Princeton University

4,500 Ton Steam Turbine Chiller Controls Panel Retrofit For Optimized Control

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Chiller Plant - **20,000 Tons**

A. (5) Electric Chillers
B. (3) Steam Turbine Driven Chillers
C. Thermal Storage Tank - **40,000 Ton-Hours**

Cogen Plant

A. (1) Gas Turbine – **15 MW**
B. (1) Solar PV Field – **4.5 MW**
C. (1) HRSG - **180,000 lb/hr**
D. (2) Aux Boilers -**150,000 lb/hr**

Chiller 1

A. 4,500 Ton
B. Carrier 17DA
C. Design 8.99 lb/ton-hr

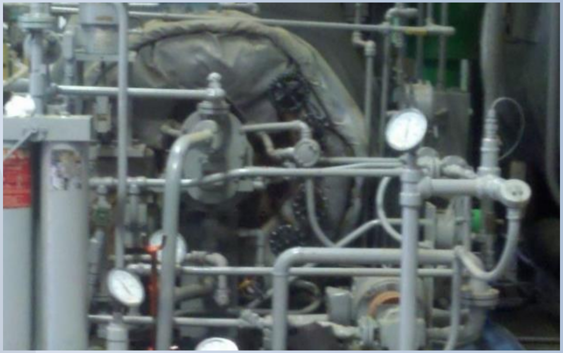
CHILLER 1 OPERATIONS

1. Plant Work Horse
2. Critical for Cogen
3. Most Efficient Steam Machine
4. Newest Steam Machine

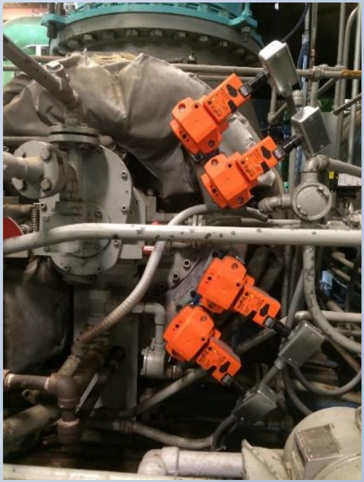
SAMPLE OPTIMIZATION MEASURES

1. Turbine Hand Valve Optimization
2. Improved Refrigerant Level Control
3. Improved Refrigeration Migration
4. Heat/Mass Balance with Torque Telemetry
5. Reactive Surge Control

1 – OPTIMIZATION MEASURES – TURBINE HAND VALVE OPTIMIZATION



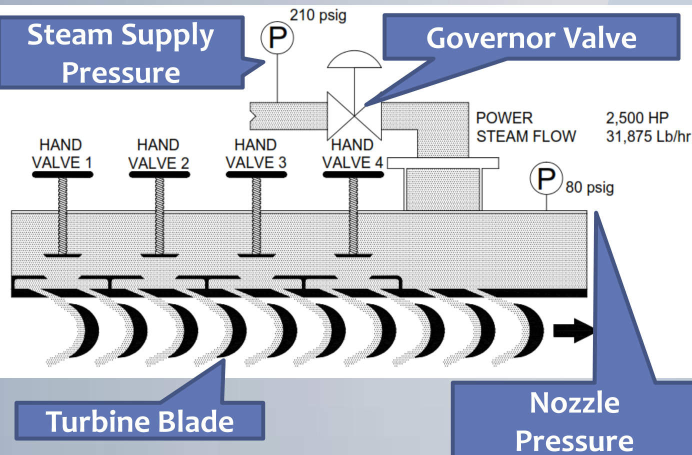
1. **Turbine power** is the function of:
   A. Inlet steam pressure
   B. Inlet steam temperature
   C. Steam flow
   D. Outlet steam pressure (vacuum)

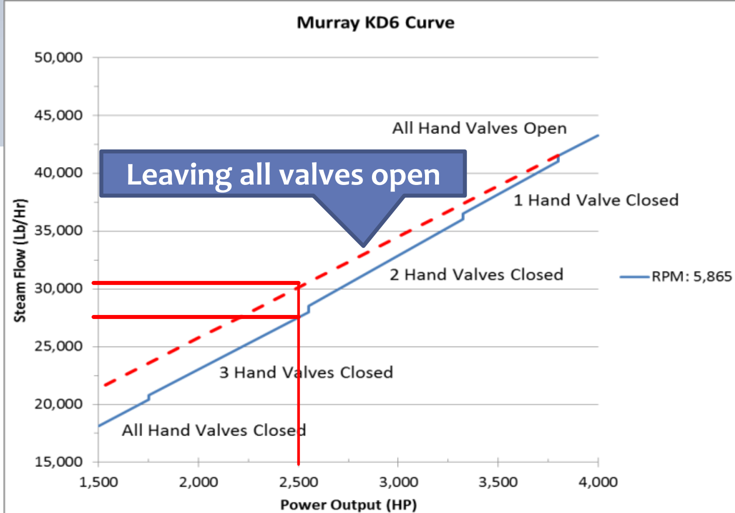


2. **Closing hand valve(s) allows the governor to open:**
   1. More pressure at the nozzle
   2. Results in less steam flow at a given horsepower

