Chiller Plant Efficiency

CW & CHW Temperature Reset

Centrifugal Chiller AFDs

Variable Primary Pumping (VPP)

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Abstract

- Adjustable frequency drives (AFDs) on chiller compressor motors, condenser water temperature reset, and variable primary flow are three means of improving energy efficiency in water cooled chiller plants.
  - But are the savings claimed by the manufacturers really true?
  - How cold can you run the condenser water system before running into problems? How is the condenser water system temperature controlled?
  - How do you retrofit a fixed primary system to variable flow and how is it controlled? Do the economics work?
- We will discuss the results of retrofitting these technologies to a very large chiller plant at a large semiconductor facility.

Project Scope

- CWS Temperature Reset
  - Two OSA WB transmitters, wiring
  - FMS programming and graphics
- Chiller AFD Project
  - One new 1700 ton chiller with AFD (pilot)
  - Six existing 1700 ton chillers retrofitted with AFDs
  - Chiller LCPs upgraded with latest color touchscreen displays and controls
  - Existing 4160 V chiller MCCs needed control wiring modifications
  - Power and control wiring
  - Seismic structural for AFDs
  - FMS programming, mostly for new monitoring points & graphics
- VPP Project:
  - AFDs added to all CHW primary pumps
  - Flow meter added to each chiller
  - Redundant flow meter added to DCBP
  - Thermal dispersion flow switches replaced PDS’s
  - FMS control changes for VPP & graphics
  - Power and control wiring

Historical Chiller Plant Design

- Centrifugal chiller plants designed for 45F CHW, 80-90F CW temps
  - Constant setpoints, regardless of load or weather
  - Compressor design efficiencies improved over the years from .75 kw/ton to around 0.56 kw/ton at design conditions
- *We can do significantly better during off-peak conditions.*
  - *By 1999 I determined that 70 F was the optimum <u>fixed</u> CWS temperature SP for our equipment*
    - *But what if we allowed that SP to vary?*
    - *If so, how would we control that SP?*
    - *That is the $64k question!*

Chiller Plant Design Power

Constant Primary/Variable Secondary

Component	KW/ton	%
Chillers	.560	**79.0**
Cooling Tower Fans	.047	6.6
CW Pumps	.045	6.3
SCHW Pumps	.039	5.5
PCHW Pumps	.018	2.5
Total	.709	99.9

Where would you focus your attention?

System Strategy 1
Temperature Reset

- Reduce compressor refrigerant lift
  - Increase CHW Temp
  - Decrease CW Temp
- Eliminate wasted work done by the compressor
- *This can be applied to existing plants*

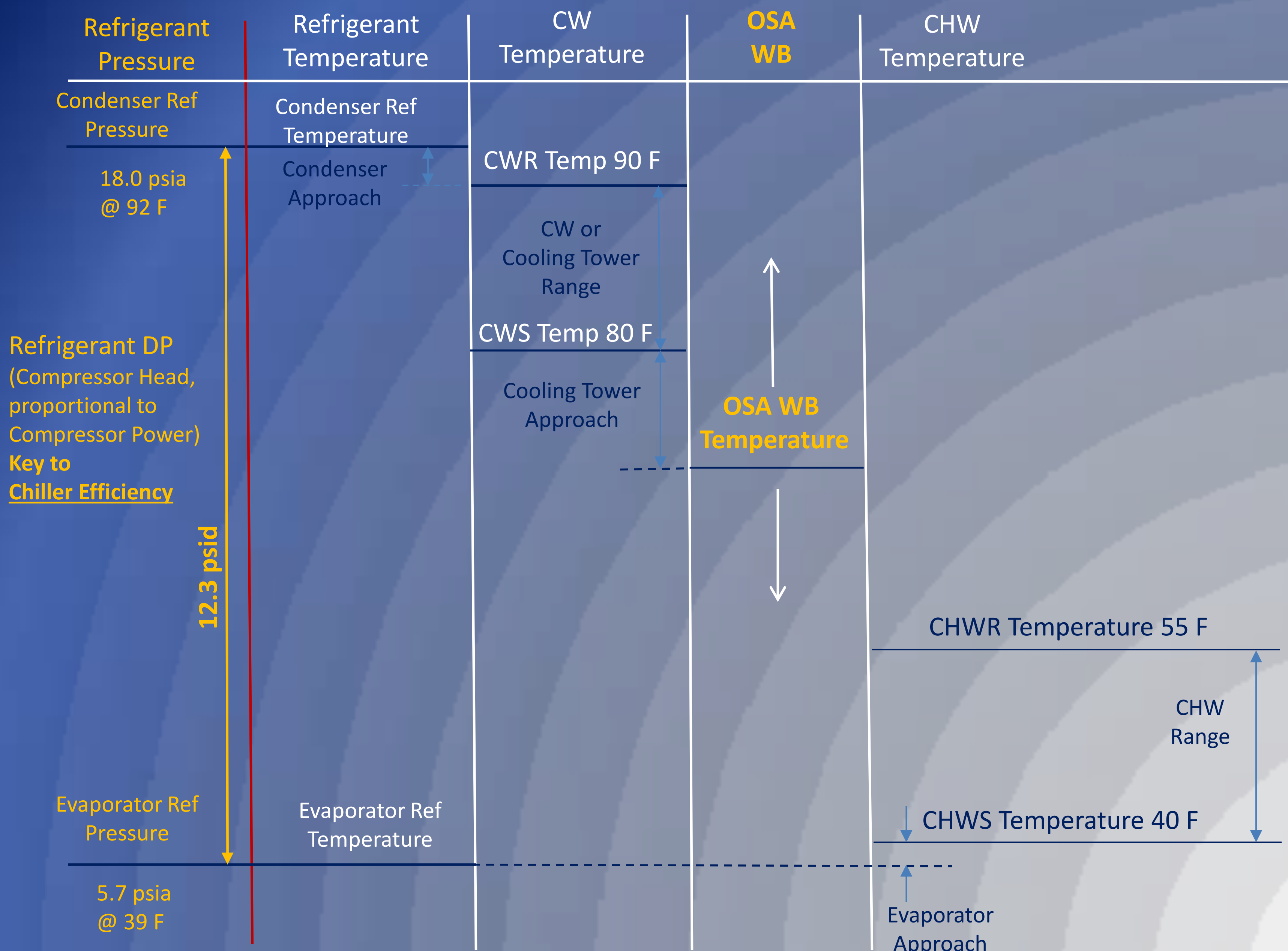
Condenser Water Temperature

- **It all starts with OSA WB temperature**
- PDX 0.4% (35 hrs/yr) WB = 69.5 F (ASHRAE)
  - Typical design might use 70 F
- CWS = WB + Cooling Tower Approach
  - CT size and range determines approach
  - Typical design values: 6 to 12 deg F
  - Bigger towers = smaller approach = lower CWS temp
    - *More capital cost, but lower system operating cost*

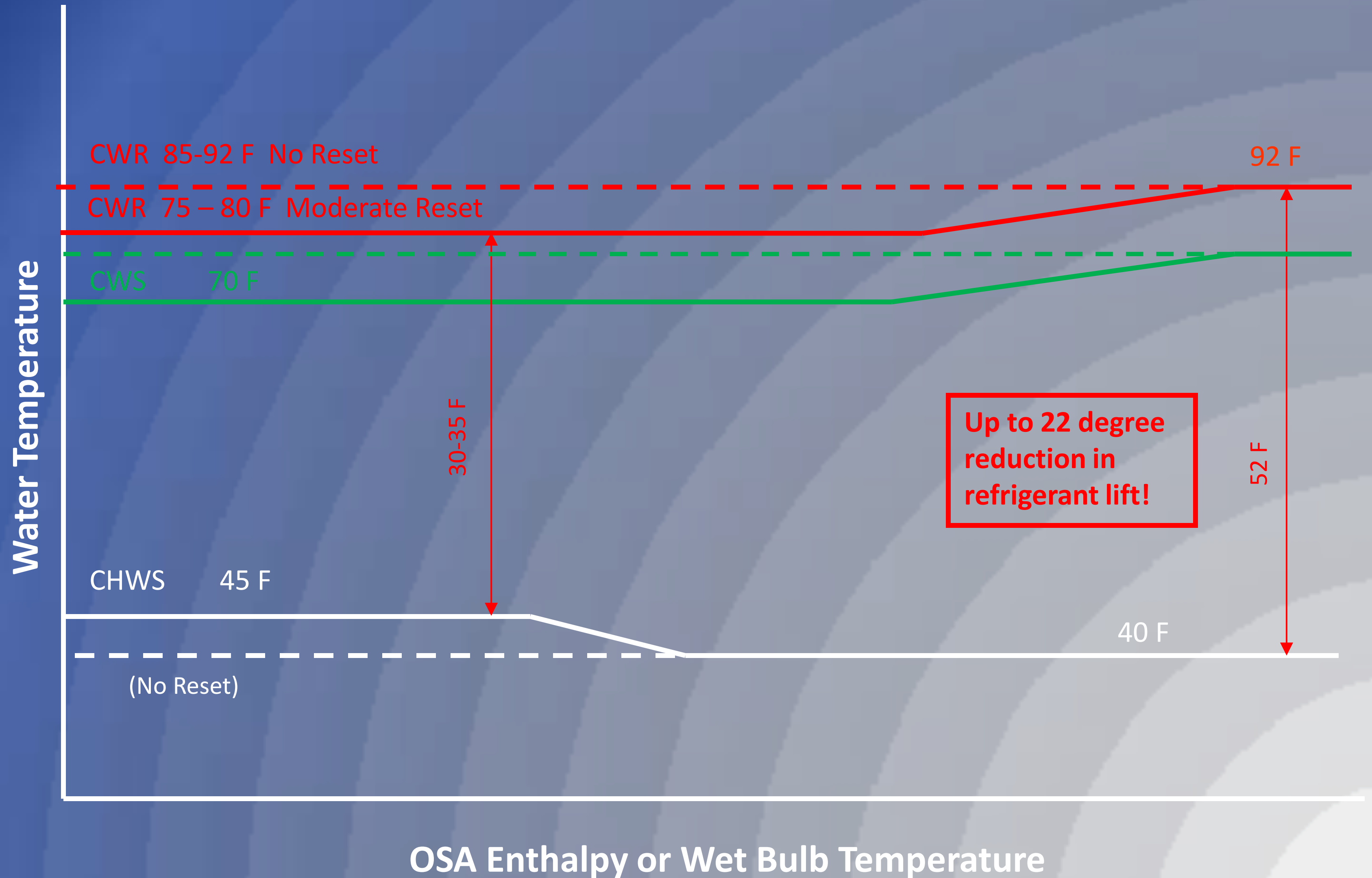
Cooling Tower Example

- Cooling tower design for PDX weather
- WB = 70 F
- CT sized for 10 deg F approach
- Design CWS = 70 F + 10 F = 80 F
- Chillers must be selected for peak load at 80 F CWS
  - Chillers should also be selected for peak efficiency under conditions it spends the most ton-hours/yr.
- Chiller efficiency is a function of CWR not CWS temp.
  - Larger range (CWR – CWS temp) reduces pipe size and pumping costs, ***but increases chiller energy costs***.

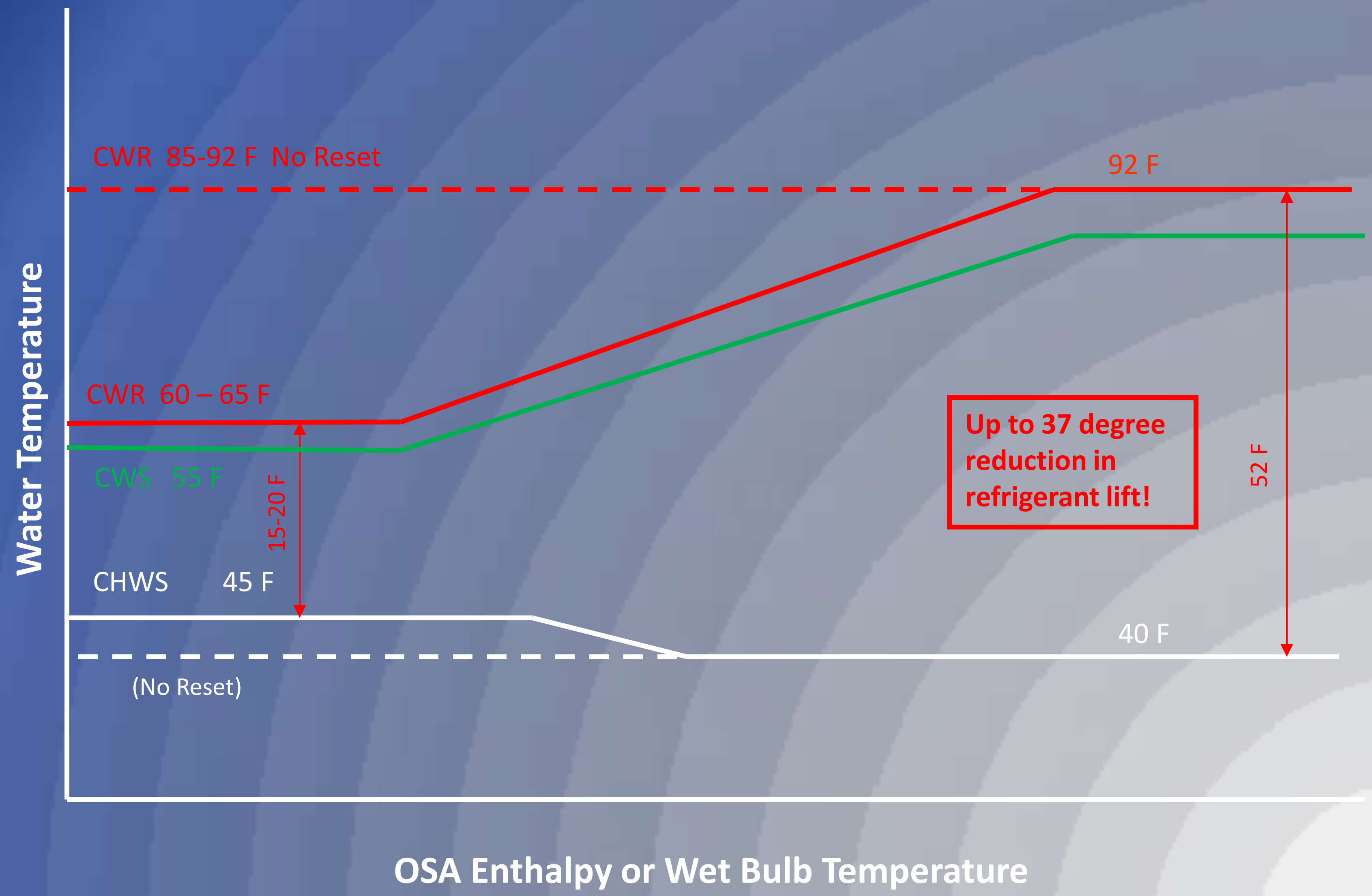
Temperature and Pressure Relationships



Chiller Reset Schedules



Chiller Reset Schedules



CHWS Reset Option 1

- CHWS SP = f (OSA DB)

- Advantage: Better than Constant SP
- Disadvantages:
  - Open loop control, no feedback from load side
  - Blind to load changes: When coil face velocities change, load characteristics change and algorithm should be changed.
  - MAH dehumidification loads are not linear with OSA DB

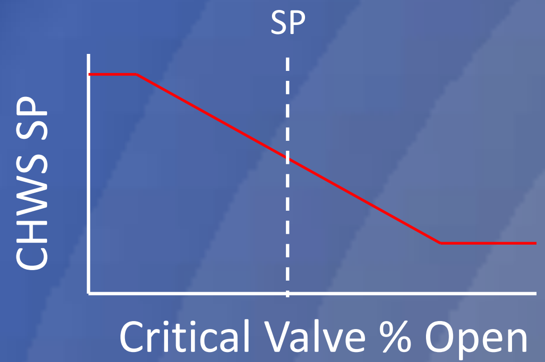
CHWS Reset Option 2

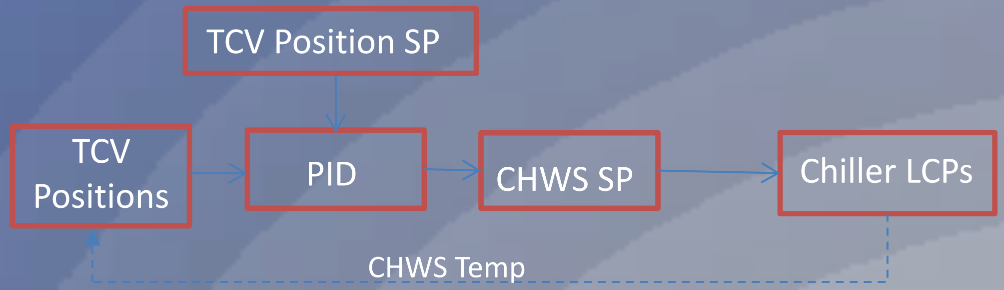
- CHWS SP = f (OSA enthalpy)

- Advantage: Better than Constant SP or OSA DB
- Disadvantages:
  - Open loop control system, no feedback
  - Blind to load changes: When coil face velocities change, load characteristics change and algorithm should be changed.
  - Still doesn't accommodate humidification transitions

CHWS Reset Option 3

- CHWS SP = f (Critical CHW TCV position)





Note: 3-segment linear function is shown, but PID function offers best control. PID output (CHWS SP) is limited between min and max values.

- Advantages:
  - Closed loop feedback
  - Irrespective of face velocities, air or sediment in coils; TCV position is the indicator of the coil's relative load
  - No adjustments needed due to rebalanced system or OSA conditions.
  - Maximizes CHW temperature while keeping zones satisfied, regardless of system changes
- Disadvantages:
  - Slightly more complicated to understand
  - Need to define which is the critical TCV
    - Typically the most or second -most open of all or a subset of CHW TCVs, or some function of a set of CHW TCVs
    - Using the most open TCV can result in the tail wagging the dog.

CWS Temperature Reset

- Far more complicated than CHWS reset
  - Dependent upon cooling tower size, OSA WB, load, cooling tower fan performance curve, air density, CWS & CWR temperatures, chiller performance curves as a function of load and CWS and CWR temperature and flow
- Siemens' algorithm
  - Very complicated. Monitors all CHW TCVs in system and tries to anticipate load changes.
- Trane's algorithm
  - Patented 'black box' algorithm so you can't see what it is doing.
  - Patent reveals a polynomial equation, but the coefficients need to be established.
- Numerous other algorithms are out there. None that I have seen are simple *and* truly optimize total plant energy.

