Performance of a Thermal Energy Storage System, 25 Years On

Christian Weber, Ryan Stroupe, and David Sellers

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Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

Learning Objectives

1. Commission a thermal-energy storage (TES) system
2. Determine the operating efficiency of an air-cooled chiller
3. Determine the storage capacity of a ice storage system
4. Analyze the operating economics of a TES system

SPEAKERS: *Learning Objectives must indicate what attendees will "do" (not simply "understand" or "learn") with your information. Read About Learning Objectives Required for AIA Continuing Education Credit: www.aia.org/education/providers/AIAB040189?dvid=&recspec=AIAB040189*

PG&E Pacific Energy Center San Francisco

Building description:

Street address:	851 Howard Street
City:	San Francisco, CA
Type of building:	Conference center/educational facility/office space
Year constructed:	1990 - 91
Total conditioned area:	26,000 sq.ft. (6,000 sq.ft. unconditioned basement garage)
Mechanical systems:	Roof-top air cooled chiller; Boiler; Variable-air-volume air handler; multi-zone air handler; thermal energy ice storage tanks in basement; VAV air conditioned air distribution system.
HVAC control system:	Automated Logic Controls BAS. Previously Trane.
Major building loads:	Space heating & cooling, occupant loads

Study part of PG&E's year-long "Existing Building Commissioning Workshop Series" targeted at building professionals

Background to RCx Study

- PEC chiller and TES system installed in 1990
- Upgrade to ventilation air controls in …
- Replacement of Trane BMS with Automated Logic in 19xy

⇩

- Original sequence of operation can't be duplicated with ALC BMS
  - Not integrated with chiller on-board controls
- System performance & operating characteristics changed over time
- Original sequence of operation for different electric utility rate structure

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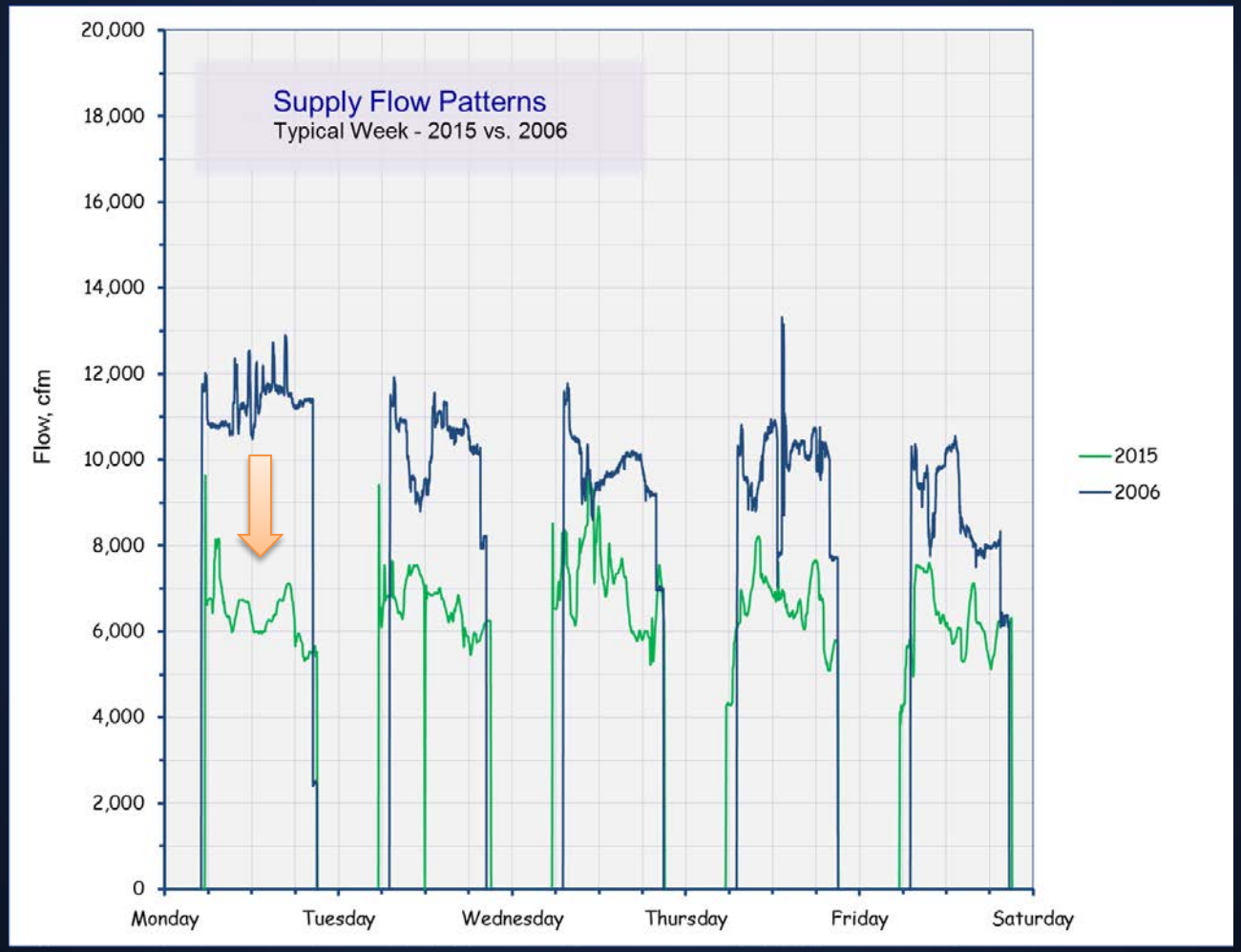
Study Goals:

- Measure current system performance
- Evaluate opportunities for improving system performance

AHU-1 Air Flow Profiles: Before & After

- 2006: Constant CFM ventilation
- 2015: Demand controlled ventilation?



AHU-1 SAT Profiles: Before & After

- 2006: Constant CFM ventilation
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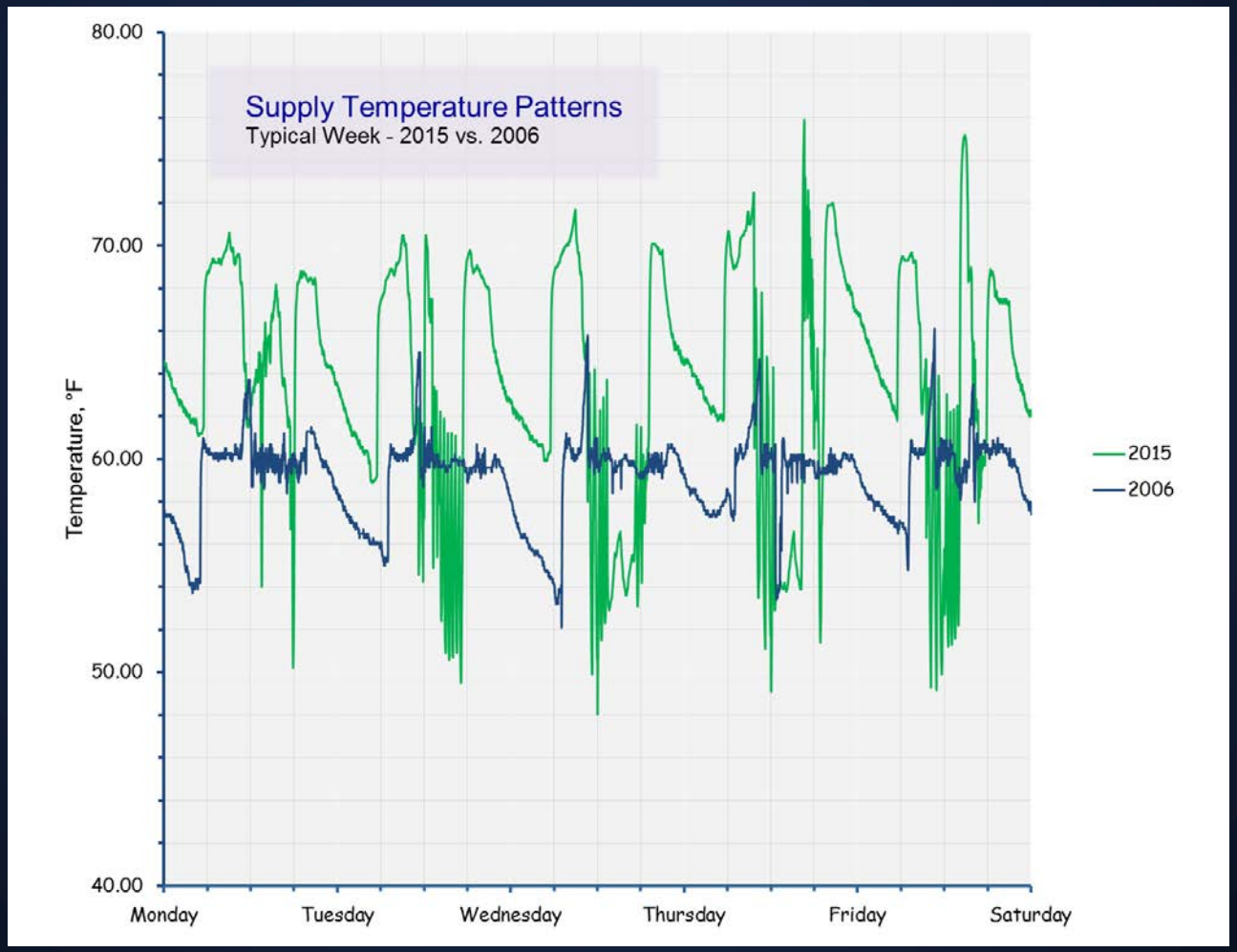
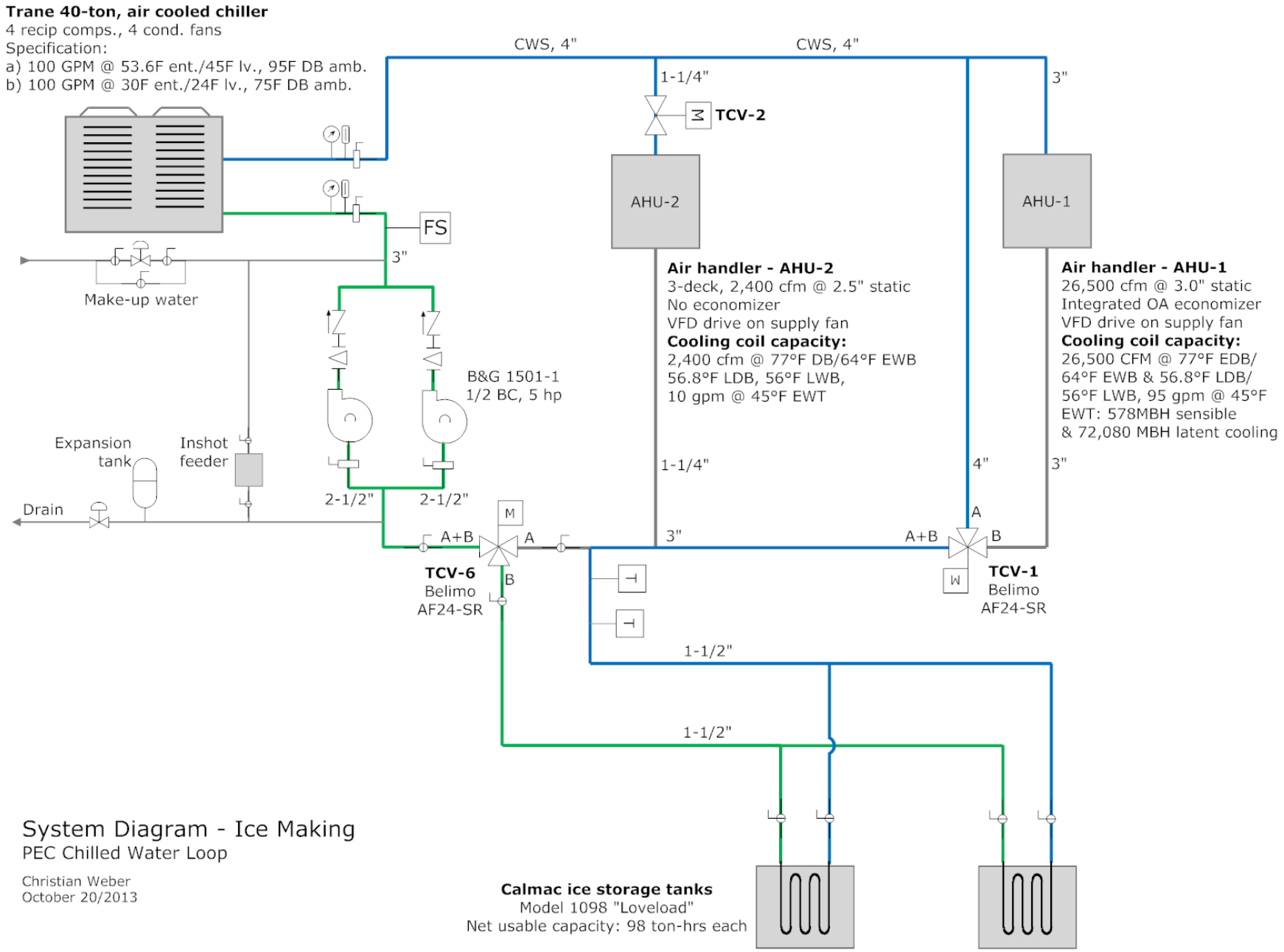


