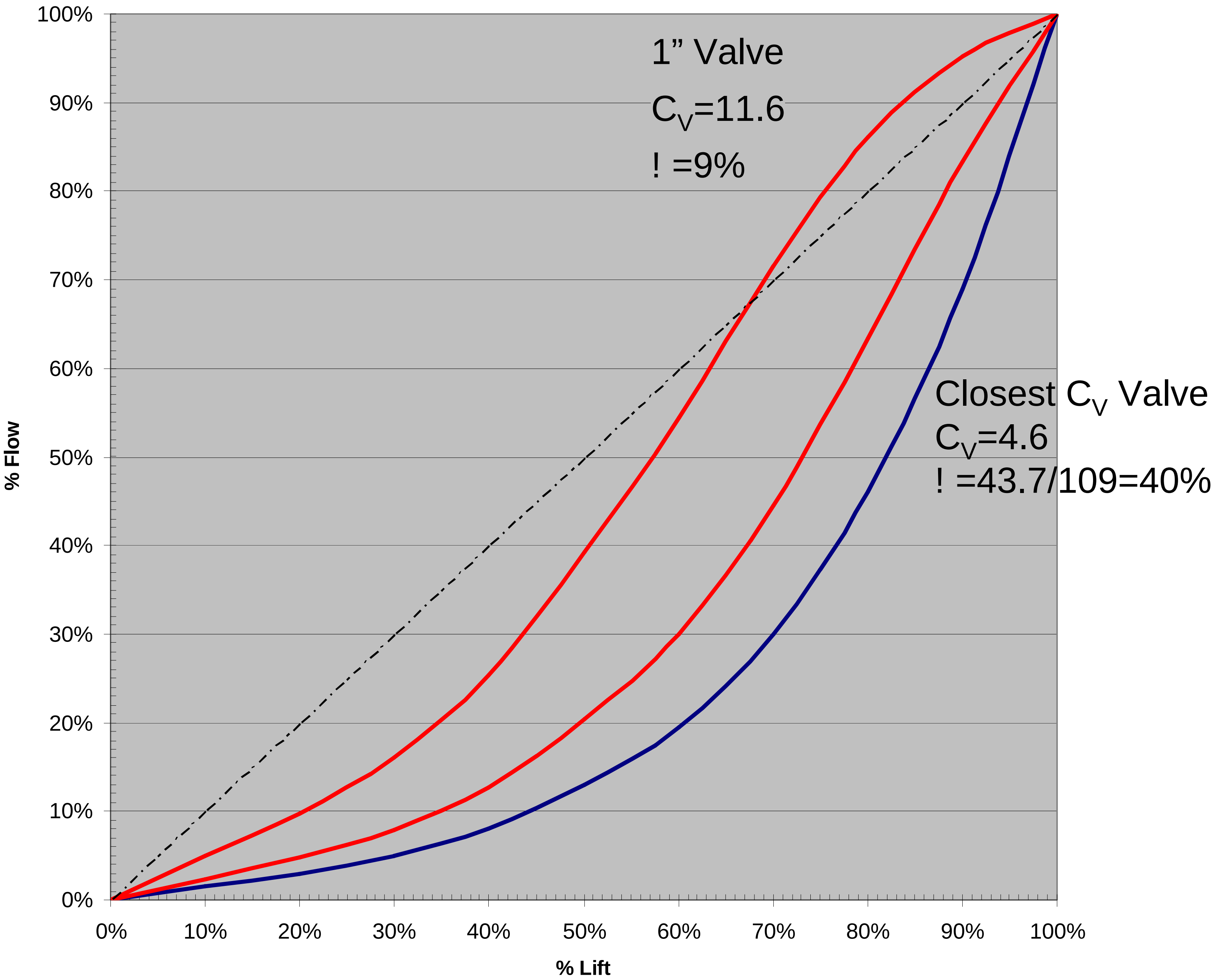
Valve Authority



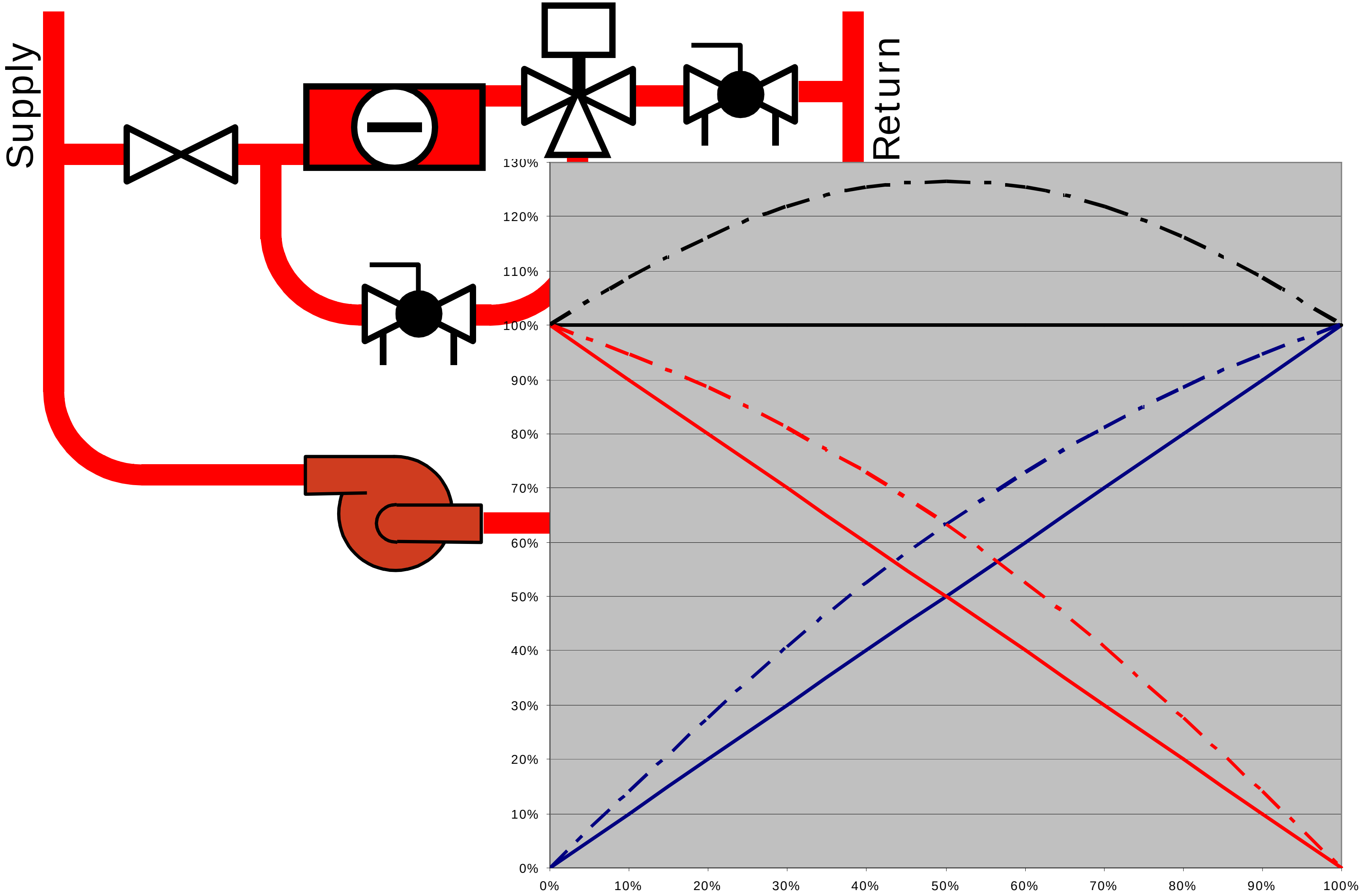
$$\beta = \frac{\Delta P_{MIN}}{\Delta P_{MAX}}$$

- Components have constant flow coefficient
- Valve coefficient is variable
- Calculate equivalent coefficient at valve stroke using spreadsheet

$$C_{VE} = \frac{C_{V-Valve} \cdot C_{V-Comp}}{\sqrt{C_{V-V}^2 + C_{V-C}^2}}$$

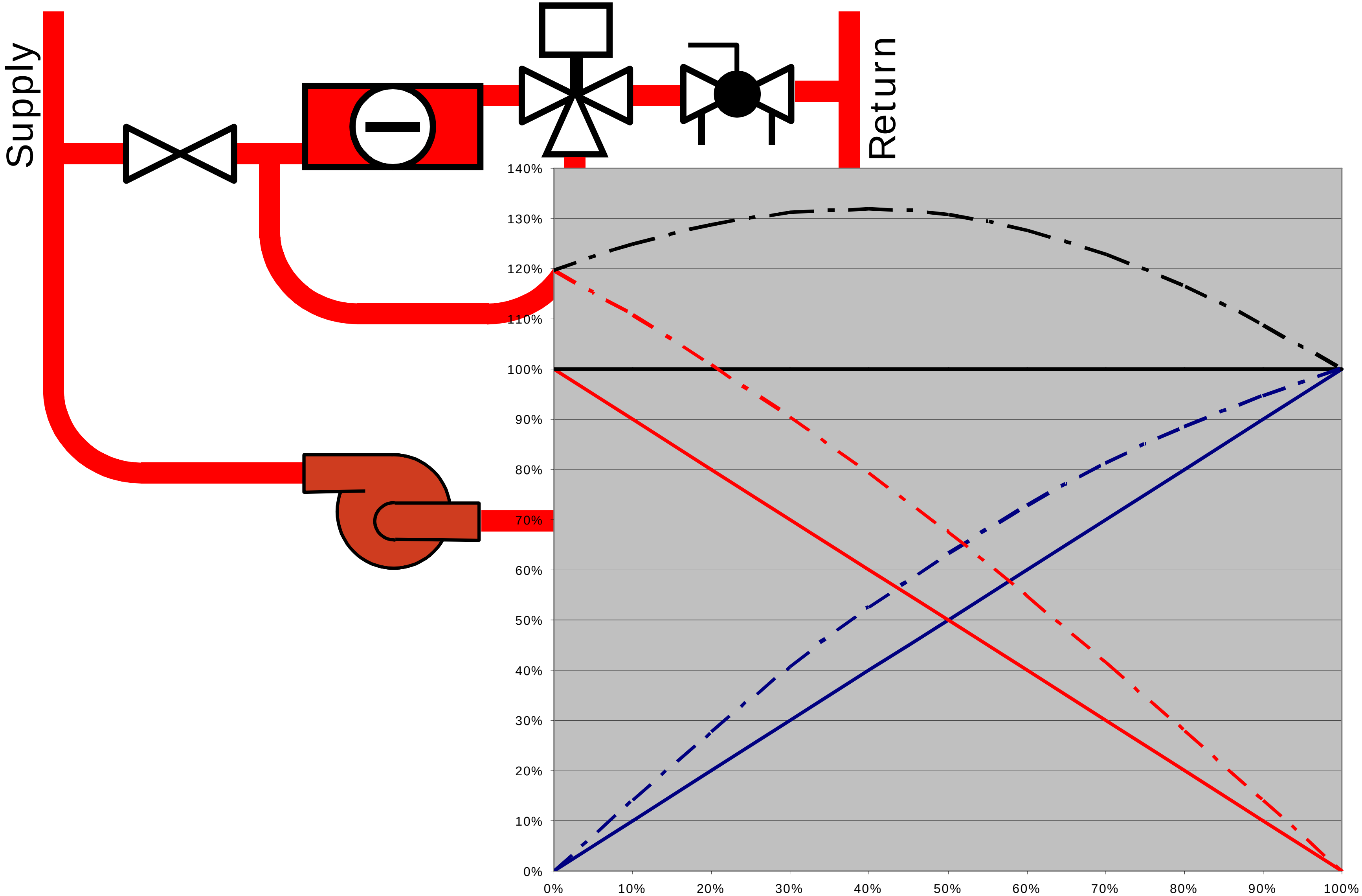

1” Valve
C_V=11.6
! =9%
Closest C_V Valve
C_V=4.6
! =43.7/109=40%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Flow
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
% Lift