ASHRAE 2012 Handbook
HVAC Systems and Equipment

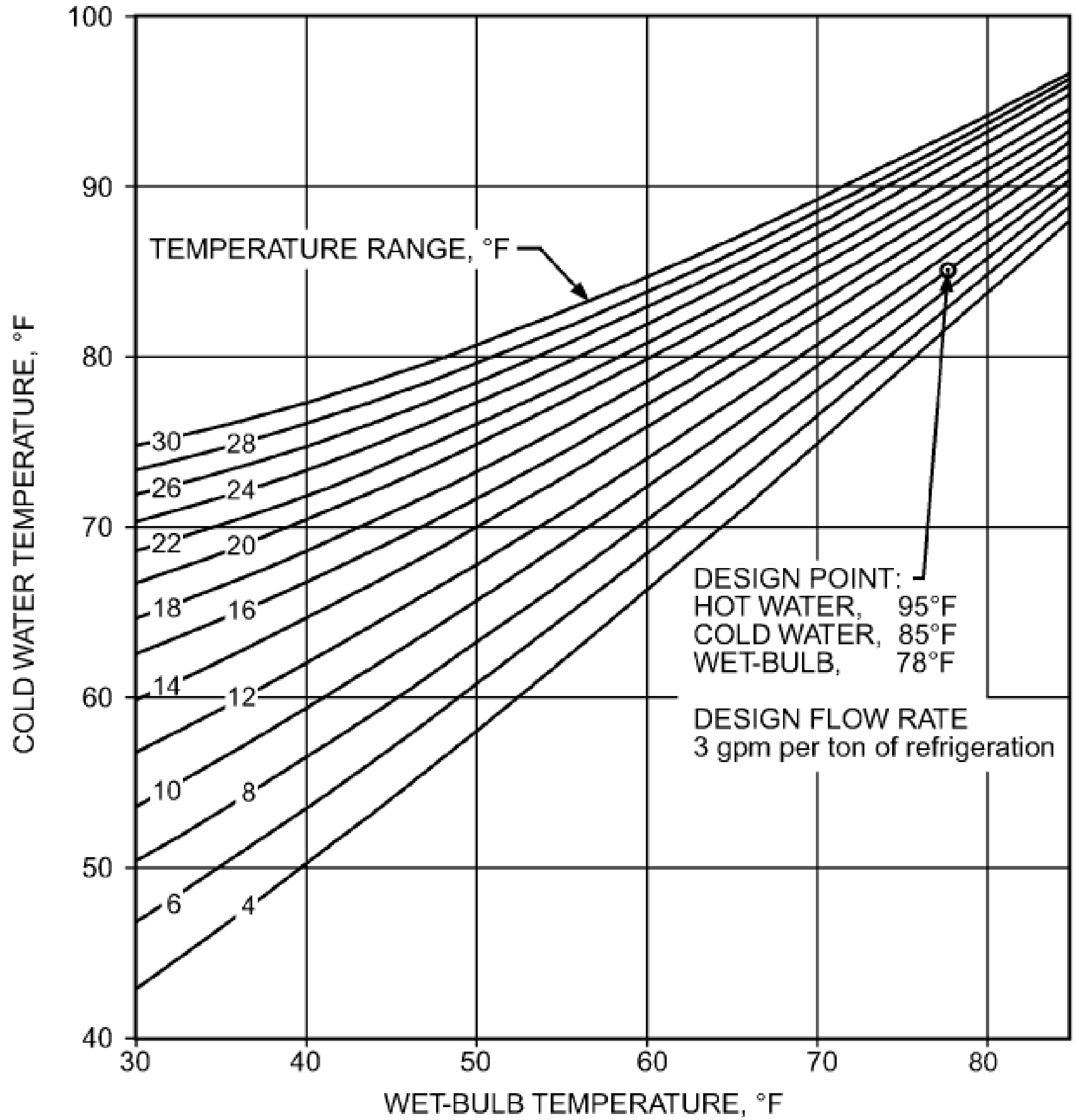
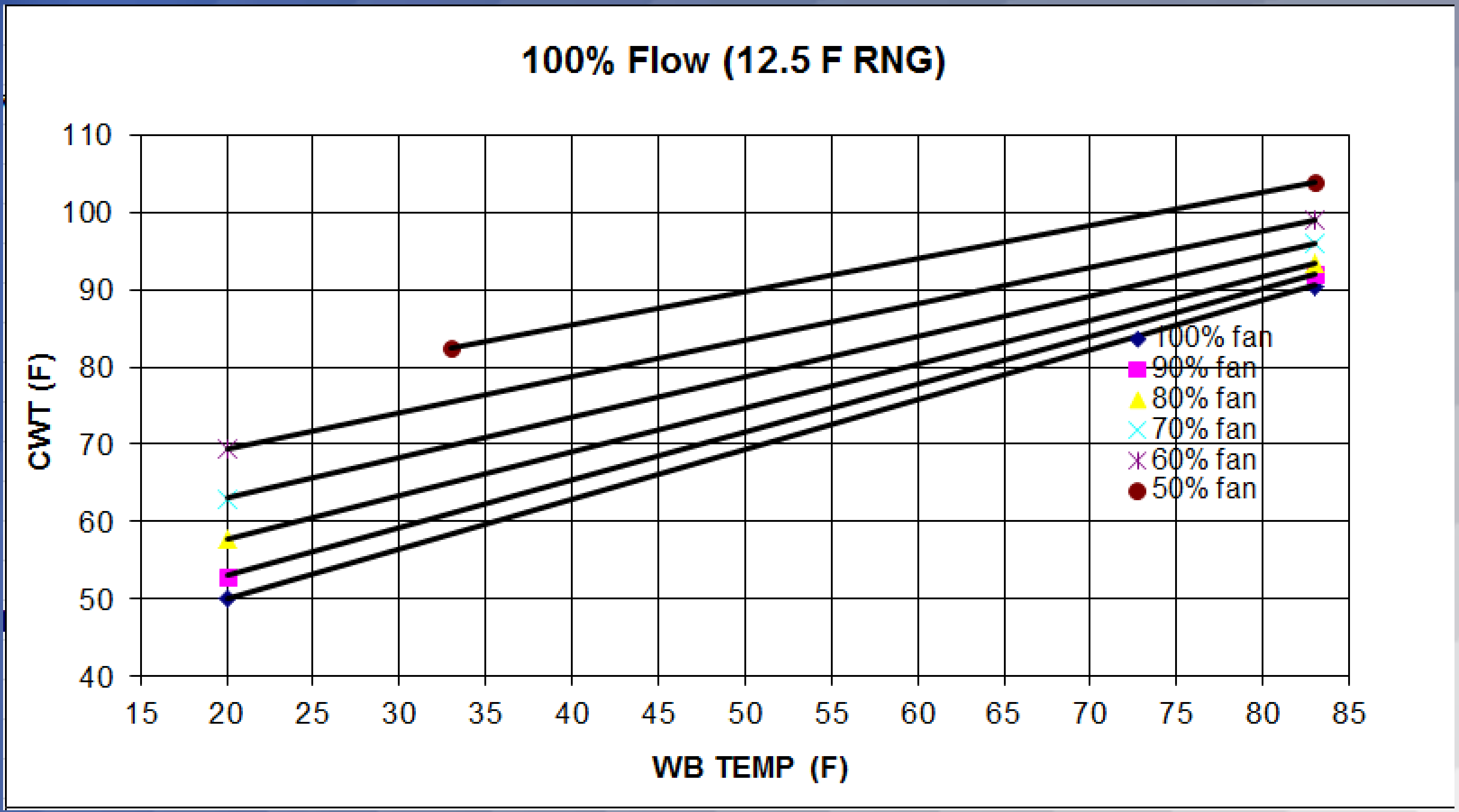
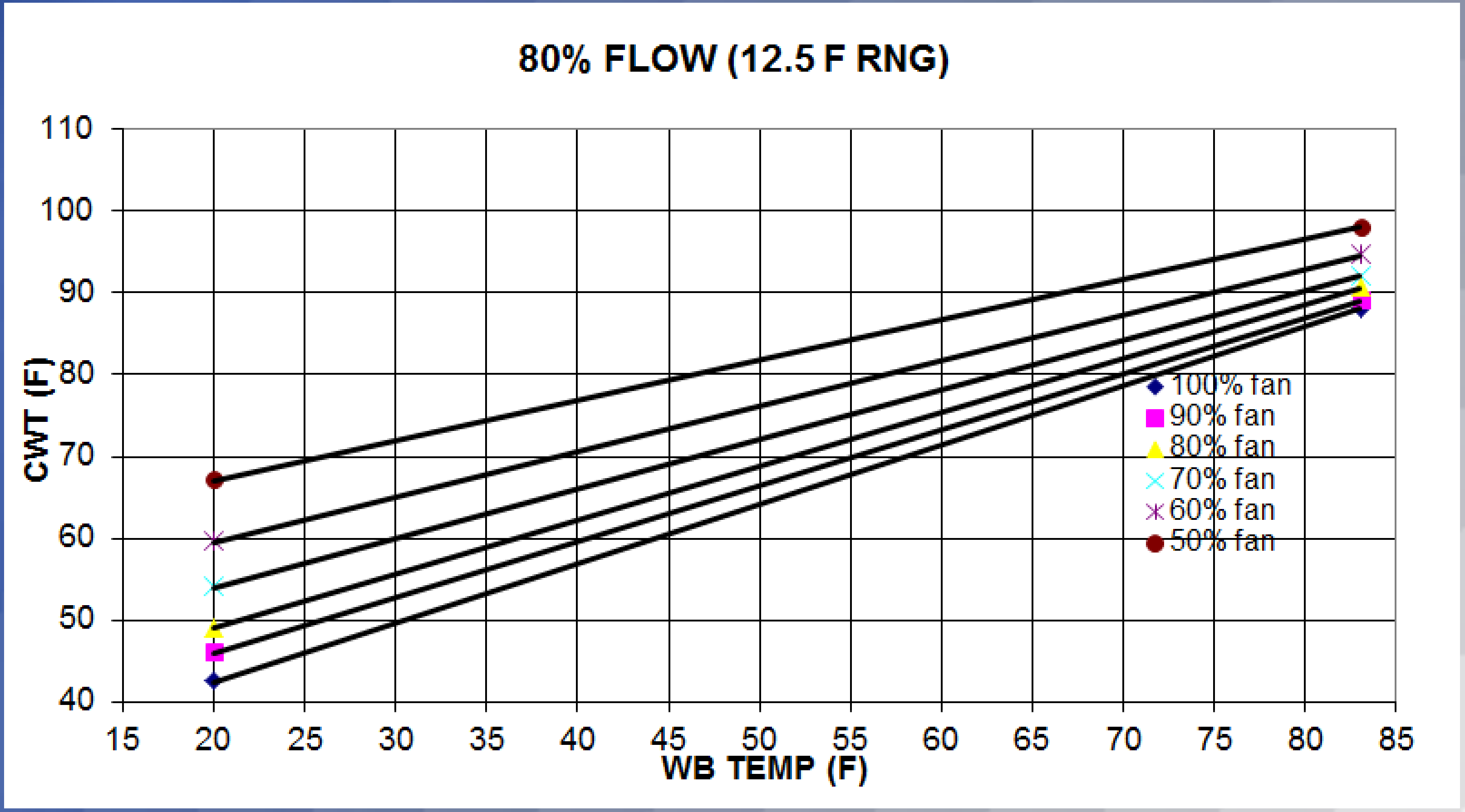


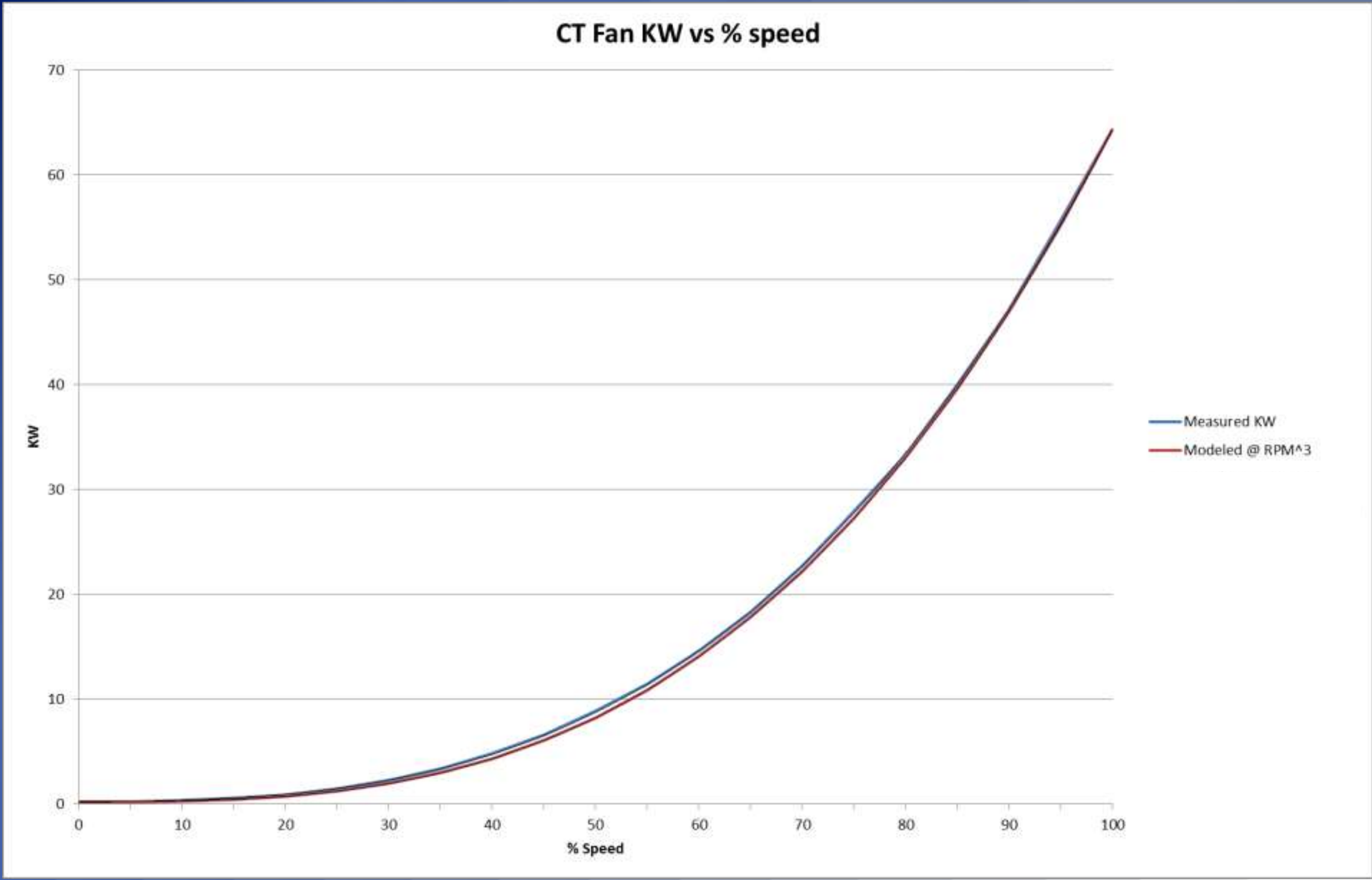
Fig. 26 Cooling Tower Performance—100% Design Flow

Cooling Tower Performance Curves



Reduced Flow CT performance





Cooling tower fan power measured very close to cubic fan law.
100 HP motor load.

Cooling Tower Example

100% — $1 \times (1.00)^3 \times 100\text{ kw} = 100\text{ kw}$

50% 50% — $2 \times (0.50)^3 \times 100\text{ kw} = 25\text{ kw}$

33% 33% 33% — $3 \times (0.33)^3 \times 100\text{ kw} = 11.1\text{ kw}$

Note: *At some point, performance becomes non-linear. Monitor and set sequencing setpoints accordingly.*

Cooling Tower Observations

- More towers at slower speeds consume much less power.
- Keeping fan speeds (sequencer SP) under 70% when conditions allow will limit fan power to half of design.
- This results in less water flow per tower.
- ‘Dumping’, where tower water distribution is compromised and heat transfer is non-linear, may happen with too many towers on line.
- If you add another tower and the fan speed goes up, performance is non-linear and you are running too many towers.
  - Adjust sequencer settings accordingly.

Typical Sequencer

Stage	Start (upstage) %	Stop (downstage) %
1	60	N/A
2	63	15
3	66	16
4	68	18
5	70	20
6	N/A	25
Time Delay	300 sec	600 sec

Sequencer should have an instantaneous upstaging for low (or high) process variable, and an anti-cycling timer. Parameters can be AFD %, Sigma %RLA, tonnage, BoHP, etc.

Any headered sets of fans, pumps, chillers, cooling towers, boilers, etc., can use this sequencing method. Customize setpoints with equipment performance curves to maximize efficiency.

AHRI CW Reset for Rating Purposes

AHRI STANDARD 550/590 (I-P)-2011

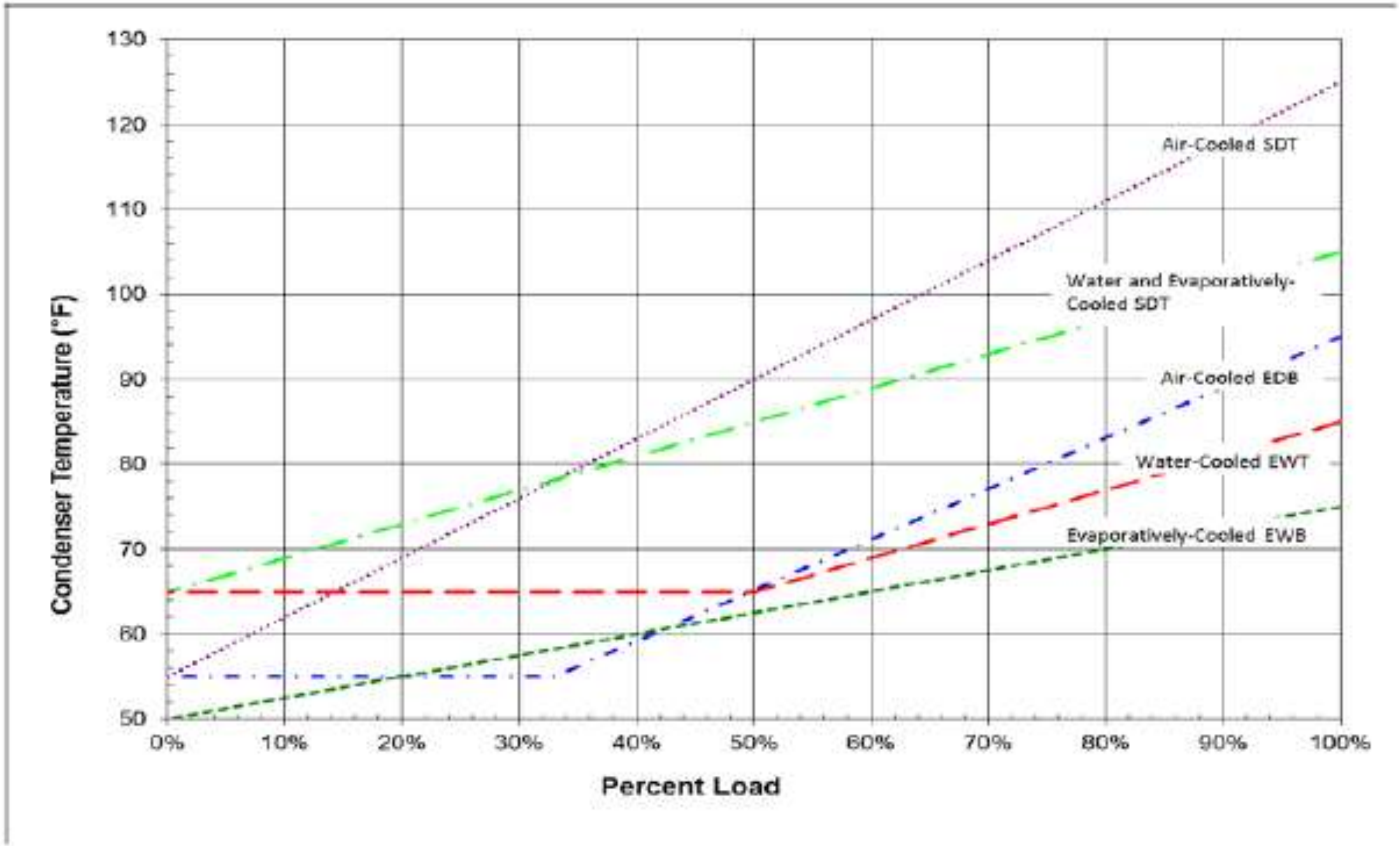


Figure 1. Part Load Condenser Temperature for IPLV Test Points

Lower CW Temp

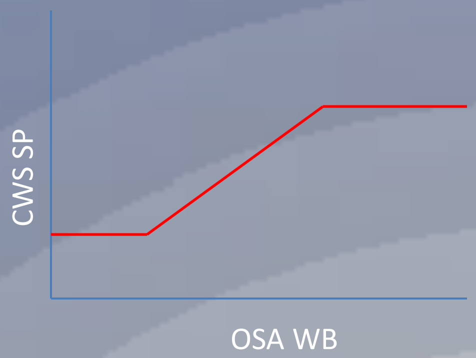
- Lower CWT generally drops compressor power by .006 to .007 kw/ton/deg F.
- Initially, every KW spent on CT fan energy saves 5 or 6 KW of compressor energy.
  - This ratio drops off with temperature
  - There is a point of diminishing returns
  - 'As cold as possible' is <u>not</u> the optimum strategy
    - Nor does it work well operationally

Cold CW Issues

- Low temperatures can cause oil migration.
  - Maintaining a minimum refrigerant DP can help avoid oil migration.
  - Add component to temperature controller to avoid oil migration: If RDP is less than a defined SP, bias the CWS SP upward. This will increase RDP, but only when necessary.
- Very low temperatures and high loads can contribute to refrigerant stacking in fixed orifice chillers.
  - Refrigerant DP (RDP) is too low for the required mass flow rate through the chiller at higher loads. Increased refrigerant viscosity may play a role.
  - Liquid refrigerant 'stacks up' in the condenser, but the level drops in the evaporator.
  - This provides added static head to achieve equilibrium for the required mass flow, but causes efficiency problems
  - Because top row evaporator tubes are not externally flooded with liquid refrigerant, effective tube heat transfer area is reduced and evaporator approach temperatures increase. This is detectable.
  - Control algorithm adder avoids this: If CWS temp is < 56 F and normalized evaporator approach is over ~ 2 deg F, bias the CWS SP upward.

