$$Bhp_{New} = Bhp_{Old} \times \left(\frac{Flow_{New}}{Flow_{Old}}\right)^{\eta}$$

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
η = 3 for a true fixed system with a single system curve that goes through the origin at 0 f.t.w.c and 0 gpm. For variable flow systems, which operate on a range of system curves, this is an expontent selected to approximate the impact of variable flow plant operation, fixed pressure set points, and other operational factors to allow the affinity law to predict pump or fan power.

Note that the relationship can be applied using kW or any other power metric as long as you keep the units consistent. In other words:

$$kW_{New} = kW_{Old} \times \left(\frac{Flow_{New}}{Flow_{Old}}\right)^{\eta}$$

The exponent will be dependent on the specific nature of the system in terms of the control pressure that is maintained relative to the design pressure, the location of the controlling sensor, the ratio of distribution main losses to losses through the branches to the loads and similar factors. You can develop one for a particular system based on an analysis for limiting conditions and specific operating conditions.

Alternatively, you can use an exponent cited from a credible source like a University, and organization like ASHRAE, or supporting technical information from a utility incentive program. One example of suggested exponents for HVAC fan and pump systems was published by Southern California Edison in a document titled *Fan and Pump Affinity Law Clarification.* The exponents below are from that publication and are intended to be used as guidelines.

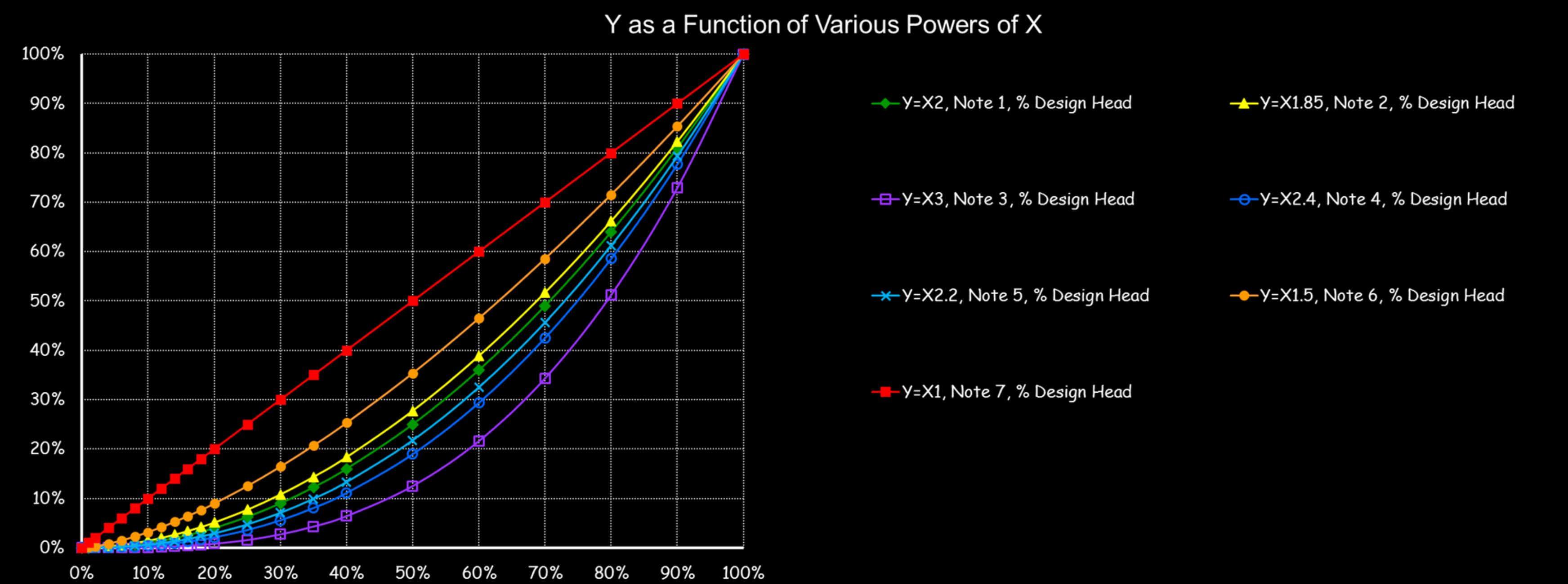
Engineering judgement can be used to modify them slightly based on the specific operating conditions for a specific system or to come up with similar coefficients based on a more rigorous analysis of the system. Definitions of open, closed, fixed and variable systems follow the exponent list.

Closed, fixed water systems; η = 2.4
Open, fixed water systems; η = 2.2

Fixed air systems serving enclosures like CRAC units serving enclosed hot or cold aisles; η = 2.2
Fixed air systems serving enclosures like CRAC units serving open plenums; η = 2.0

Variable air or water systems with a fixed pressure control set point
- Fixed set point is 20% or less of the total pressure required at design flow; η = 2.4
- Fixed set point is 20% - 50% of the total pressure required at design flow; η = 2.0
- Fixed set point is 50% - 80% of the total pressure required at design flow; η = 1.5
- Fixed set point is greater than 80% of the total pressure required at design flow; η = 1.0

Variable air or water systems with a variable pressure control set point; η = 2.4