Balanced 3 Way Valve Authority



Shown @ ! = 50%

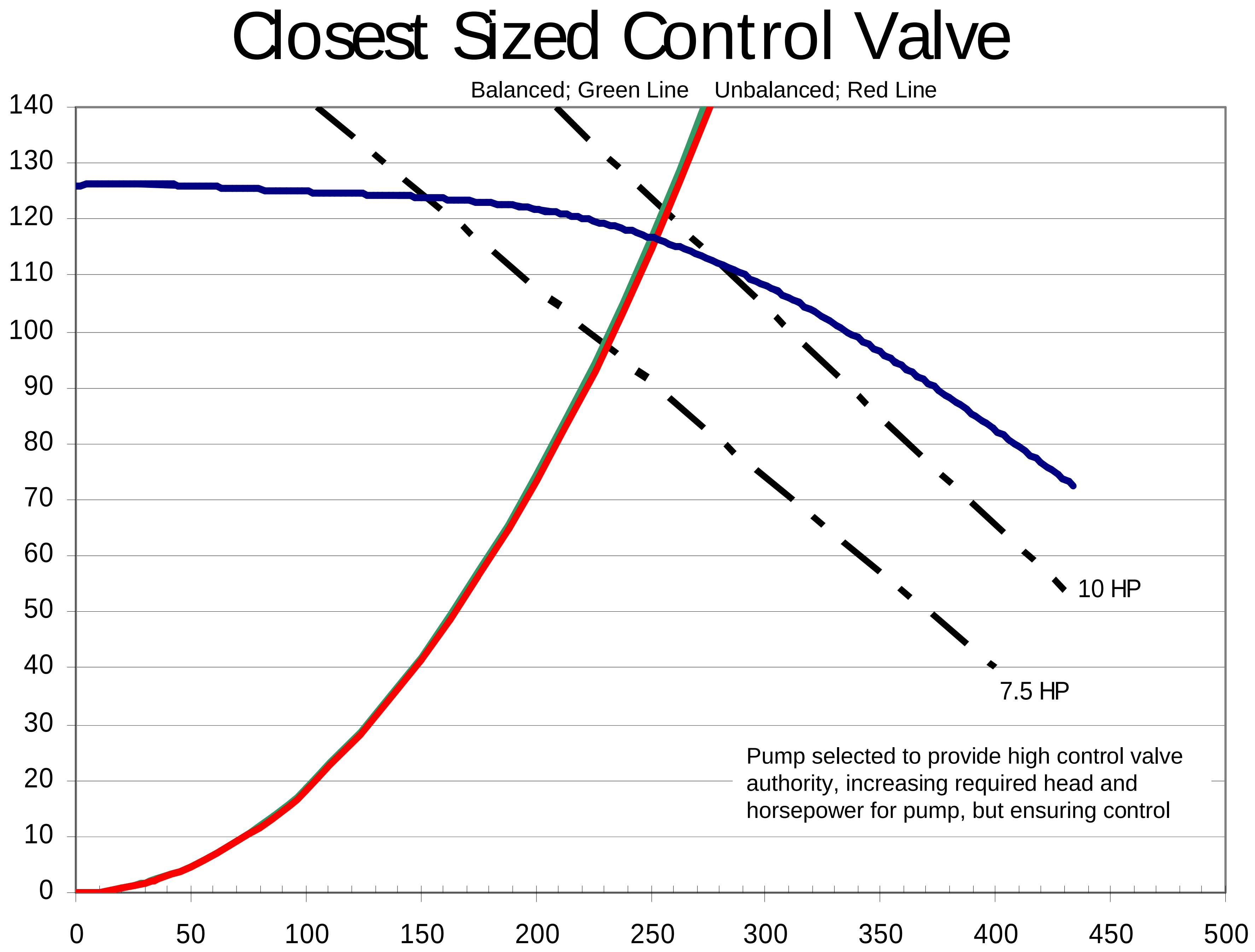
Un-balanced 3 Way Valve Authority



Shown @ ! = 50%

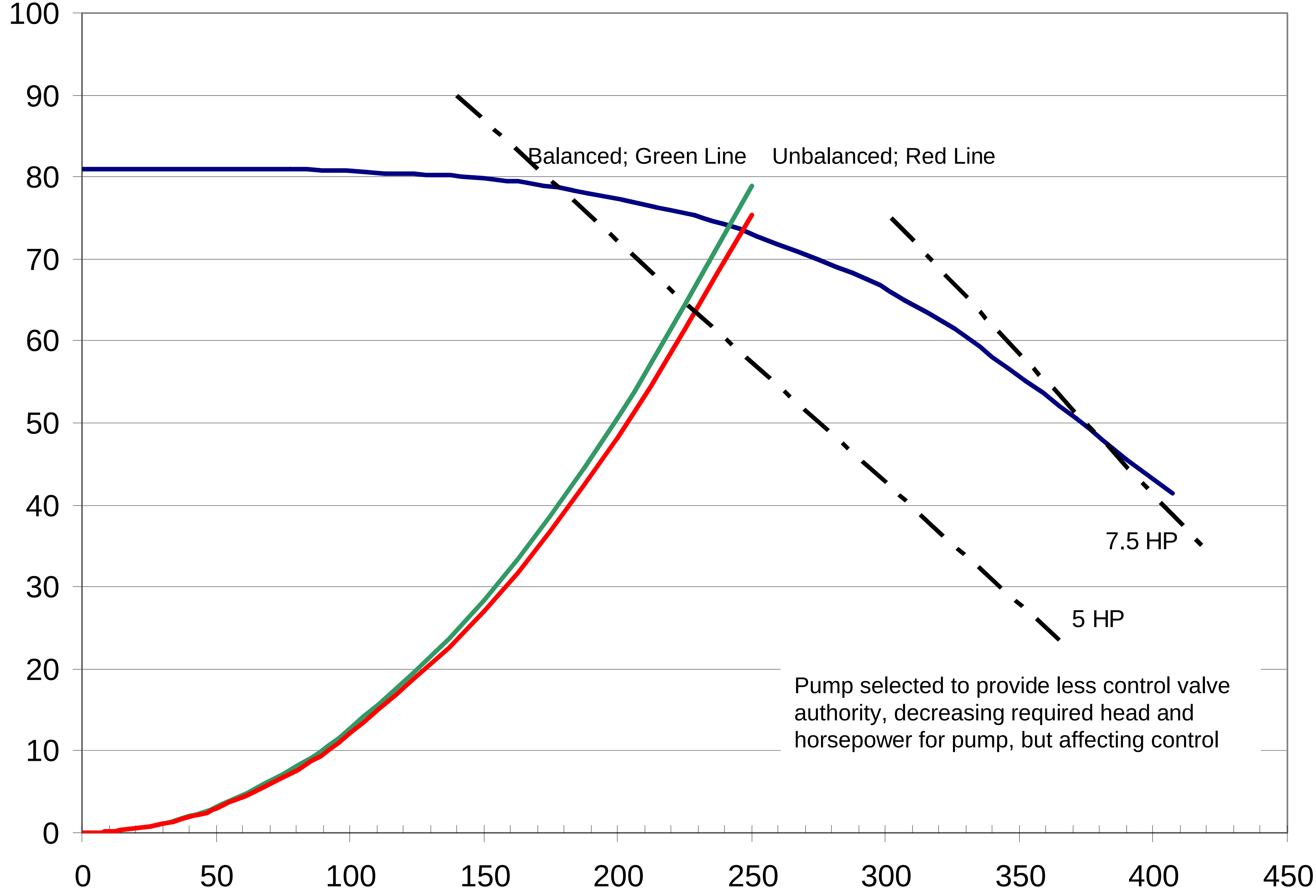
Balance?

- In this case “balance” would adjust the coil balance valves in Branches 2 & 3 to account for riser loss of about 2’ and 4’
- Large systems become complicated adjustments
  - Broken up into logical groups
  - System changes often require major re-balance
- Example: Look at pump and system curve intersection points

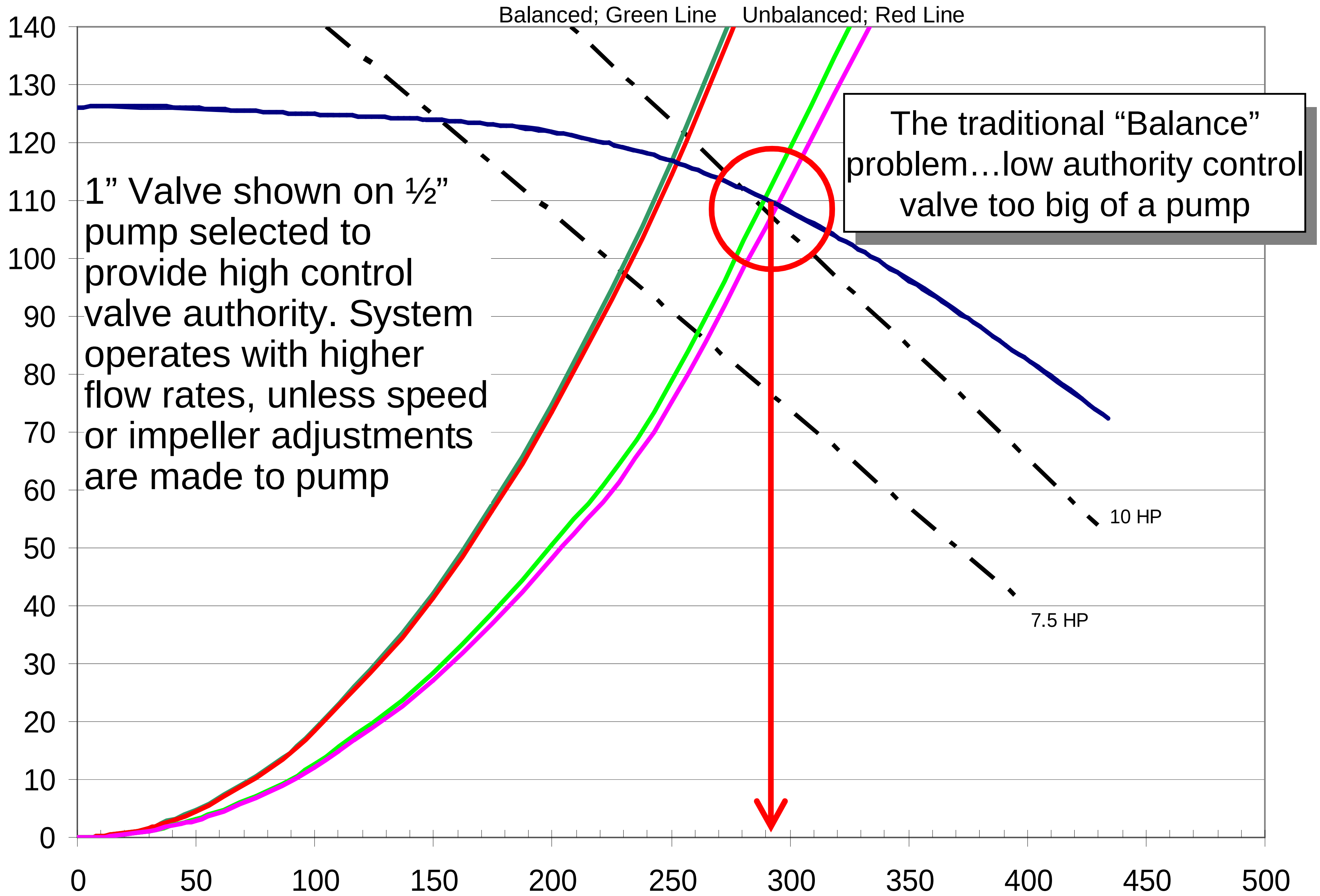


Closest Sized Control Valve
Balanced; Green Line
Unbalanced; Red Line
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400
450
500
10 HP
7.5 HP
Pump selected to provide high control valve authority, increasing required head and horsepower for pump, but ensuring control

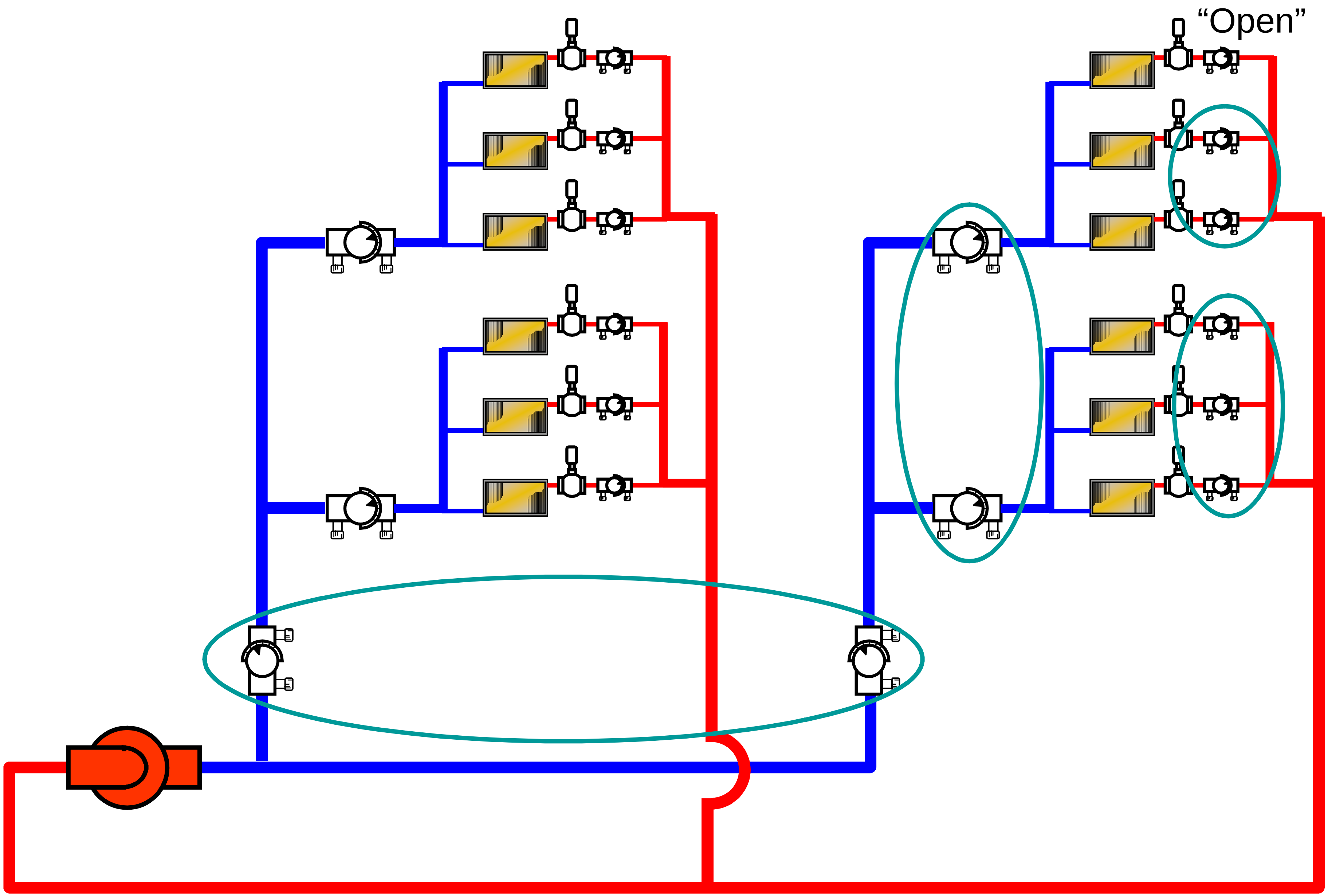
1” Control Valve



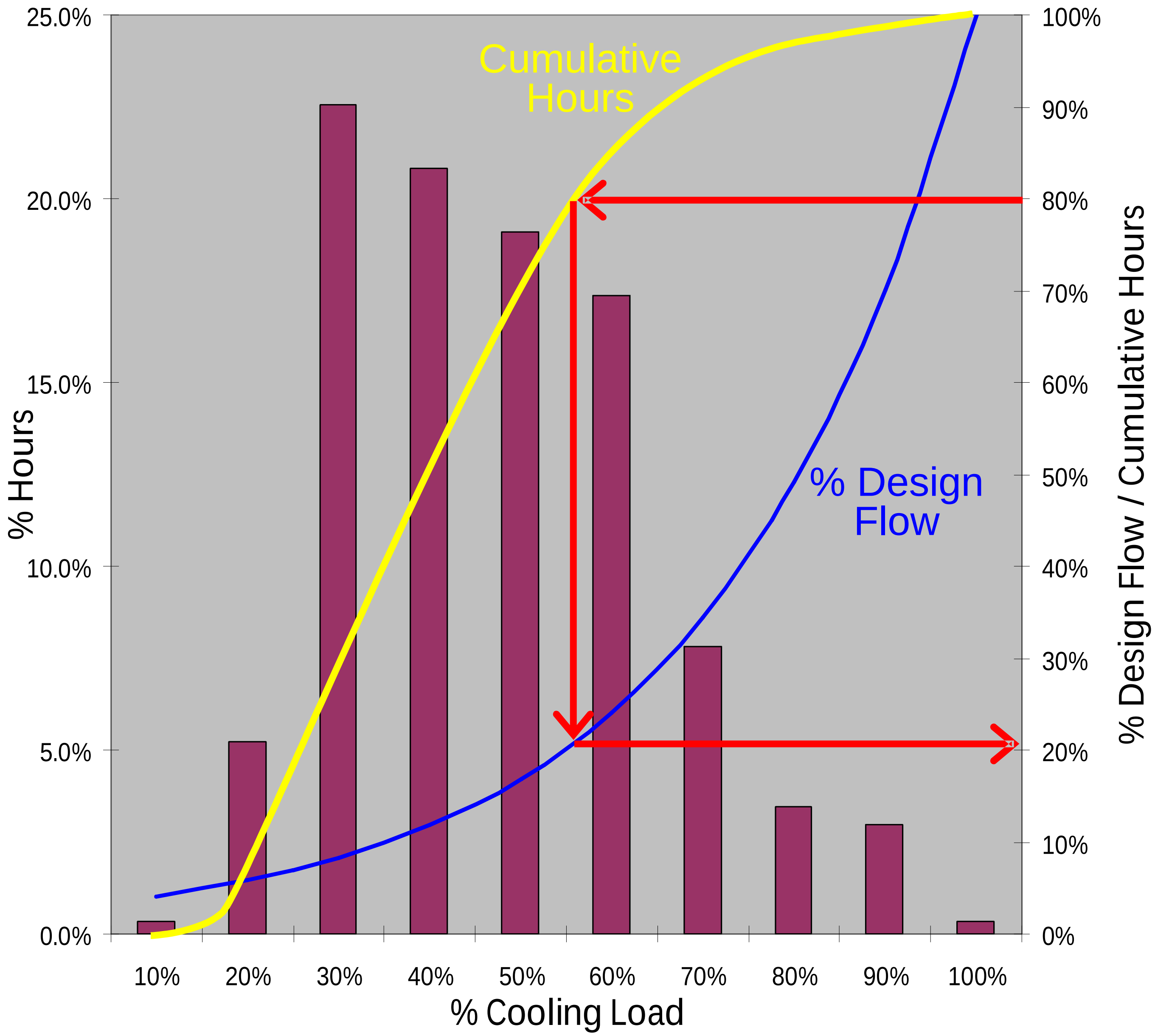
Larger Pump Comparison of Control Valves



Static Balance; "Riser Balance"



Why the Emphasis on Control Valve?