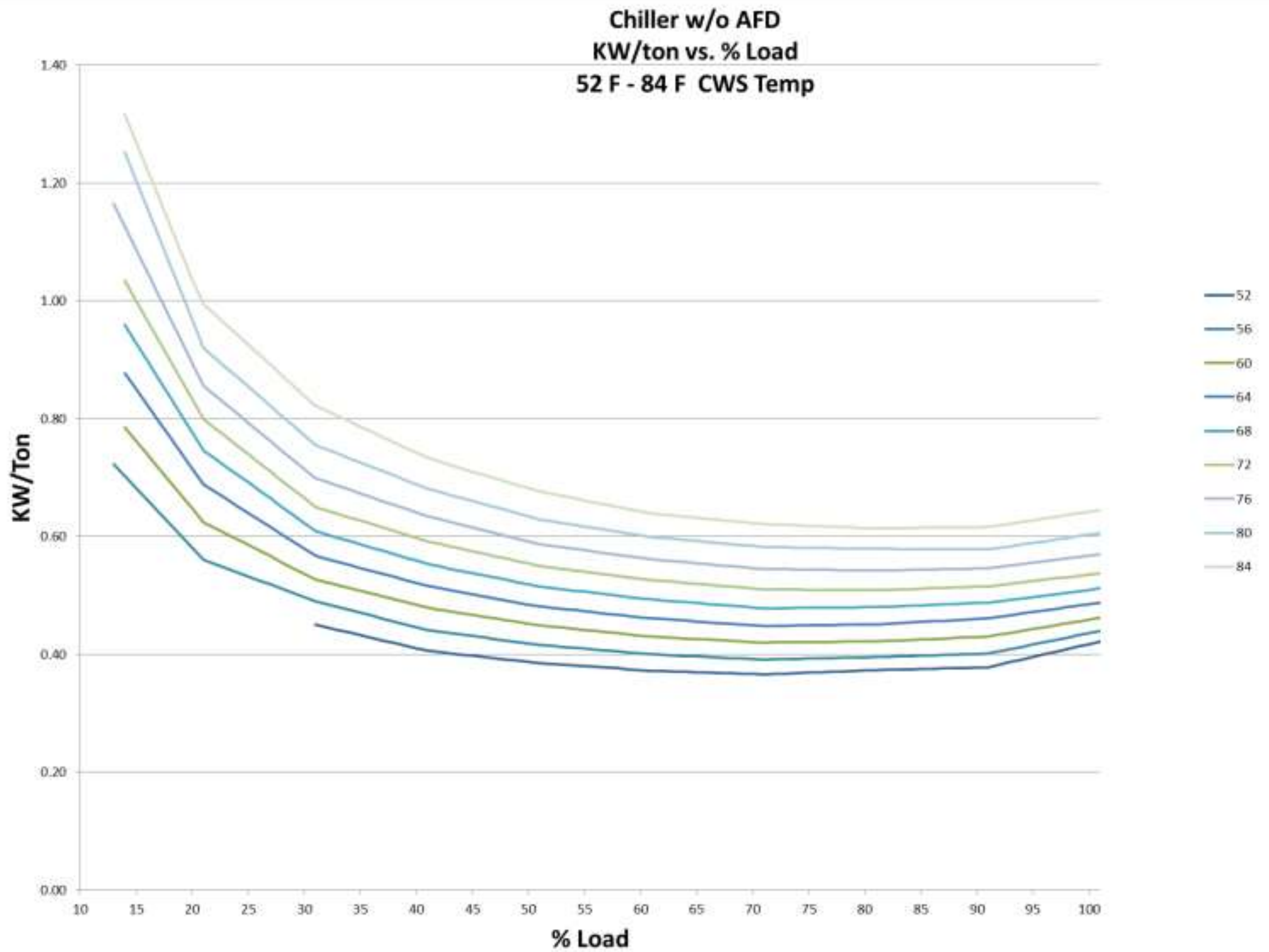
CWS Temp SP Control

- CWS SP = f(OSA WB) + PID1 + PID2
  - f(OSA WB): three segment function
    - Constant SP_{max} when OSA WB > WB_{max}
      - CT fans are maxed out much above this
      - CWS temp won't keep up—it's OK.
    - Constant SP_{min} when OSA WB < WB_{min}
    - Varies linearly between these points
  - PID1: Normally 0, but starts adding to SP when RDP drops too low
  - PID2: Normally 0, but starts adding to SP when CWS SP < 56 and normalized evaporator approach exceeds normal values (2 deg F.) May not be needed on variable orifice machines.

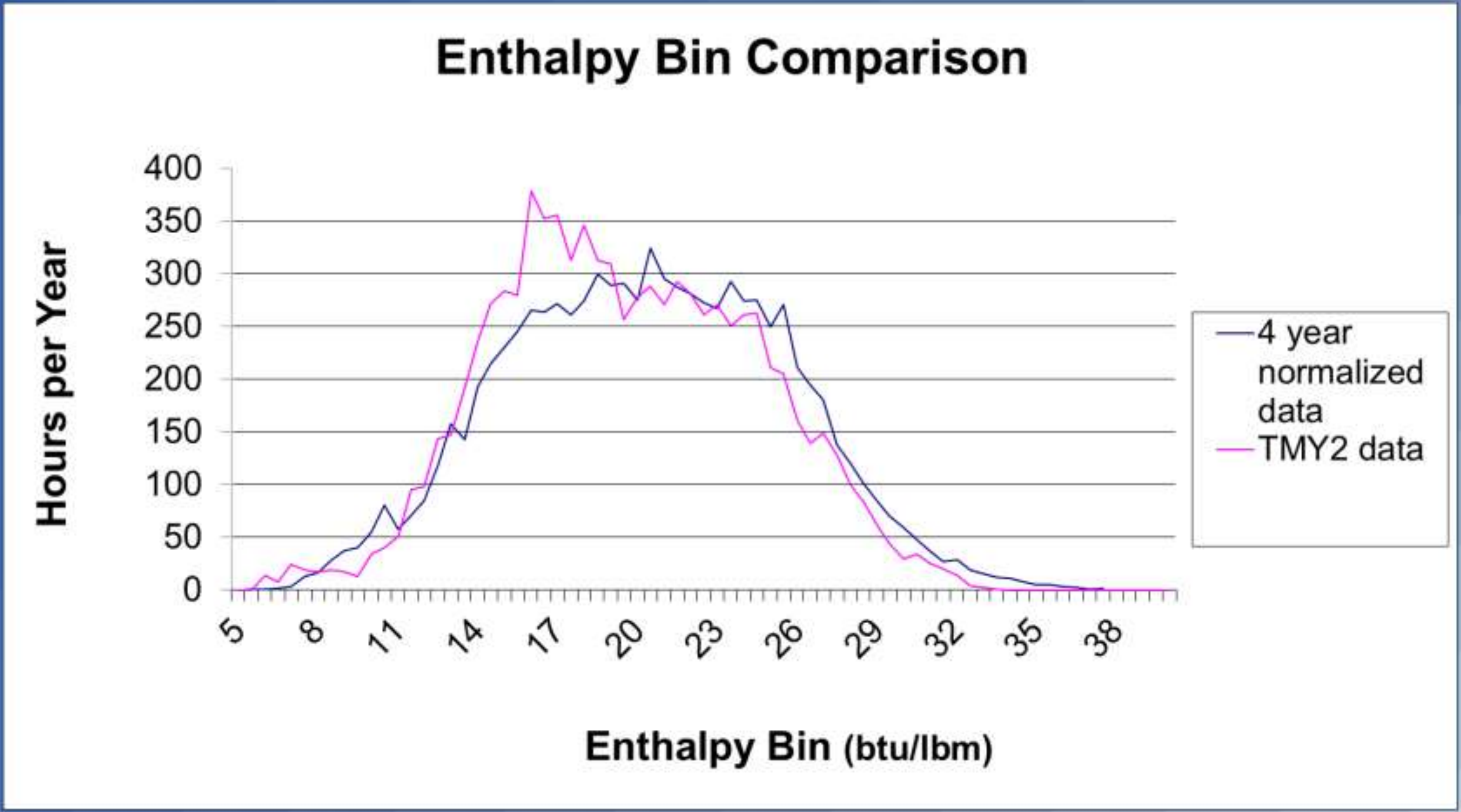


How Low Can You Go?

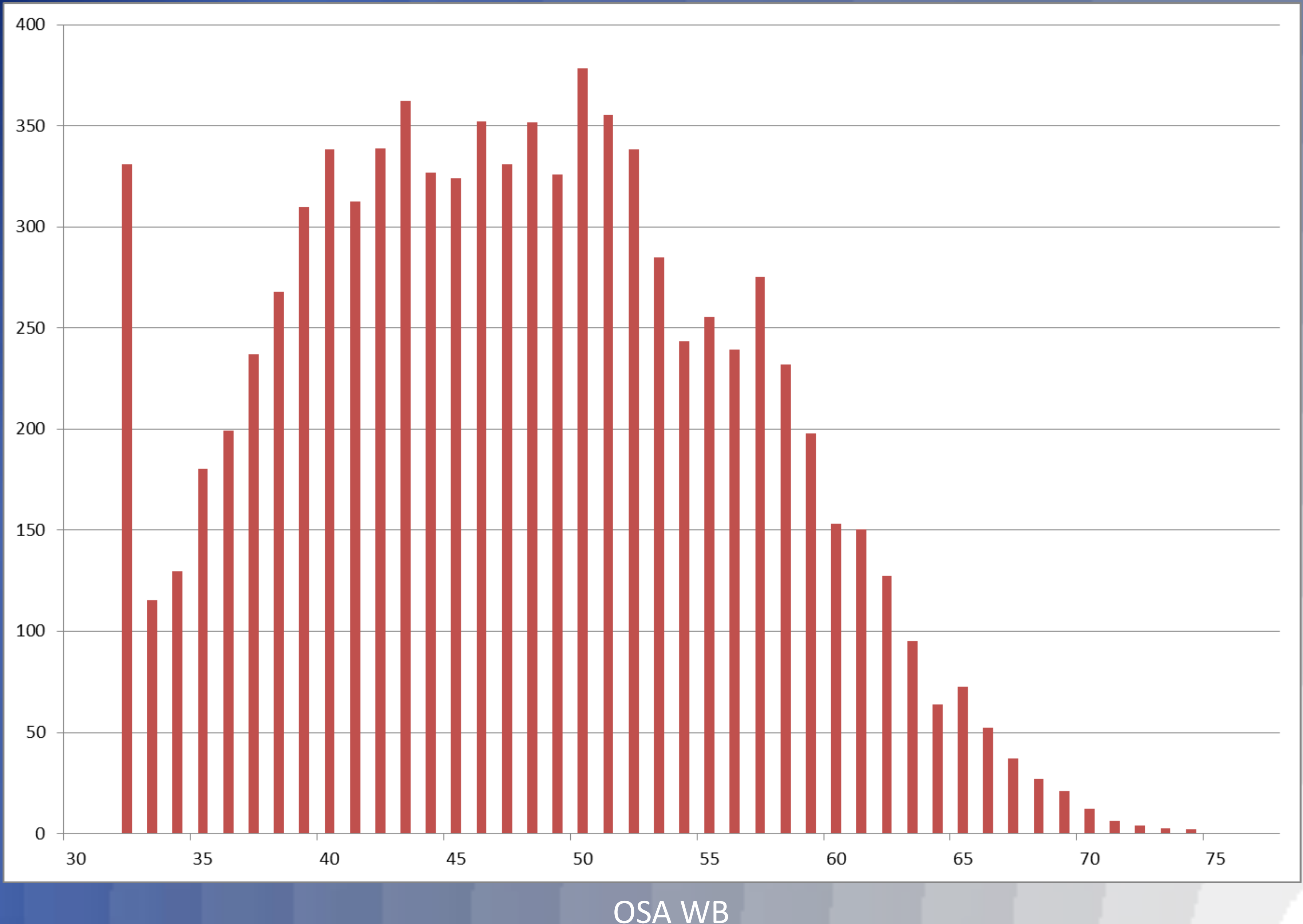
- Varies dependent upon equipment, CHWS temp and load.
  - Without an algorithm 70 F was the lowest ‘safe’ temperature.
  - Adding the oil migration PID algorithm temperatures could reach 52-55 F before seeing refrigerant stacking at high chiller loads.
  - The refrigerant stacking algorithm should allow temperatures down into the upper 40’s, but only under moderate to high load conditions.
  - In this climate, hours/year and chiller performance improvements with colder water limit the effectiveness of dropping CWS temperatures much further.
- Different chillers will have varying CWS temp vs load envelopes. Chiller manufacturer’s technical support can help.
- Different climates and load profiles will also impact the economics of the bottom end temperature.


Chiller w/o AFD
KW/ton vs. % Load
52 F - 84 F CWS Temp
KW/Ton
% Load
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
52
56
60
64
68
72
76
80
84

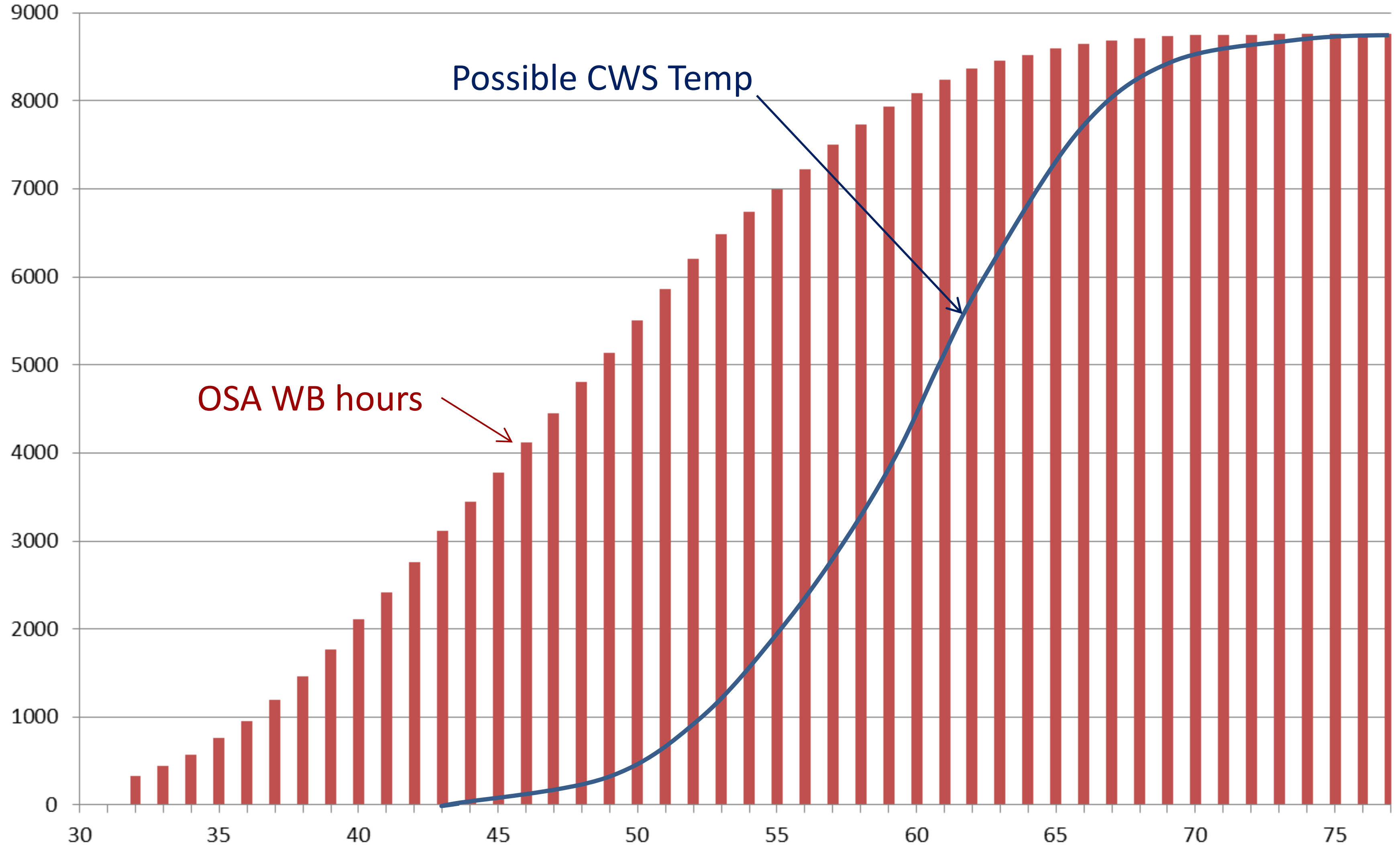
Portland Weather - Enthalpy



Portland OSA WB vs. Bin Hours/Year



Cumulative Bin Hours at or below Indicated OSA WB & Possible CWS Temp



CWS Temp Reset Savings

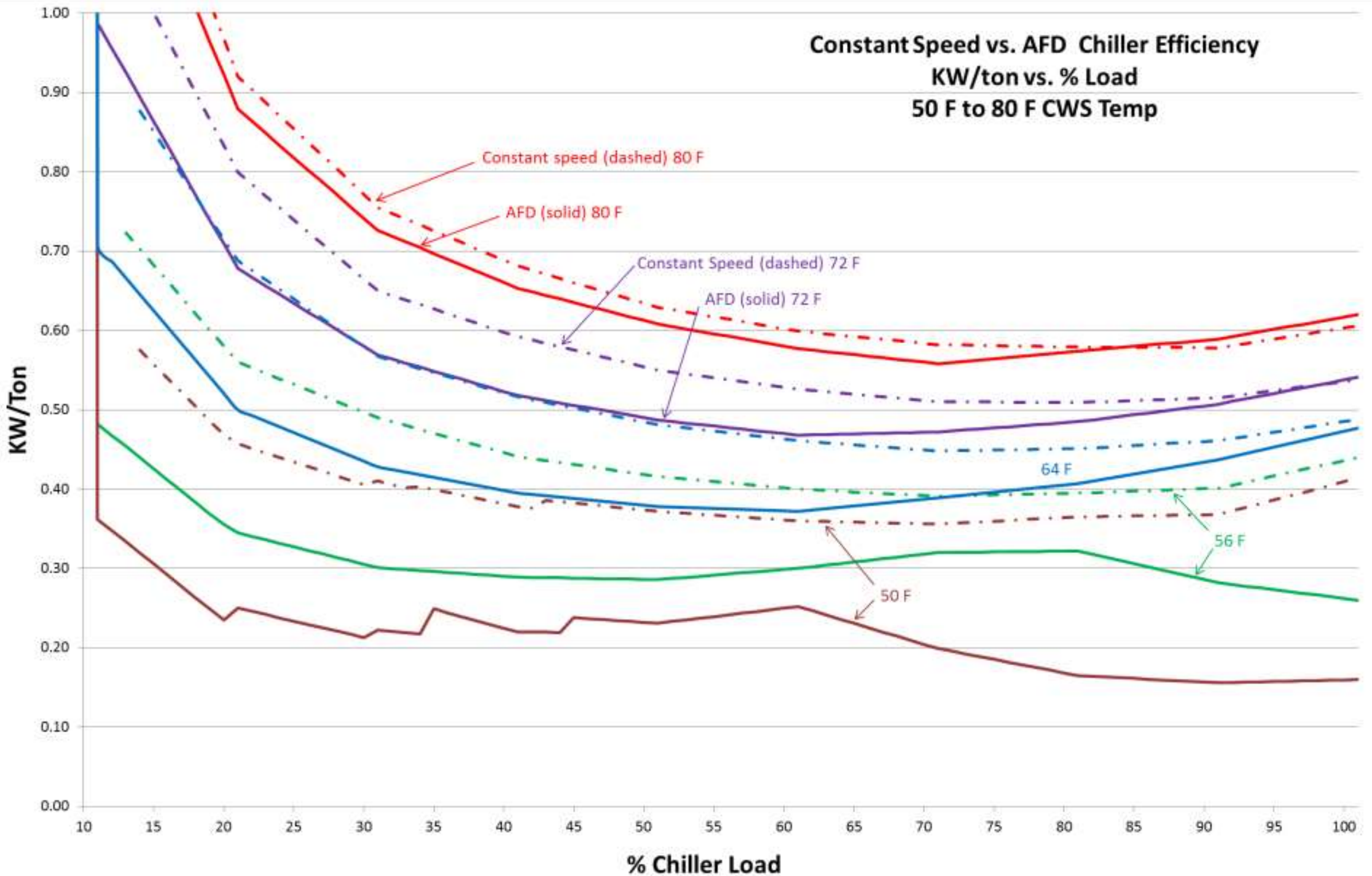
Compressor Savings		746,819	KWH/yr
CT Fan Penalty		181,078	KWH/yr
Net Savings		565,741	KWH/yr
Electrical Savings		2.47%	

Savings relative to previous strategy of constant 70 F CWS SP.