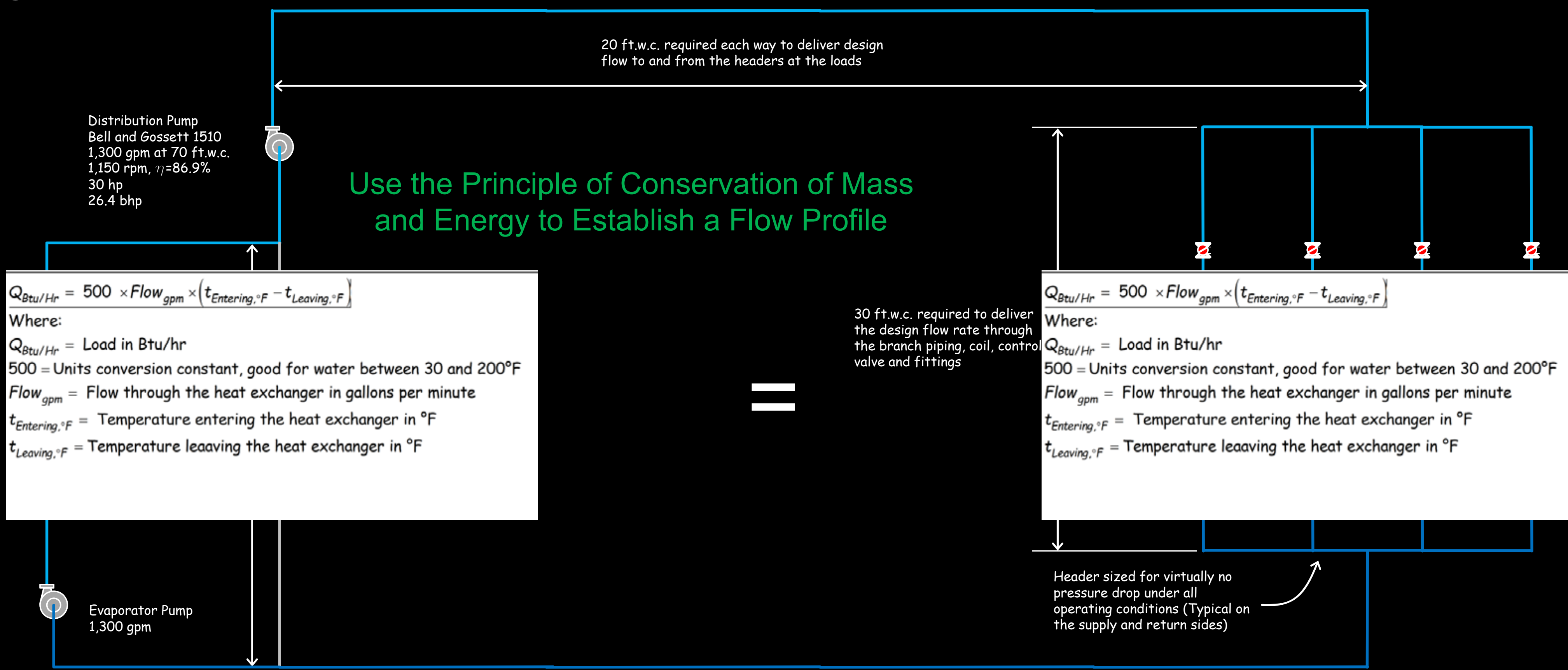


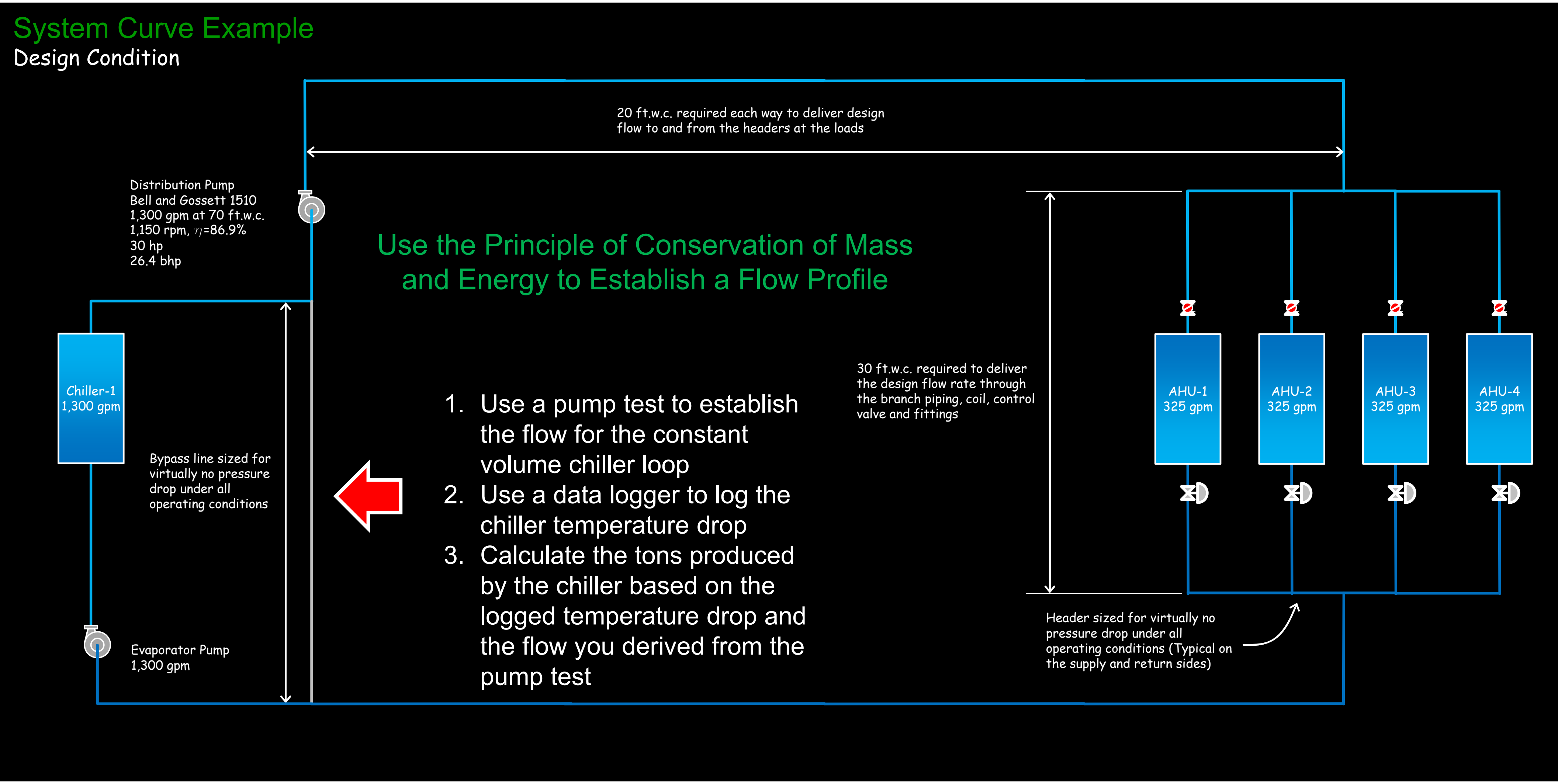
Notes:

1. The "Square Law" defining the system flow versus pressure drop relationship for a piping or duct system with fully developed turbulent flow. It is also the exponent recommended by Southern California Edison to adjust the "Cube Rule" for:
   a. A constant volume air system serving open plenums.
   b. A variable flow air or water system with a fixed set point that is 20% - 50% of the total pressure required at design flow.
2. The ASHRAE research based system curve relationship for typical HVAC systems due to the fact that in some parts of the system, there is not fully developed turbulent flow.
3. The "Cube Rule" or Affinity Law defining the relationship between pump or fan power and flow or speed.
4. Southern California Edison's suggested affinity law exponent for:
   a. A closed constant volume water system.
   b. A variable flow air or water system with a fixed set point that is 20% or less of the total pressure required at design flow.
   c. A variable flow air or water system with a reset set point.
5. Southern California Edison's suggested affinity law exponent for:
   a. An open constant volume water system.
   b. A constant volume air system like a CRAC (Computer Room Air Conditioning) unit serving enclosed hot or cold aisles.
6. Southern California Edison's suggested affinity law exponent for a variable flow air or water system with a fixed set point that is 50% - 80% of the total pressure required at design flow.
7. The equation of a straight line and also Southern California Edison's suggested affinity law exponent for a variable flow air or water system with a fixed set point that is greater than 80% of the total pressure required at

System Curve Example

Design Condition

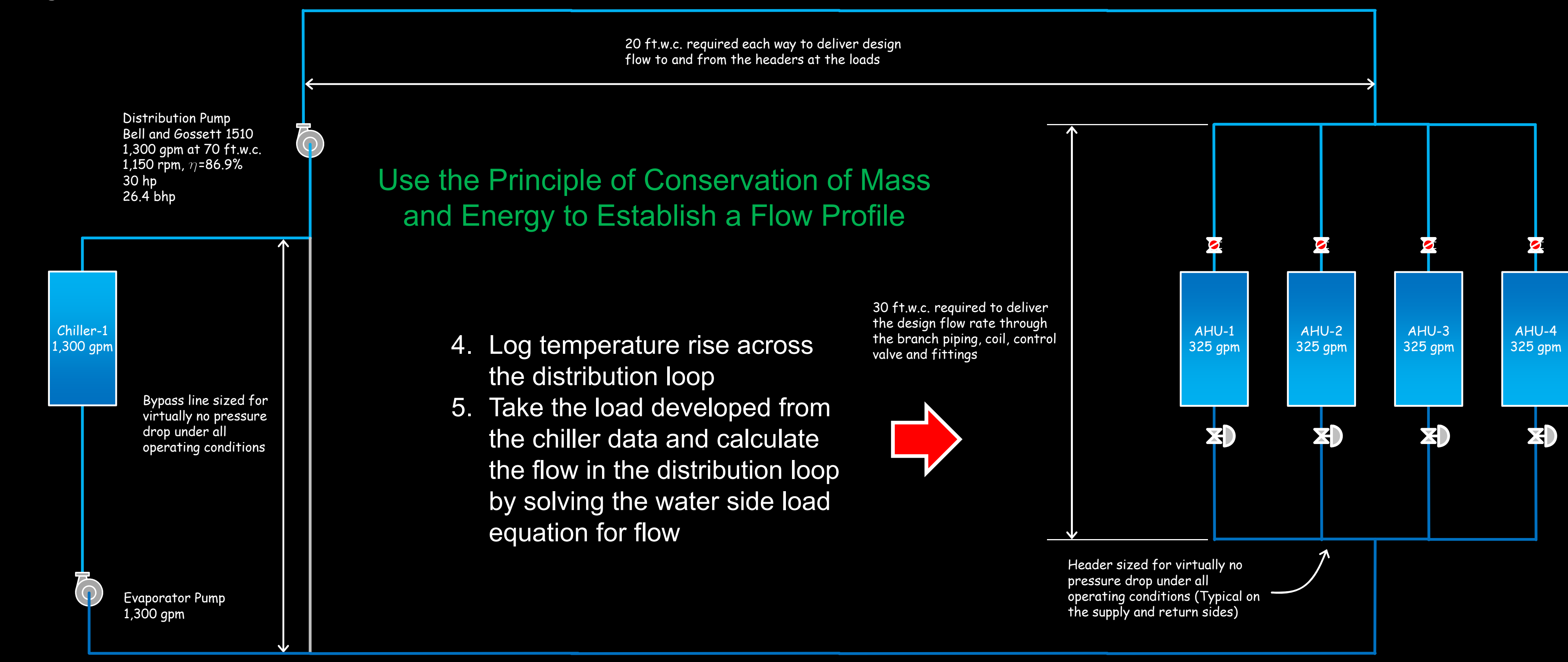




System Curve Example
Design Condition
20 ft.w.c. required each way to deliver design flow to and from the headers at the loads
Distribution Pump
Bell and Gossett 1510
1,300 gpm at 70 ft.w.c.
1,150 rpm, η=86.9%
30 hp
26.4 bhp
Use the Principle of Conservation of Mass and Energy to Establish a Flow Profile
Chiller-1
1,300 gpm
Bypass line sized for virtually no pressure drop under all operating conditions
1. Use a pump test to establish the flow for the constant volume chiller loop
2. Use a data logger to log the chiller temperature drop
3. Calculate the tons produced by the chiller based on the logged temperature drop and the flow you derived from the pump test
30 ft.w.c. required to deliver the design flow rate through the branch piping, coil, control valve and fittings
AHU-1
325 gpm
AHU-2
325 gpm
AHU-3
325 gpm
AHU-4
325 gpm
Evaporator Pump
1,300 gpm
Header sized for virtually no pressure drop under all operating conditions (Typical on the supply and return sides)