- 80% of operational cooling uses less than 20% of design flow
- 97% of operational hours covered by 50% design flow
- 50% flow can be 12.5% design horsepower

Optimizing Hydronic System Energy Efficiency

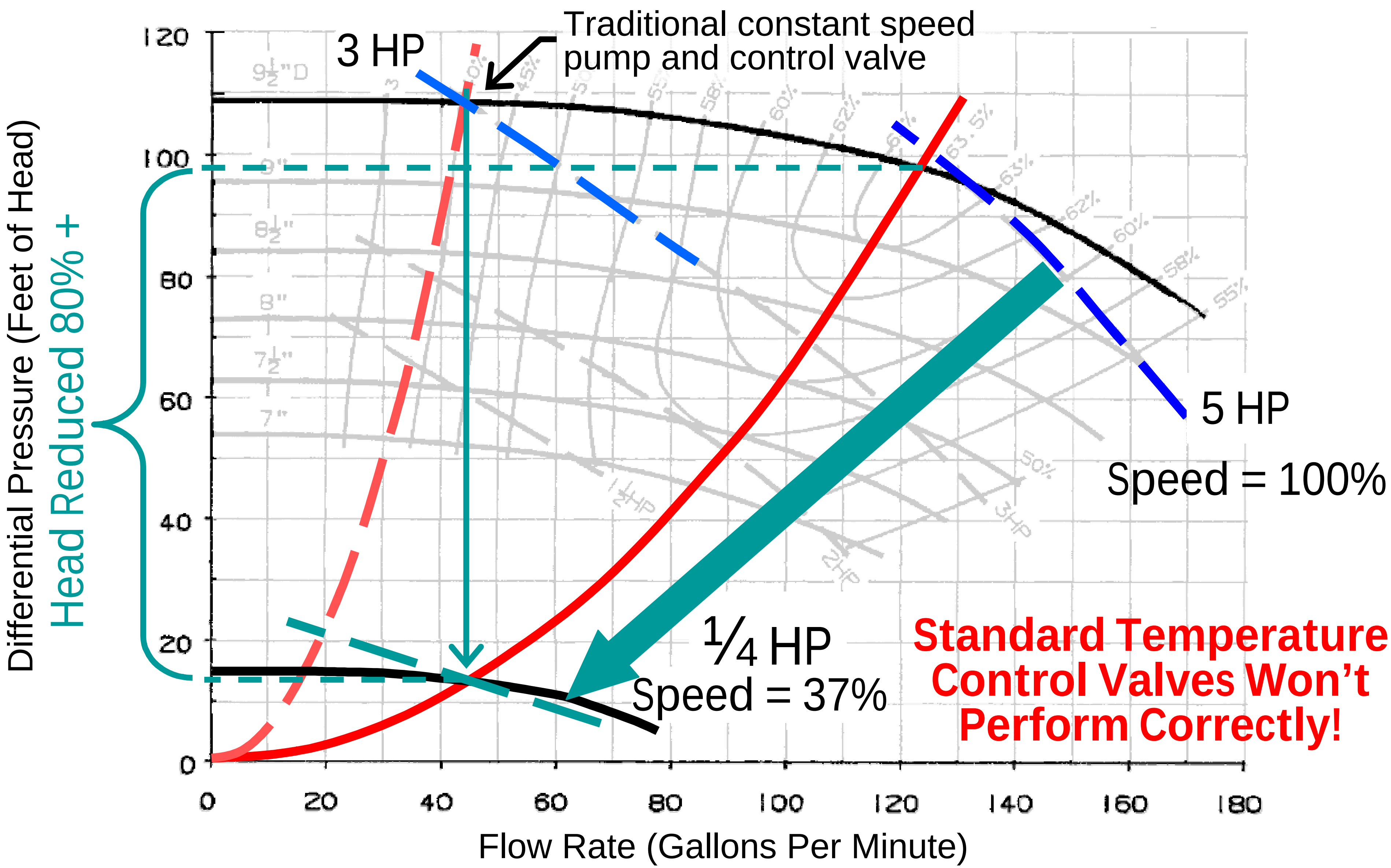
$$! \text{ Flow } \dagger \sqrt[3]{! \text{ BHP}}$$

- Means applying variable speed drives to save maximum energy
  - Small changes in flow mean big savings in pump horsepower
- Hydronic system and controls must be designed to take advantage of potential savings
- Many variable speed pump systems don't achieve their predicted performance

Building Code

- IECC 503.4.3.4
- Hydronic Systems ! 300,000 Btu/Hr. in design output capacity supplying heated or chilled water to have special controls
  - Temperature to be capable of being reset by 35% of the design supply to return water temperature difference
  - Capable of reducing system pump flow by 50% of design flow utilizing adjustable speed drives on pumps where 1/3 of total horsepower is automatically turned off or modulated

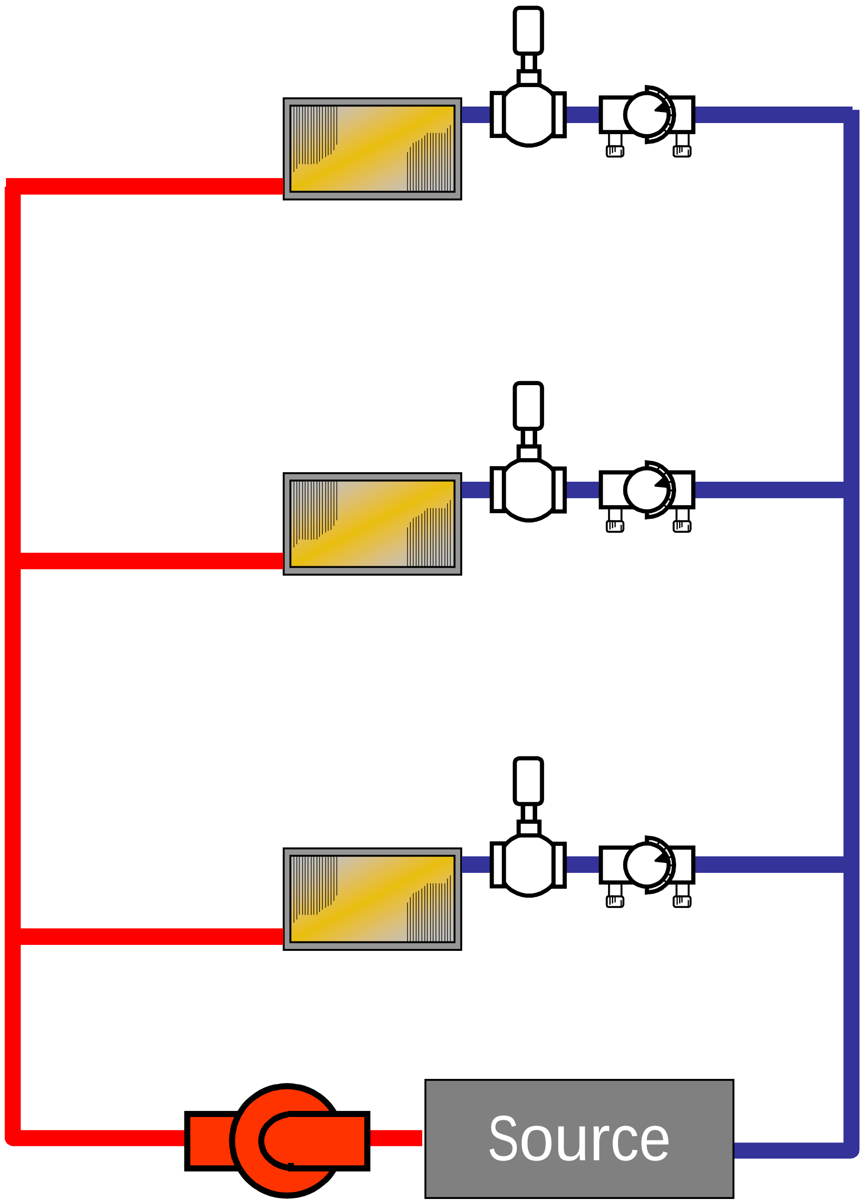
Variable Speed Pumping Offers Tremendous Energy Saving Potential



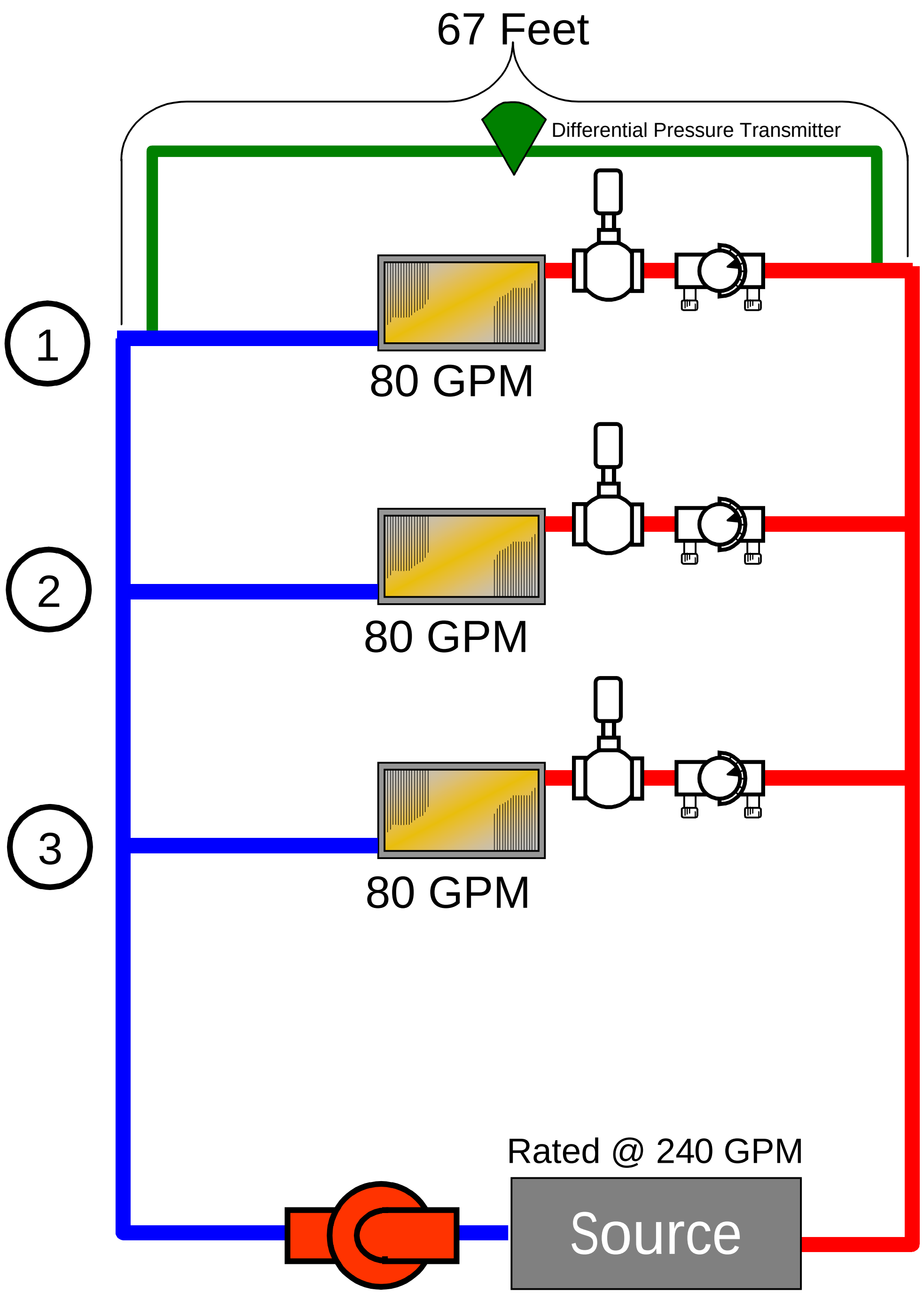
Variable Speed Pump “Problems”

- Temperature control worse or unstable
- How to balance a VS pump system
  - ASHRAE techies have debated subject for years
- Diversity: Short flow
- Paradigm change; System curve & commissioning
  - Systems don’t seem to follow “system curve”
  - Work in “area” of operation
- Variable speed systems don’t seem to achieve desired savings