Chiller AFDs

Similar Application To Pumps And Fans

- Modulates RPM to match refrigerant head and flow rates to system curve as loads change
- IGVs (inlet guide vanes) stay open through most of the operating range, reducing pressure drop & saving energy.
- Turndown ratio is limited due to the reduced stall and surge envelopes
  - Compressor vanes, like wings, stall at low speed
  - Control algorithms are added to detect surge under varying load conditions.



Constant Speed vs. AFD Chiller Efficiency
KW/ton vs. % Load
50 F to 80 F CWS Temp
Constant speed (dashed) 80 F
AFD (solid) 80 F
Constant Speed (dashed) 72 F
AFD (solid) 72 F
64 F
56 F
50 F
KW/Ton
% Chiller Load
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100

Chiller AFD Bin Analysis

WB Bin data and Load Profile												Constant Speed CO Chillers		AFD Driven CO Chillers	
WB	Hrs/yr	Inc Sum	Decr Sum	New CWS	Old CWS	New App	Old App	Est Tons	# CO CHs	% RLA	ton-hrs/yr	KW/ton	KWH/yr	Est KW/ton	KWH/yr
31	58	291	8527	50.00	57.00	19.00	26.00	1169	1	69	67,811	0.400	27,111	0.178	12,081
32	92	383	8469	50.00	57.00	18.00	25.00	1321	1	78	121,518	0.401	48,705	0.149	18,097
33	82	465	8377	50.00	57.00	17.00	24.00	1473	1	87	120,749	0.405	48,903	0.136	16,381
34	129	594	8295	50.00	57.00	16.00	23.00	1624	2	48	209,529	0.432	90,537	0.199	41,764
35	121	715	8166	50.00	57.00	15.00	22.00	1776	2	52	214,891	0.421	90,383	0.200	42,961
36	154	869	8045	50.00	57.00	14.00	21.00	1928	2	57	296,860	0.414	122,840	0.207	61,468
37	216	1085	7891	50.00	57.00	13.00	20.00	2079	2	61	449,142	0.406	182,397	0.210	94,183
38	205	1290	7675	50.00	57.00	12.00	19.00	2231	2	66	457,368	0.403	184,091	0.192	87,666
39	279	1569	7470	51.00	58.00	12.00	19.00	2383	2	70	664,792	0.405	269,241	0.193	128,272
40	237	1806	7191	52.00	58.00	12.00	18.00	2534	2	75	600,669	0.406	243,992	0.199	119,371
41	291	2097	6954	52.00	59.00	11.00	18.00	2686	2	79	781,676	0.415	324,161	0.180	141,057
42	339	2436	6663	53.00	59.00	11.00	17.00	2838	2	83	962,039	0.417	401,266	0.192	184,481
43	340	2776	6324	54.00	60.00	11.00	17.00	2990	2	88	1,016,455	0.428	434,636	0.203	206,406
44	348	3124	5984	55.00	60.00	11.00	16.00	3414	3	67	1,188,022	0.424	503,721	0.259	307,187
45	355	3479	5636	56.00	61.00	11.00	16.00	3838	3	75	1,362,540	0.428	583,167	0.273	371,769
46	364	3843	5281	56.00	62.00	10.00	16.00	4262	3	84	1,551,522	0.440	682,204	0.264	408,826
47	326	4169	4917	57.00	62.00	10.00	15.00	4687	4	69	1,527,866	0.436	666,455	0.275	419,995
48	311	4480	4591	58.00	63.00	10.00	15.00	5111	4	75	1,589,517	0.443	703,361	0.296	470,179
49	267	4747	4280	59.00	63.00	10.00	14.00	5535	4	81	1,477,917	0.445	657,673	0.313	462,795
50	314	5061	4013	60.00	64.00	10.00	14.00	5960	5	70	1,871,300	0.448	838,342	0.298	558,302
51	296	5357	3699	60.00	64.00	9.00	13.00	6384	5	75	1,889,616	0.450	849,382	0.309	583,041
52	318	5675	3403	61.00	65.00	9.00	13.00	6808	5	80	2,164,982	0.458	991,562	0.326	704,810
53	347	6022	3085	62.00	66.00	9.00	13.00	7232	5	85	2,509,644	0.470	1,179,532	0.346	868,211
54	327	6349	2738	63.00	66.00	9.00	12.00	7657	6	75	2,503,736	0.464	1,161,733	0.331	828,924
55	321	6670	2411	64.00	67.00	9.00	12.00	8081	6	79	2,593,991	0.473	1,226,179	0.344	893,422
56	301	6970	2091	64.00	67.00	8.00	11.00	8354	6	82	2,514,418	0.474	1,191,583	0.349	876,275
57	357	7327	1790	65.00	68.00	8.00	11.00	8626	6	85	3,079,528	0.483	1,488,028	0.363	1,119,285
58	261	7588	1433	66.00	68.00	8.00	10.00	8899	7	75	2,322,563	0.479	1,112,043	0.353	819,679
59	249	7837	1172	67.00	69.00	8.00	10.00	9171	7	77	2,283,651	0.486	1,110,768	0.366	835,839
60	204	8041	923	68.00	69.00	8.00	9.00	9444	7	79	1,926,550	0.487	937,844	0.378	727,407
61	204	8245	719	68.00	70.00	7.00	9.00	9716	7	82	1,982,156	0.495	980,771	0.381	755,311
62	167	8412	515	69.00	71.00	7.00	9.00	9989	7	84	1,668,168	0.504	840,423	0.393	654,948
63	114	8526	348	70.00	71.00	7.00	8.00	10262	7	86	1,169,824	0.506	591,463	0.407	476,095
64	94	8620	234	71.00	72.00	7.00	8.00	10534	8	77	990,214	0.509	504,316	0.400	396,011
65	45	8665	140	72.00	72.00	7.00	7.00	10807	8	79	486,305	0.509	247,578	0.411	199,942
66	45	8710	95	72.00	73.00	6.00	7.00	11079	8	81	498,571	0.518	258,010	0.414	206,468
67	34	8744	50	73.00	73.00	6.00	6.00	11352	8	83	385,966	0.519	200,123	0.426	164,560
68	13	8757	16	74.00	74.00	6.00	6.00	11625	9	76	151,119	0.526	79,488	0.425	64,290
69	3	8760	3	75.00	75.00	6.00	6.00	11897	9	78	35,691	0.535	19,081	0.436	15,572
70	0	8760	0	77.00	77.00	7.00	7.00	12170	9	80	-	0.551	-	0.457	-
71	0	8760	0	78.00	78.00	7.00	7.00	12442	9	81	-	0.560	-	0.469	-
72	0	8760	0	79.00	79.00	7.00	7.00	12715	9	83	-	0.570	-	0.482	-
73	0	8760	0	81.00	81.00	8.00	8.00	12987	9	85	-	0.587	-	0.503	-
74	0	8760	0	82.00	82.00	8.00	8.00	13260	9	87	-	0.595	-	0.515	-
Totals													22,156,097		15,382,427
												Energy Savings			6,773,669

Cooling Tower Bin Analysis

WB	Hrs/yr	New CWS	Old CWS	New App	Old App	COC Tons	# COCs	# CTs	# CTs old	CHW Tons	New %	Old %	New kW	Old kW	New kWh	Old kWh
32	92	50	57	18	25	1321	1	3	2	5900	23%	25%	2.35	1.98	217	182
33	82	50	57	17	24	1473	1	3	2	5900	27%	29%	3.87	3.10	317	254
34	129	50	57	16	23	1624	2	3	3	5900	32%	22%	6.23	2.10	804	271
35	121	50	57	15	22	1776	2	3	3	5900	37%	25%	9.89	3.13	1,196	379
36	154	50	57	14	21	1928	2	3	3	5900	43%	29%	15.55	4.61	2,394	709
37	216	50	57	13	20	2079	2	3	3	5900	50%	33%	24.37	6.69	5,265	1,446
38	205	50	57	12	19	2231	2	3	3	5900	58%	37%	38.28	9.64	7,847	1,977
39	279	51	58	12	19	2383	2	3	3	5900	62%	39%	46.63	11.75	13,010	3,278
40	237	52	58	12	18	2534	2	4	3	5900	50%	44%	31.57	16.63	7,481	3,941
41	291	52	59	11	18	2686	2	4	3	5900	57%	47%	48.79	19.80	14,198	5,760
42	339	53	59	11	17	2838	2	4	3	5900	61%	52%	57.53	27.71	19,503	9,393
43	340	54	60	11	17	2990	2	4	3	5900	64%	55%	67.26	32.39	22,868	11,014
44	348	55	60	11	16	3414	3	5	4	6173	58%	50%	64.10	32.54	22,306	11,326
45	355	56	61	11	16	3838	3	6	4	6445	55%	56%	63.26	46.25	22,456	16,419
46	364	56	62	10	16	4262	3	7	4	6718	57%	63%	84.72	63.35	30,839	23,058
47	326	57	62	10	15	4687	4	7	5	6990	63%	59%	112.62	65.41	36,715	21,322
48	311	58	63	10	15	5111	4	8	5	7263	60%	64%	111.83	84.83	34,779	26,381
49	267	59	63	10	14	5535	4	8	6	7535	65%	62%	142.06	92.04	37,929	24,573
50	314	60	64	10	14	5960	5	9	7	7808	62%	57%	140.08	84.39	43,986	26,498
51	296	60	64	9	13	6384	5	10	8	8081	67%	58%	191.31	99.19	56,628	29,360
52	318	61	65	9	13	6808	5	10	8	8353	71%	62%	232.05	120.31	73,791	38,258
53	347	62	66	9	13	7232	5	10	9	8626	76%	58%	278.19	113.96	96,533	39,545
54	327	63	66	9	12	7657	6	10	10	8898	80%	60%	330.08	139.25	107,936	45,536
55	321	64	67	9	12	8081	6	10	10	9171	85%	63%	388.05	163.71	124,564	52,550
56	301	64	67	8	11	8354	6	10	10	9444	98%	71%	610.33	234.78	183,710	70,668
57	357	65	68	8	11	8626	6	10	10	9716	100%	74%	643.00	258.52	229,551	92,292
58	261	66	68	8	10	8899	7	10	10	9989	100%	84%	643.00	377.75	167,823	98,593
59	249	67	69	8	10	9171	7	10	10	10261	100%	86%	643.00	413.54	160,107	102,971
60	204	68	69	8	9	9444	7	10	10	10534	100%	99%	643.00	619.37	131,172	126,350
61	204	68	70	7	9	9716	7	10	10	10806	100%	100%	643.00	643.00	131,172	131,172
62	167	69	71	7	9	9989	7	10	10	11079	100%	100%	643.00	643.00	107,381	107,381
63	114	70	71	7	8	10262	7	10	10	11352	100%	100%	643.00	643.00	73,302	73,302
64	94	71	72	7	8	10534	8	10	10	11624	100%	100%	643.00	643.00	60,442	60,442
65	45	72	72	7	7	10807	8	10	10	11897	100%	100%	643.00	643.00	28,935	28,935
66	45	72	73	6	7	11079	8	10	10	12169	100%	100%	643.00	643.00	28,935	28,935
67	34	73	73	6	6	11352	8	10	10	12442	100%	100%	643.00	643.00	21,862	21,862
68	13	74	74	6	6	11625	9	10	10	12715	100%	100%	643.00	643.00	8,359	8,359
69	3	75	75	6	6	11897	9	10	10	12987	100%	100%	643.00	643.00	1,929	1,929
70	0	77	76	7	6	12170	9	10	10	13260	100%	100%	643.00	643.00	0	0
71	0	78	77	7	6	12442	9	10	10	13532	100%	100%	643.00	643.00	0	0
72	0	79	78	7	6	12715	9	10	10	13805	100%	100%	643.00	643.00	0	0
73	0	81	79	8	6	12987	9	10	10	14077	100%	100%	643.00	643.00	0	0
74	0	82	82	8	8	13260	9	10	10	14350	100%	100%	643.00	643.00	0	0
Totals															2,118,578	1,346,757
															Energy Penalty	771,821

Chiller AFD Economics

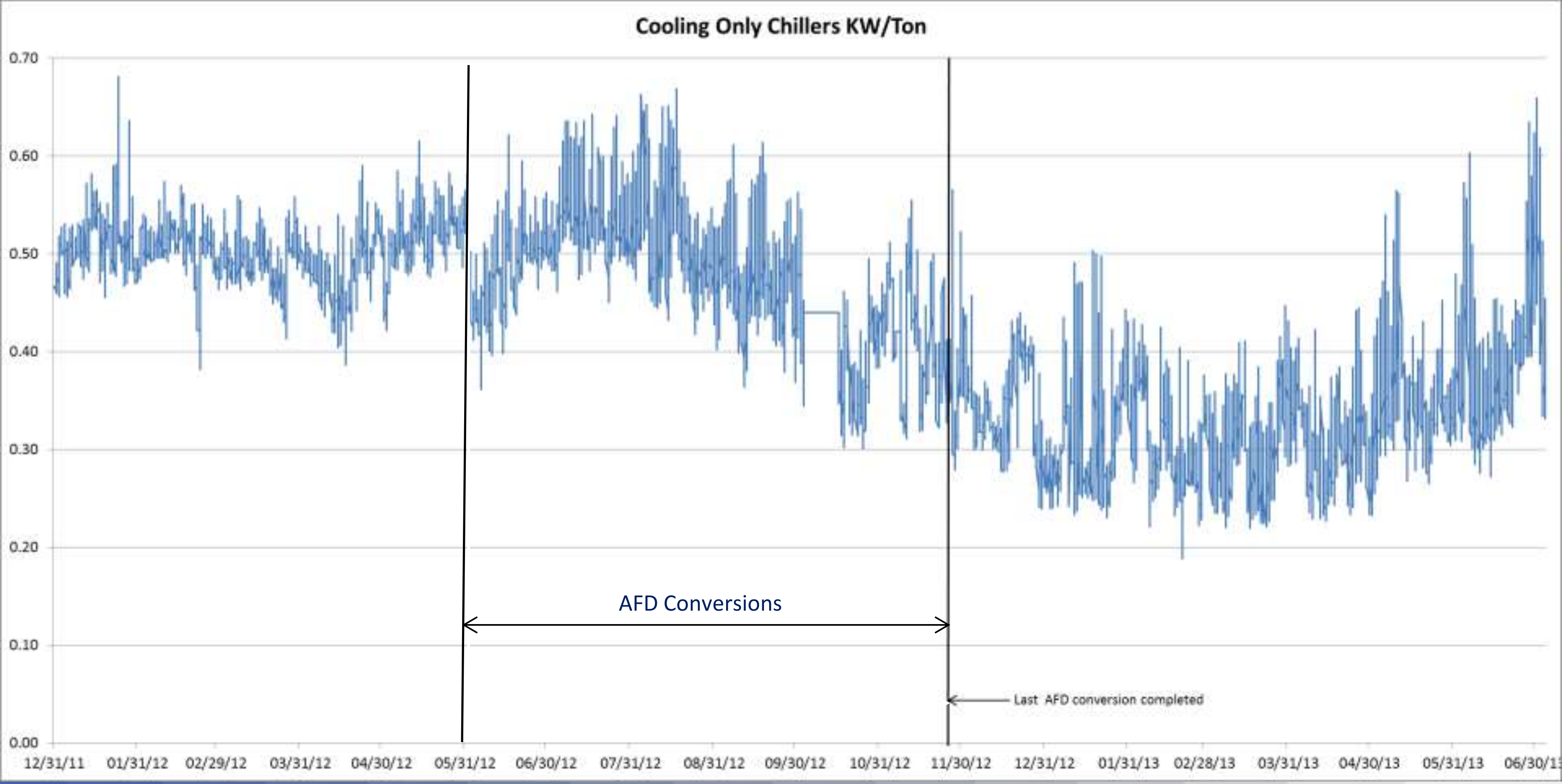
Annual Chiller Plant Energy Usage			
	Chiller	CT	Total
Const Speed CHs (actual) [kWh]	22,156,097	1,346,757	23,502,854
AFD CHs (actual/estimated) [kWh]	15,382,427	2,118,578	17,501,006
Energy Savings [kWh]	6,773,669	(771,821)	6,001,848

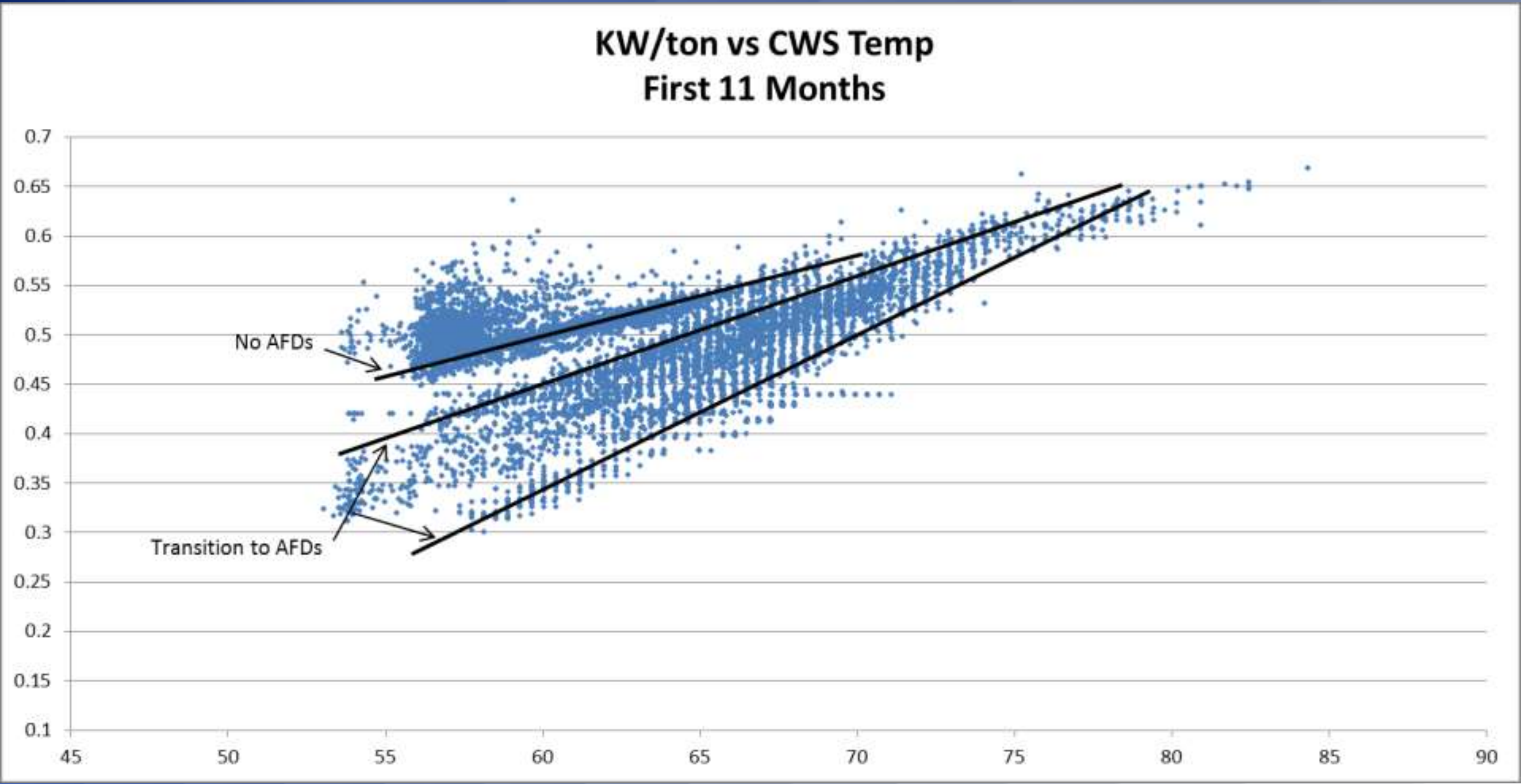
Note: Predicted bin analysis estimated 5,627 MWH/yr savings, vs. verification of 6,001 MWH/yr.