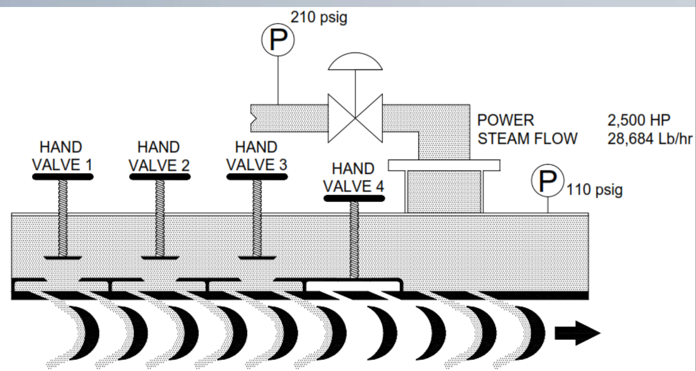
1 – OPTIMIZATION MEASURES – TURBINE HAND VALVE OPTIMIZATION

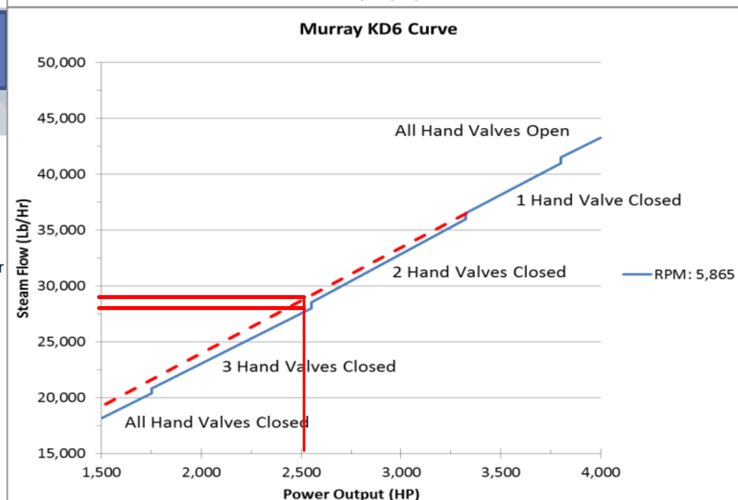
All hand valves open: Inefficient





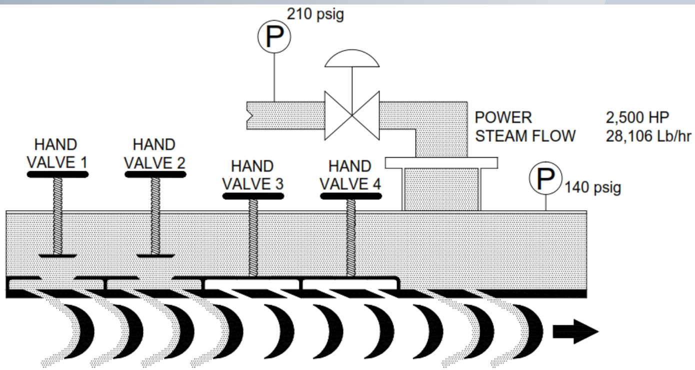
One hand valve closed: Better

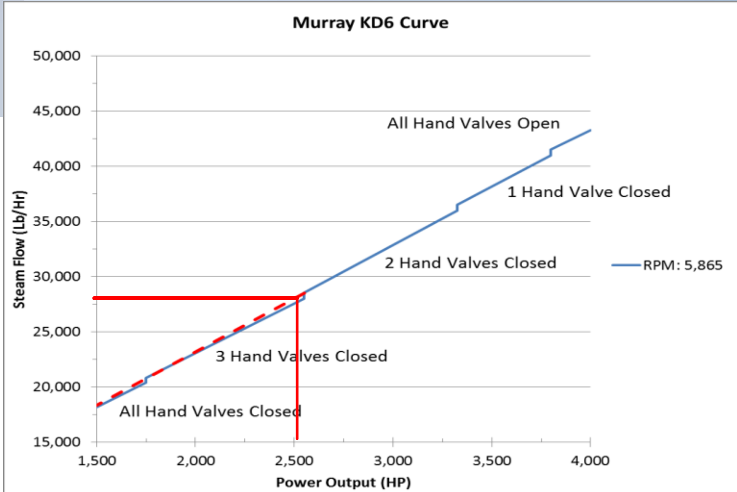




1 – OPTIMIZATION MEASURES – TURBINE HAND VALVE OPTIMIZATION

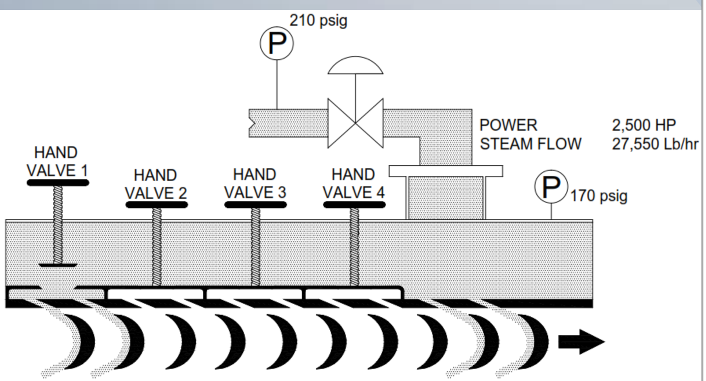
Two hand valves closed: Even Better

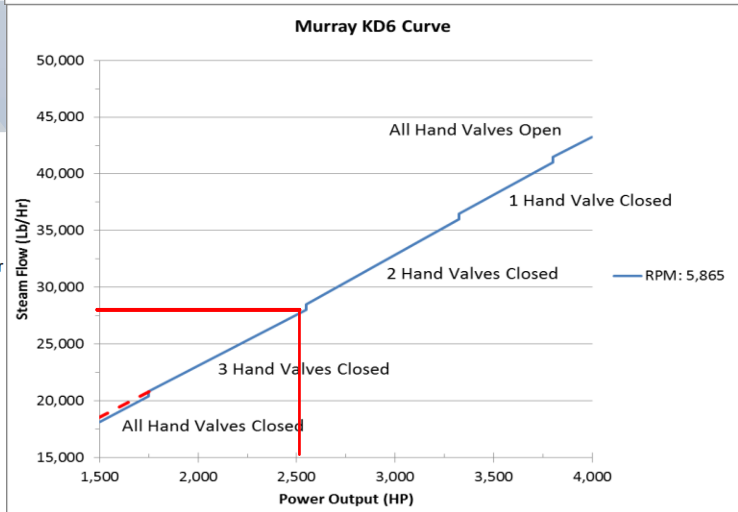




Three hand valves closed: Best

Over 3,500 lb/hr reduction

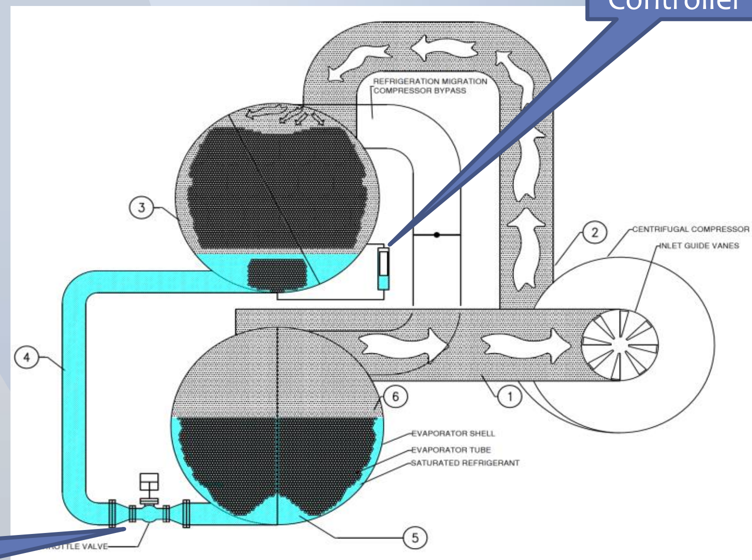




2 – OPTIMIZATION MEASURES – IMPROVED LEVEL CONTROL

Level Control Concept

The 17DA uses a Fisher lever controller to maintain a liquid refrigerant level above the subcooler in the condenser.



Level Controller

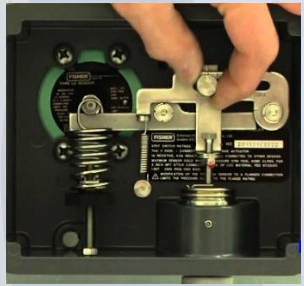
Level Control Valve

2 – OPTIMIZATION MEASURES – IMPROVED LEVEL CONTROL

Original Control

Pneumatically controlled refrigerant throttling valve

Maintains liquid level in the subcooler by controlling ED valve



Improved Control

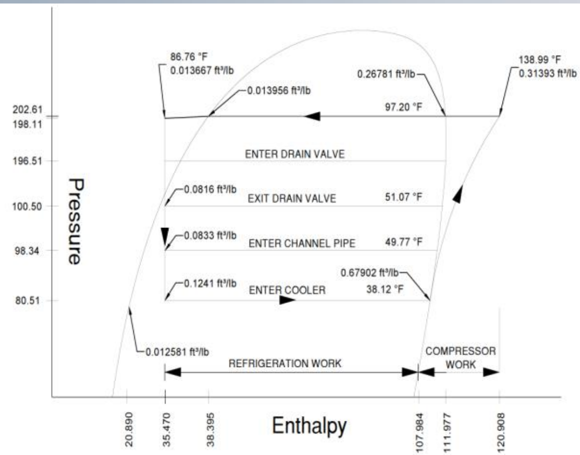
Electronic controller

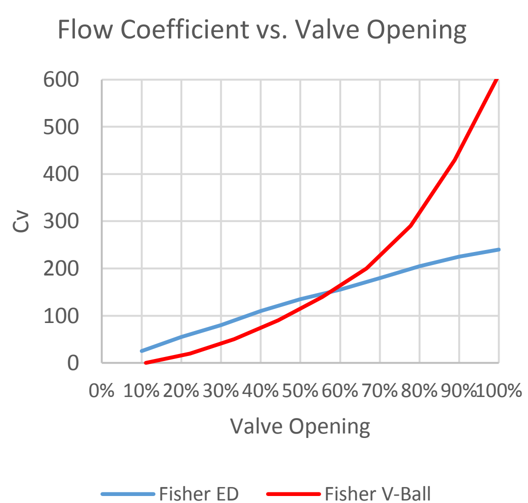
V-ball level control valve

ED Cage

V-Ball

2 – OPTIMIZATION MEASURES – IMPROVED LEVEL CONTROL

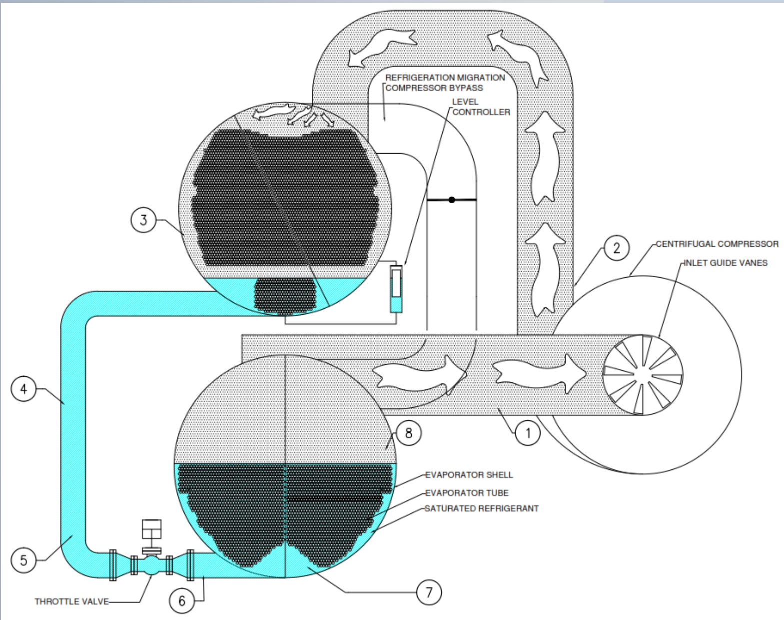




- Original ED valve full open Cv of 240.
- Chiller design condition required Cv of 260
- Reduced lift and full load requires Cv of > 600
- The V-Ball allows a much higher Cv at full load (full refrigerant flow).