Example Modification



- Convert to three floors
- Group valves into one

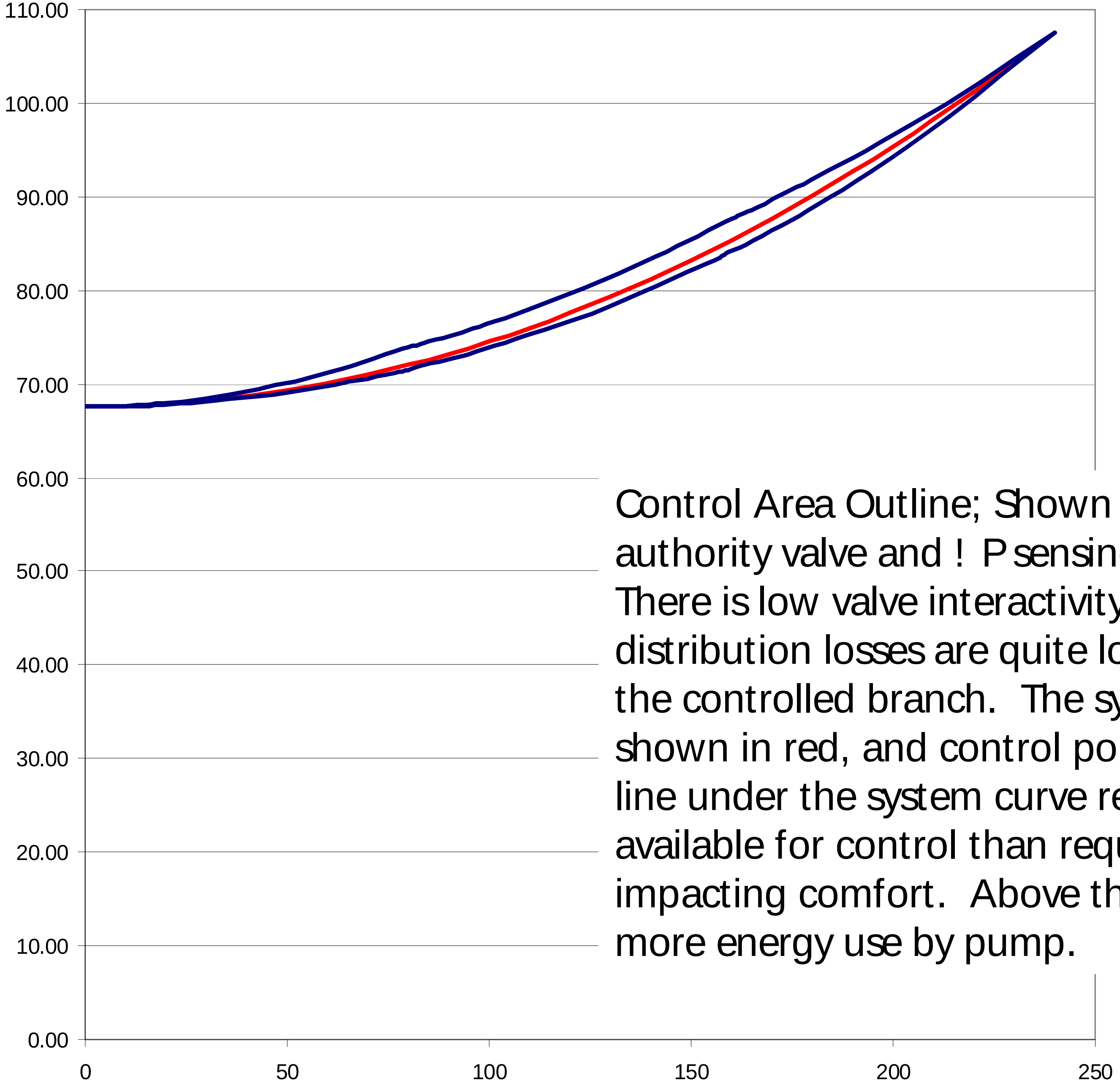


System Requires 240 GPM
Chiller Rated @ 200 Tons, 400 GPM
Pump Specified 400 GPM @ 70 Feet

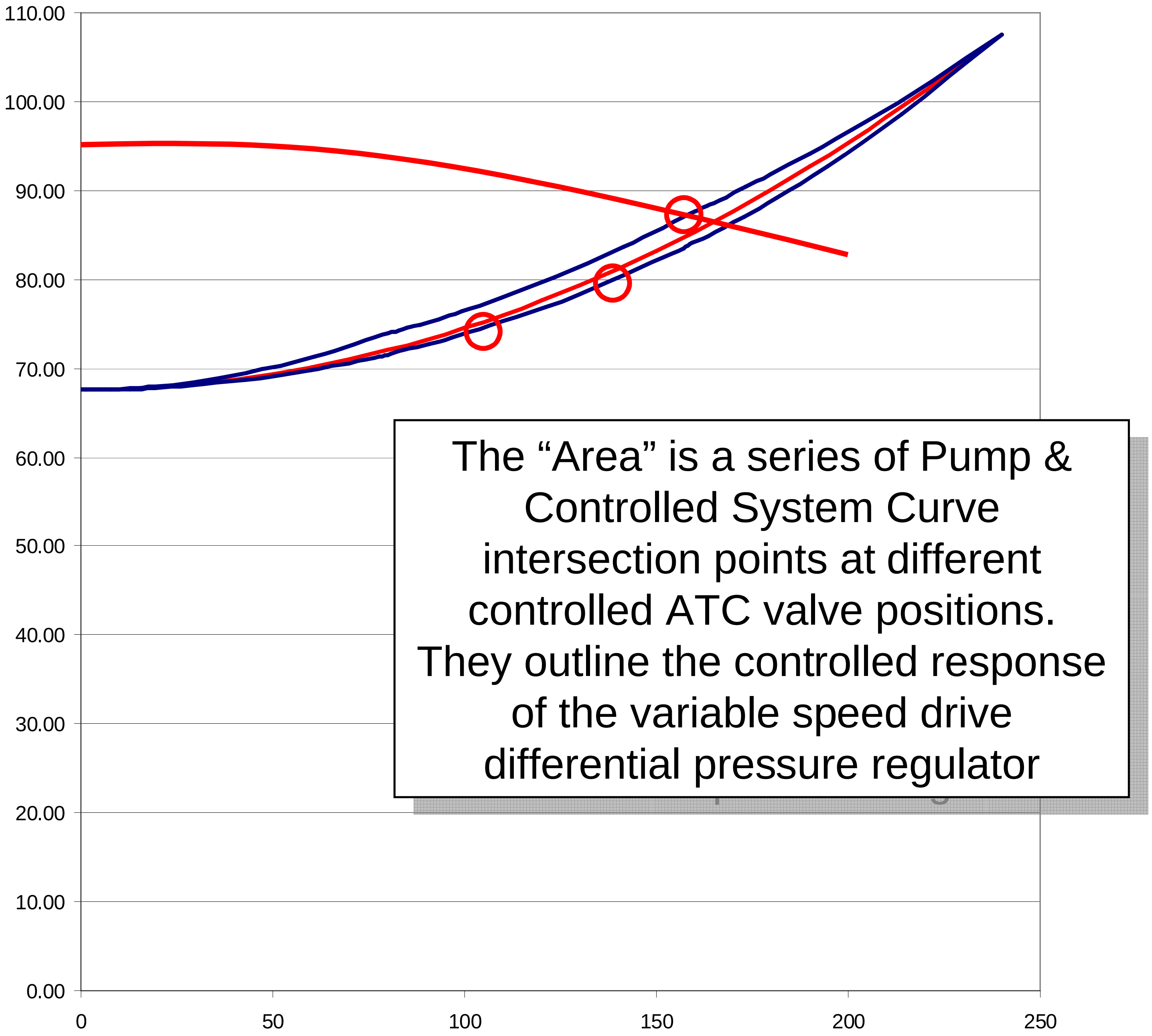
Branch Pipe, Valves, Coil and TC Valve specified at 67' Loss, via set point specified for variable speed pump system.

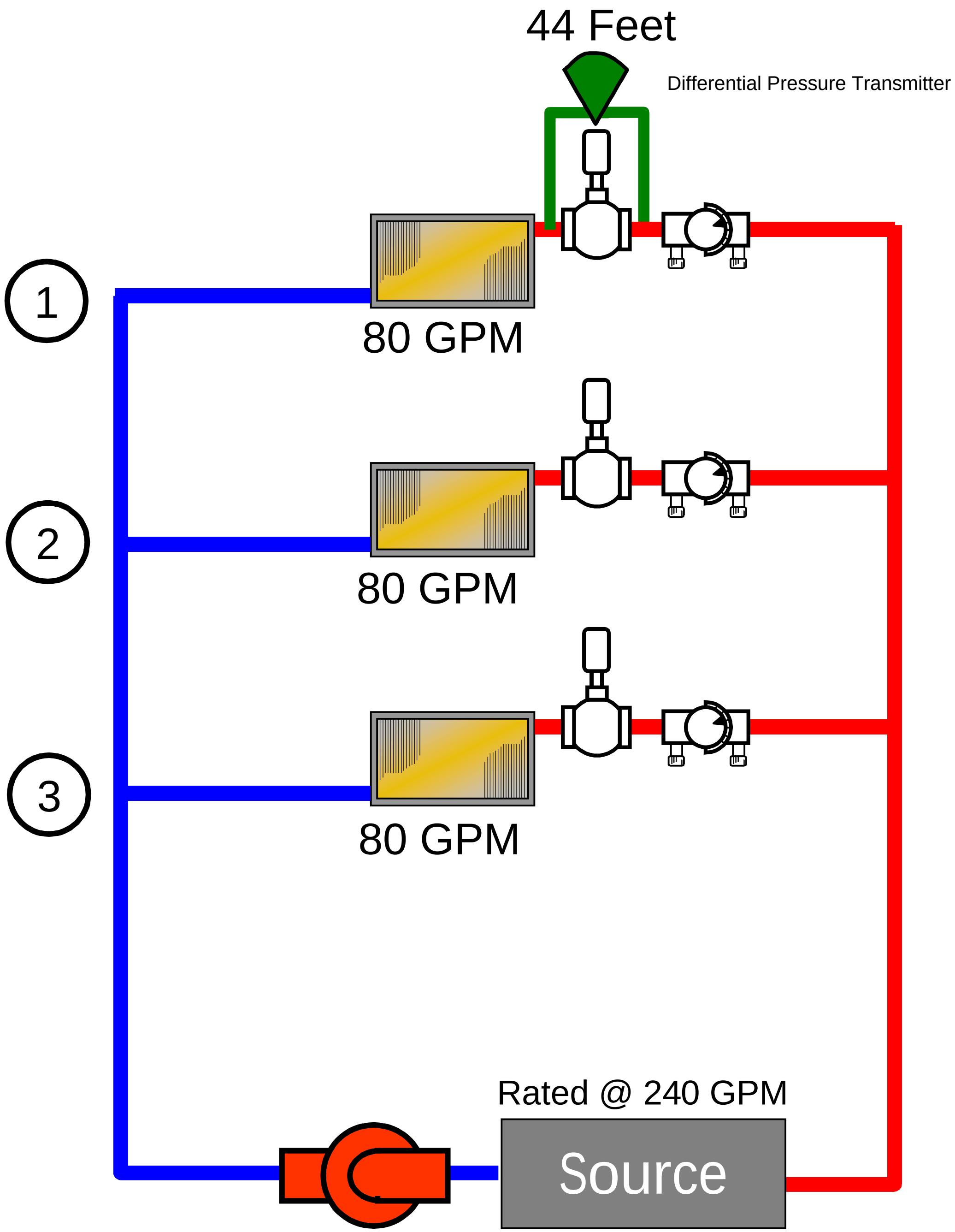
Branch 1 required balance: Maximum Pump speed set to match flow and head required for branch.

Branch 2 & 3 required balance: Balancing valves adjusted to make up for distribution head loss due to location. Note: Preferable application of dynamic balance method



Control Area Outline; Shown for balanced high authority valve and ! P sensing across far branch. There is low valve interactivity because riser distribution losses are quite low as compared to the controlled branch. The system curve is shown in red, and control points in blue. The line under the system curve reflects less water available for control than required, potentially impacting comfort. Above the curve reflects more energy use by pump.


110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
50
100
150
200
250
The “Area” is a series of Pump & Controlled System Curve intersection points at different controlled ATC valve positions. They outline the controlled response of the variable speed drive differential pressure regulator

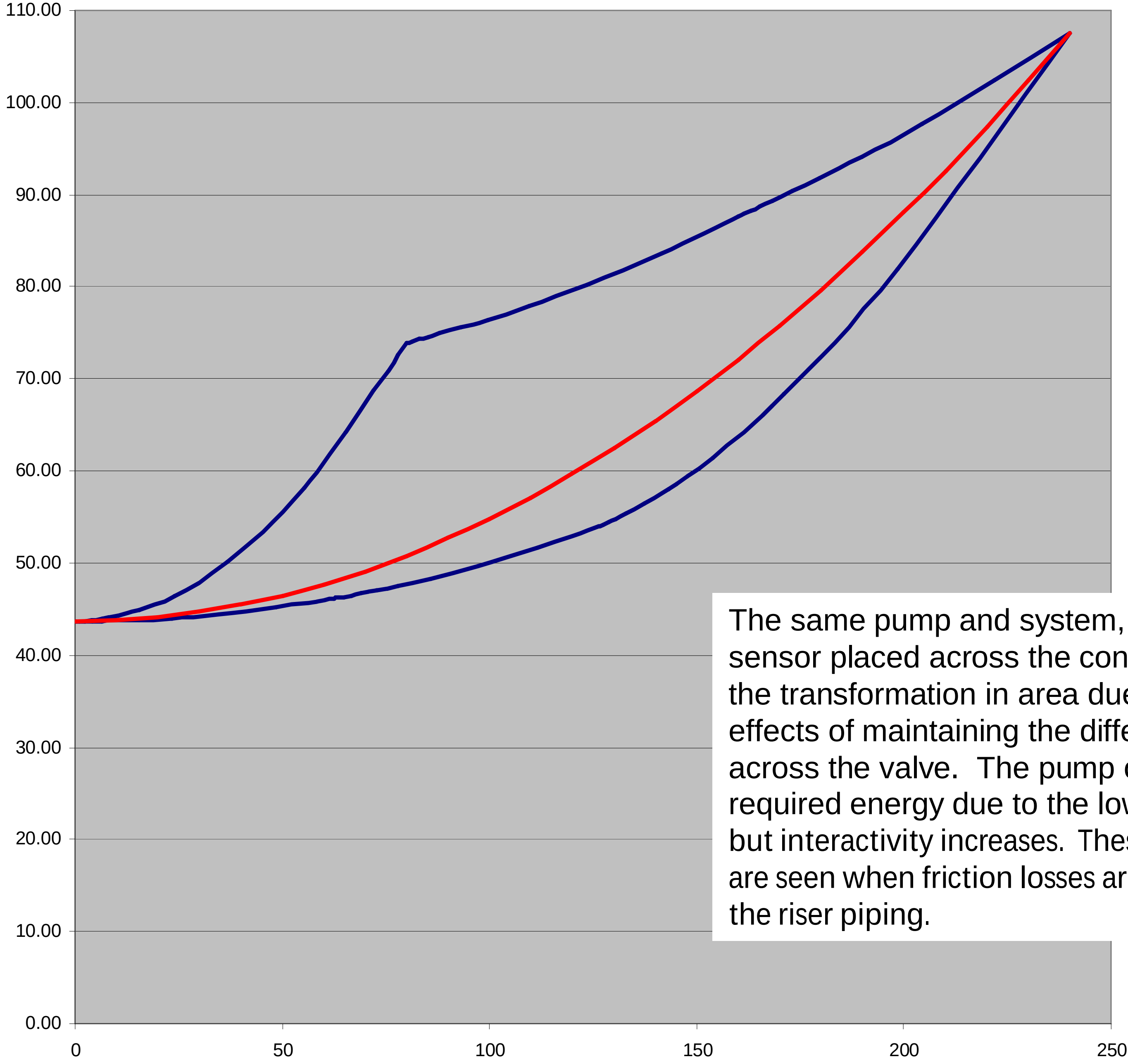


System Requires 240 GPM
Pump Specified 240 GPM @ 110 Feet

TC Valve specified at 44’ loss, via set point specified for variable speed pump system.

Branch 1 required balance: Maximum Pump speed set to match flow and head required for valve.

Branch 2 & 3 required balance: Balancing valves adjusted to make up for distribution head loss due to location. Note: Branch 1 coil loss now added to distribution system piping due to control sensor location.