Payback was around 7.5 years. 10 year NPV was around $900k.

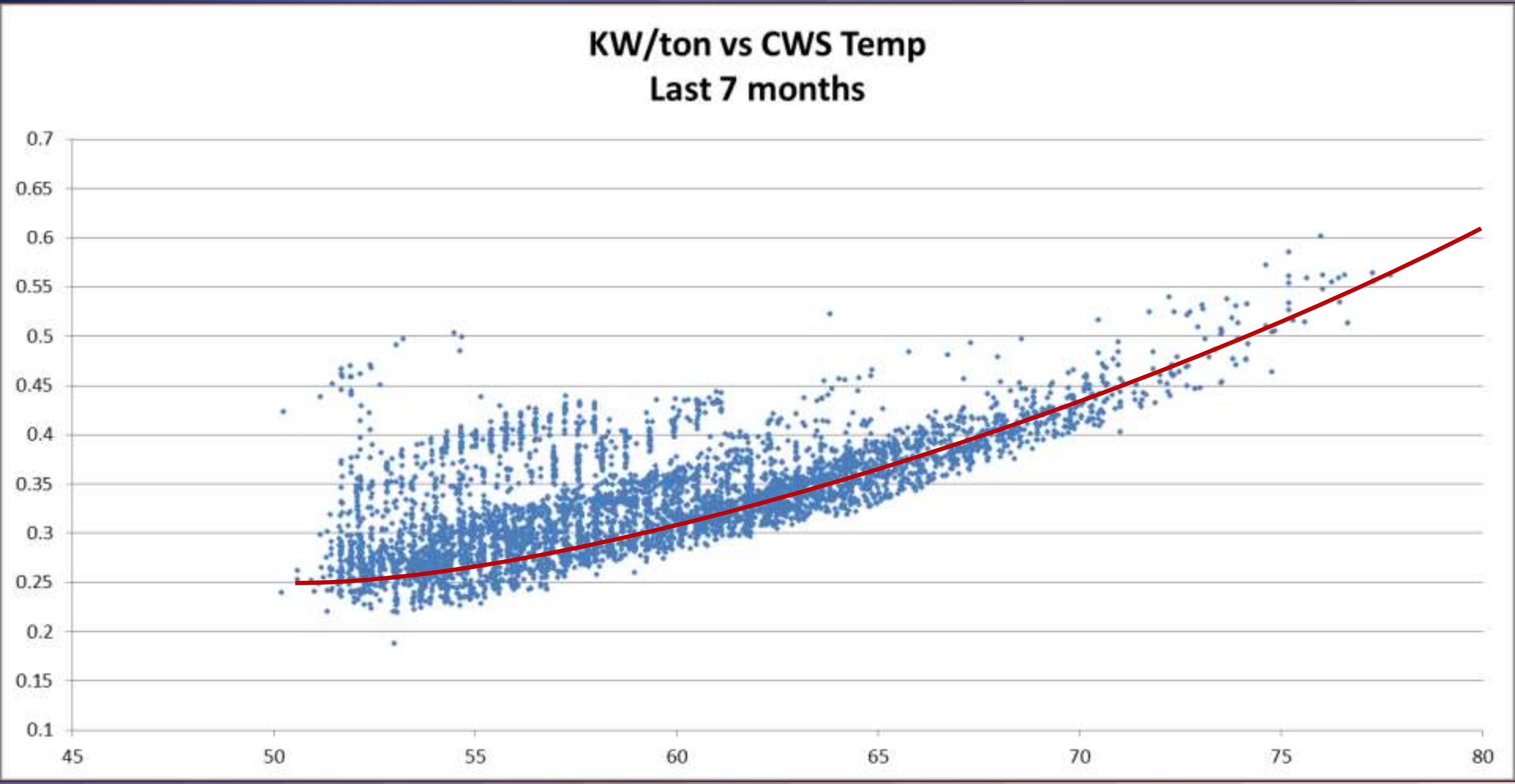
Project costs were high due to early adopter status with 4160 V AFDs plus construction costs are higher in the Fab world than elsewhere. This was more about demonstrating what is possible and minimizing use of resources and emissions.

18 months of KW/Ton, Before and After





CWS Temperature



CWS Temperature

AFD Scoping Recommendations

- Scope the project carefully
- Add any instrumentation necessary for verification of results.
- Work out the economics for funding (NPV, ROI, presentations.)
  - Verify qualification for energy credit subsidies.
- Work with chiller vendor
  - more complex than adding an AFD to a pump.
  - significant control issues. Vendor deals with these, and they have it worked out.
- Physical footprint and electrical clearances
- Maximum electrical line length between AFD and motors.
- Verify the AFD has low line harmonics, preferably < 5% THD
- Verify that the manufacturer will warrantee the chiller/AFD/motor combination
- AFDs generate ~2% of energy as heat: may drive additional room AC requirements
- Network and map <u>all</u> available control points to FMS (via Modbus, BACNET, etc.) Put them on tables and set up trends. There are about 100 points per chiller. Most are helpful for condition monitoring of the chiller plant.
- Verify that every point is working properly and mapped correctly during commissioning.

AFD/CW Temp Summary

- The manufacturer's claimed savings are real.
  - Compressor energy reduction of 30.7%.
- For decades, chiller efficiency improvements have been evolutionary. AFDs are now available to do for centrifugal chillers what has been done for pumps and fans 20-30 years ago.
- In moderate climates AFDs on chillers can shave 20-30% off of annual energy consumption.
- AFDs are optimized with CWS temperature reset.
- Capital costs are significant and may not pay back without appropriate duty cycles, load profiles, weather conditions, and utility rates. Subsidies help.

Variable Primary Pumping

Fixed Primary/Fixed Secondary

- Before the days of AFDs
  - Pumps had triple duty valves
  - CHW Loads had flow limiting valves
  - 3-port control valves prevailed to keep flow more or less equal across each load
  - Piping systems had reverse returns to equalize DP across loads

1980's: Fixed Primary/Variable Secondary

- AFDs applied to SCHW pumps
- Triple duty and flow limiting valves virtually disappeared along with reverse returns
- Better control valve sizing helped
- Chillers still had constant flow, varying DT
- Standard by the 1990's
- There are a lot of plants with this design.
    - Candidates for conversion to VPP or VPOP.

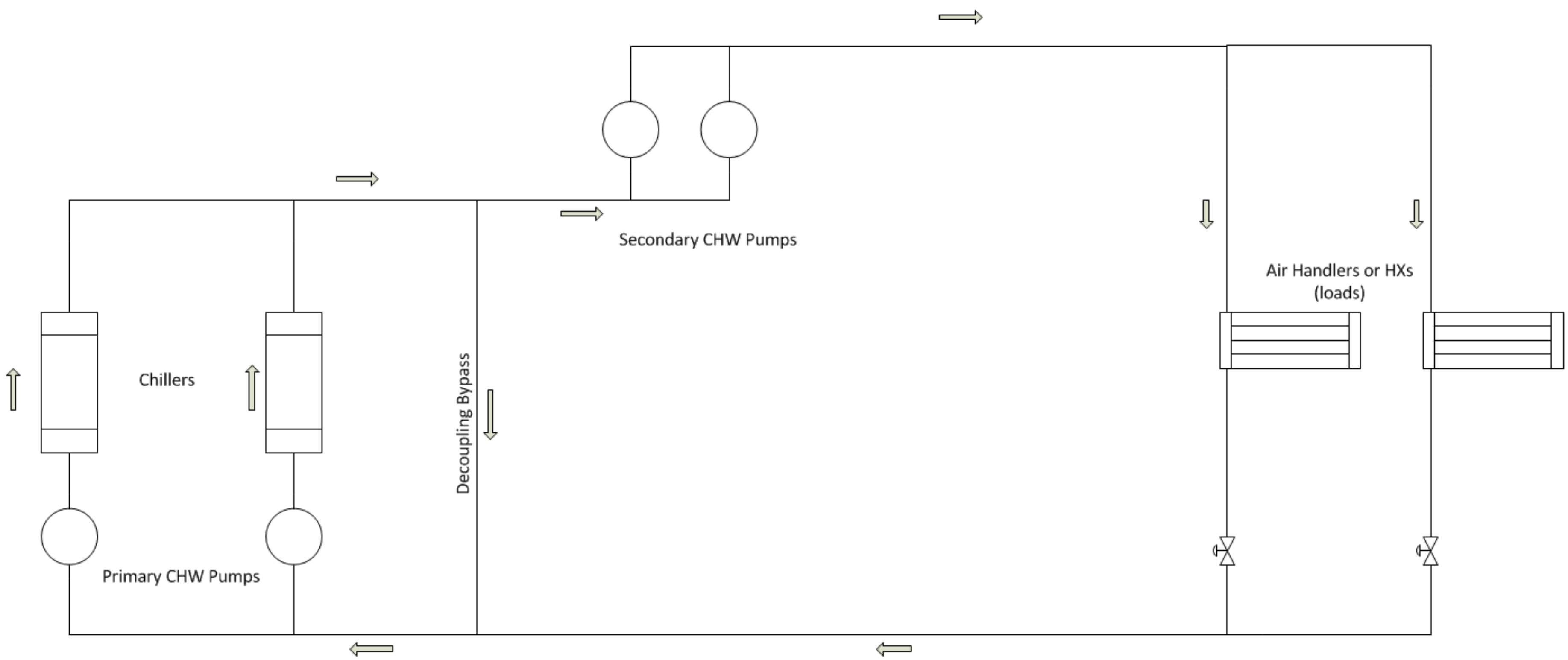
1990's: Variable Primary/Variable Secondary

- AFDs added to PCHW pumps
- Flow varies through chillers,
  - Required better chiller controls, which became available via microprocessor controls in the chiller LCPs
  - Mfgrs started supporting variable flow, within limits
- Less pumping energy
  - PCHW flow is nearly matched to SCHW flow
  - minimizes over-pumping the primary loop
  - Minimizes low DT across chillers (low CHWR temperature)
- Reduces the number of chillers running much of the year
  - PCHWR temp is close to SCHWR temp, so chillers load up and are usually sequenced thermally rather than hydraulically.
  - Chillers can be sequenced to operate in their most efficient load range
    - One chiller operating at 70% load will be more efficient than 2 chillers at 35%
    - Fewer chillers running saves CW pumping energy.

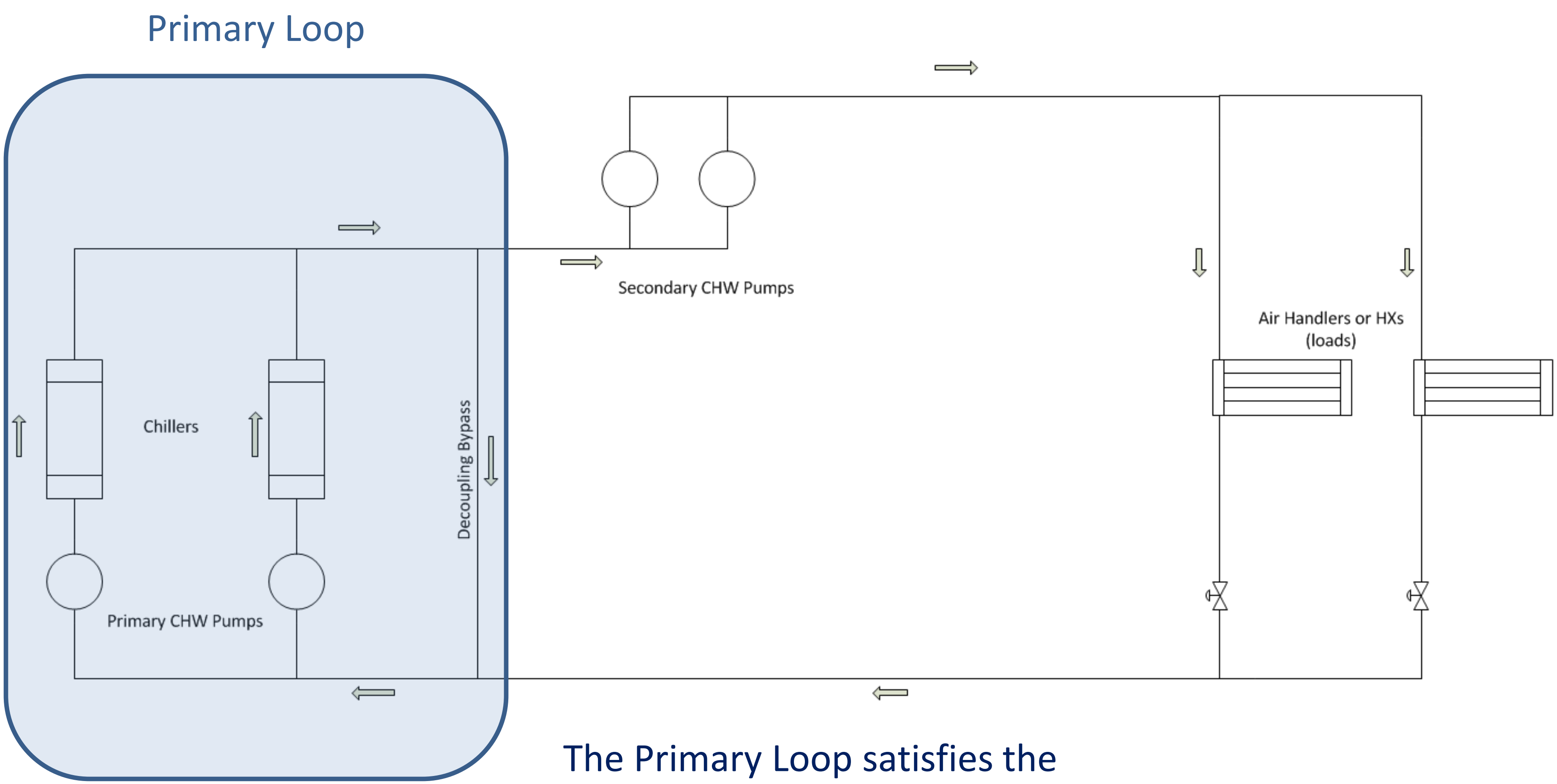
2000's: Variable Primary Only Pumping (VPOP)

- One set of pumps that combines the work of the PCHW and SCHW pumps
- Can be put before or after the chillers
- DCBP turns into a MFBP (minimum flow bypass) with FCVs to maintain minimum flow through the chillers during high DT, chiller starting, or upset conditions.
- Less physical footprint, lower first cost, fewer pumps to maintain, but more control complexity