Condenser Refrigerant Temperature (F)	Condenser Refrigerant Pressure (PSI)	Evaporator Refrigerant Pressure (PSI)	Delta P (PSI)	Refrigerant Mass Flow (lbs/min)	Cv
95	182	80.5	101.5	12,416	276
90	168	80.5	87.5	12,416	295
85	156	80.5	75.5	12,416	315
80	144	80.5	63.5	12,416	341
75	132	80.5	51.5	12,416	376
70	121	80.5	40.5	12,416	421
65	111	80.5	30.5	12,416	481
60	102	80.5	21.5	12,416	569
55	92.6	80.5	12.1	12,416	753
50	84	80.5	3.5	12,416	1,391

3 – OPTIMIZATION MEASURES – IMPROVED REFRIGERATION MIGRATION



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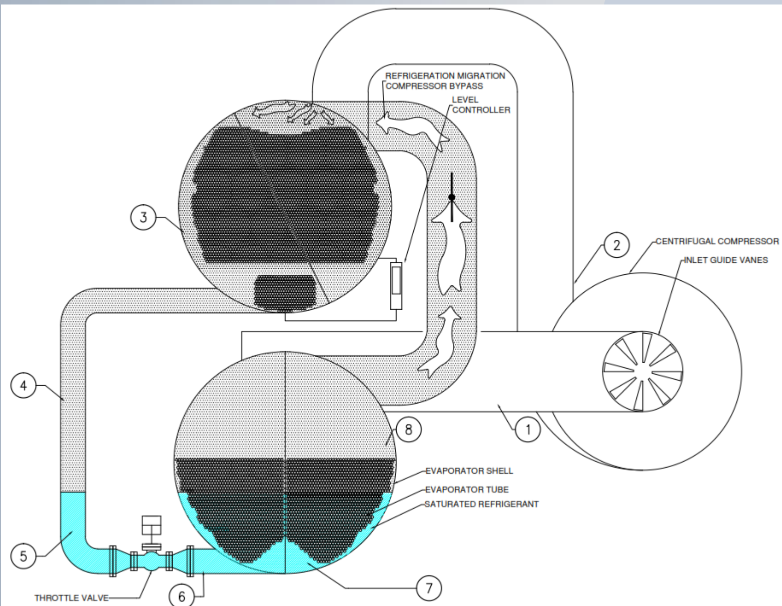
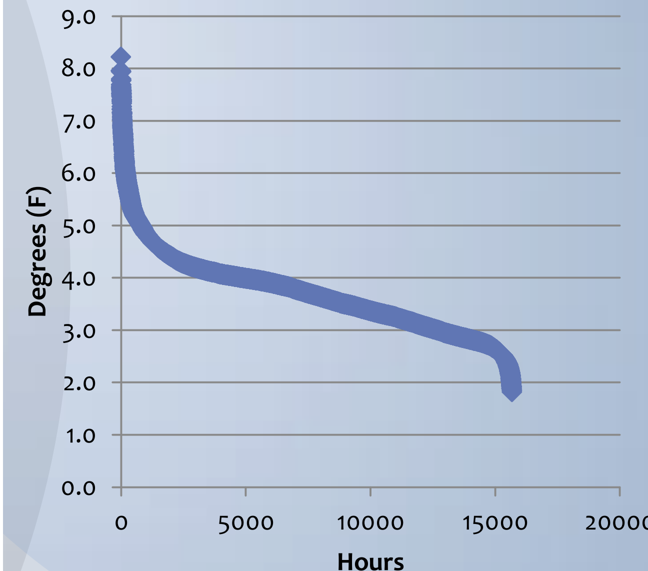
3 – OPTIMIZATION MEASURES – IMPROVED REFRIGERATION MIGRATION

The top 10” of evaporator tubes accounts for 35% of the tubes (and flow)





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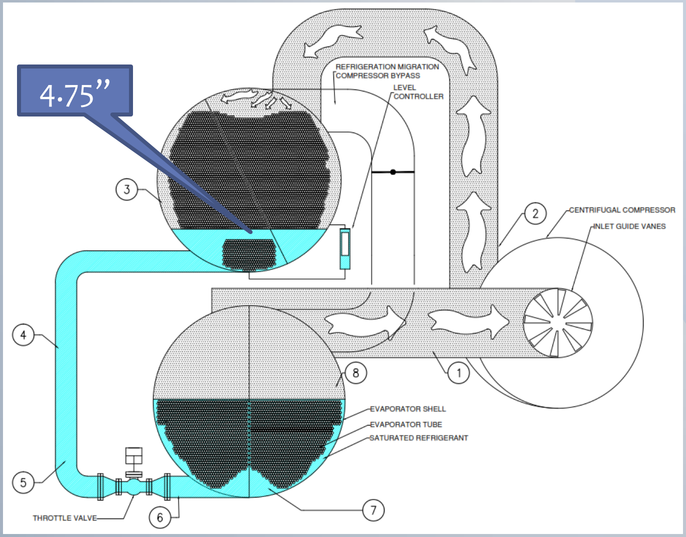
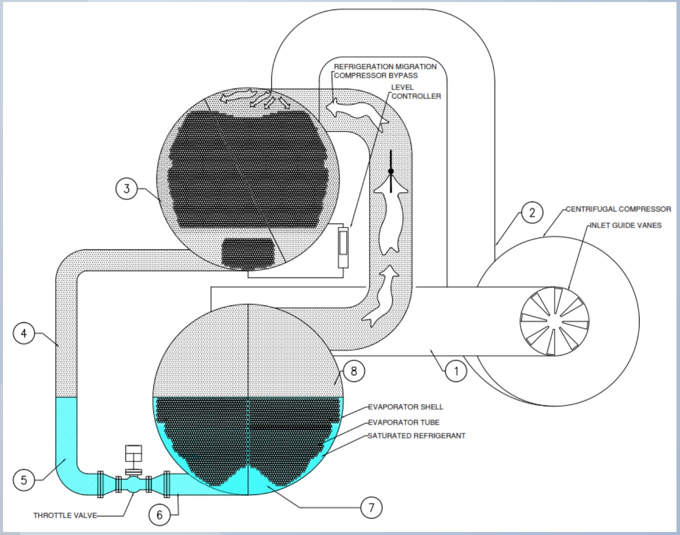
3 – OPTIMIZATION MEASURES – IMPROVED REFRIGERATION MIGRATION