System Curve Example

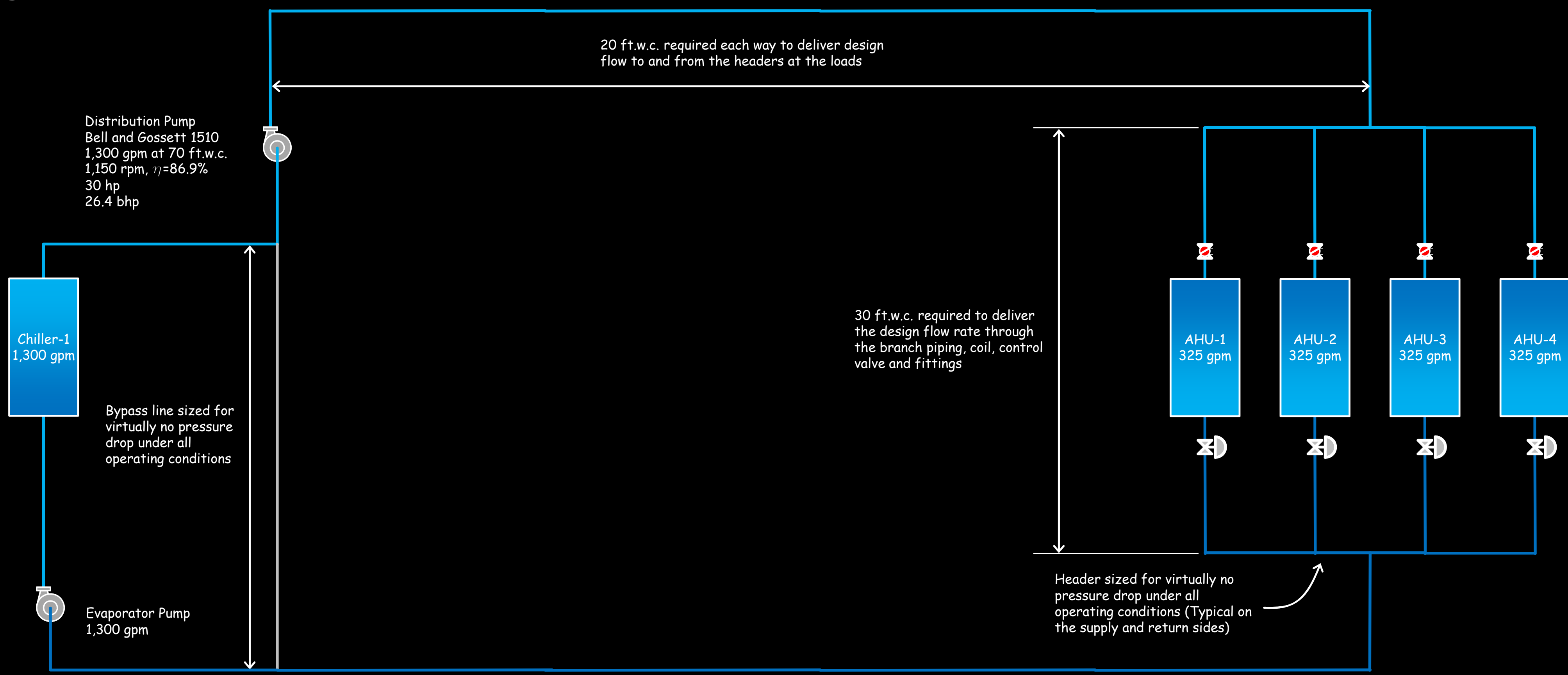
Design Condition



4. Log temperature rise across the distribution loop
5. Take the load developed from the chiller data and calculate the flow in the distribution loop by solving the water side load equation for flow

System Curve Example

Design Condition



System Curve Points		
Condition	Flow	Pressure
140% of known flow	1,820	137.20
120% of known flow	1,560	100.80
Known	1,300	70.00
80% of known flow	1,040	44.80
60% of known flow	780	25.20
40% of known flow	520	11.20
30% of known flow	390	6.30
20% of known flow	260	2.80
18% of known flow	234	2.27
16% of known flow	208	1.79
14% of known flow	182	1.37
12% of known flow	156	1.01
10% of known flow	130	0.70
8% of known flow	104	0.45
6% of known flow	78	0.25
4% of known flow	31	0.04
2% of known flow	16	0.01
No Flow	0	0.00

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

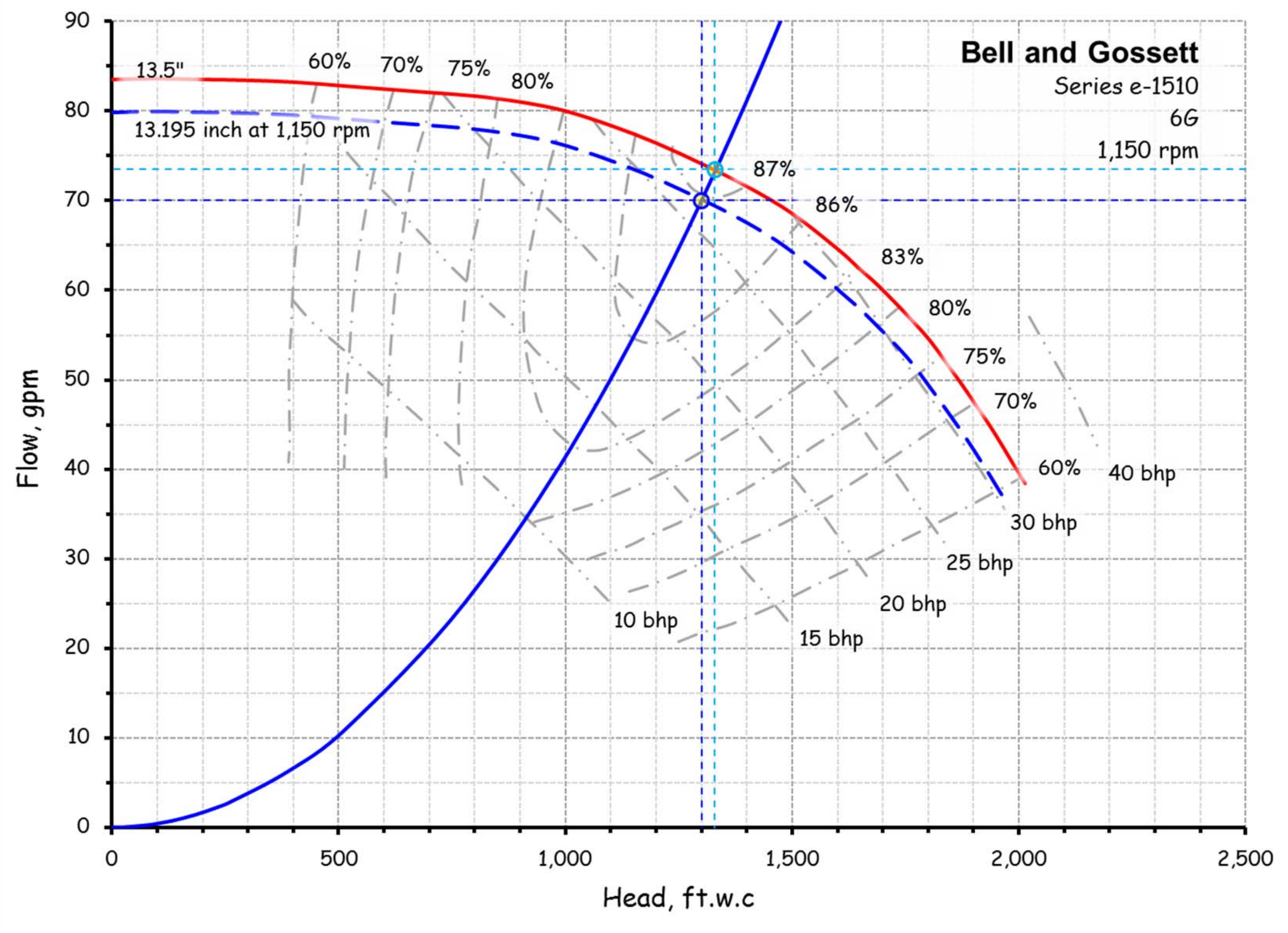
Where:

$Pressure_{New}$ = 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

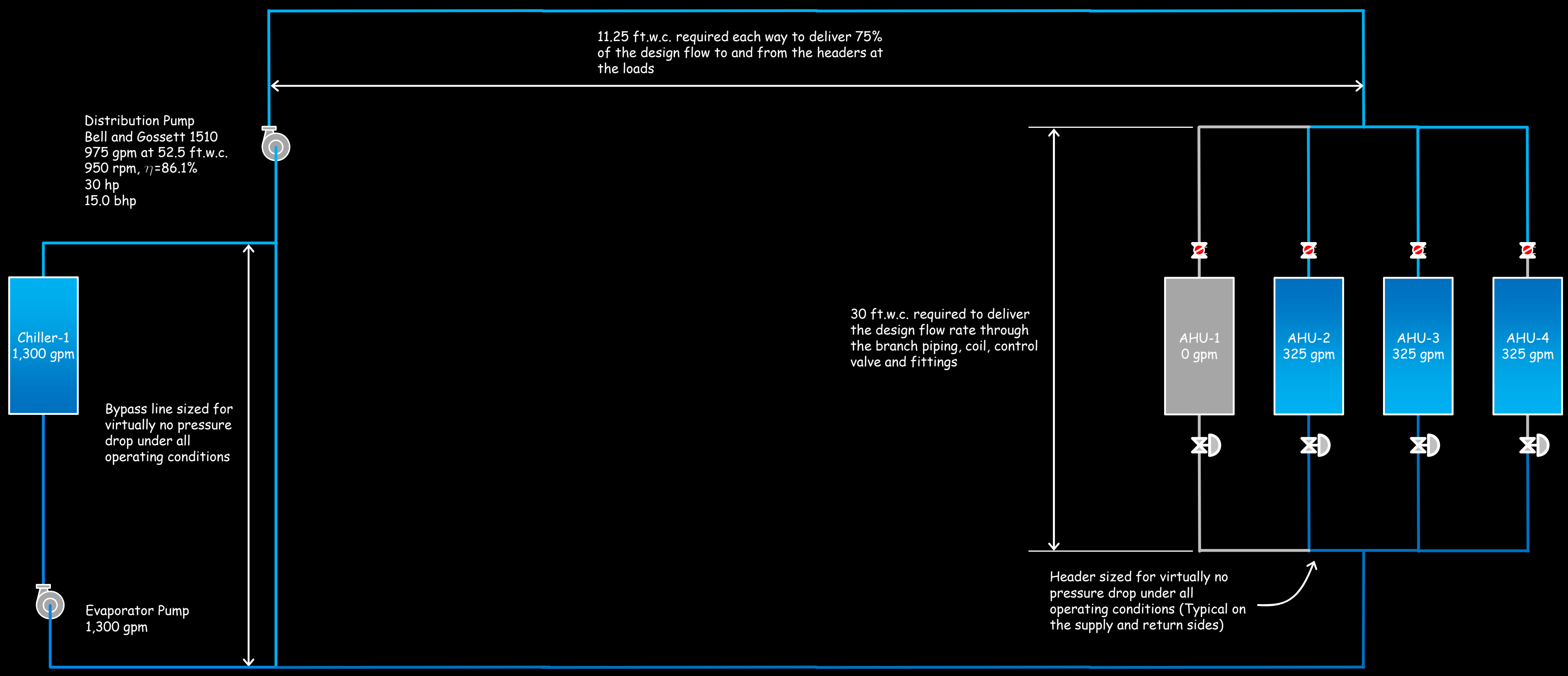


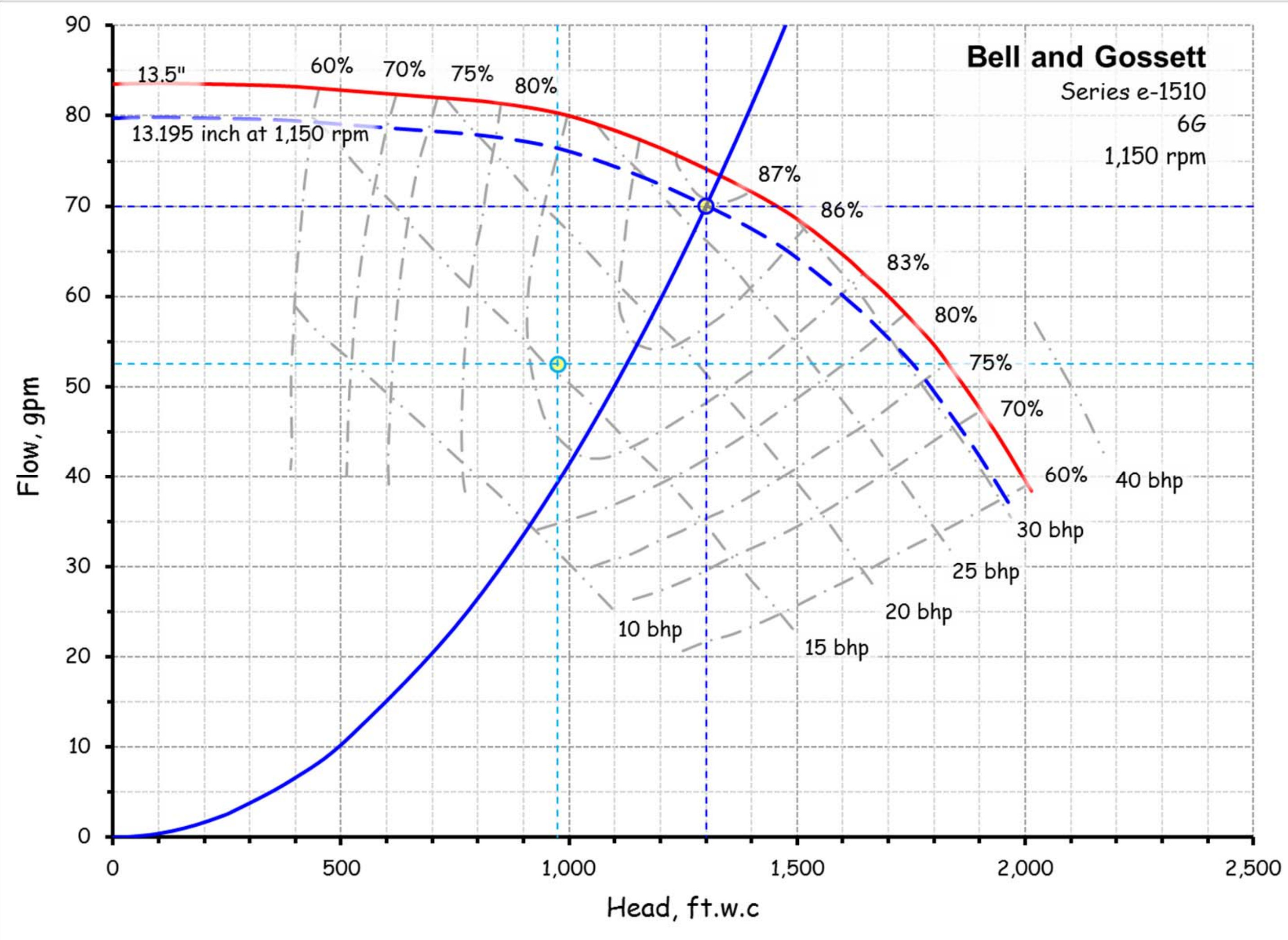
Summary													
Load Condition	Flow Rate, gpm	Head, ft.w.c	Pump Speed, rpm	Pump Efficiency	Pump Bhp	Motor Efficiency	VFD Efficiency	Projected kW	"Cube Rule" kW	kW vs. Flow$^{2.4}$	kW vs. Flow$^{2.0}$	kW vs. Flow$^{1.5}$	Head vs. Flow$^{2.0}$
Design	1,300.0	70.000	1,150	86.9%	26.4	94%	98%	28.8	28.8	28.8	28.8	28.8	70.0

$$hp = \left(\frac{Flow_{gpm} \times Head_{ft.w.c.}}{3{,}960 \times \eta_{Pump} \times \eta_{Motor} \times \eta_{VSD}} \right)$$

System Curve Example

75% Load Condition




Bell and Gossett
Series e-1510
6G
1,150 rpm
13.5"
13.195 inch at 1,150 rpm
60%
70%
75%
80%
87%
86%
83%
80%
75%
70%
60%
40 bhp
30 bhp
25 bhp
20 bhp
15 bhp
10 bhp
Flow, gpm
Head, ft.w.c
0
10
20
30
40
50
60
70
80
90
0
500
1,000
1,500
2,000
2,500

System Curve Points		
Condition	Flow	Pressure
160% of known flow	1,560	134.40
120% of known flow	1,170	75.60
Known	975	52.50
80% of known flow	780	33.60
60% of known flow	585	18.90
40% of known flow	390	8.40
30% of known flow	293	4.73
20% of known flow	195	2.10
18% of known flow	176	1.70
16% of known flow	156	1.34
14% of known flow	137	1.03
12% of known flow	117	0.76
10% of known flow	98	0.53
8% of known flow	78	0.34
6% of known flow	59	0.19
4% of known flow	23	0.03
2% of known flow	12	0.01
No Flow	0	0.00

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

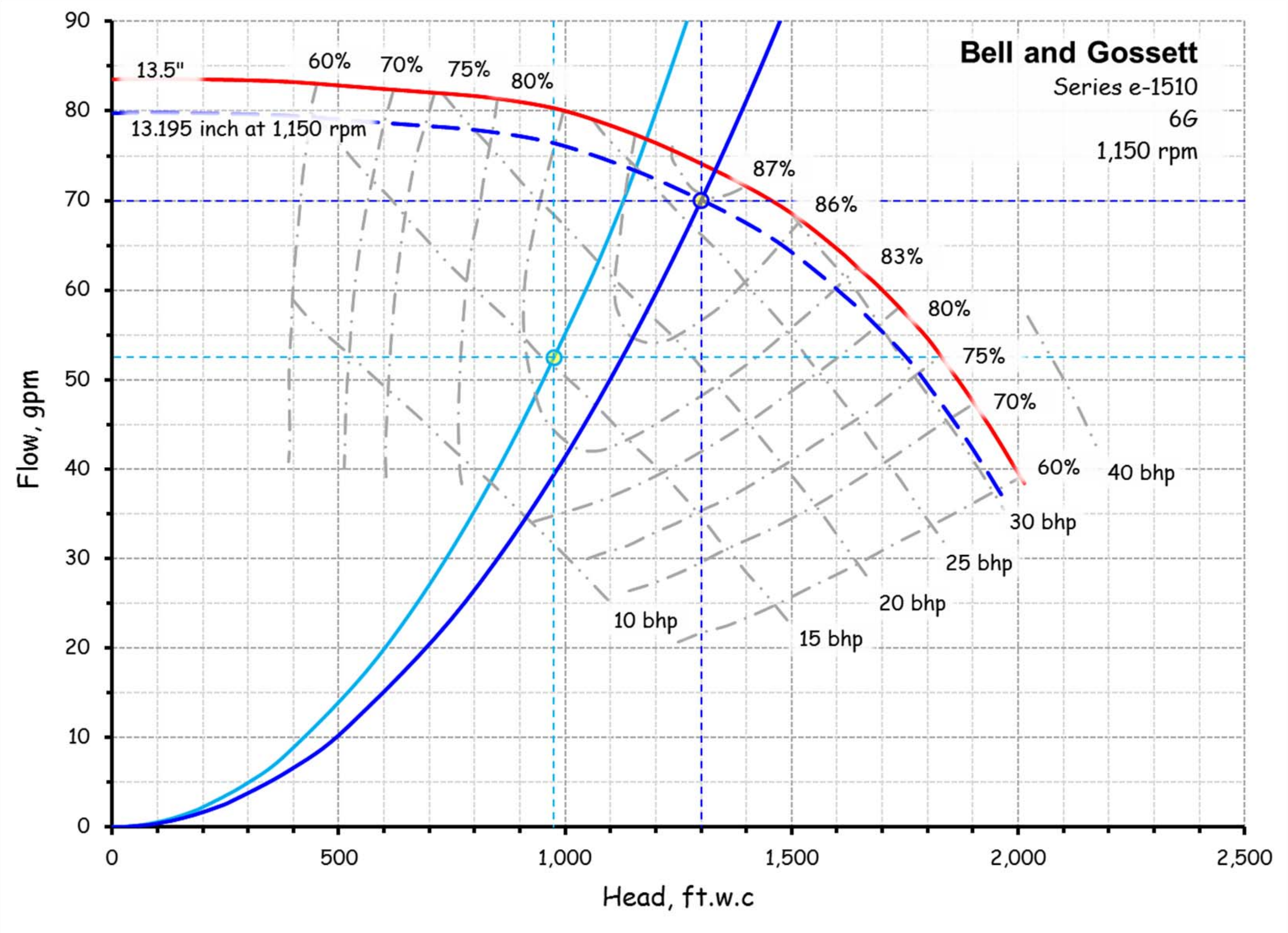
Where:

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

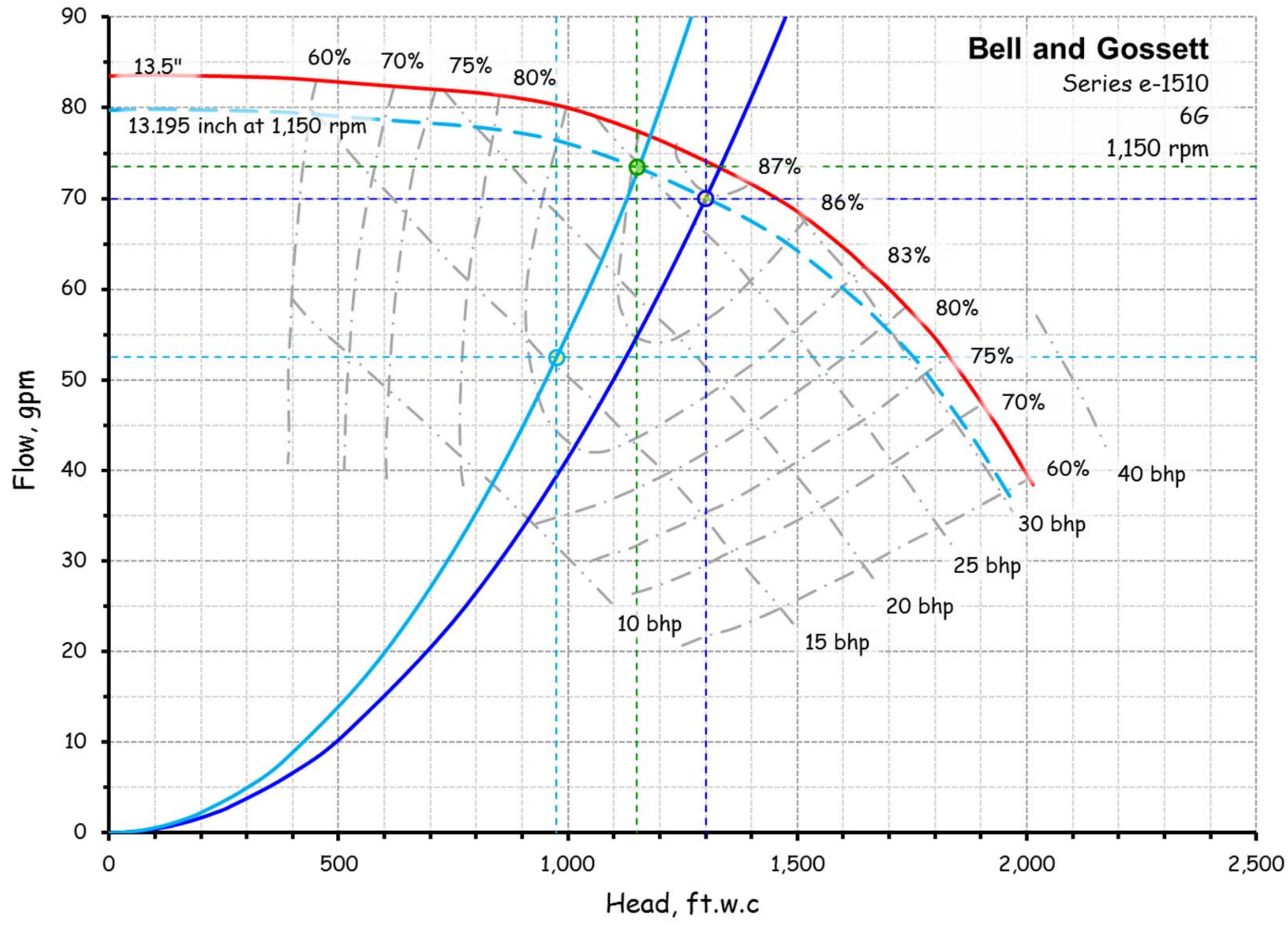
$Pressure_{Old}$ = The pressure you know in consistent units

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

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



System Curve Points		
Condition	Flow	Pressure
160% of known flow	1,560	134.40
120% of known flow	1,170	75.60
Known	975	52.50
80% of known flow	780	33.60
60% of known flow	585	18.90
40% of known flow	390	8.40
30% of known flow	293	4.73
20% of known flow	195	2.10
18% of known flow	176	1.70
16% of known flow	156	1.34
14% of known flow	137	1.03
12% of known flow	117	0.76
10% of known flow	98	0.53
8% of known flow	78	0.34
6% of known flow	59	0.19
4% of known flow	23	0.03
2% of known flow	12	0.01
No Flow	0	0.00



Speed projection from the 75% System Curve		
Desired Flow -	975	gpm (given)
Known flow -	1,150	gpm (from75% system curve)
Known impeller speed -	1,150	rpm (rated speed)
"Tweak" value -	-25	rpm (Manual ajustment)
Desired impeller speed -	950	rpm

$$Flow_{New} = Flow_{Old} \times \left(\frac{Speed_{New}}{Speed_{Old}}\right)$$

Where:

$Flow_{New}$ = The flow rate you are trying to predict in consistent units

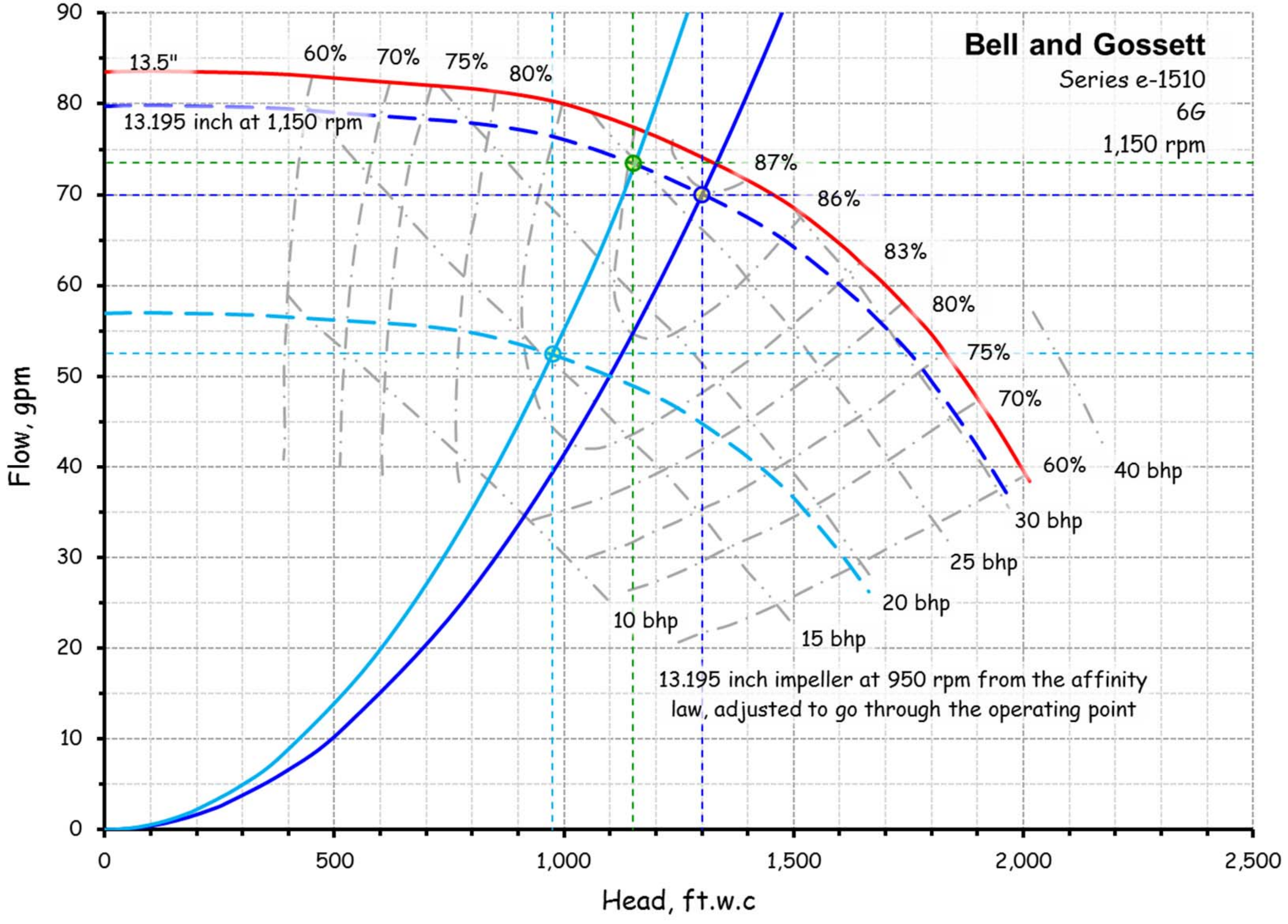
$Flow_{Old}$ = The flow rate you know in consistent units

$Speed_{New}$ = The rated impeller speed used for the original curve in consistent units