Primary/Secondary Pumping Geometry

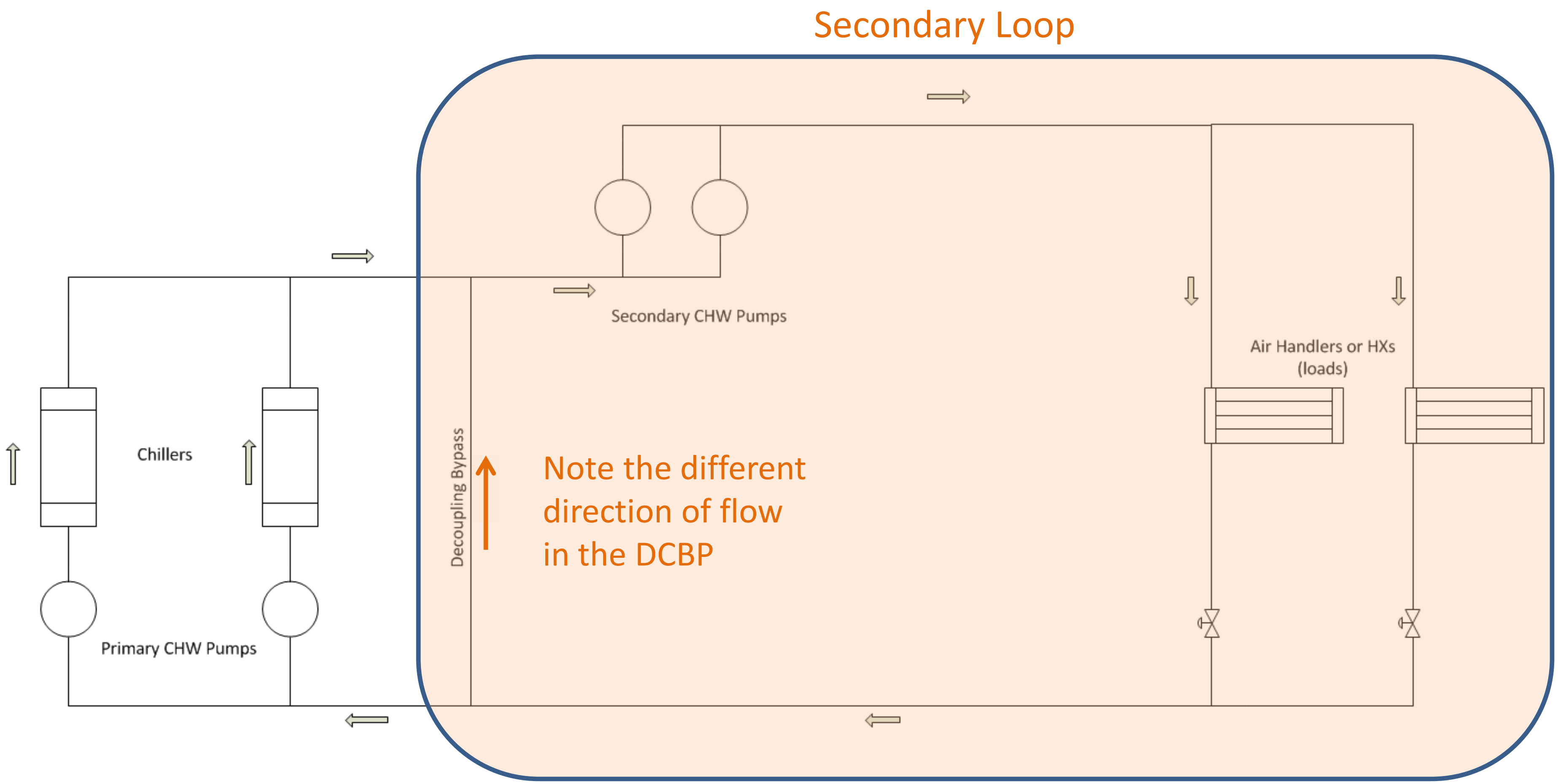


Primary/Secondary Pumping Geometry



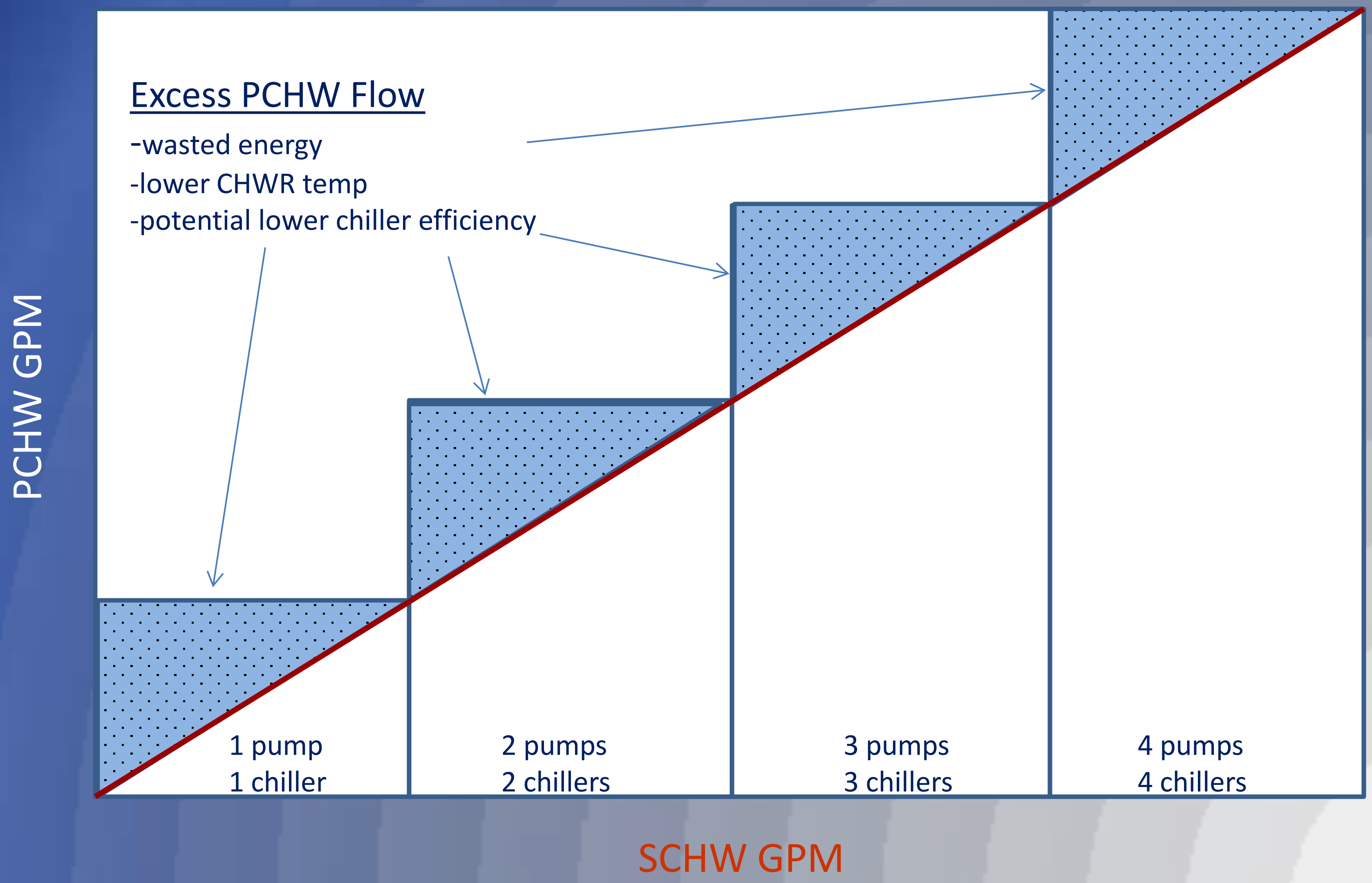
The Primary Loop satisfies the <u>THERMAL</u> requirements of the system via the chillers

Primary/Secondary Pumping Geometry

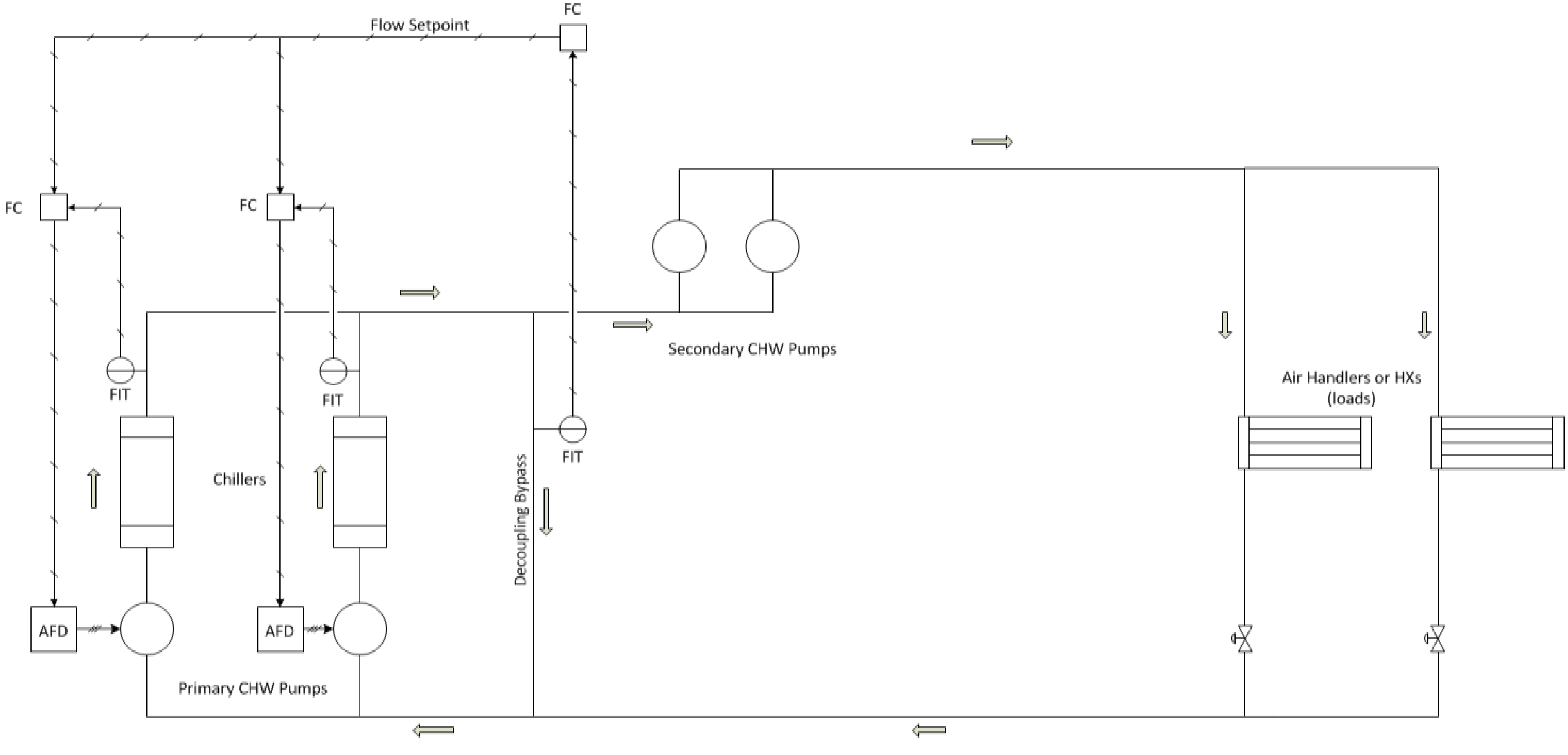


The Secondary Loop satisfies the HYDRAULIC (flow) requirements of the system via the SCHW Pumps

Problem with fixed Primary Flow



Flow controls for VPP

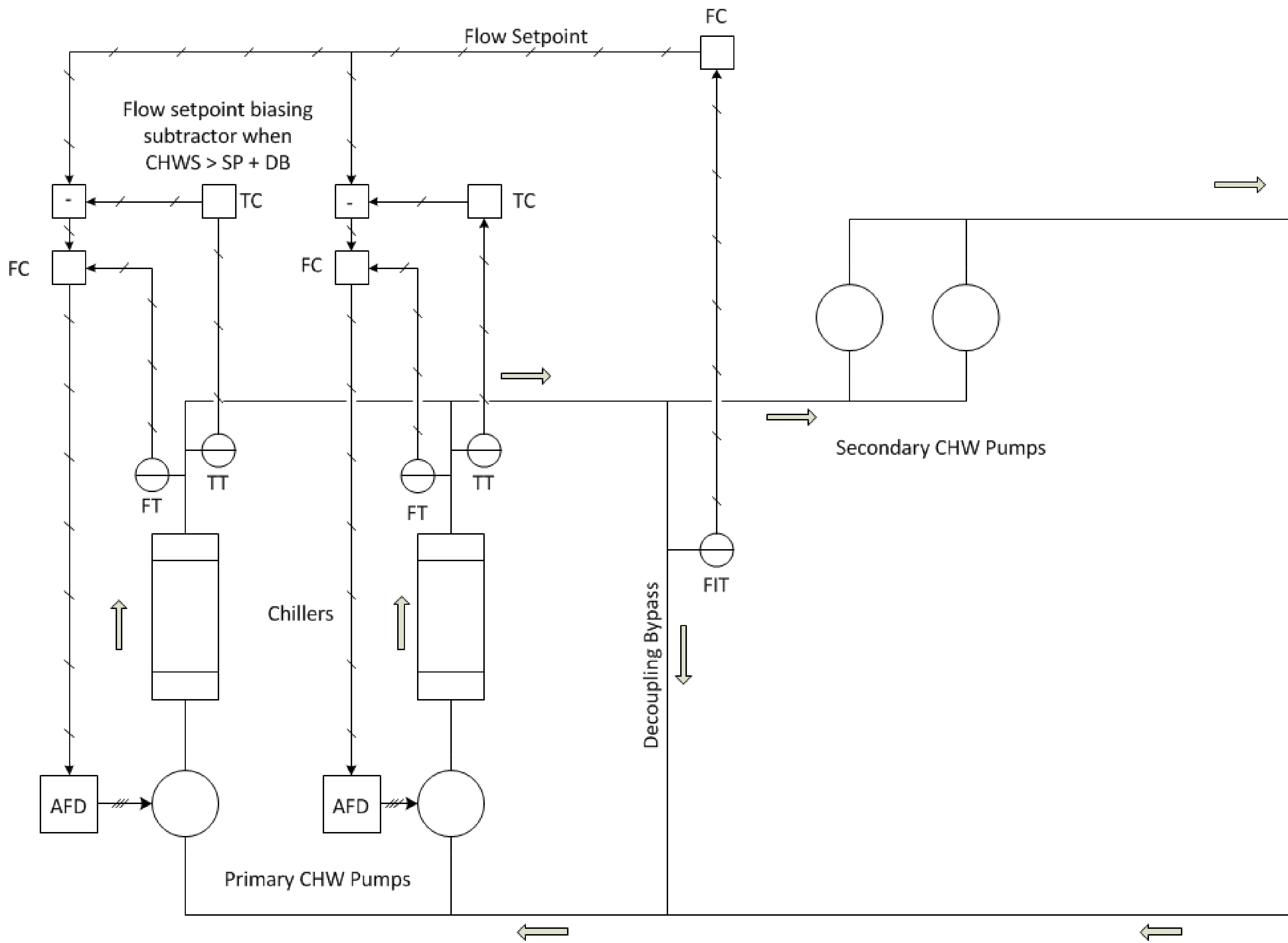


What Can Go Wrong?

- Not all chillers are created equally (or perform equally)
- Chillers may not fully load equally:
  - Temperature stratification for the closest chiller to the DCBP line
  - Low evaporator temperature limiting
    - Low refrigerant level
  - Current limiting
  - High refrigerant condenser pressure limiting
    - Fouled tubes
  - Air in low pressure chillers
  - Manufacturing differences
  - Flow meter calibration

Temperature Biasing

- Add temperature biasing from each chiller
  - Subtracts CHWS SP from CHWS temp from each chiller
  - Delta is used as the Process Variable for biasing PID
  - Biasing PID uses 0.5 to 1.0 F ‘deadband’ as its setpoint
  - Biasing PID outputs a GPM which is subtracted from the master FC to that chiller’s slave FC
  - Slows down the CHW flow to any chiller that cannot keep up no matter the reason
  - Absolutely loads up all chillers to the best of their current capability, regardless of their condition.


FC
Flow Setpoint
Flow setpoint biasing subtractor when CHWS > SP + DB
TC
TC
FC
FC
FT
TT
FT
TT
FIT
Secondary CHW Pumps
Chillers
Decoupling Bypass
AFD
AFD
Primary CHW Pumps

VPP (new or retrofitting) Suggestions

- For most mechanical engineers, the pumps, chillers, and piping is the easy part.
- The difficulty in VPP is the controls.
- Spend the time to understand the complete operational envelope of the plant over its lifetime.
- Conceptualize what can go wrong at low loads, high loads, sequencing up and down, power outages and recovery.
  - Think about redundancy: What happens if the DCBP FIT fails or drifts?
  - Be careful on where you place instruments and how they are installed.
- Scope the project carefully, whether it is a new installation or a retrofit.
  - Install enough instrumentation and controls to keep the plant operating between the guardrails.

VPP Suggestions

- For retrofits with older chiller LCPs, it is a good time to consider upgrading and networking to FMS.
  - the latest generation of color touch screen panels are worth it.
  - All parameters are visible; user settings and setpoints; recent trend data; USB connectivity to a laptop or tablet for higher level factory settings.
  - Look for wireless and internet connectivity for factory/3rd party support, diagnostics, and predictive service support to be coming soon.
- Network everything you can from the chiller LCPs to FMS and let FMS do the system level control functions.
  - Master flow and individual chiller flow controllers, because one flow rate affects all flow rates.
  - CHW temperature reset: This comes from TCVs on the load side. Let FMS figure this out and pass the SP to each chiller's LCP. Each chiller will control its own temperature to that SP.

VPP Suggestions

- Flow metering
  - Most chillers come with commercial quality PDTs. Consider replacing these with industrial quality PDITs with flushing ports and air vents.
  - Match the range and output to the vendor's standards and send that signal to the LCP, if the chiller has flow measurement capability.
  - If not, send the signal to FMS and calculate the flow based on measured DP. The equation should have constants derived from the individual chillers factory test data. Flow = a * DP ^ (1/1.85). Some manufacturer's may have an exponent different than 1.85.
  - Alternative chiller flow transmitters are magnetic, ultrasonic, annubars, and paddle wheel flow meters. Very few chiller installations have the required straight line pipe lengths recommended by the instrument manufacturers.   Do the best you can (typically 2/3 of the distance down a straight section of pipe) and keep them accessible for maintenance.

VPP Suggestions

- CHWS TTs should be moved well downstream of the chiller nozzles. Because minimum flows can be half or less than design, thermal stratification errors can be significant (> 5 deg F) and worse, it varies with flow.
  - Move the TT past the first bend in the pipe and place in vertical pipe, 10 to 15 feet from chiller nozzle.
- Add shaft grounding to motors when adding AFDs unless you enjoy dealing with bearing failures.

VPP Suggestions

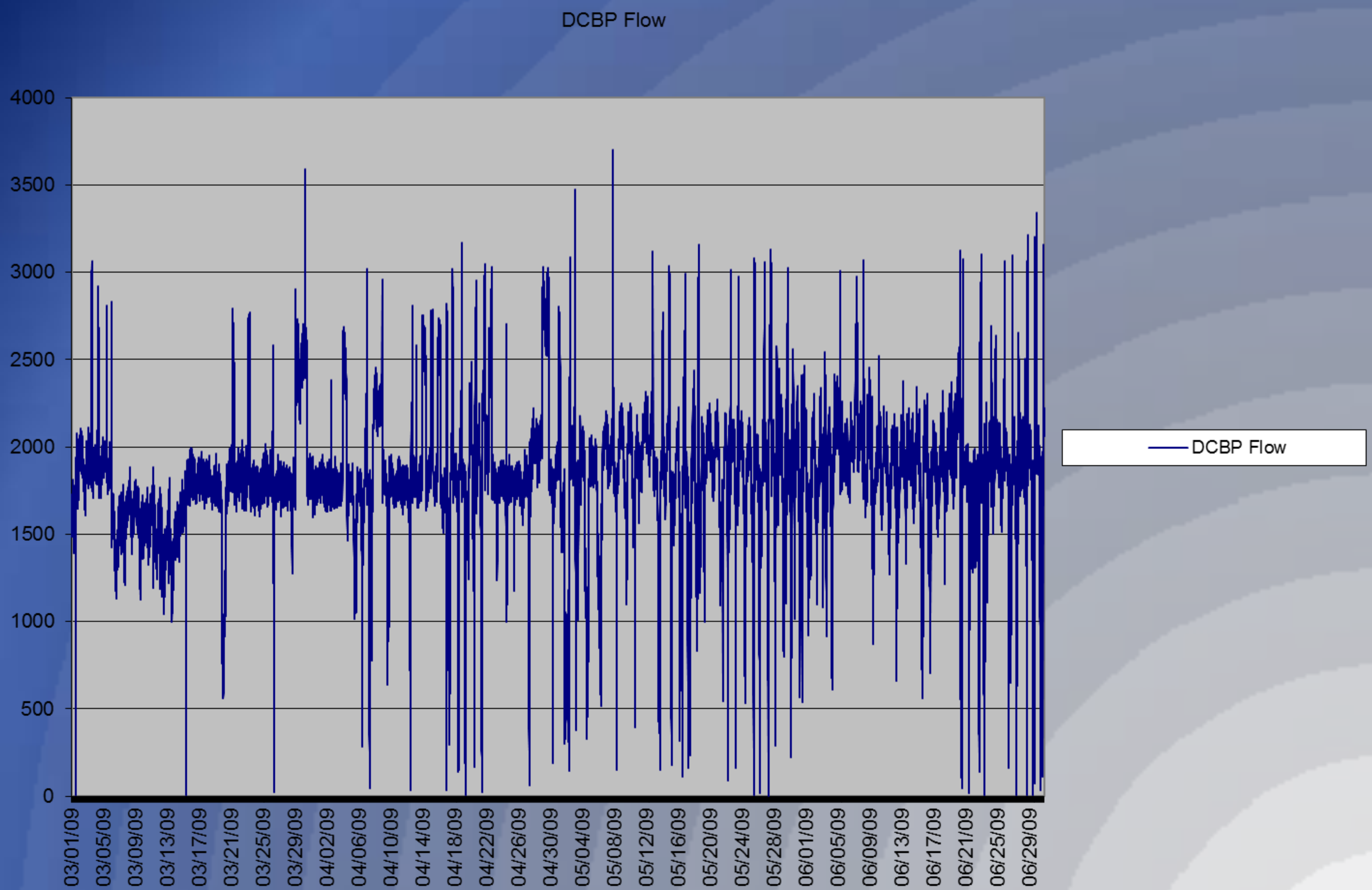
- Most primary/secondary pumping plants sequence chillers up when:
  - CHWS Temp > Hi SP with a time delay, or > Hi Hi SP instantly
  - DCBP Flow < Sp_{low} with a time delay
- Most plants sequence down when
  - DCBP Flow > Sp_{hi} with a time delay
- Because VPP actively controls the DCBP flow to a low constant this sequencer won't sequence down
  - Need to add a tonnage, sum of %RLA table, or some other means of sequencing down since the conventional means of sequencing down is unlikely to happen.
  - A tonnage table is an opportunity to tweak the start and stop staging points to maximize the efficiency of the plant

Plant Efficiency

	Constant Primary/Variable Secondary		Chiller AFDs, CWS Reset, & VPP	
Component	KW/ton	%	KW/ton	%
Chillers	.560	79.0	.392*	71.9
Cooling Tower Fans	.047	6.6	.060	11.0
CW Pumps	.045	6.3	.048	8.8
SCHW Pumps	.039	5.5	.039	7.2
PCHW Pumps	.018	2.5	.006	1.1
Total	.709	99.9	.545	100.0

* Not all chiller AFDs installed at start of last 12 months. Estimate 0.382 kw/ton for full year implementation. Last 6 months of all AFD operation (Jan-June) was 0.328 kw/ton.

Questions?