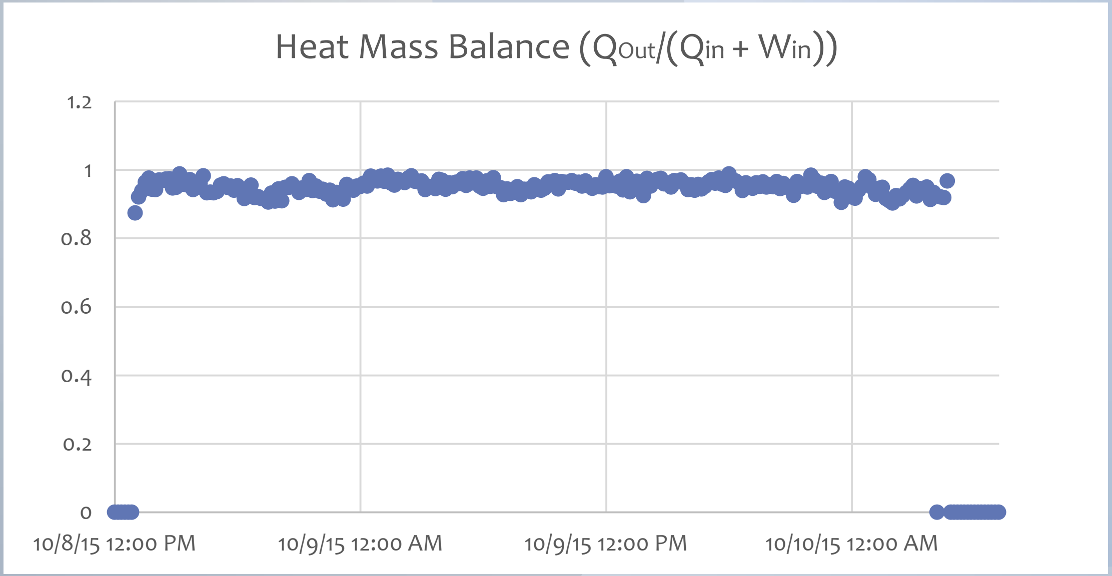
1. Saturated refrigerant density in evaporator is 1/10 the density in the condenser
2. 2.6" of refrigerant above the sub cooler = 10" in the evaporator upper tube



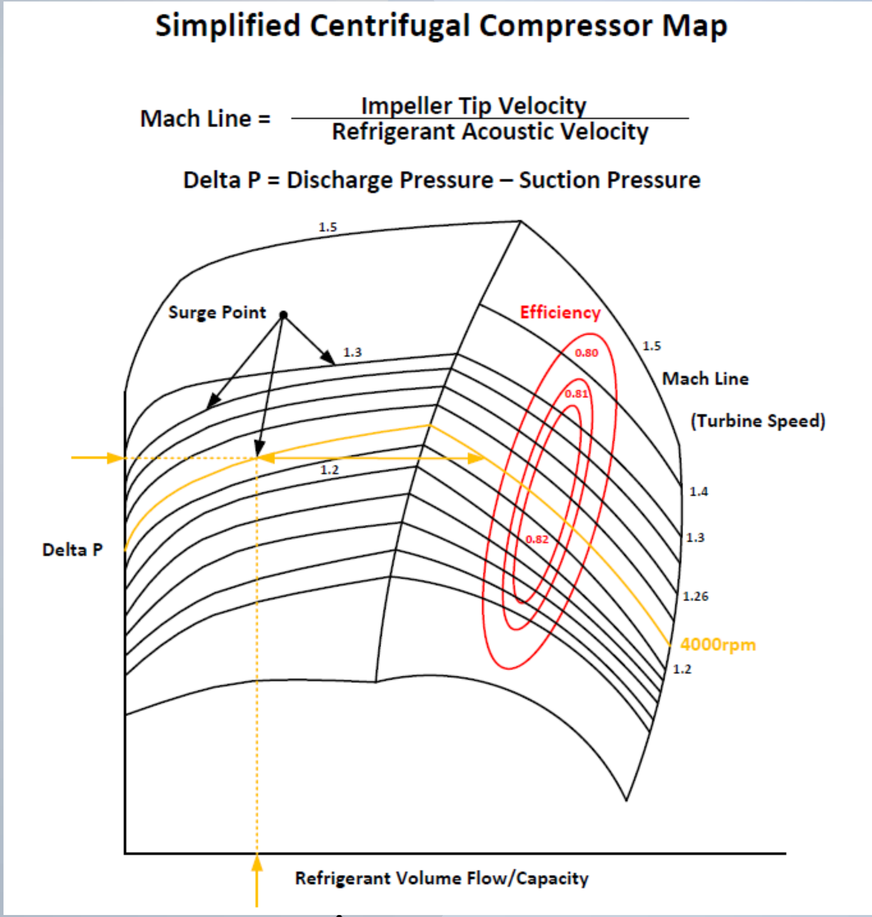


4 – OPTIMIZATION MEASURES – HEAT MASS BALANCE

- Continuous AHRI 550 heat / mass balance to:
    - Ensures the instrumentation is calibrated
    - Confirms validity of M&V data



5 – OPTIMIZATION MEASURES – REACTIVE SURGE CONTROL



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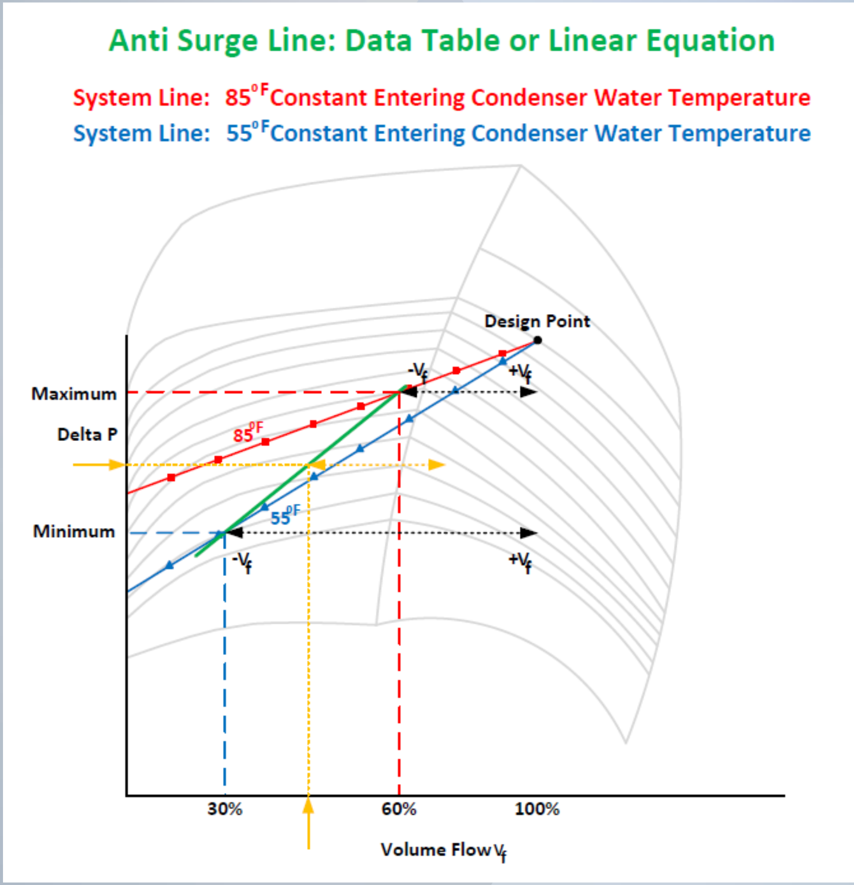