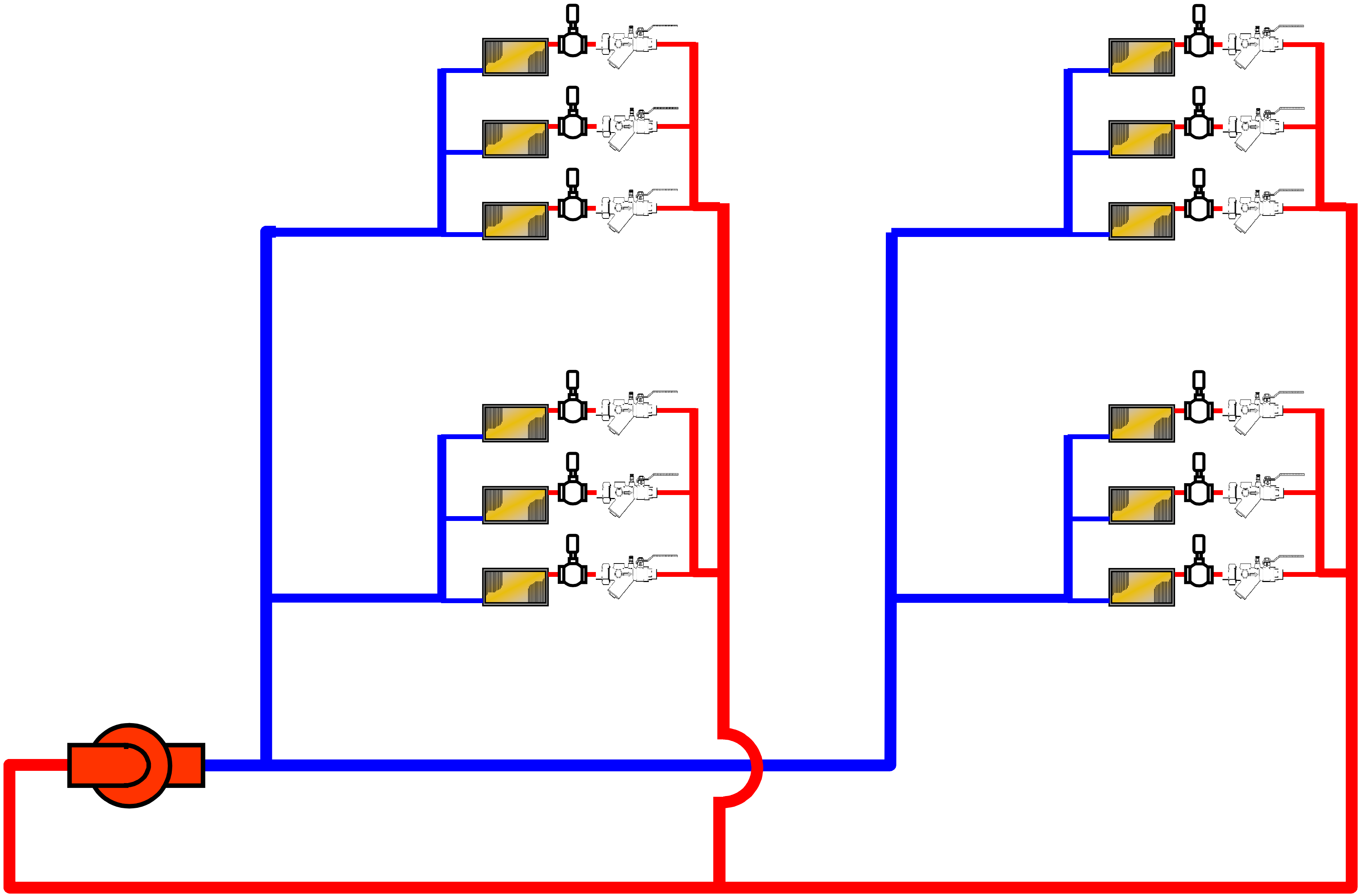


The same pump and system, this time with the sensor placed across the control valve. Note the transformation in area due to the control effects of maintaining the differential pressure across the valve. The pump operates at lower required energy due to the lower ! P setpoint, but interactivity increases. These same effects are seen when friction losses are distributed to the riser piping.

Solutions: Automatic Flow Limiting

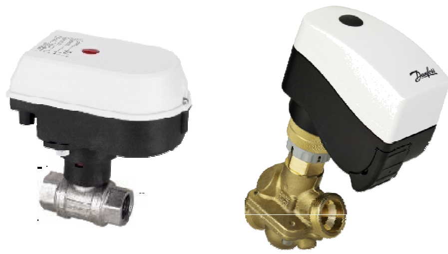
- Flow limiting valves fix variable speed control area problems
- Flow limiting valves do not proportionally balance
  - Diversity selection less than coil block load leads to issues
- Control valve still has fundamental controller gain problem under variable speed

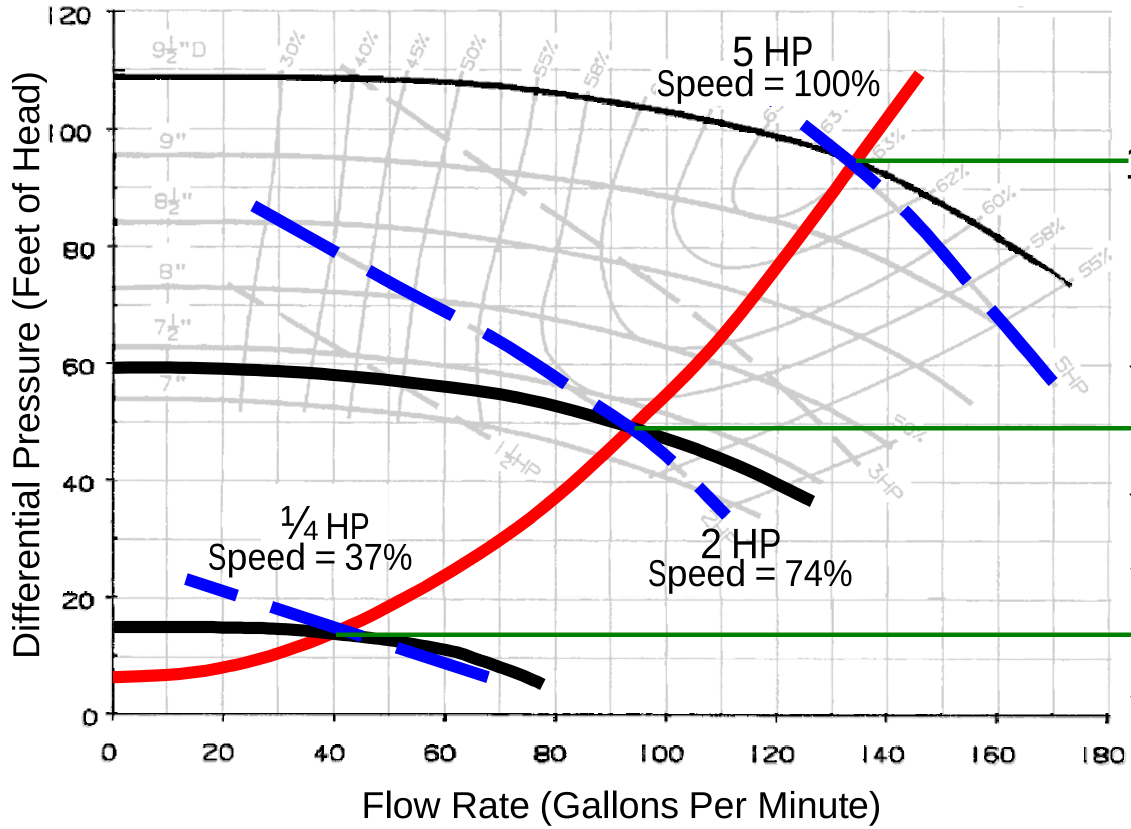
Dynamic Balance; Pre-adjusted Branch



Adding to Problem

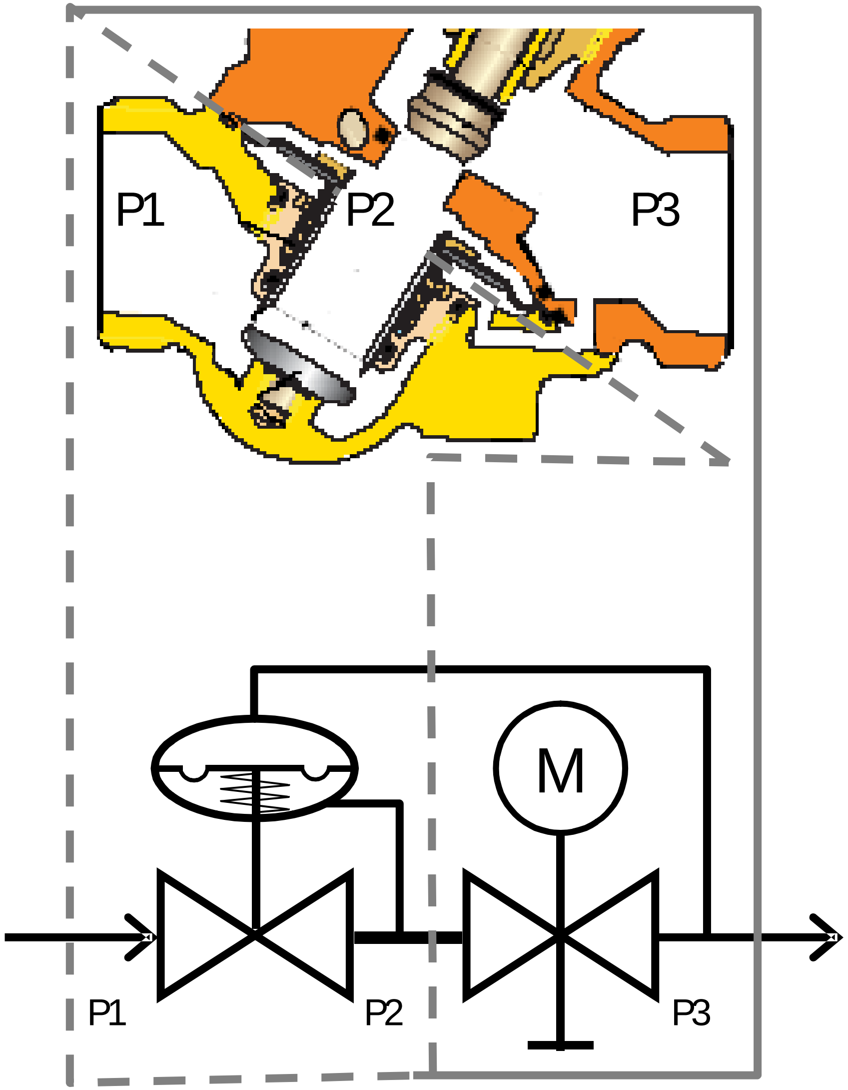
- Proportional control dynamic is changed in conventional modulating valves
- Controller begins to hunt





Load (Control Signal)	Flow Required	Conventional Valve	Regulated Valve
100%	Need	10 GPM	10 GPM
	Get's	10 GPM	10 GPM
74%	Need	4 GPM	4 GPM
	Get's	3 GPM	4 GPM
37%	Need	1 GPM	1 GPM
	Get's	.4 GPM	1 GPM

Two Valves Integrated In One Body



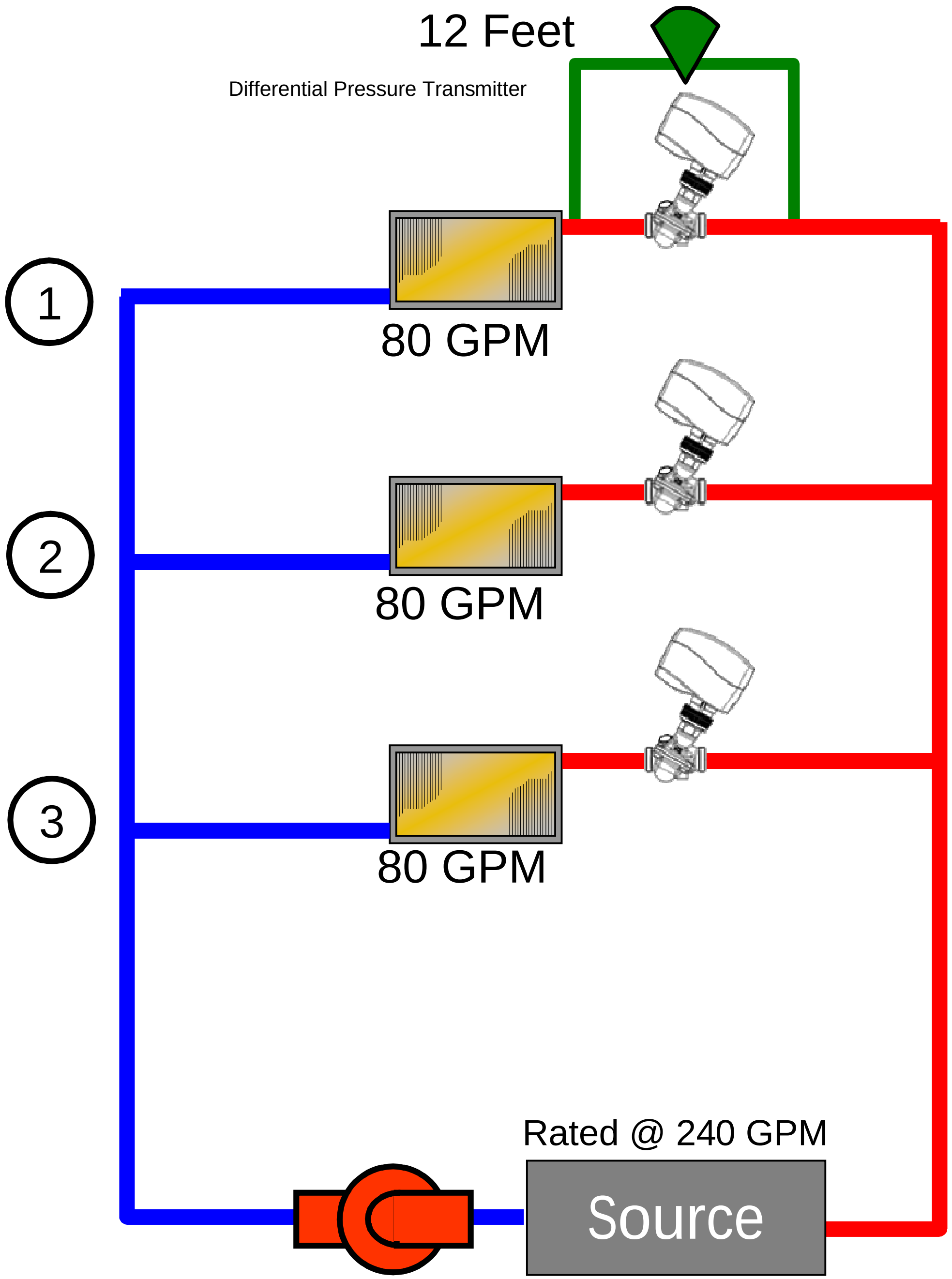
- The advanced design ensures stable pressure on temperature control valve at all times
- TC Valve always has 100% authority
  - Other designs do not