$Speed_{Old}$ = The new impeller speed at the test condition in consistent units

Solving this for $Speed_{New}$ yields:

$$\left(\frac{Flow_{New}}{Flow_{Old}}\right) \times Speed_{Old} = Speed_{New}$$

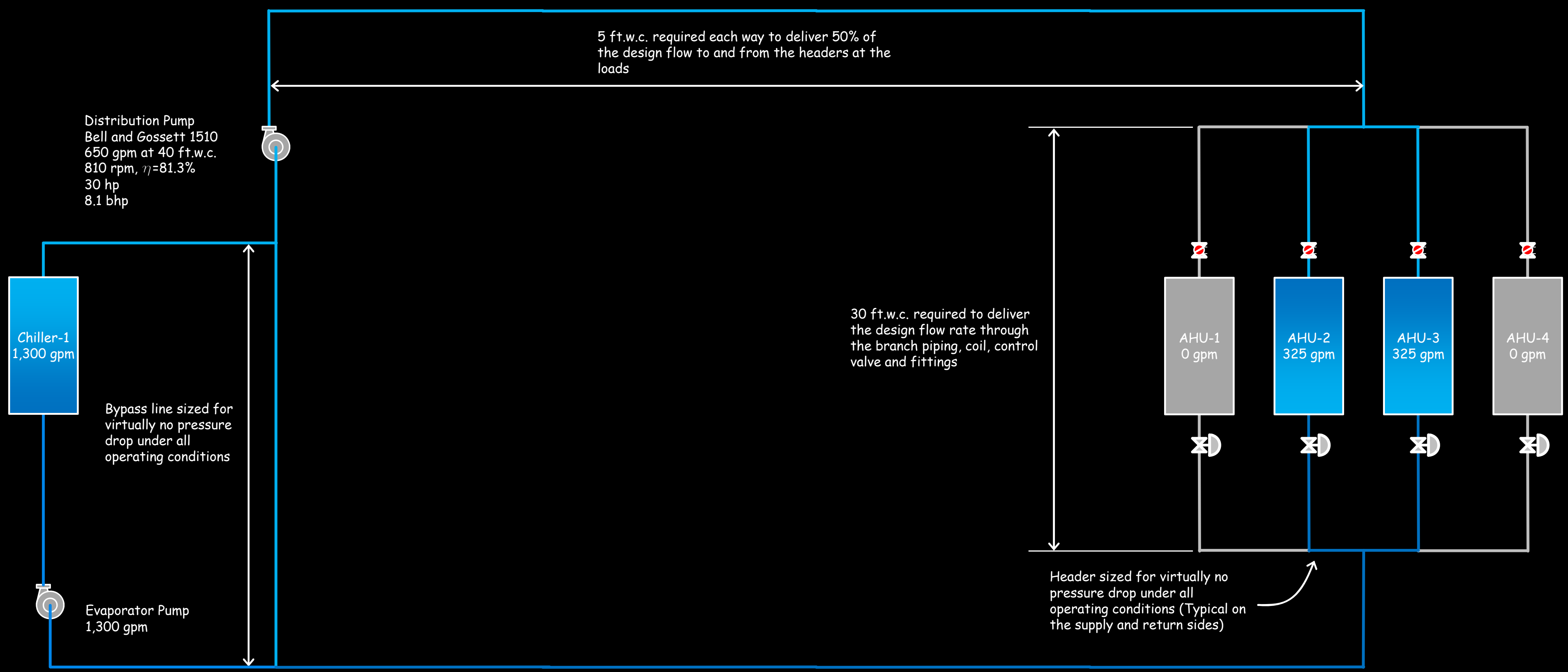


Summary													
Load Condition	Flow Rate, gpm	Head, ft.w.c	Pump Speed, rpm	Pump Efficiency	Pump Bhp	Motor Efficiency	VFD Efficiency	Projected kW	"Cube Rule" kW	kW vs. $Flow^{2.4}$	kW vs. $Flow^{2.0}$	kW vs. $Flow^{1.5}$	Head vs. $Flow^{2.0}$
Design	1,300.0	70.000	1,150	86.9%	26.4	94%	98%	28.8	28.8	28.8	28.8	28.8	70.0
75.0%	975.0	52.500	950	86.1%	15.0	94%	94%	17.0	12.2	14.4	16.2	18.7	52.5

$$hp = \left(\frac{Flow_{gpm} \times Head_{ft.w.c.}}{3{,}960 \times \eta_{Pump} \times \eta_{Motor} \times \eta_{VSD}} \right)$$

System Curve Example

50 % Load Condition

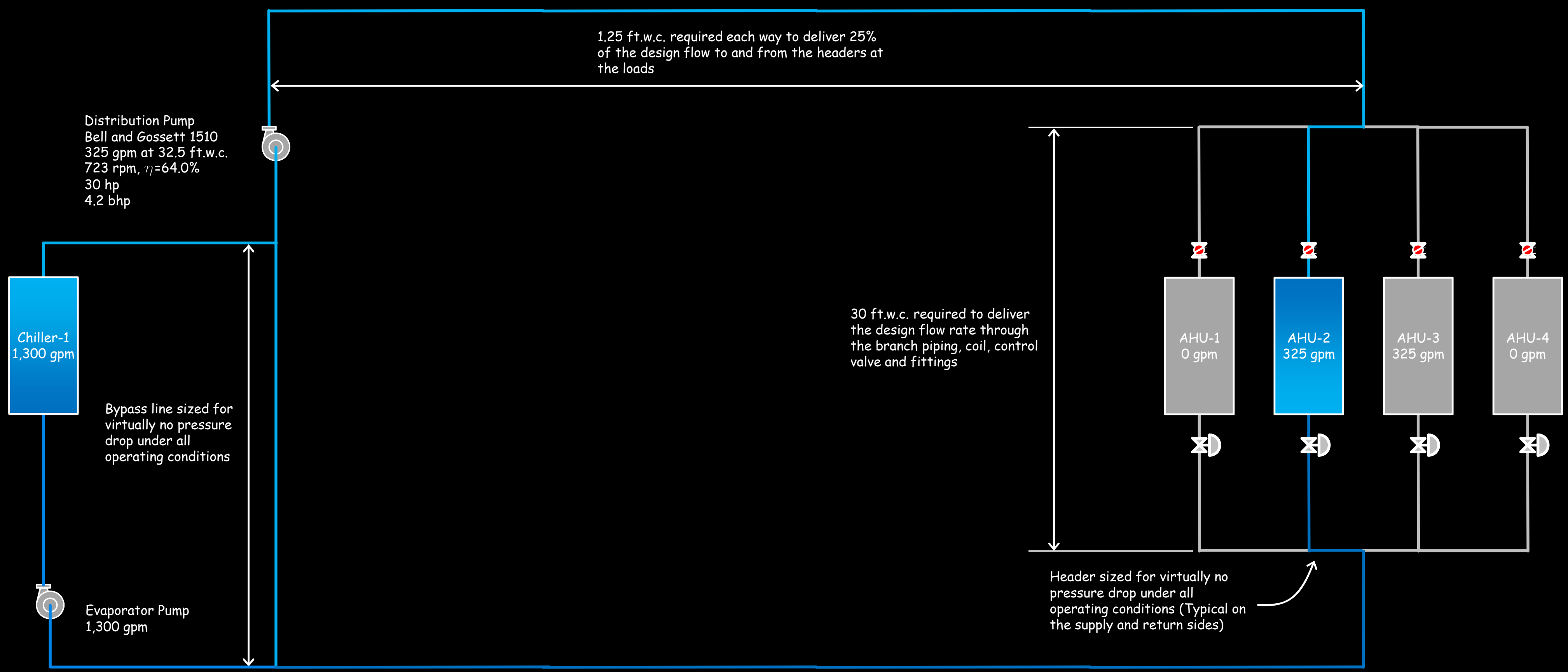


Summary													
Load Condition	Flow Rate, gpm	Head, ft.w.c	Pump Speed, rpm	Pump Efficiency	Pump Bhp	Motor Efficiency	VFD Efficiency	Projected kW	"Cube Rule" kW	kW vs. $Flow^{2.4}$	kW vs. $Flow^{2.0}$	kW vs. $Flow^{1.5}$	Head vs. $Flow^{2.0}$
Design	1,300.0	70.000	1,150	86.9%	26.4	94%	98%	28.8	28.8	28.8	28.8	28.8	70.0
75.0%	975.0	52.500	950	86.1%	15.0	94%	94%	17.0	12.2	14.4	16.2	18.7	52.5
50.0%	650.0	40.000	810	81.3%	8.1	93%	94%	9.3	3.6	5.5	7.2	10.2	40.0

$$hp = \left(\frac{Flow_{gpm} \times Head_{ft.w.c.}}{3{,}960 \times \eta_{Pump} \times \eta_{Motor} \times \eta_{VSD}} \right)$$