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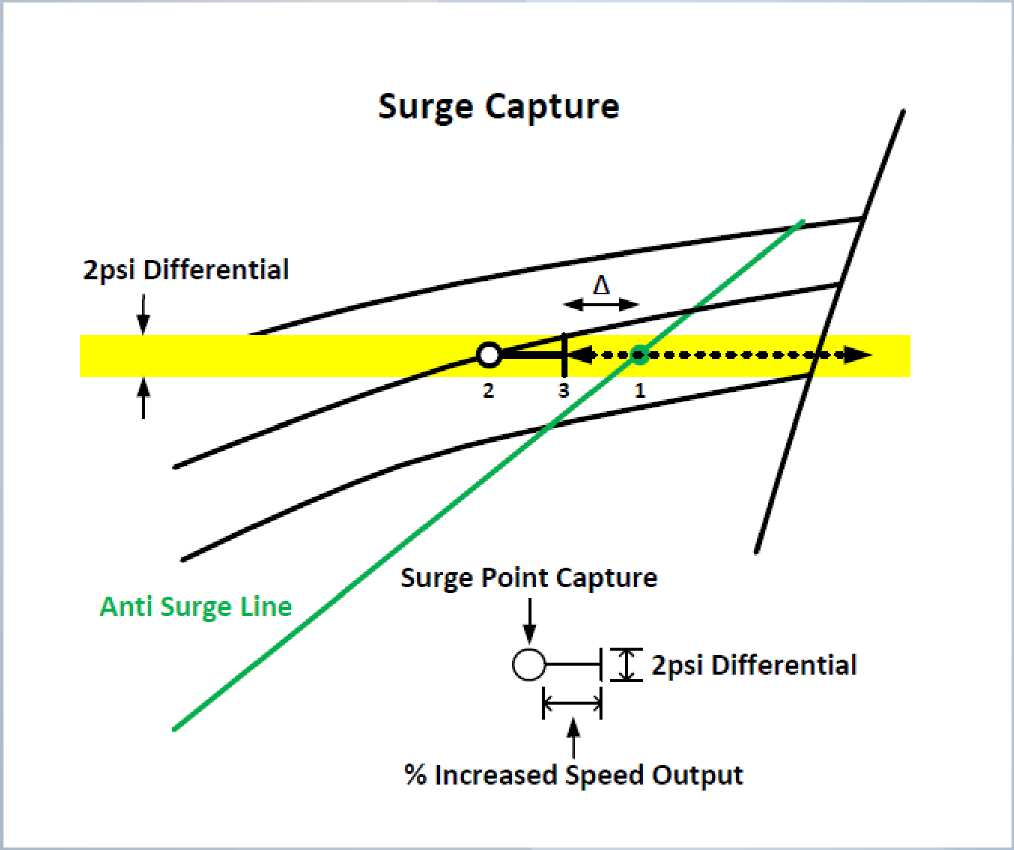
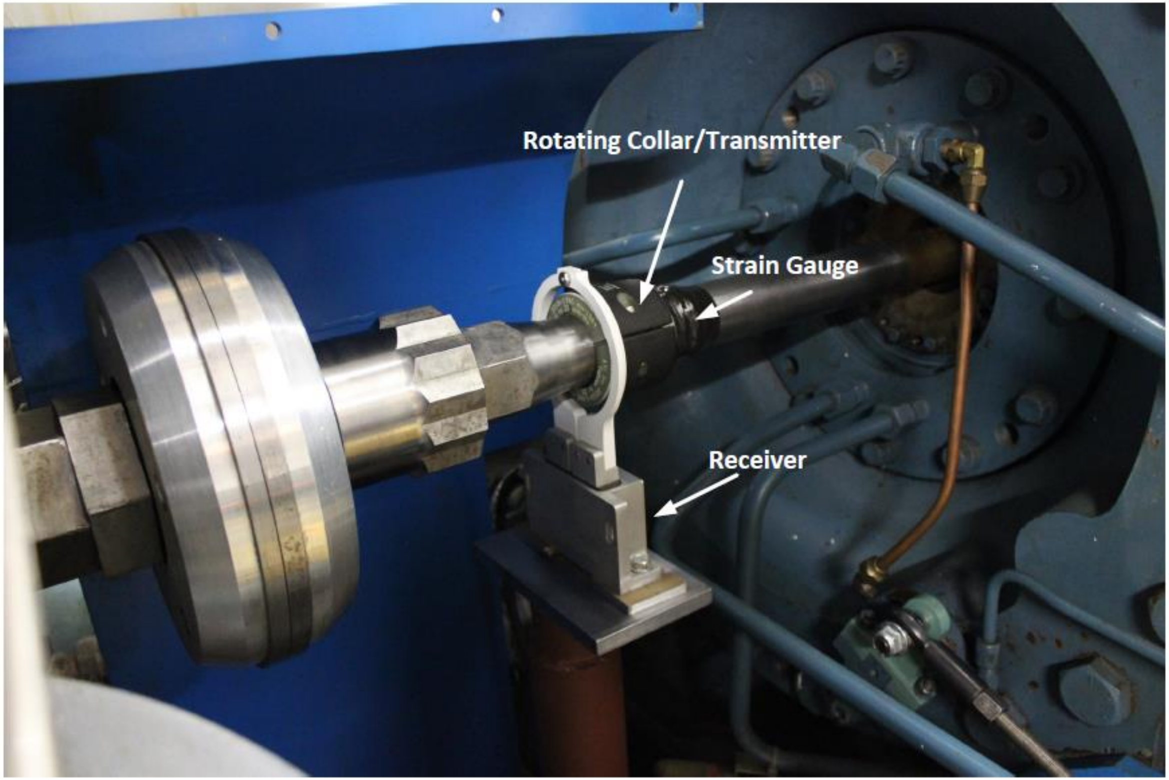
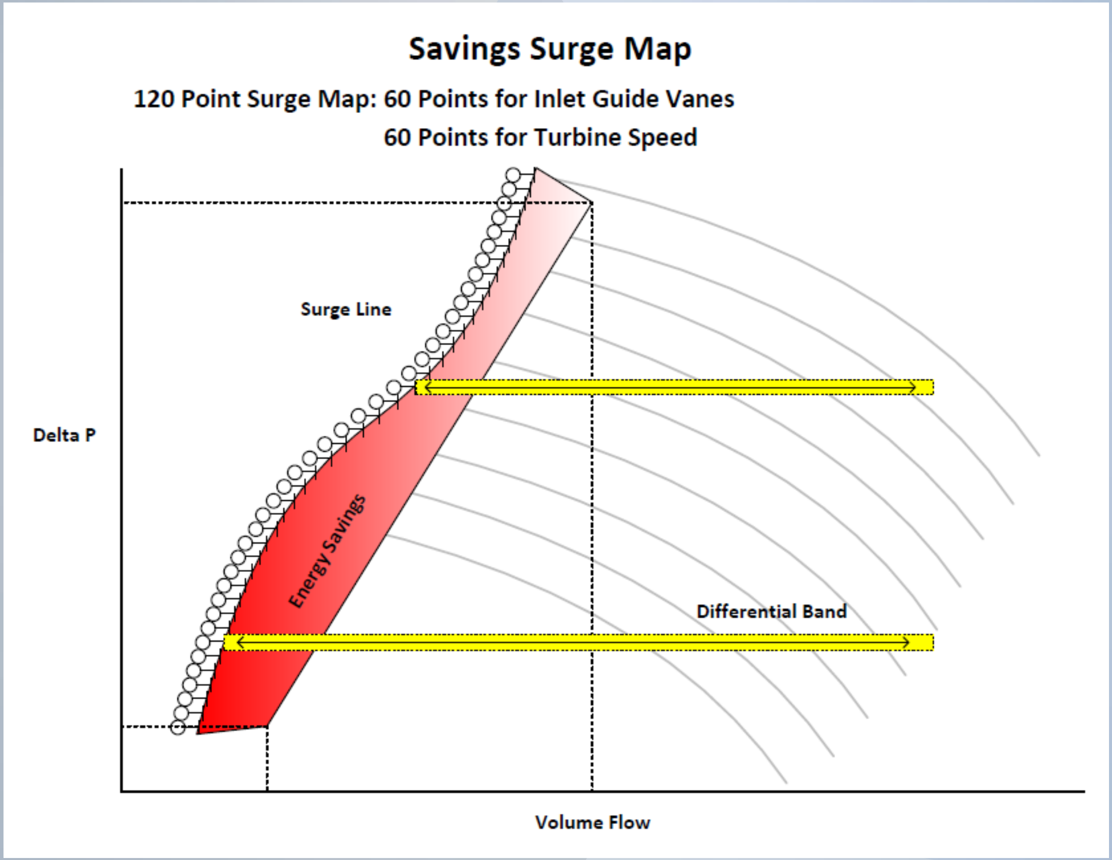