DCBP Flow
4000
3500
3000
2500
2000
1500
1000
500
0
03/01/09
03/05/09
03/09/09
03/13/09
03/17/09
03/21/09
03/25/09
03/29/09
04/02/09
04/06/09
04/10/09
04/14/09
04/18/09
04/22/09
04/26/09
04/30/09
05/04/09
05/08/09
05/12/09
05/16/09
05/20/09
05/24/09
05/28/09
06/01/09
06/05/09
06/09/09
06/13/09
06/17/09
06/21/09
06/25/09
06/29/09
DCBP Flow

gpm	head	HP	KW	KW Saved	
3300	42.01	42.32	33.94		
3200	39.69	38.76	31.09		
3100	37.42	35.41	28.40		
3000	35.22	32.25	25.87		
2900	33.08	29.28	23.49		
2800	31.00	26.49	21.25		
2700	28.98	23.89	19.16	2.09	
2600	27.03	21.45	17.21	4.05	
2500	25.14	19.18	15.39	5.87	
2400	23.31	17.07	13.70	7.56	
2300	21.54	15.12	12.13	9.12	Average savings on PCHW pump
2200	19.84	13.32	10.69	10.56	
2100	18.21	11.67	9.36	11.89	
2000	16.64	10.16	8.15	13.11	
1900	15.13	8.77	7.04	14.21	
1800	13.69	7.52	6.03	15.22	
1700	12.32	6.39	5.13	16.13	
1600	11.01	5.38	4.31	16.94	
Chiller	Hrs/yr				
1	5409				
2	5722				
3	5419				
4	3345				
5	4309				
Chiller hrs/yr	24204				
KW	9.12				
	220,747	KWH/yr	Avg PCHWP speed slowed down, not throttled		
	117,460	KWH/yr	not overpumping the DCBP		
	338,207	KWH/yr	Total primary pumping energy savings		
	0.09				
	$ 30,439	per year			

PORTLAND INTL ARPT, OR, USA

WMO#: 726980

Lat: 45.59N Long: 122.60W Elev: 108 StdP: 14.64 Time Zone: -8 (NAP) Period: 86-10 WBAN: 24229

Annual Heating and Humidification Design Conditions

	Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB		
				99.6%			99%			0.4%		1%				
		99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	
(1)	12	25.2	29.5	9.6	9.0	29.8	16.9	13.0	34.9	30.1	36.0	27.2	39.7	10.2	120	(1)

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

	Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB		
			0.4%		1%		2%		0.4%		1%		2%				
			DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	
(2)	8	21.8	91.4	67.3	87.5	66.5	83.6	65.3	69.5	86.9	67.9	84.5	66.2	81.1	10.5	310	(2)

	Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 & 55/69	
	0.4%			1%			2%			0.4%		1%		2%			
	DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB		
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	
(3)	63.2	87.0	75.1	61.6	82.3	73.1	60.3	78.4	71.5	33.6	87.5	32.1	84.5	30.8	81.1	1108	(3)

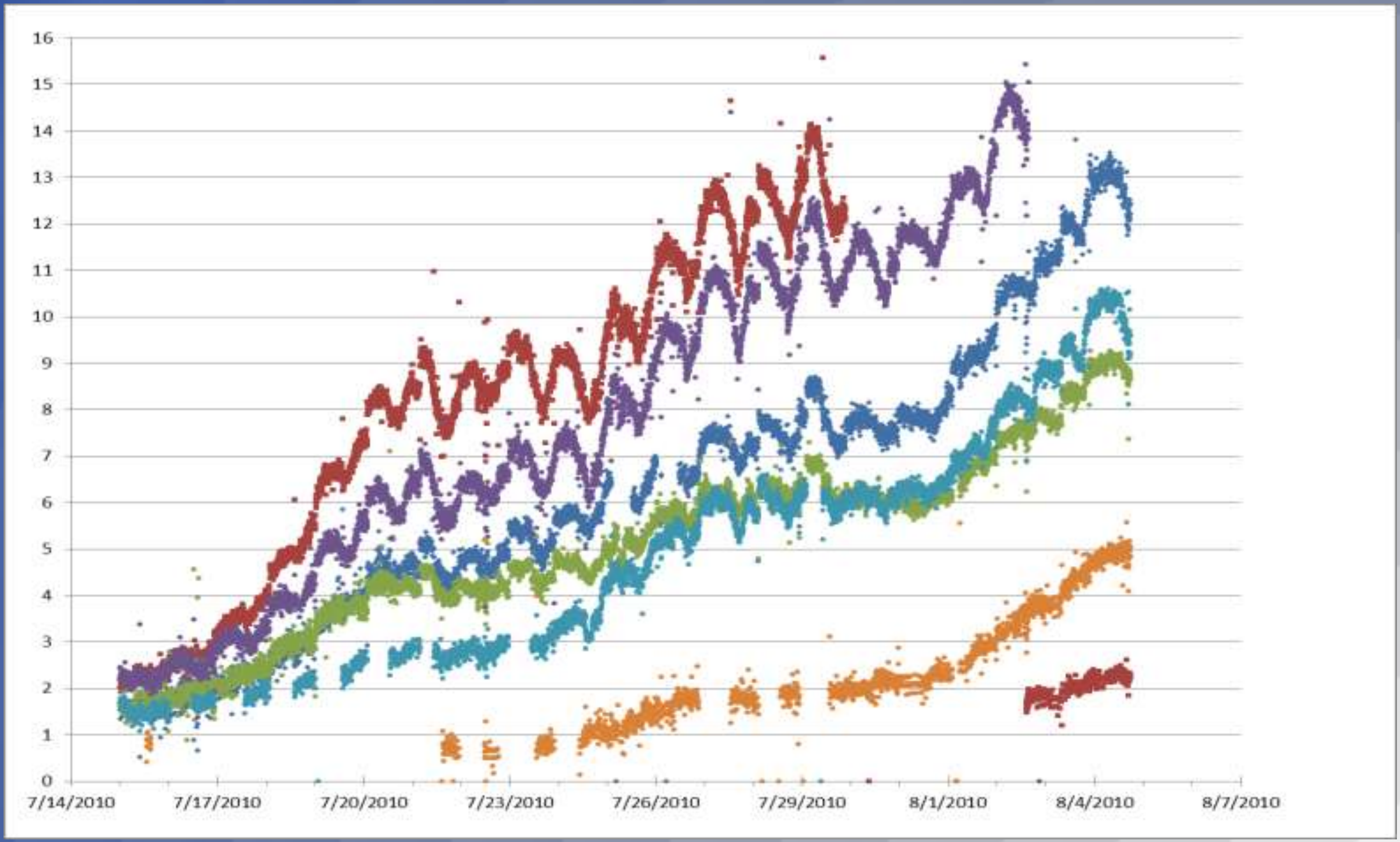
Extreme Annual Design Conditions

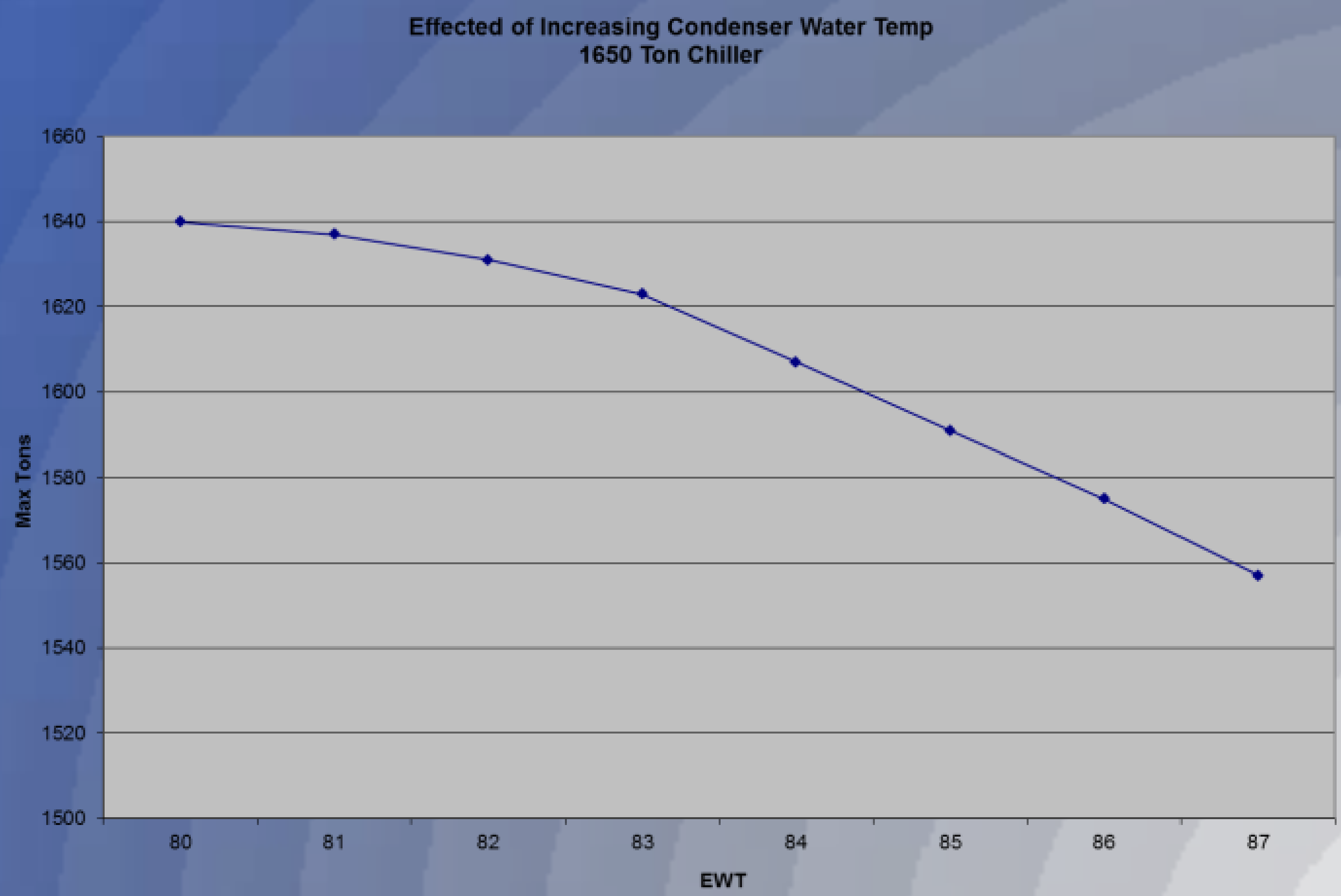
	Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB								
					Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years		
	1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	
(4)	23.6	19.7	17.5	77.2	20.9	99.2	5.6	3.6	16.9	101.8	13.6	103.9	10.4	105.9	6.4	108.5	(4)

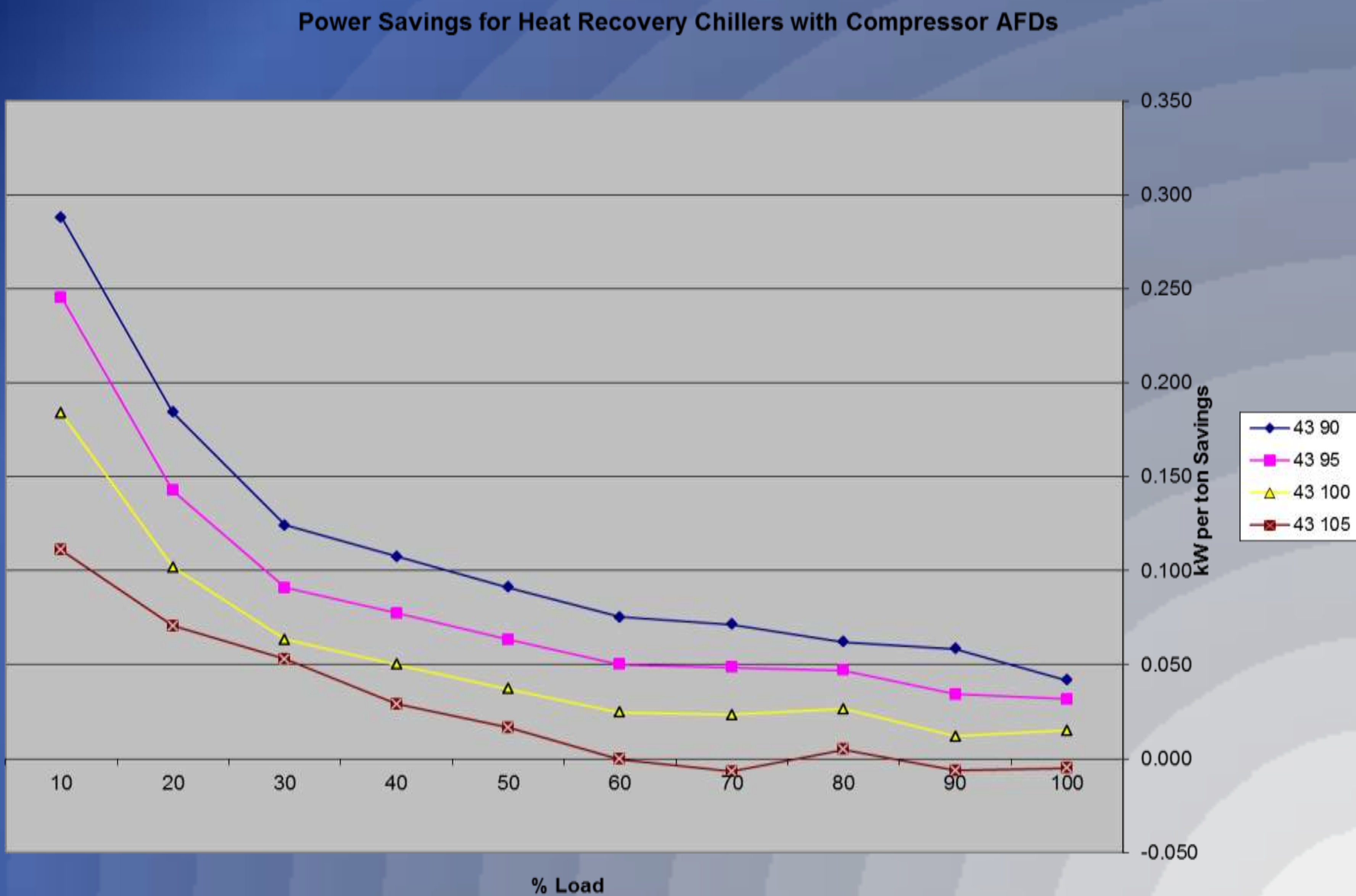
Monthly Climatic Design Conditions

			Annual (d)	Jan (e)	Feb (f)	Mar (g)	Apr (h)	May (i)	Jun (j)	Jul (k)	Aug (l)	Sep (m)	Oct (n)	Nov (o)	Dec (p)	
(5)	**Temperatures, Degree-Days and Degree-Hours**	Tavg	54.6	41.6	43.8	48.1	52.5	58.4	63.5	69.1	69.5	65.0	55.4	47.0	40.9	(5)
(6)		Sd		5.51	5.74	4.68	5.35	6.23	5.62	5.58	4.87	5.27	5.24	5.57	6.01	(6)
(7)		HDD50	988	264	180	93	31	4	0	0	0	0	12	119	285	(7)
(8)		HDD65	4214	726	592	524	376	223	93	19	11	66	298	539	747	(8)
(9)		CDD50	2685	4	8	34	106	264	406	593	606	449	181	30	4	(9)
(10)		CDD65	433	0	0	0	1	19	49	146	152	64	2	0	0	(10)
(11)		CDH74	4423	0	0	0	36	268	565	1439	1383	692	40	0	0	(11)
(12)		CDH80	1696	0	0	0	5	84	205	600	554	240	8	0	0	(12)
(13)	**Precipitation**	PrecAvg	36.3	5.4	3.9	3.6	2.4	2.1	1.5	0.6	1.1	1.8	2.7	5.3	6.1	(13)
(14)		PrecMax	64.6	13.6	11.0	8.3	4.7	4.3	2.7	2.0	4.3	4.9	6.1	11.5	12.9	(14)
(15)		PrecMin	22.6	1.1	1.3	1.3	1.0	0.9	0.5	0.0	0.1	0.0	0.4	0.8	1.4	(15)
(16)		PrecSD	9.8	3.4	2.1	2.0	1.0	1.1	0.7	0.5	1.1	1.3	1.6	2.8	3.0	(16)

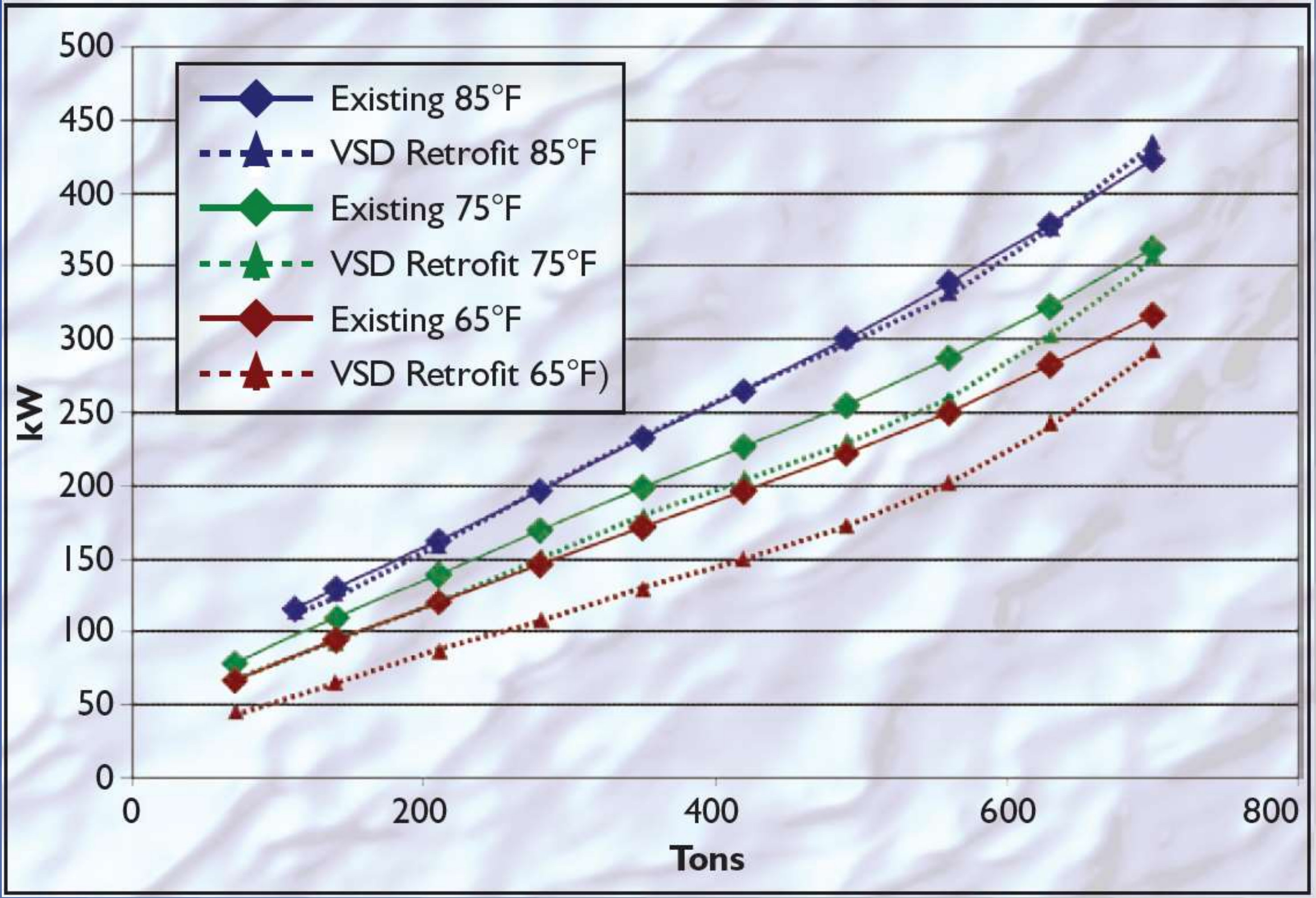
Chiller Condenser Approaches
Bio-Fouling




Effected of Increasing Condenser Water Temp
1650 Ton Chiller
Max Tons
1660
1640
1620
1600
1580
1560
1540
1520
1500
80
81
82
83
84
85
86
87
EWT