System Curve Example

25 % Load Condition

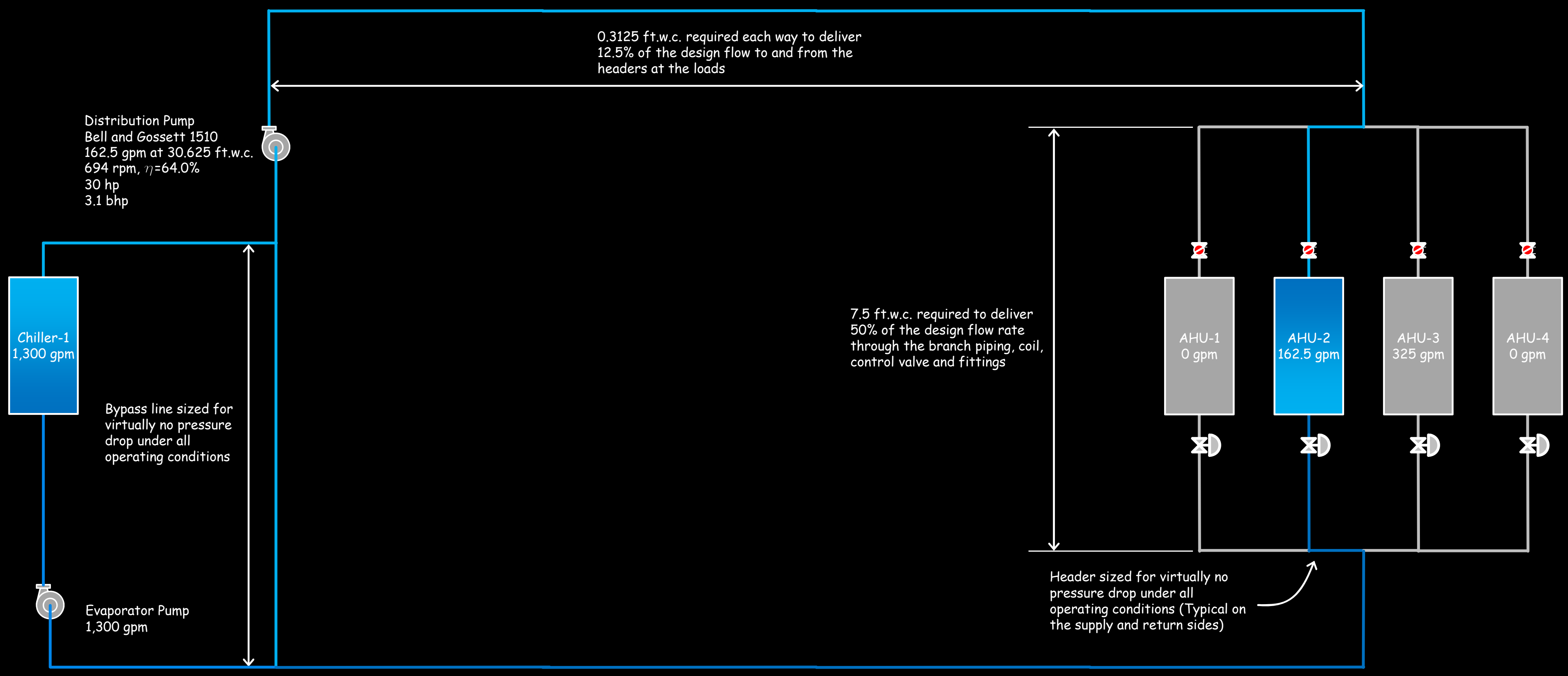


Summary													
Load Condition	Flow Rate, gpm	Head, ft.w.c	Pump Speed, rpm	Pump Efficiency	Pump Bhp	Motor Efficiency	VFD Efficiency	Projected kW	"Cube Rule" kW	kW vs. $Flow^{2.4}$	kW vs. $Flow^{2.0}$	kW vs. $Flow^{1.5}$	Head vs. $Flow^{2.0}$
Design	1,300.0	70.000	1,150	86.9%	26.4	94%	98%	28.8	28.8	28.8	28.8	28.8	70.0
75.0%	975.0	52.500	950	86.1%	15.0	94%	94%	17.0	12.2	14.4	16.2	18.7	52.5
50.0%	650.0	40.000	810	81.3%	8.1	93%	94%	9.3	3.6	5.5	7.2	10.2	40.0
25.0%	325.0	32.500	723	64.0%	4.2	87%	88%	5.5	0.5	1.0	1.8	3.6	32.5

$$hp = \left(\frac{Flow_{gpm} \times Head_{ft.w.c.}}{3{,}960 \times \eta_{Pump} \times \eta_{Motor} \times \eta_{VSD}} \right)$$

System Curve Example

12.5 % Load Condition

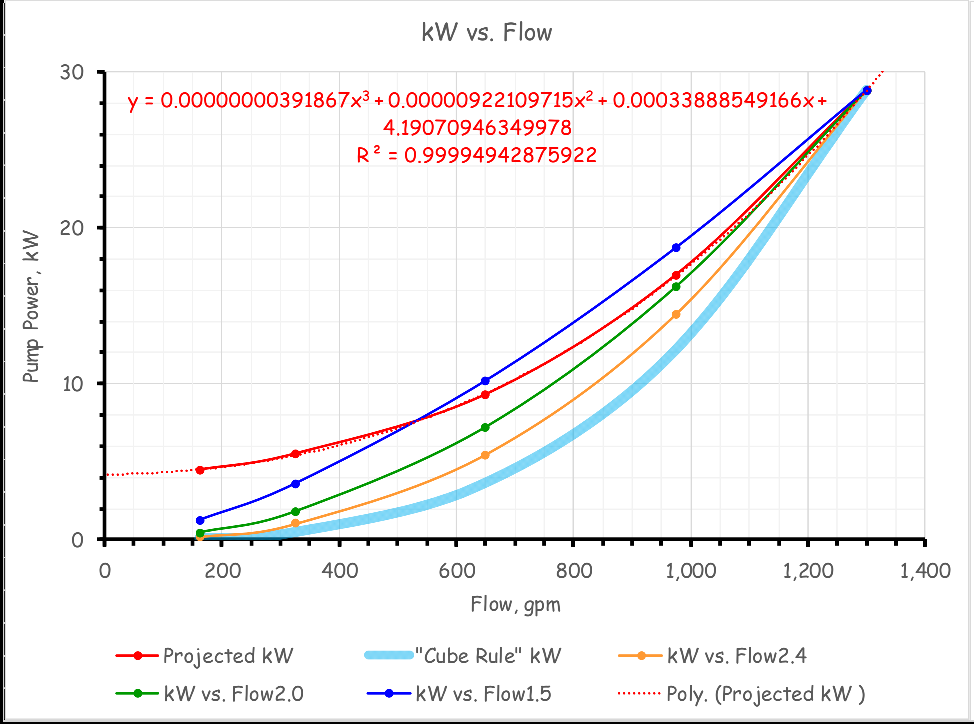


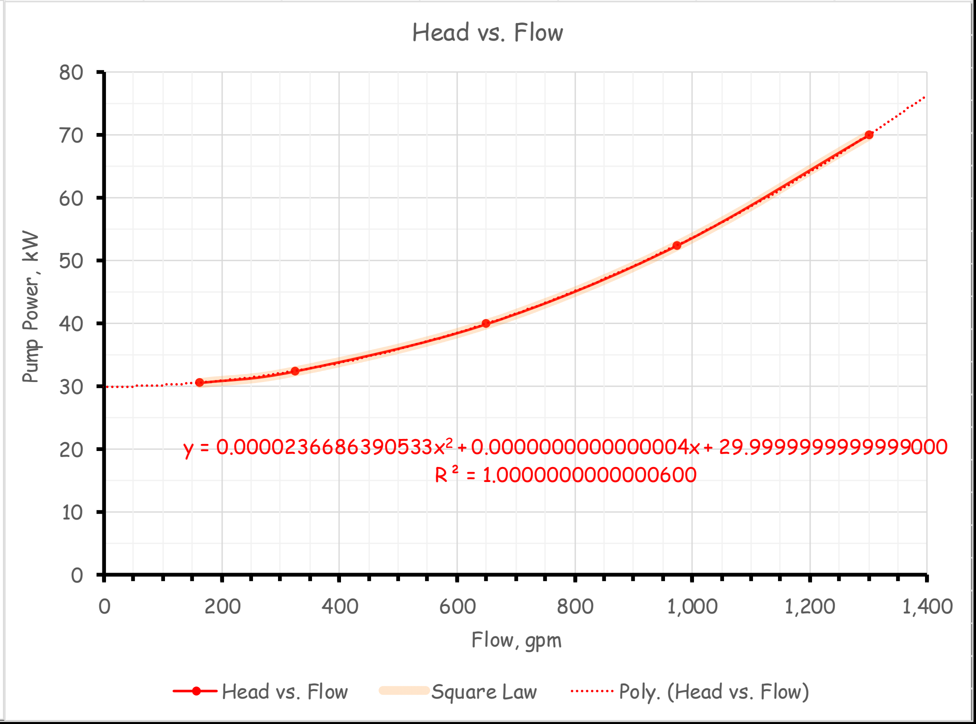
Summary													
Load Condition	Flow Rate, gpm	Head, ft.w.c	Pump Speed, rpm	Pump Efficiency	Pump Bhp	Motor Efficiency	VFD Efficiency	Projected kW	"Cube Rule" kW	kW vs. $Flow^{2.4}$	kW vs. $Flow^{2.0}$	kW vs. $Flow^{1.5}$	Head vs. $Flow^{2.0}$
Design	1,300.0	70.000	1,150	86.9%	26.4	94%	98%	28.8	28.8	28.8	28.8	28.8	70.0
75.0%	975.0	52.500	950	86.1%	15.0	94%	94%	17.0	12.2	14.4	16.2	18.7	52.5
50.0%	650.0	40.000	810	81.3%	8.1	93%	94%	9.3	3.6	5.5	7.2	10.2	40.0
25.0%	325.0	32.500	723	64.0%	4.2	87%	88%	5.5	0.5	1.0	1.8	3.6	32.5
12.5%	162.5	30.625	694	40.0%	3.1	84%	84%	4.5	0.1	0.2	0.5	1.3	30.6

$$hp = \left(\frac{Flow_{gpm} \times Head_{ft.w.c.}}{3{,}960 \times \eta_{Pump} \times \eta_{Motor} \times \eta_{VSD}} \right)$$