5 – OPTIMIZATION MEASURES – REACTIVE SURGE CONTROL

Digital Telemetry System

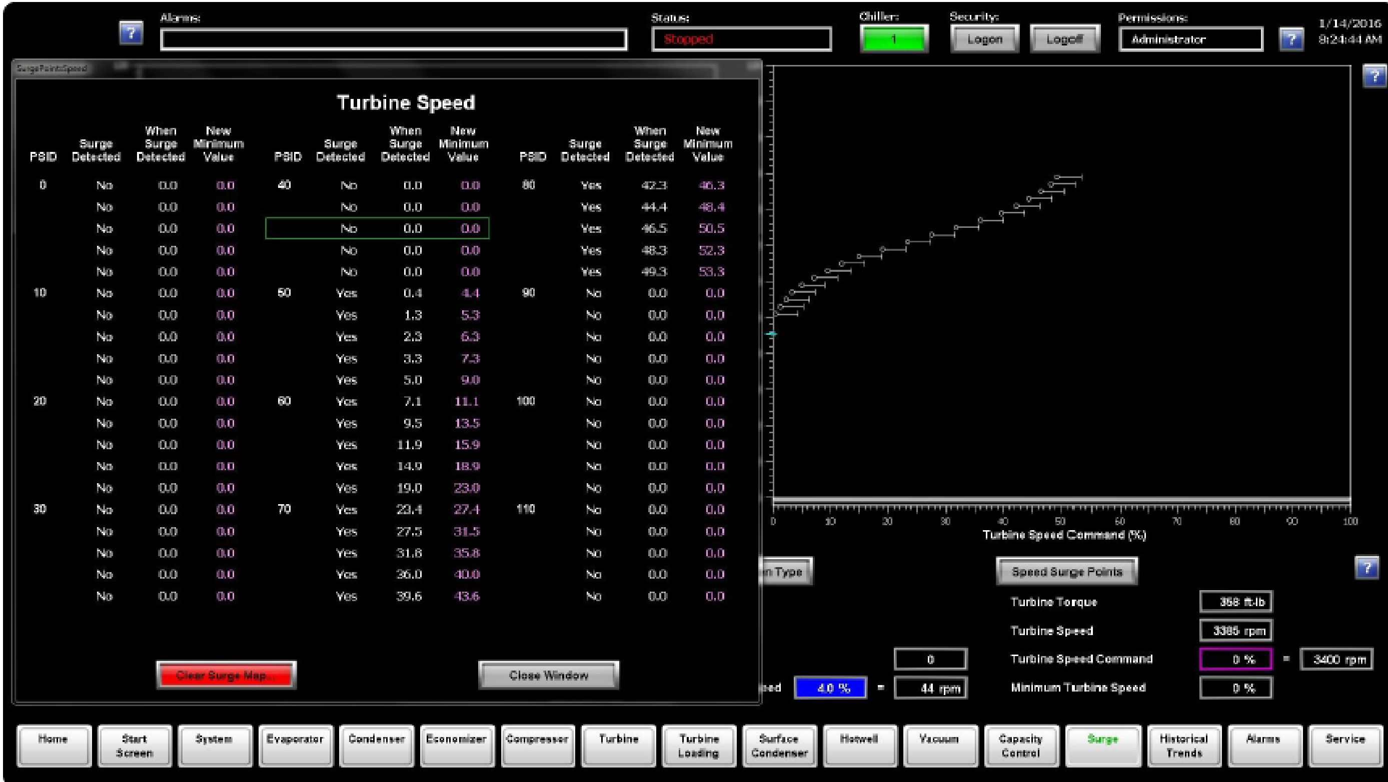


5 – OPTIMIZATION MEASURES – REACTIVE SURGE CONTROL



5 – OPTIMIZATION MEASURES – REACTIVE SURGE CONTROL

Surge Data Table: Turbine Speed

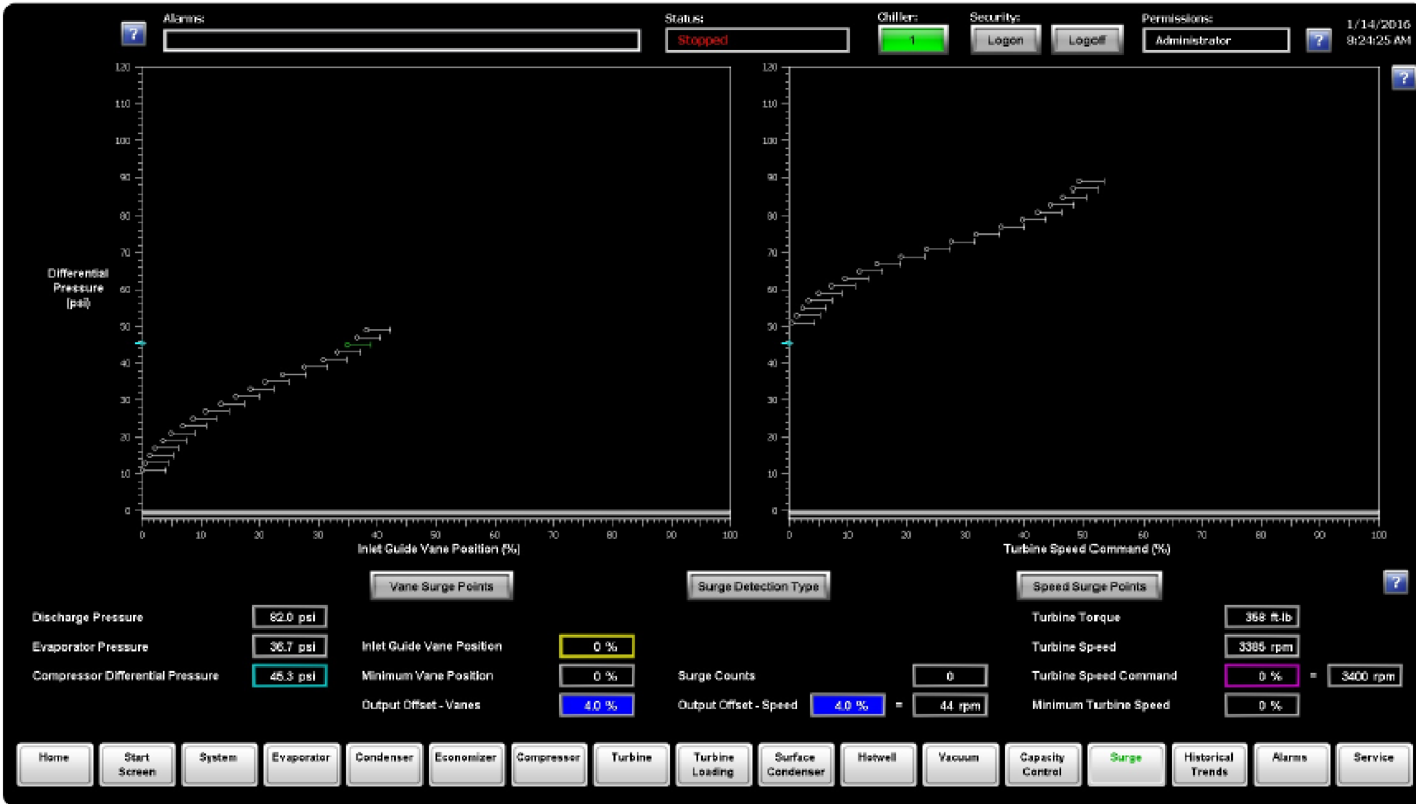


Turbine Speed

PSID	Surge Detected	When Surge Detected	New Minimum Value	PSID	Surge Detected	When Surge Detected	New Minimum Value	PSID	Surge Detected	When Surge Detected	New Minimum Value
0	No	0.0	0.0	40	No	0.0	0.0	80	Yes	42.3	46.3
	No	0.0	0.0		No	0.0	0.0		Yes	44.4	48.4
	No	0.0	0.0		No	0.0	0.0		Yes	46.5	50.5
	No	0.0	0.0		No	0.0	0.0		Yes	48.3	52.3
	No	0.0	0.0		No	0.0	0.0		Yes	49.3	53.3
10	No	0.0	0.0	50	Yes	0.4	4.4	90	No	0.0	0.0
	No	0.0	0.0		Yes	1.3	5.3		No	0.0	0.0
	No	0.0	0.0		Yes	2.3	6.3		No	0.0	0.0
	No	0.0	0.0		Yes	3.3	7.3		No	0.0	0.0
	No	0.0	0.0		Yes	5.0	9.0		No	0.0	0.0
20	No	0.0	0.0	60	Yes	7.1	11.1	100	No	0.0	0.0
	No	0.0	0.0		Yes	9.5	13.5		No	0.0	0.0
	No	0.0	0.0		Yes	11.9	15.9		No	0.0	0.0
	No	0.0	0.0		Yes	14.9	18.9		No	0.0	0.0
	No	0.0	0.0		Yes	19.0	23.0		No	0.0	0.0
30	No	0.0	0.0	70	Yes	23.4	27.4	110	No	0.0	0.0
	No	0.0	0.0		Yes	27.5	31.5		No	0.0	0.0
	No	0.0	0.0		Yes	31.8	35.8		No	0.0	0.0
	No	0.0	0.0		Yes	36.0	40.0		No	0.0	0.0
	No	0.0	0.0		Yes	39.6	43.6		No	0.0	0.0