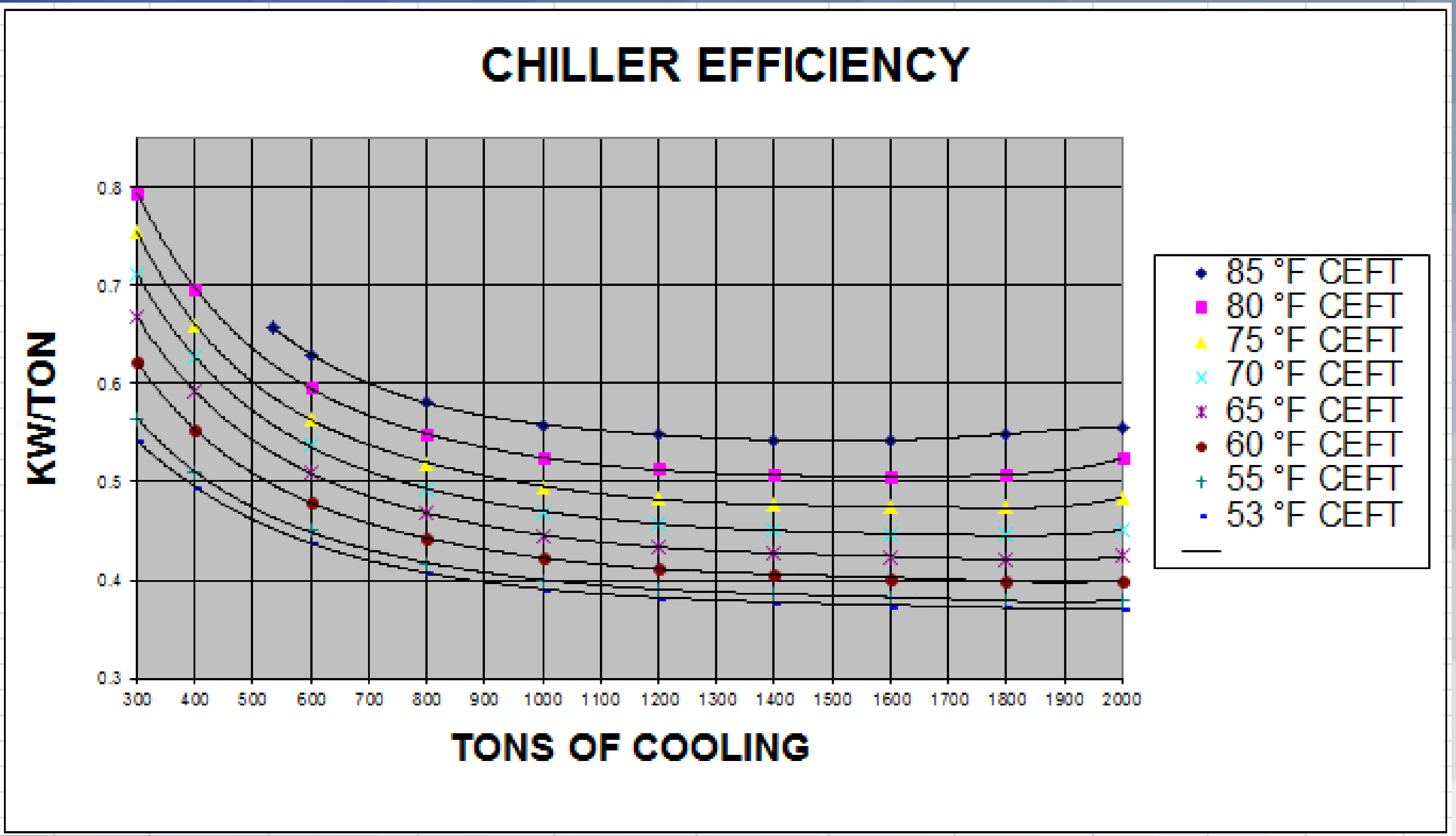

Power Savings for Heat Recovery Chillers with Compressor AFDs
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
-0.050
kW per ton Savings
10
20
30
40
50
60
70
80
90
100
% Load
43 90
43 95
43 100
43 105

Projected Savings

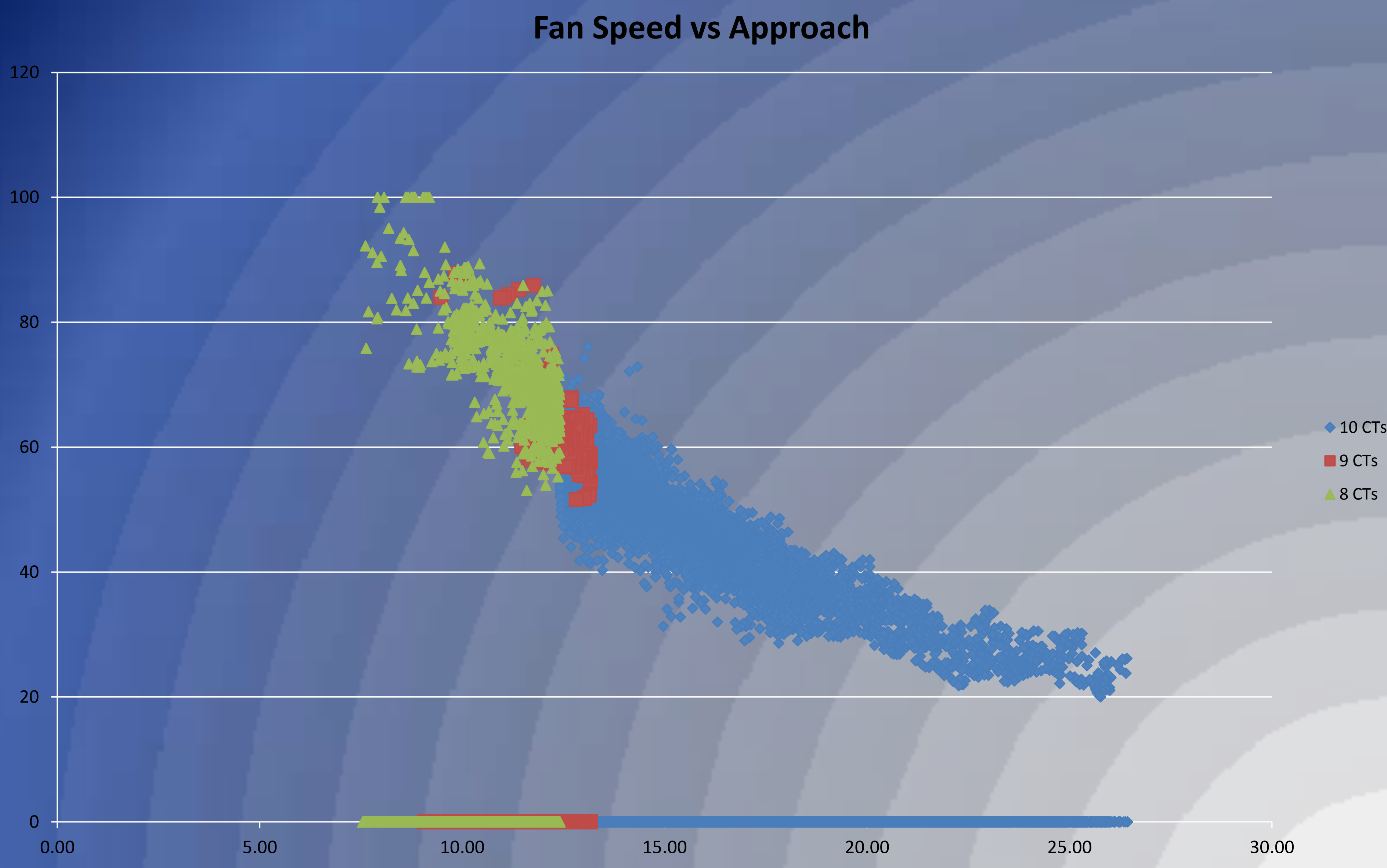


Mick Schwedler, PE, and Beth Bakkum, 'Upgrading Chilled Water Systems', ASHRAE Journal, Nov. 2009

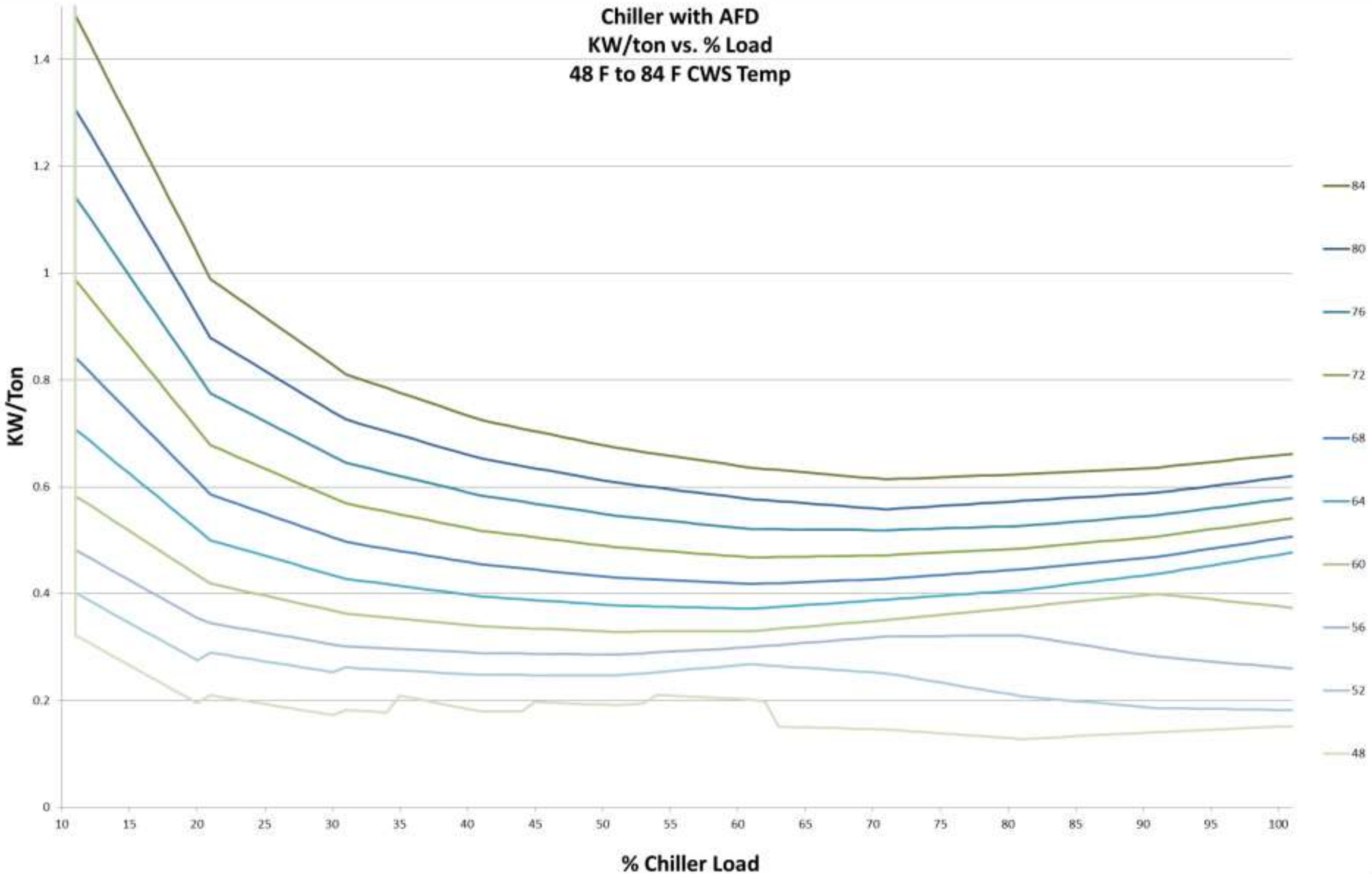
Chiller Efficiency vs. CWS Temp



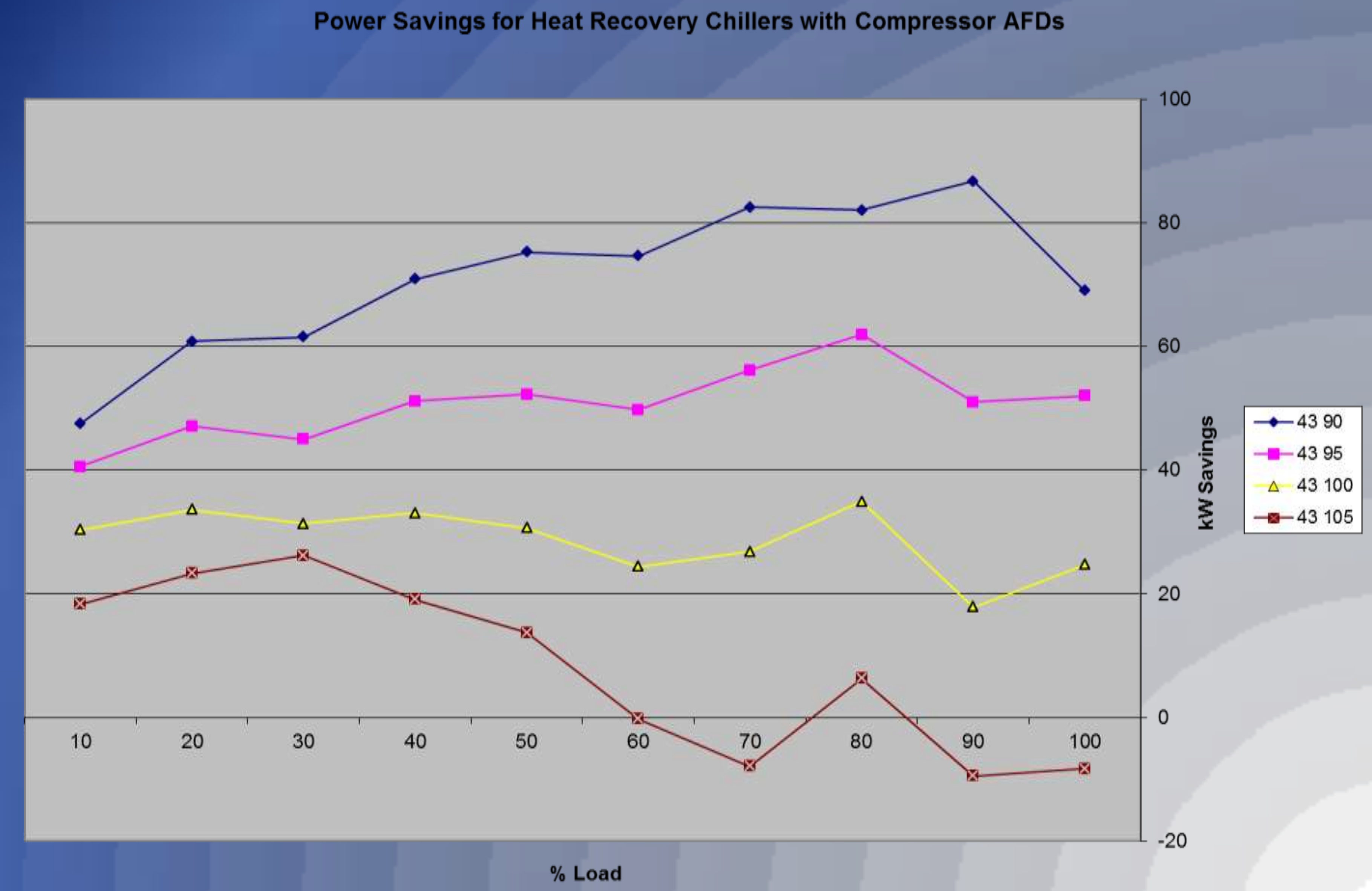
Fan Speed vs CHW Tonnage

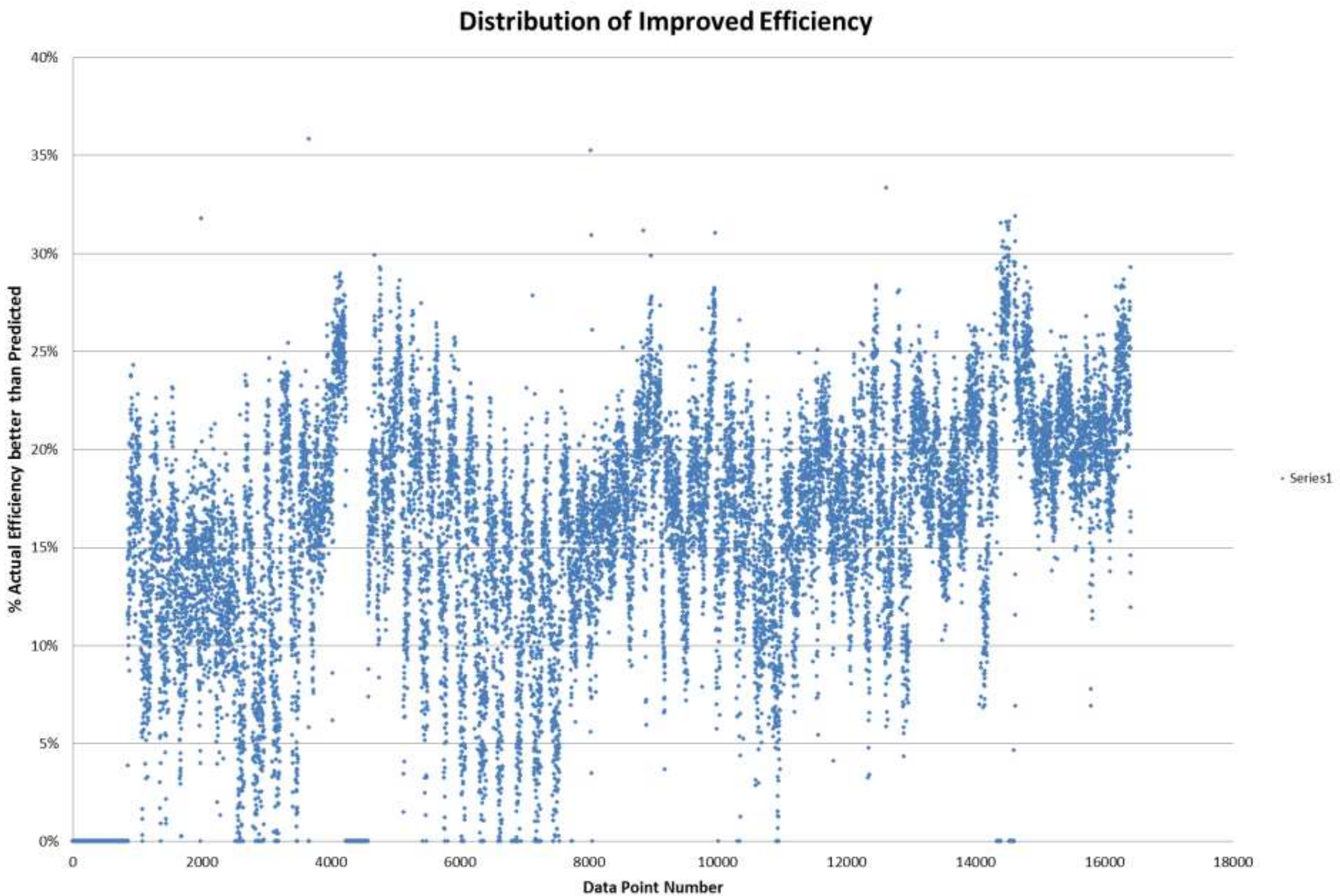


Fan Speed vs Approach
120
100
80
60
40
20
0
0.00
5.00
10.00
15.00
20.00
25.00
30.00
10 CTs
9 CTs
8 CTs



Chiller with AFD
KW/ton vs. % Load
48 F to 84 F CWS Temp
KW/Ton
% Chiller Load
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
84
80
76
72
68
64
60
56
52
48


Power Savings for Heat Recovery Chillers with Compressor AFDs
100
80
60
40
20
0
-20
kW Savings
10
20
30
40
50
60
70
80
90
100
% Load
43 90
43 95
43 100
43 105


Distribution of Improved Efficiency
% Actual Efficiency better than Predicted
40%
35%
30%
25%
20%
15%
10%
5%
0%
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Data Point Number
Series1