Conventional Control Valves Require

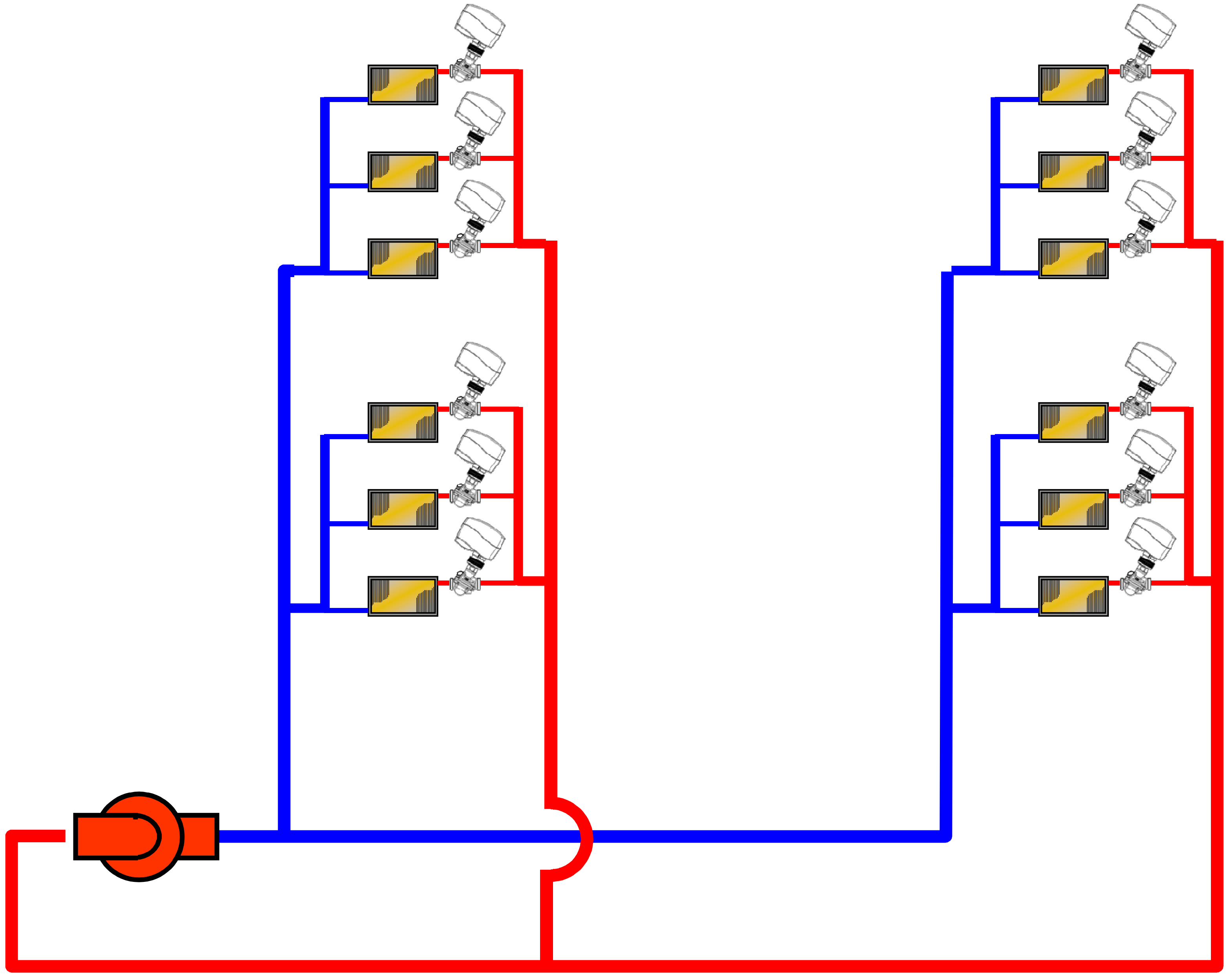
- Iterative design calculation
  - First pass; determine piping losses
  - Second pass; size valve, determine pressure drops and balance pipe sizes and pressure drops
- Stable Differential Pressure
- Balancing to tune valve to system
- Need extra flow? re-size or increase pressure

Regulated Valve Provides

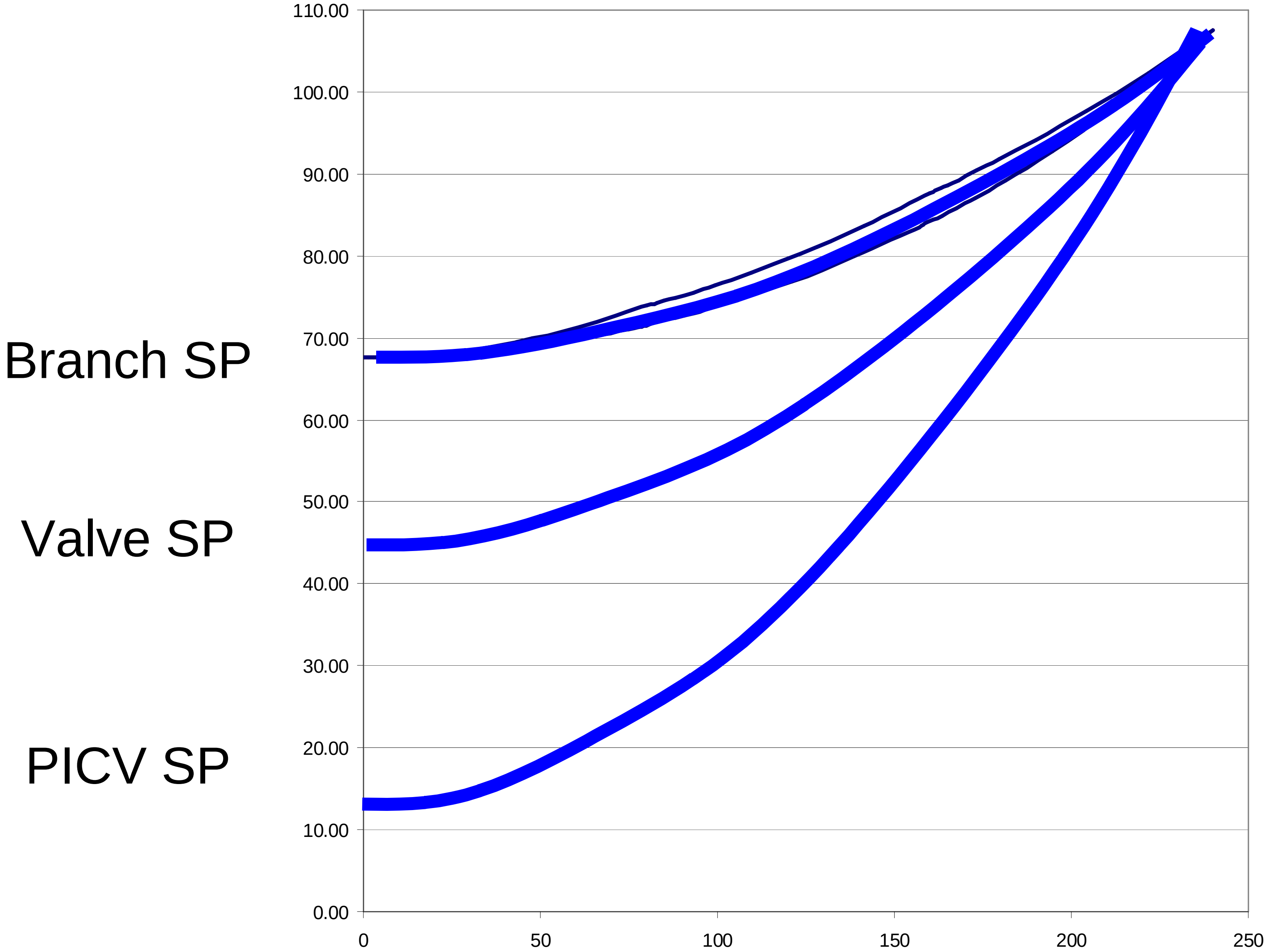
- Known pressure drop
  - Calculate pipe and pump size once
  - Less required ! P for control set point
- Consistent flow characteristic
- Valve inherently balances system and can proportion flow for “diverse” flow applications
- Need extra flow? adjust valve setting in field


12 Feet
Differential Pressure Transmitter
1
80 GPM
2
80 GPM
3
80 GPM
Rated @ 240 GPM
Source

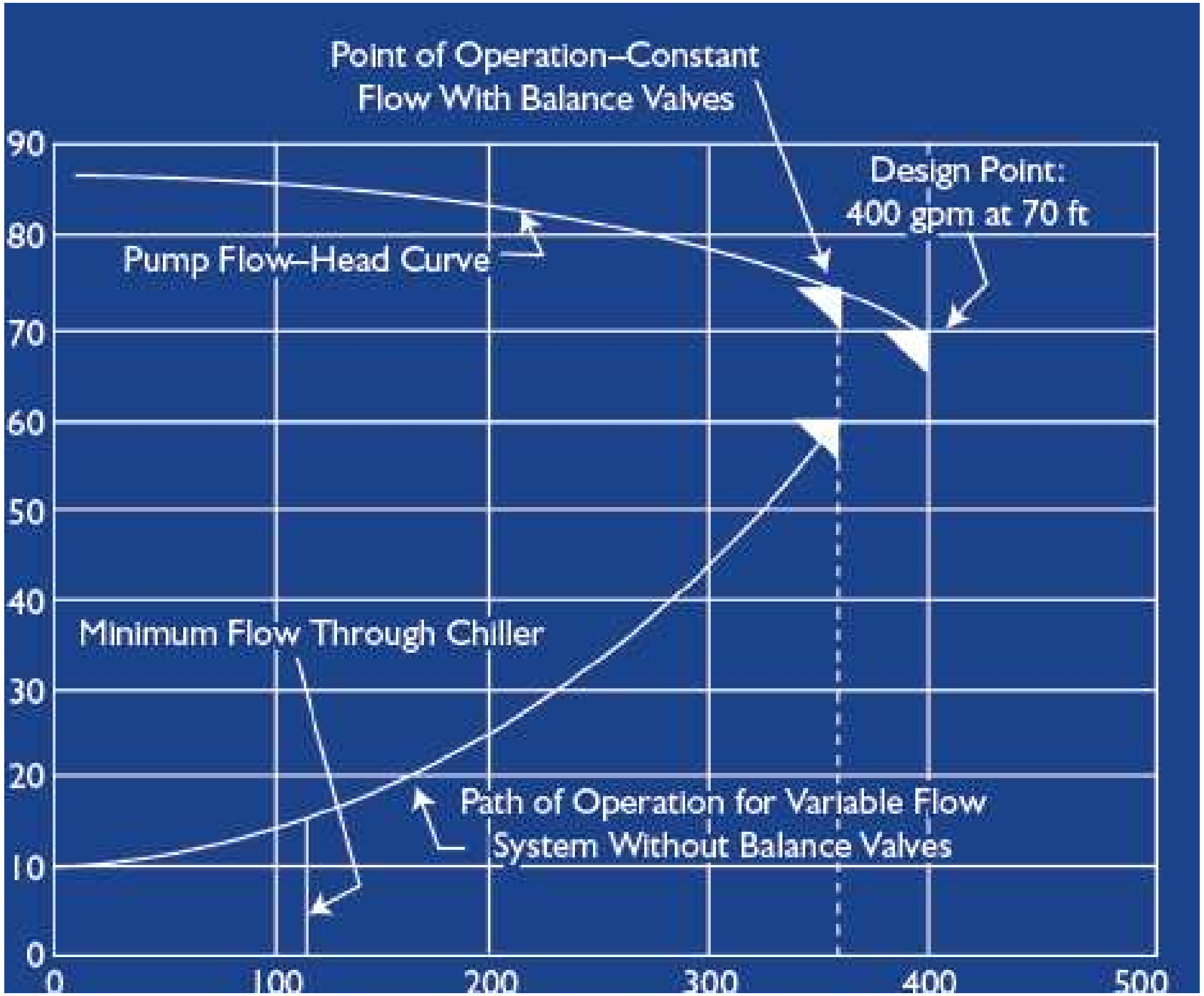
Dynamic Balance; PICV Controlled Pressure & ATC