5 – OPTIMIZATION MEASURES – REACTIVE SURGE CONTROL

Surge Maps for Vanes and Turbine Speed



OPTIMIZATION RESULTS – M&V

Example:

	Lift	Load	Avg Lbs/Ton-Hr
Pre	40F	40%	8.56
Post	40F	40%	7.41
Reduction	40F	40%	1.15*

*13.4% Reduction

May to September 2014 - 2015

CH-1 Efficiency Map (Lbs/Ton-Hr) - 2014

Chiller Percent Load (Load/Design Load)

CWRT - CHWST (°F)	20	30	40	50	60	70	80	90	100
56							10.38	10.25	10.15
52						9.31	9.41	9.66	9.30
48					8.93	9.10	8.88	8.79	8.79
44				8.51	8.13	8.12	8.21	8.24	
40			8.56	7.96	7.64	7.51	7.52	7.39	
36		8.62	8.02	7.55	7.20	6.84	6.78		
32	11.56	8.54	7.62	6.75	6.79				
28			10.09						
24									

CH-1 Efficiency Map (Lbs/Ton-Hr) - 2015

Chiller Percent Load (Load/Design Load)

CWRT - CHWST (°F)	20	30	40	50	60	70	80	90	100
56							9.30	9.67	
52						8.53	8.69	9.01	9.06
48					8.11	8.04	8.07	8.30	8.89
44				8.01	7.56	7.46	7.41	7.57	8.45
40			7.41	7.18	7.05	7.01	6.98	7.09	
36		8.99	7.00	6.77	6.67	6.55	6.35		
32			6.50	6.15	6.09	6.13			
28									
24									

CH-1 Efficiency Map (Lbs/Ton-Hr Reduction)

Chiller Percent Load (Load/Design Load)

CWRT - CHWST (°F)	20	30	40	50	60	70	80	90	100
56							1.09	0.57	
52						0.78	0.72	0.65	0.24
48					0.82	1.06	0.81	0.49	
44				0.50	0.57	0.66	0.80	0.67	
40			1.14	0.78	0.59	0.50	0.54	0.30	
36			1.02	0.78	0.52	0.29	0.43		
32			1.12	0.60	0.70				
28									
24									

OPTIMIZATION RESULTS – M&V

May to September 2014 - 2015

CH-1 Efficiency Map (Lbs/Ton-Hr) - 2014

Chiller Percent Load (Load/Design Load)

CWRT - CHWST (°F)	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96
52																												9.75		9.24	9.54	9.41	9.85	9.86		9.91	9.43	
50																								9.50	9.53		9.29	9.44	9.53	9.27	9.10	9.33	9.21	9.36	9.25	8.89	9.14	8.93
48																				9.12		9.30	9.03	9.26	9.36	9.35	9.27	9.12	8.91	8.96	8.89	8.92	8.92	8.82	8.73	8.60	8.96	8.79
46																				8.65	8.77	8.36	8.89	8.81	9.04	8.78	8.73	8.62	8.67	8.53	8.58	8.50	8.46	8.52	8.35	8.35		
44																8.73		8.35	8.12	8.21	8.12	8.24	8.31	8.21	8.26	8.05	7.89	8.04	8.19	8.26	8.21	8.22	8.18	8.22	8.18	8.22		
42														8.59	8.38	8.36	8.21	8.04	7.95	8.02	7.97	7.89	7.88	7.77	7.78	7.79	7.79	7.81	7.76	7.74	7.74	7.76	7.65	7.40	7.93	7.68		
40										8.31	8.51	8.41	8.49	8.17	8.01	7.98	7.98	7.78	7.73	7.57	7.58	7.67	7.52	7.52	7.48	7.47	7.48	7.52	7.46	7.39	7.31	7.14	6.91	7.17				
38								9.28	8.90	8.24	8.27	8.32	8.04	7.90	7.87	7.60	7.58	7.42	7.36	7.27	7.23	7.19	7.20	7.20	7.08	6.74	6.99	6.92	6.73	7.13	6.95							
36					9.96		8.25	8.14	8.07	7.91	7.81	7.61	7.74	7.64	7.32	7.30	7.34	7.16	7.17	7.07	7.65	6.94	6.84	6.91	6.65	6.35		7.06		6.79	6.52							
34		11.56			8.96	8.49		7.99	8.18	7.71	7.69	7.99	7.38	7.23	7.23	7.33	6.88	6.63	7.12	7.15	6.46				6.61	6.59												
32					8.66	8.50	8.07	7.99	7.90	7.34	6.84					6.34	6.50	6.65																				
30												6.58			6.36	6.24																						
28										10.09																												
26																																						
24																																						

CH-1 Efficiency Map (Lbs/Ton-Hr) - 2015

Chiller Percent Load (Load/Design Load)

CWRT - CHWST (°F)	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96
52																																8.61	8.62	8.63	8.54	8.60		
50																								8.42		8.62	8.31	8.25	8.43	8.35	8.35	8.40	8.40	8.44	8.47	8.45		
48																									8.18	8.16	8.08	8.10	8.06	8.11	8.12	8.09	8.13	8.17	8.26	8.26	8.39	8.41
46																				7.98	8.15	8.01		8.04	7.91	7.85	7.75	7.73	7.76	7.77	7.70	7.76	7.81	7.88	7.85	7.96	8.27	8.11
44														8.36	7.61	8.06	8.14	8.02	7.65	7.78	7.64	7.42	7.49	7.47	7.52	7.50	7.47	7.50	7.43	7.44	7.41	7.41	7.41	7.47	7.53	7.56	7.61	7.65
42													7.43		7.87	7.33	7.59	7.48	7.42	7.30	7.25	7.37	7.31	7.32	7.26	7.23	7.15	7.16	7.18	7.17	7.16	7.16	7.22	7.21		7.44		
40													7.54	7.16	7.38	7.32	7.15	7.13	7.11	7.13	7.08	7.06	7.02	7.01	6.93	6.95	6.91	6.89	6.91	6.84	6.90	6.97		6.88		7.01		
38										7.25	7.28	7.23	7.11	6.99	6.87	6.95	6.96	6.86	6.84	6.86	6.79	6.75	6.82	6.74	6.64	6.66	6.66	6.62	6.53									
36										7.00	6.99	6.86	6.75	6.84	6.76	6.64	6.65	6.66	6.60	6.53	6.63	6.55	6.50	6.33	6.33	6.26	6.41											
34														6.59	6.42	6.13	6.26	6.29	6.31	6.38	6.44		6.22	6.17	6.11			5.72										
32												6.50			6.16	6.24				6.10																		
30																				5.85																		
28																																						
26																																						
24																																						

CH-1 Efficiency Map (Lbs/Ton-Hr Reduction)

Chiller Percent Load (Load/Design Load)