Summary

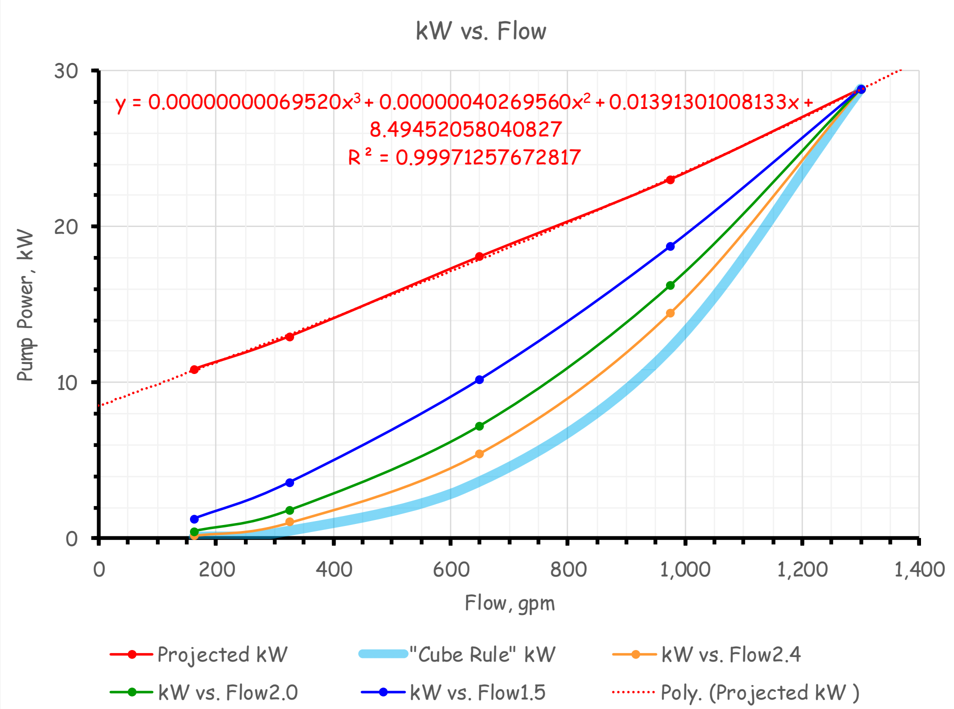
Load Condition	Flow Rate, gpm	Head, ft.w.c	Pump Speed, rpm	Pump Efficiency	Pump Bhp	Motor Efficiency	VFD Efficiency	Projected kW	"Cube Rule" kW	kW vs. $Flow^{2.4}$	kW vs. $Flow^{2.0}$	kW vs. $Flow^{1.5}$	Head vs. $Flow^{2.0}$
Design	1,300.0	70.000	1,150	86.9%	26.4	94%	98%	28.8	28.8	28.8	28.8	28.8	70.0
75.0%	975.0	52.500	950	86.1%	15.0	94%	94%	17.0	12.2	14.4	16.2	18.7	52.5
50.0%	650.0	40.000	810	81.3%	8.1	93%	94%	9.3	3.6	5.5	7.2	10.2	40.0
25.0%	325.0	32.500	723	64.0%	4.2	87%	88%	5.5	0.5	1.0	1.8	3.6	32.5
12.5%	162.5	30.625	694	40.0%	3.1	84%	84%	4.5	0.1	0.2	0.5	1.3	30.6

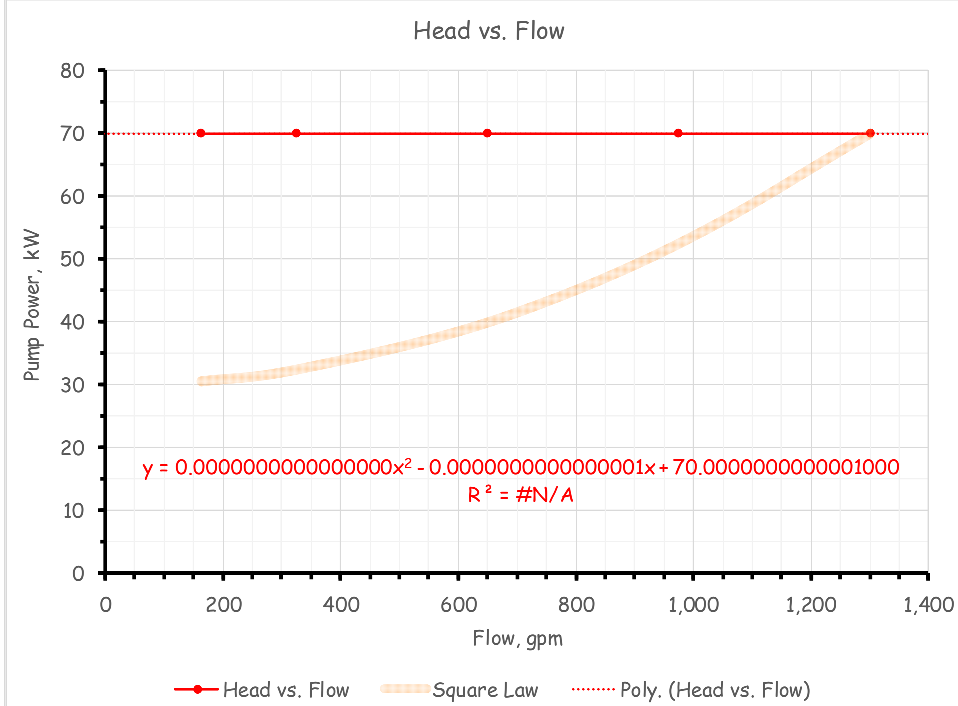




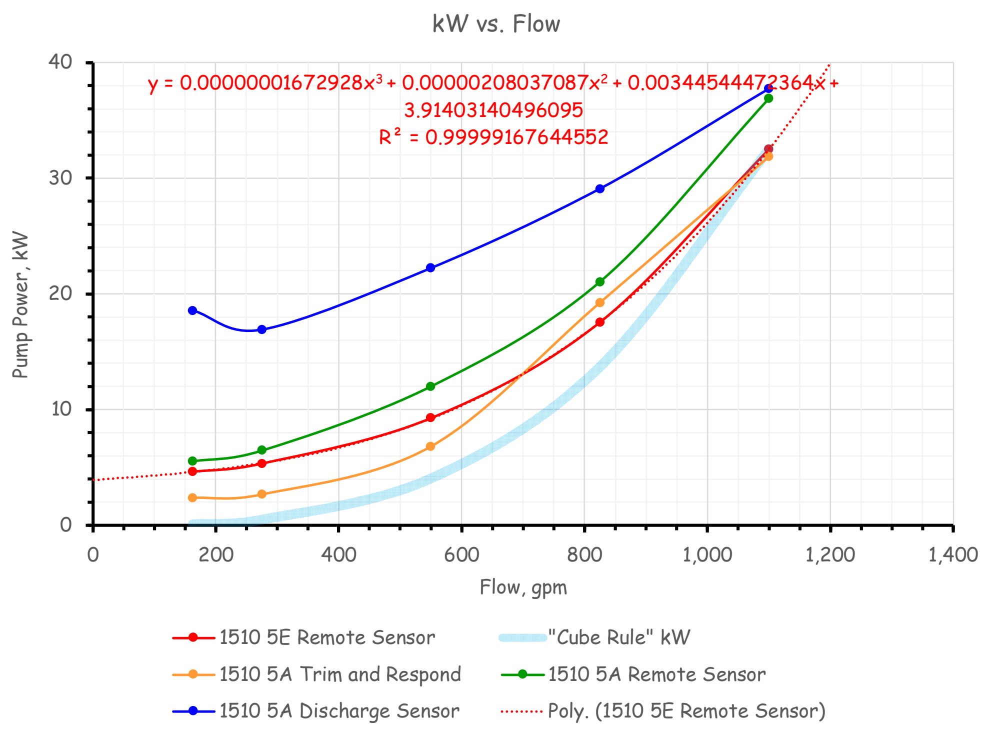
Summary

Load Condition	Flow Rate, gpm	Head, ft.w.c	Pump Speed, rpm	Pump Efficiency	Pump Bhp	Motor Efficiency	VFD Efficiency	Projected kW	"Cube Rule" kW	kW vs. $Flow^{2.4}$	kW vs. $Flow^{2.0}$	kW vs. $Flow^{1.5}$	Head vs. $Flow^{2.0}$
Design	1,300.0	70.000	1,150	86.9%	26.4	94%	98%	28.8	28.8	28.8	28.8	28.8	70.0
75.0%	975.0	70.000	1,081	83.5%	20.6	94%	96%	23.0	12.2	14.4	16.2	18.7	70.0
50.0%	650.0	70.000	1,063	72.0%	16.0	94%	94%	18.1	3.6	5.5	7.2	10.2	70.0
25.0%	325.0	70.000	1,055	50.0%	11.5	94%	95%	12.9	0.5	1.0	1.8	3.6	70.0
12.5%	162.5	70.000	1,054	30.0%	9.6	93%	95%	10.8	0.1	0.2	0.5	1.3	70.0





Summary and Comparison of Different Methods of Optimizing the Chiller Plant Model Distribution Pumps



Comparison with the Original Configuration (1510 5A, Discharge Sensor)

Option	Savings			Cost	Simple Payback, Years	Note
	kWh	$	% of Maximum			
1510 5A, Discharge Sensor			Base Case			1
1510 5A, Remote Sensor	27,070	$4,873	38%	$4,350	0.9	2
1510 5A, Trim and Respond	70,389	$12,670	100%	$7,254	0.6	3
1510 5E, Remote Sensor	57,806	$10,405	82%	$97,116	9.3	4

Notes

1. The base case has a relatively inefficient pump operating with its speed controlled based on the differential pressure between the pump headers in the central plant.
2. This options adds a sensor at a remote point in the system which is used to reset the set point of the discharge pressure control process based on the differential pressure at the remote location.
3. This option uses a trim and repond strategy to reset the discharge pressure control process set point. The trim and respond process steps the set point up and down in an effort to keep at least one AHU chilled water valve nearly fully open.
4. This option replaces the existing pump with a new pump that is 13% more efficient and then controlls it based on discharge pressure with the set point reset based on the differential pressure at a remote location in the system.