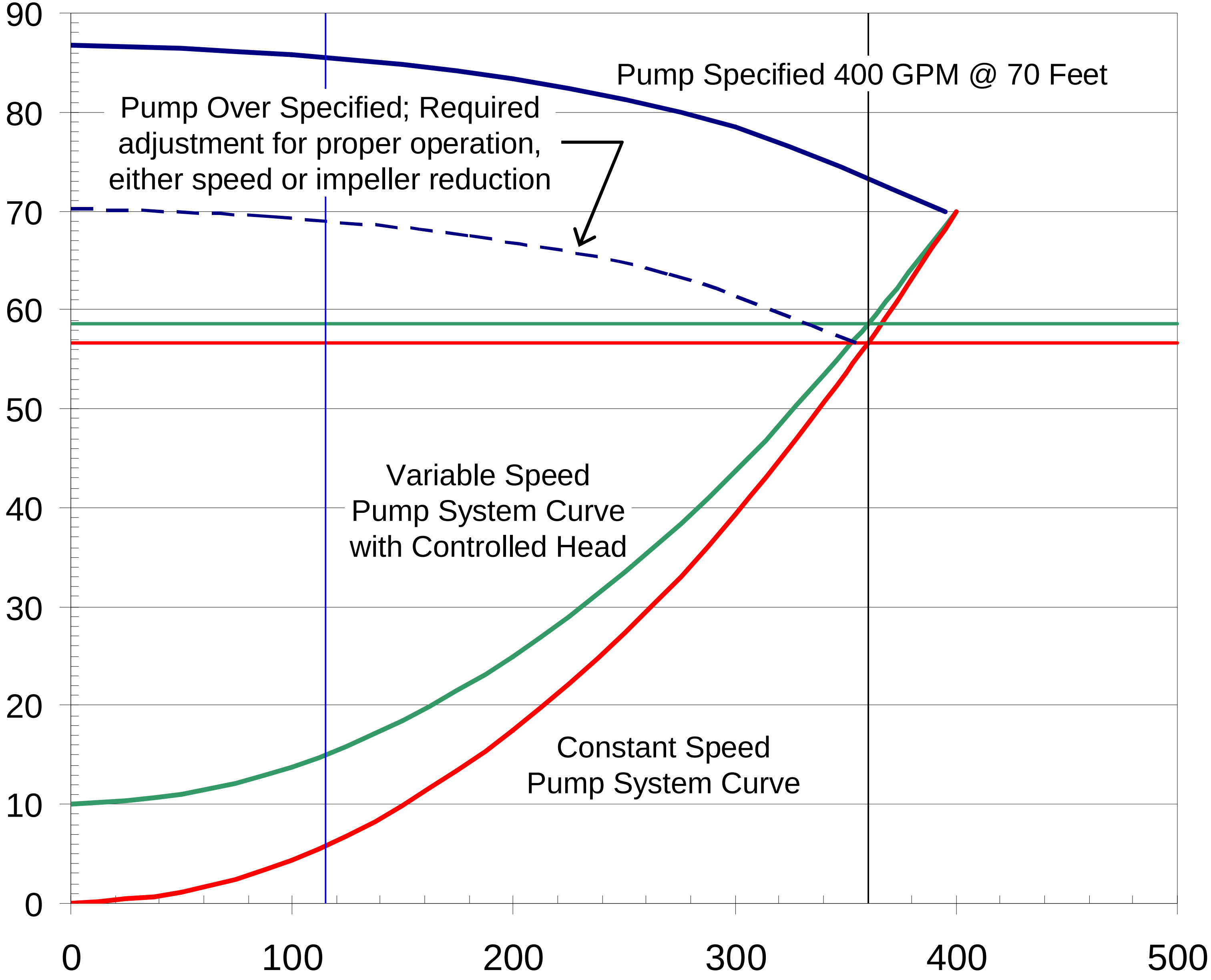


PICV Helps Move Pressure SP Down

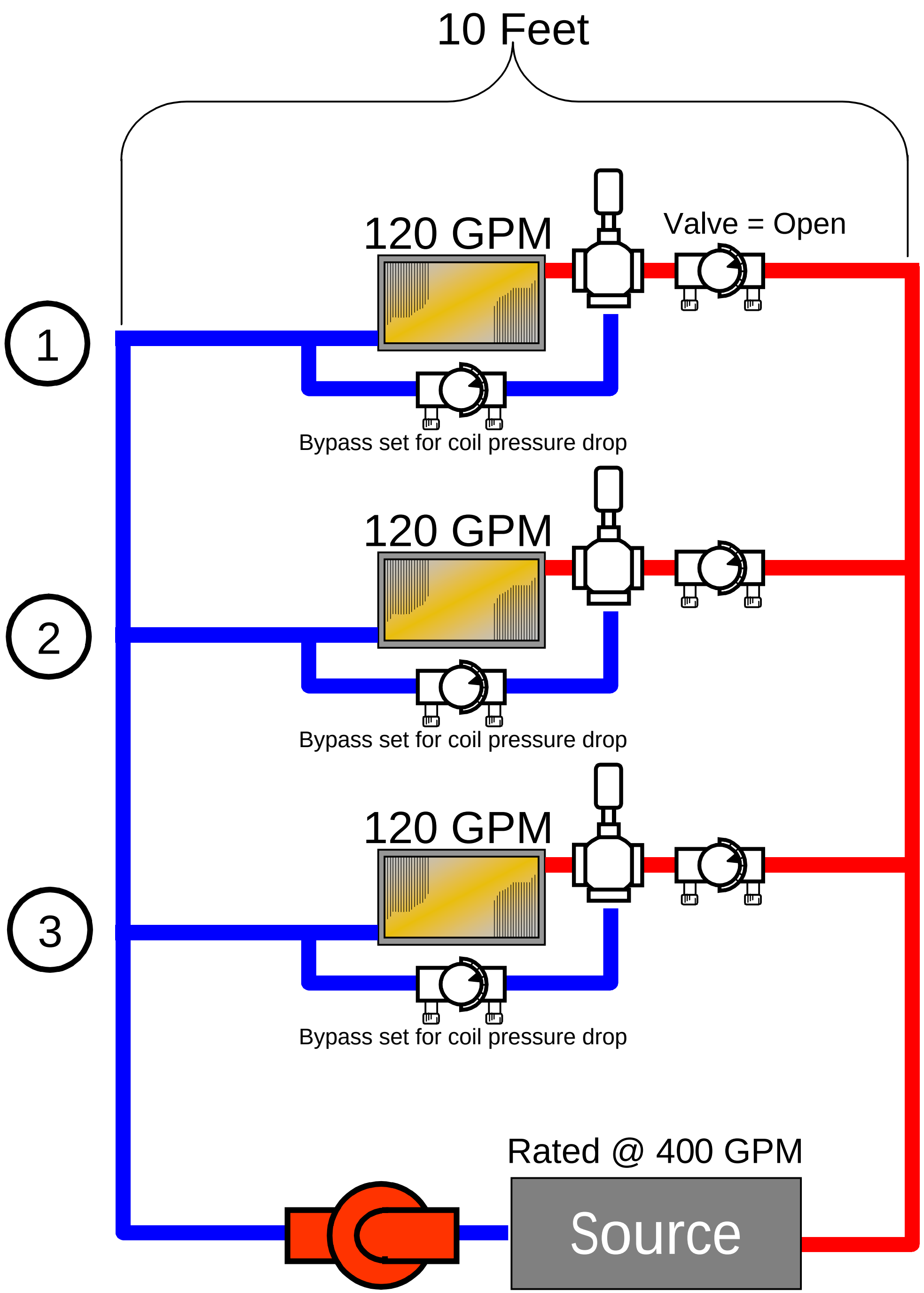


"Case Against Balancing Valves" ASHRAE Journal July 2009





Pump Specified 400 GPM @ 70 Feet
Pump Over Specified; Required adjustment for proper operation, either speed or impeller reduction
Variable Speed Pump System Curve with Controlled Head
Constant Speed Pump System Curve
0
10
20
30
40
50
60
70
80
90
0
100
200
300
400
500

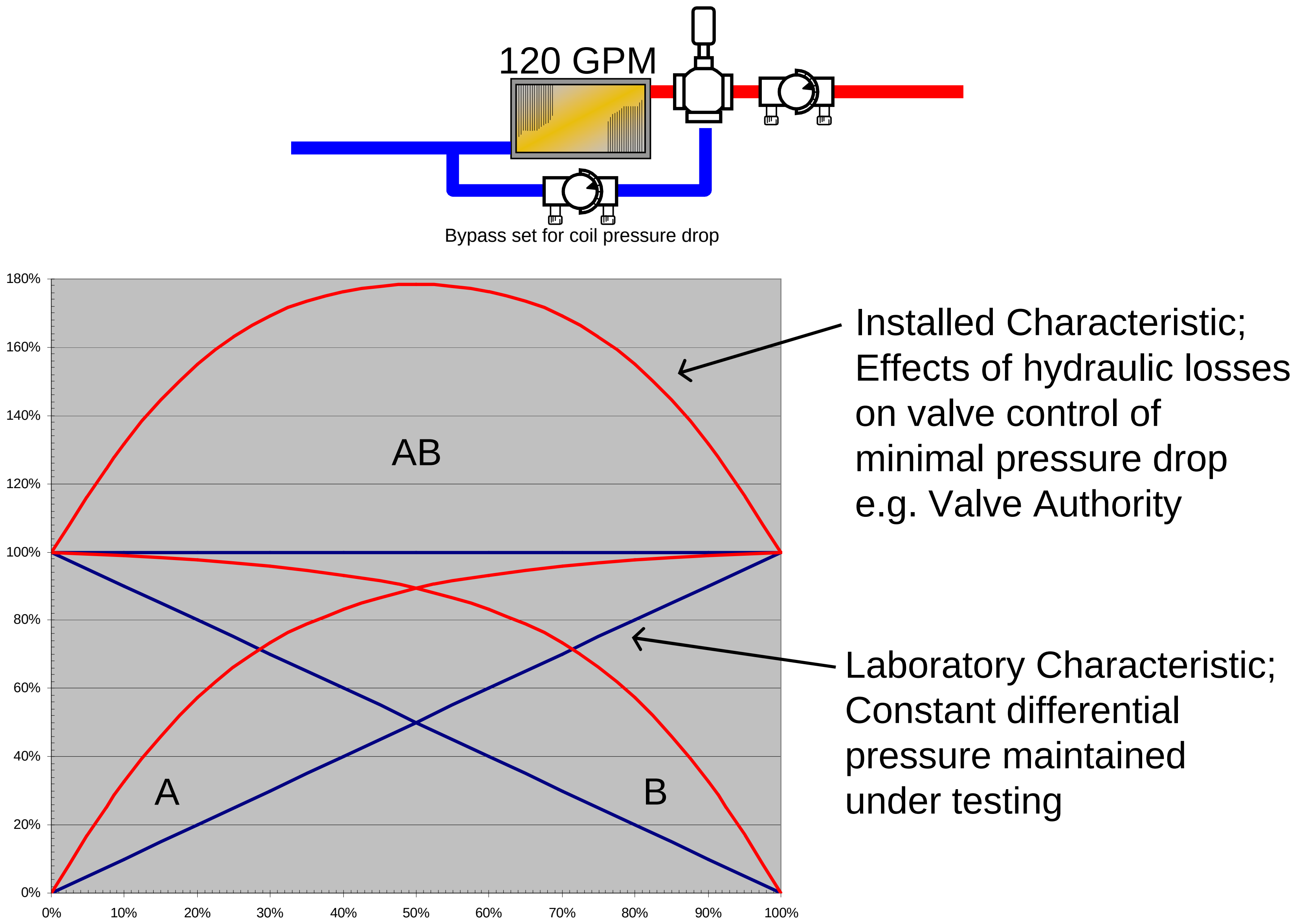


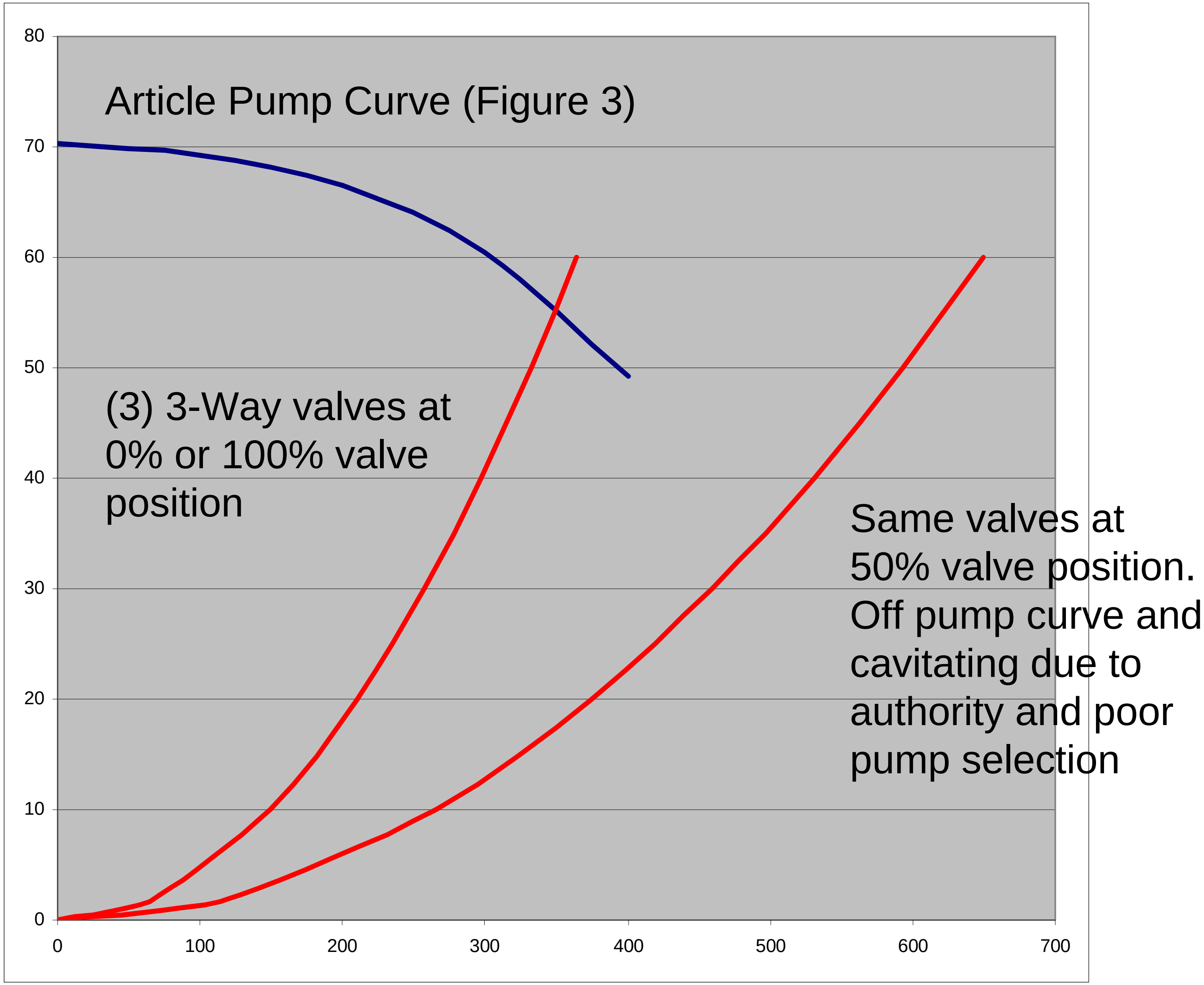
System Requires 180 Tons, 360 GPM
Chiller Rated @ 200 Tons, 400 GPM
Pump Specified 400 GPM @ 70 Feet

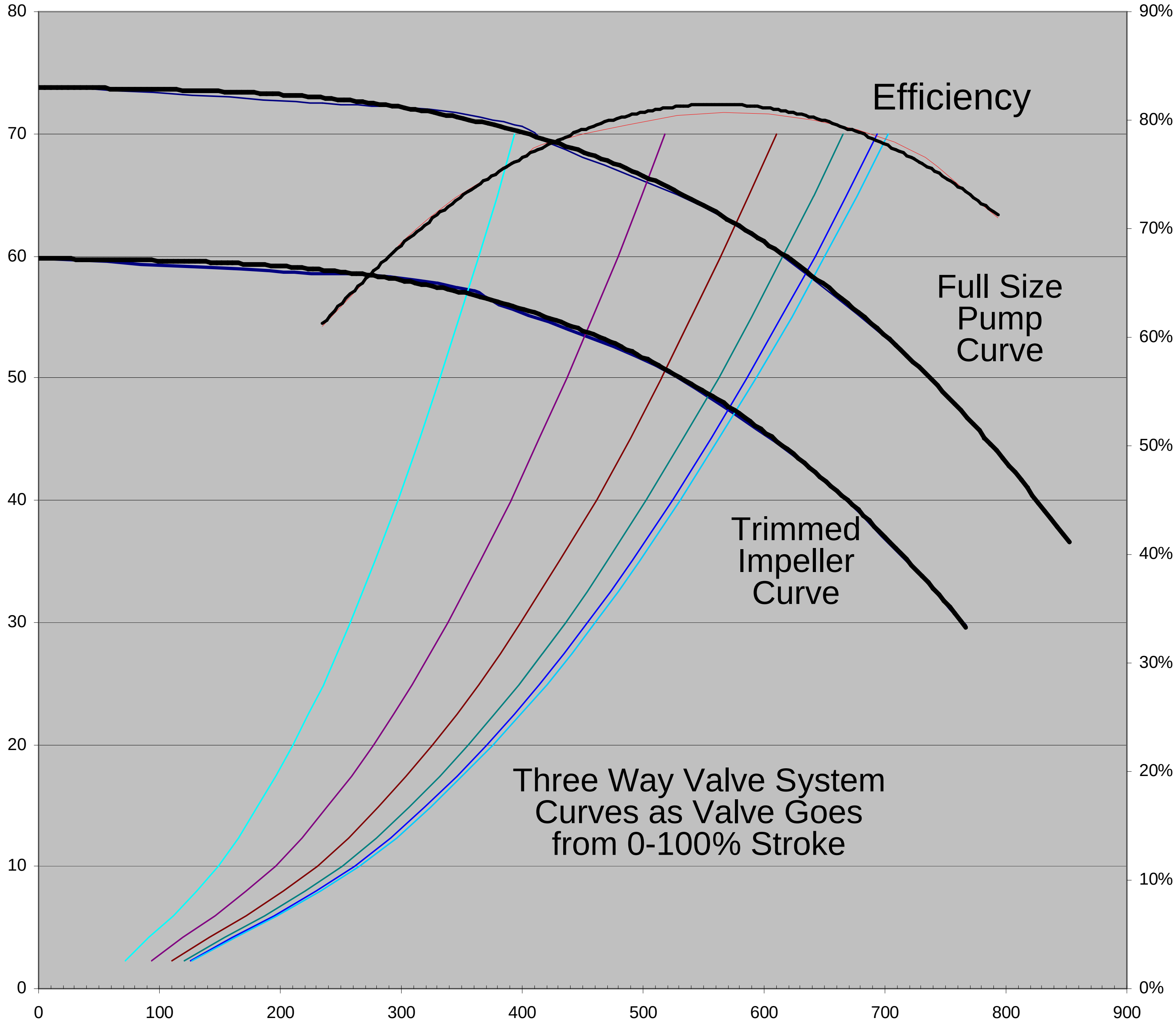
Branch Pipe, Valves, Coil and TC Valve specified at 10' Loss, via set point specified for variable speed pump system.