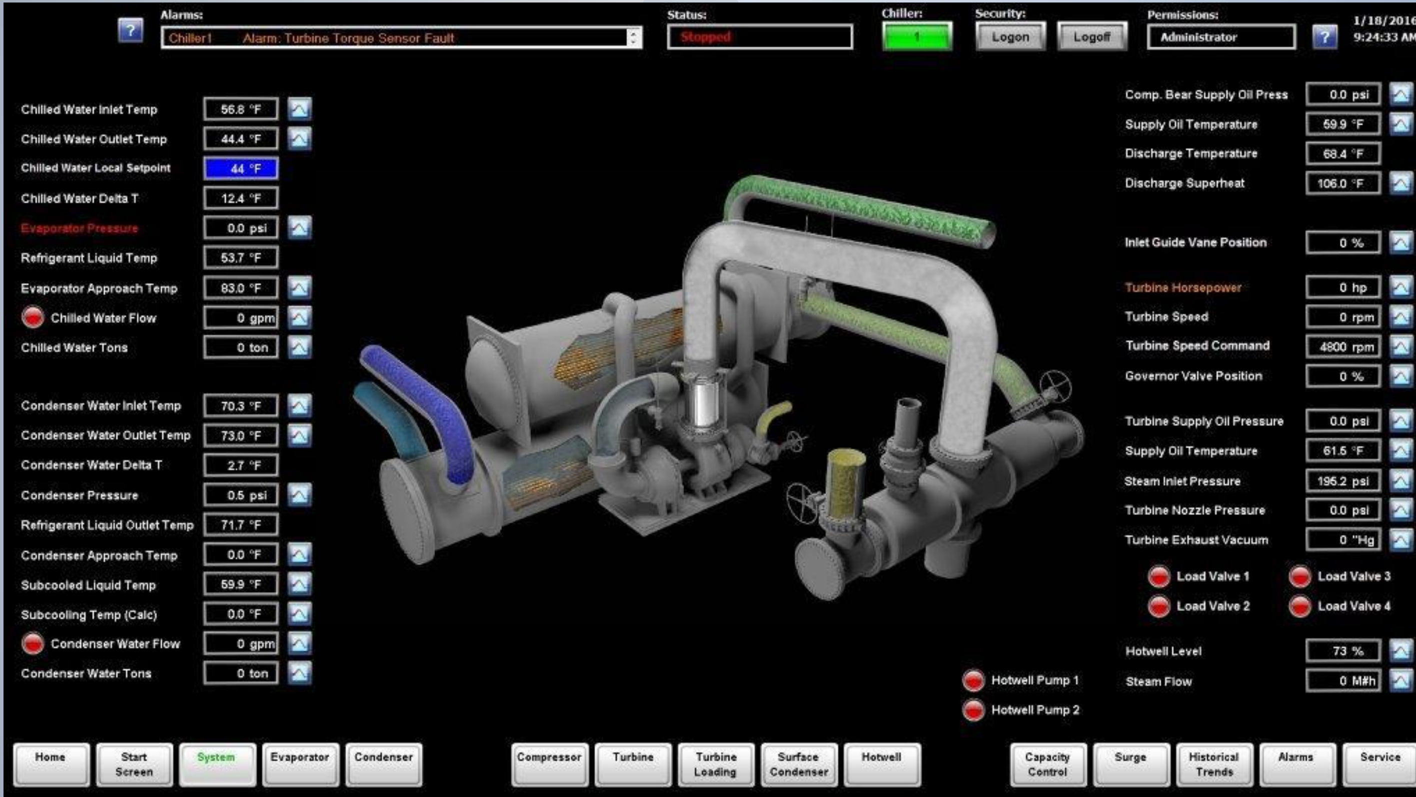
CWRT - CHWST (°F)	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96
52																																0.80	1.23	1.24		1.31		
50																								1.08			0.98	1.20	1.10	0.93	0.75	0.93	0.81	0.91	0.78	0.44		
48																									1.18	1.19	1.18	1.02	0.85	0.85	0.77	0.83	0.79	0.65	0.47	0.34	0.57	0.38
46																				0.66	0.62	0.35		0.77	1.13	0.94	0.98	0.88	0.91	0.75	0.88	0.74	0.65	0.64	0.50	0.39		
44																0.67		0.33	0.46	0.43	0.48	0.82	0.82	0.74	0.74	0.55	0.43	0.54	0.76	0.83	0.80	0.81	0.78	0.75	0.64	0.65		
42															0.52	1.03	0.62	0.56	0.53	0.72	0.71	0.52	0.57	0.45	0.52	0.56	0.64	0.65	0.58	0.57	0.59	0.61	0.43	0.19		0.24		
40													0.95	1.01	0.63	0.66	0.83	0.65	0.62	0.44	0.50	0.61	0.50	0.51	0.55	0.52	0.58	0.64	0.55	0.55	0.42	0.16		0.29				
38										0.98	0.99	1.09	0.93	0.92	1.01	0.65	0.62	0.56	0.52	0.42	0.44	0.44	0.38	0.46	0.45	0.08	0.33	0.31	0.19									
36										0.91	0.82	0.75	0.99	0.80	0.56	0.66	0.69	0.50	0.56	0.54	1.02	0.39	0.34	0.57	0.32	0.09												
34														0.63	0.81	1.21	0.62	0.34	0.81	0.77	0.02				0.49													
32																0.10																						
30																																						
28																																						
26																																						
24																																						

OPTIMIZATION RESULTS – M&V

Analyzed Option		
Option	Unit	Chiller 1 Modifications M&V
Steam Reduction	Usage Lbs / Year	7,390,818
	Demand Lbs/hr	3,971
Simple Payback	Years	1.3

Savings shown use inexpensive steam - - $12.50/klb

FMCS CONTROL PANEL – HMI



-Training Tool -Maintenance

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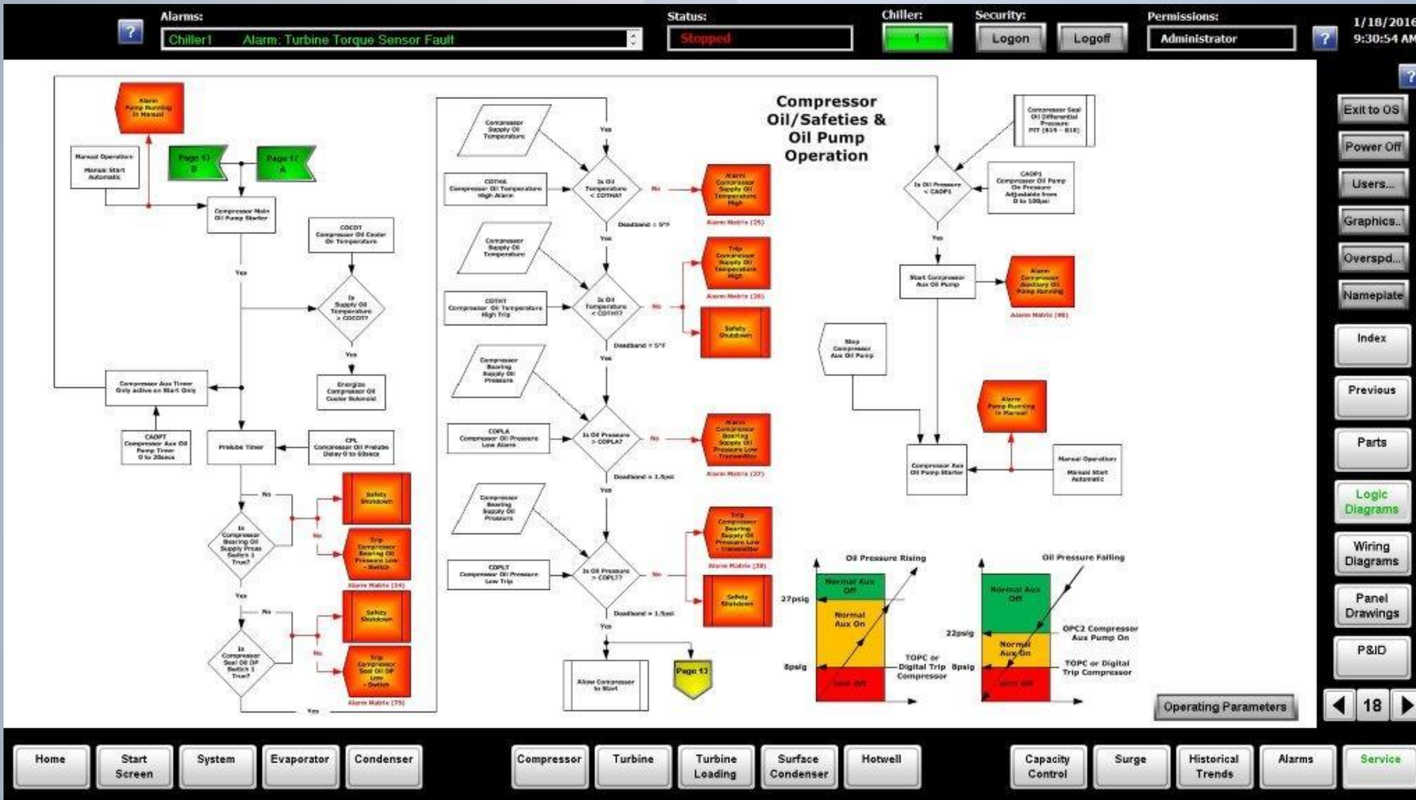
FMCS CONTROL PANEL – HMI



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PRINCETON UNIVERSITY

SMITH ENGINEERING

www.smith-eng.com

OPTIMIZATION RESULTS – OPERATIONS

1. Noticeably quieter
2. Improved turndown
3. Consistent start-up extends machine life
4. Princeton used to operate manually
5. Chiller doesn’t trip on refrigerant trip
6. Zero CHW flow during slow roll