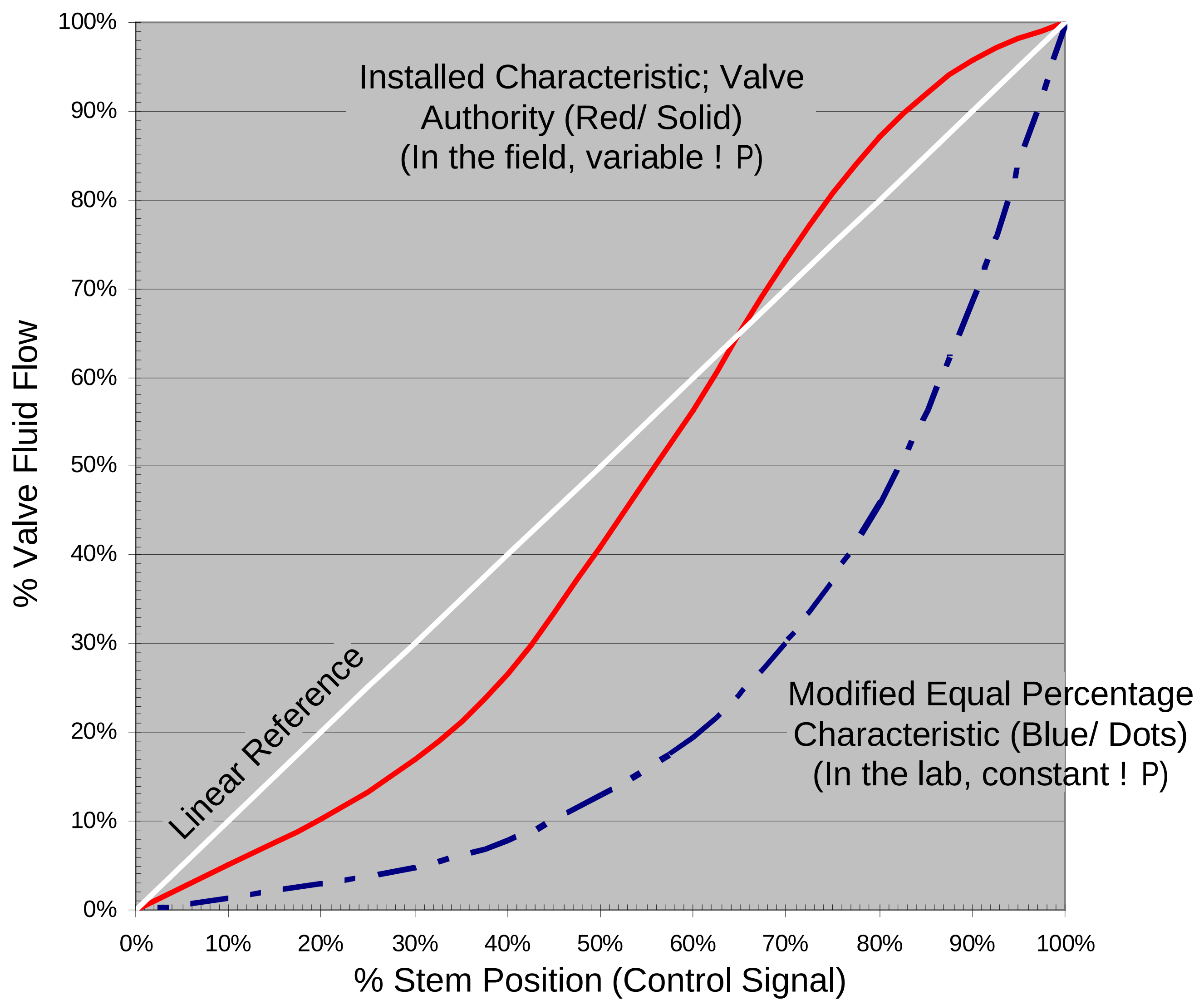
Branch 1 required balance: Bypass port must be balanced to pressure drop of coil. Either (A) Pump Impeller trimmed to match required head, 58.6 Feet, or (B) Pump speed fixed at 91.5% to match required speed for oversized pump

Branch 2 & 3 required balance: Bypass port must be balanced to pressure drop of coil. Balancing valves adjusted to make up for distribution head loss due to location.

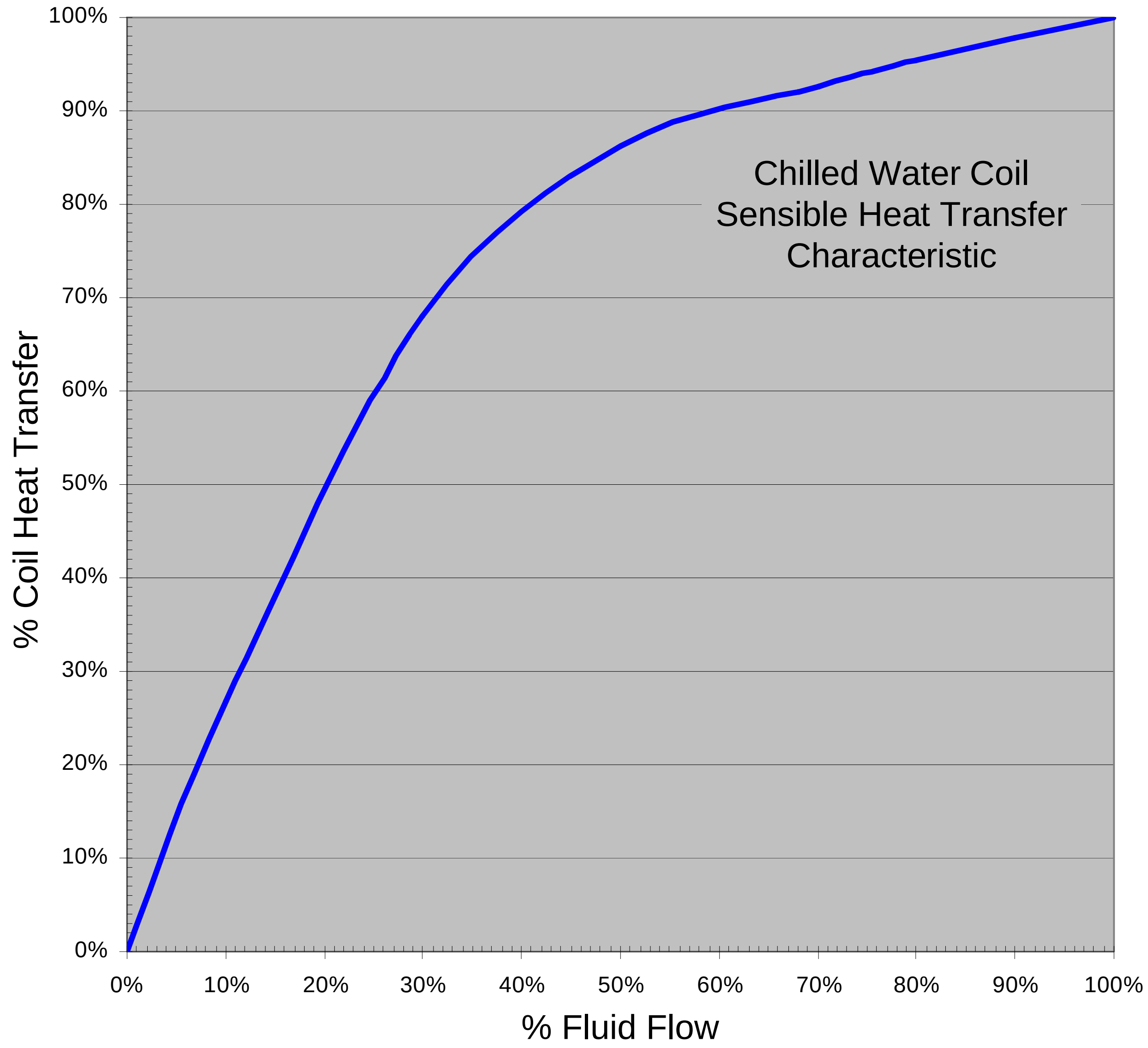

120 GPM
Bypass set for coil pressure drop
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
AB
A
B
Installed Characteristic;
Effects of hydraulic losses
on valve control of
minimal pressure drop
e.g. Valve Authority
Laboratory Characteristic;
Constant differential
pressure maintained
under testing


Article Pump Curve (Figure 3)
(3) 3-Way valves at 0% or 100% valve position
Same valves at 50% valve position. Off pump curve and cavitating due to authority and poor pump selection
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700

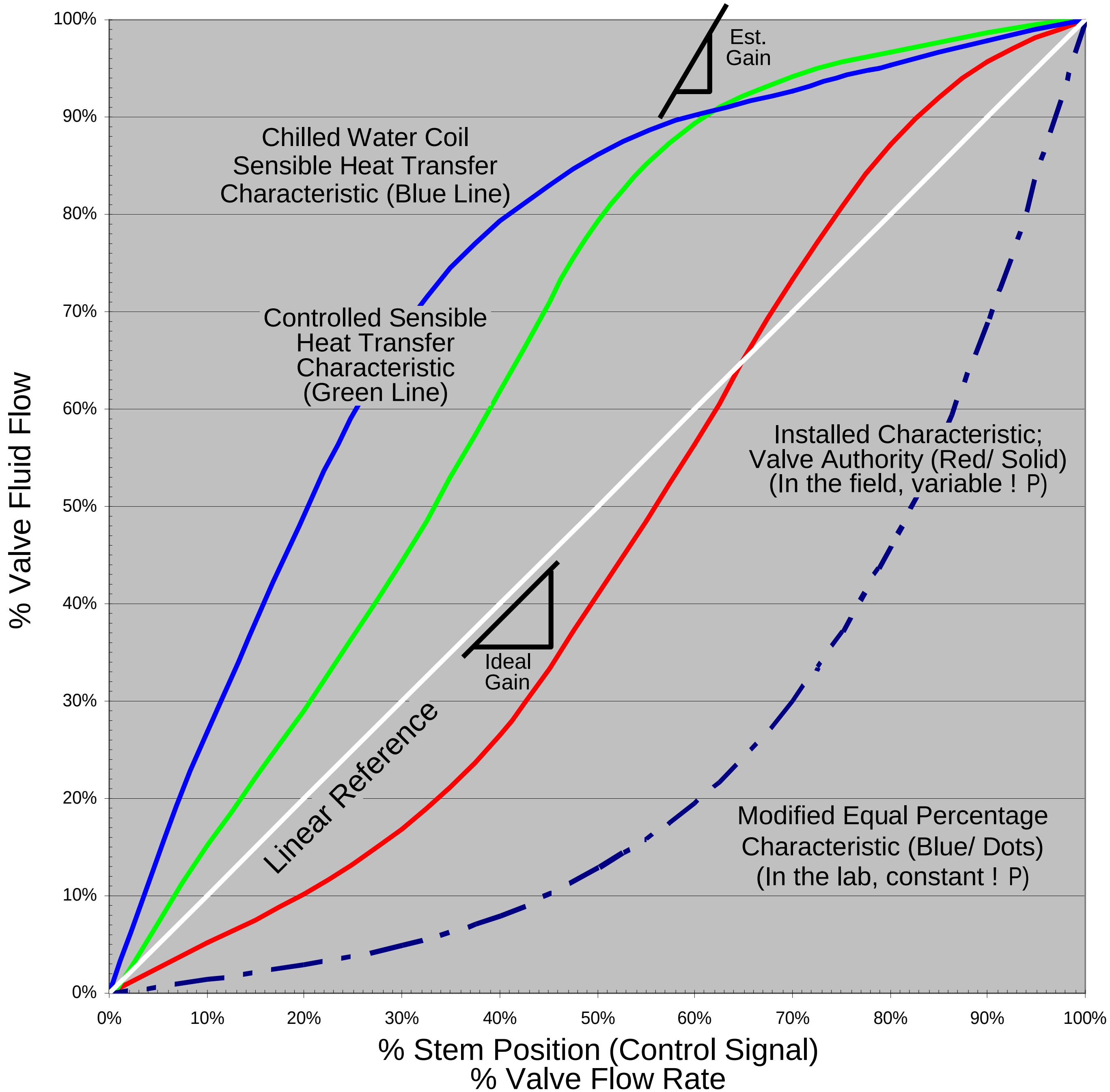

Efficiency
Full Size
Pump
Curve
Trimmed
Impeller
Curve
Three Way Valve System
Curves as Valve Goes
from 0-100% Stroke
0
10
20
30
40
50
60
70
80
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
0
100
200
300
400
500
600
700
800
900



Installed Characteristic; Valve
Authority (Red/ Solid)
(In the field, variable ! P)
Linear Reference
Modified Equal Percentage
Characteristic (Blue/ Dots)
(In the lab, constant ! P)
% Valve Fluid Flow
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
% Stem Position (Control Signal)



Chilled Water Coil
Sensible Heat Transfer
Characteristic
% Coil Heat Transfer
% Fluid Flow
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%



Est.
Gain
Chilled Water Coil
Sensible Heat Transfer
Characteristic (Blue Line)
Controlled Sensible
Heat Transfer
Characteristic
(Green Line)
Installed Characteristic;
Valve Authority (Red/ Solid)
(In the field, variable ! P)
Ideal
Gain
Linear Reference
Modified Equal Percentage
Characteristic (Blue/ Dots)
(In the lab, constant ! P)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Valve Fluid Flow
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
% Stem Position (Control Signal)
% Valve Flow Rate

Impact

- Article doesn't really point out impacts well
  - 3 Way Unbalanced and oversized pump

    58000 KWH $4423
  - 3 Way Balanced

    42000 $3224
  - 2 Way Valve with Authority Issues & Oversized Pump

    24,500 KWH $1872
  - 2 Way High Authority (PICV) No Pump Adjustment

    12900 KWH $986
  - 2 Way PICV with Pump Adjusted

    8500 KWH $647

Balance Counts

- ALL systems that move fluid probably benefit from proper adjustment
- In hydronics PIC Valves help maintain
  - Proper Temperature Control (No Hunting)
  - Reduced Pump Differential Set Point
  - Overcome with controllers "big" system issues like diversity
- Problems don't necessarily show themselves in "Commissioning"
  - Reconsider protocols with emphasis on control signals
  - Pump Curves & System Curves