Steps in RCx Study

1. **Calibrate sensors & probes:**
   - Temperature – STW, RWT
   - Water flow
   - TES ice level
2. **Perform functional tests:**
   - Measure chiller performance
     - *Ice making mode*
     - *Chilled water mode*
   - Measure thermal performance of ice storage system
3. **Analysis of system performance & sequences of operation:**
   - Minimize energy use
   - Minimize operating costs



System Diagram - Ice Making

PEC Chilled Water Loop

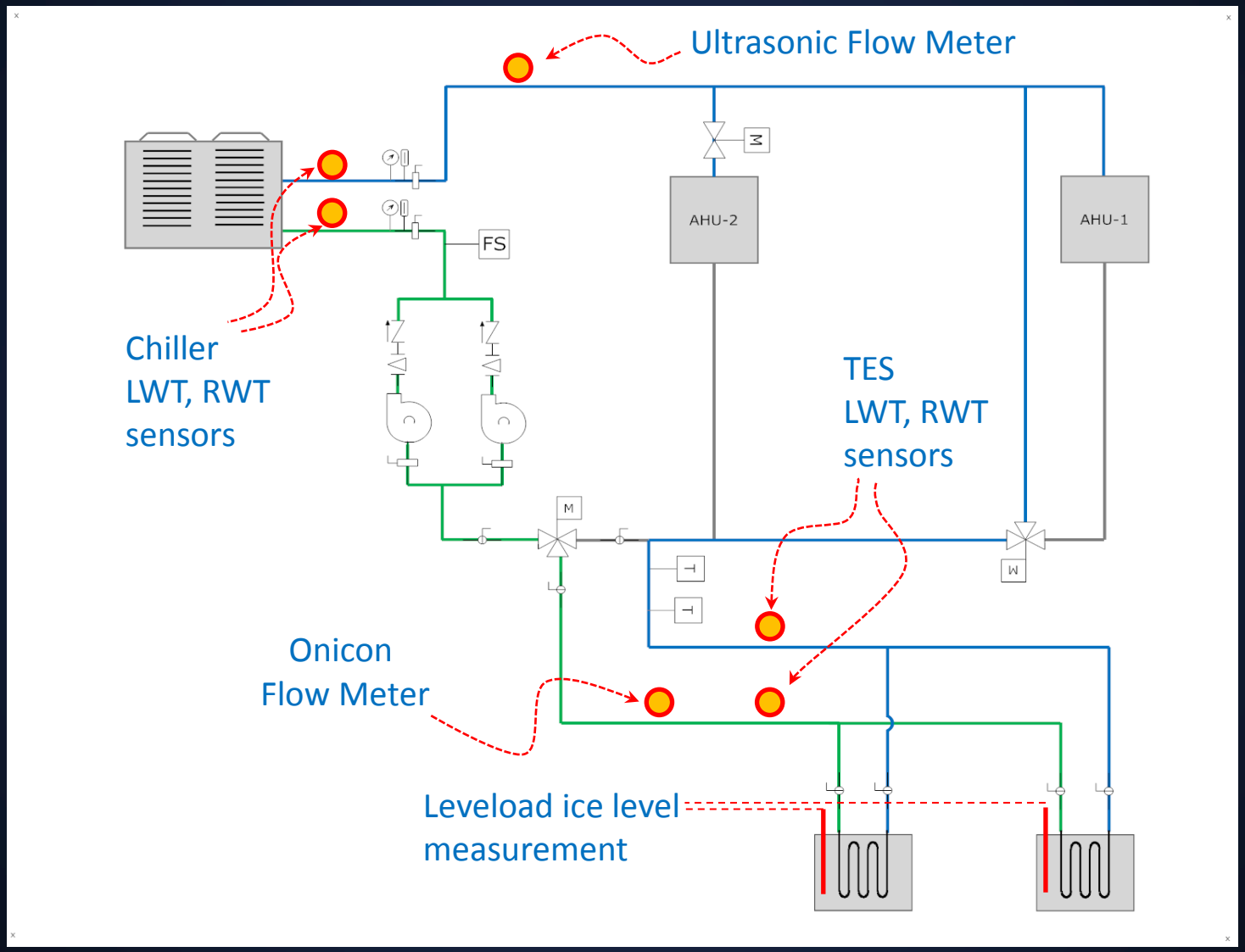
Christian Weber
October 20/2013

Part 1: Instrumentation & Sensors Calibration

1. Chiller Btuh meter:
    a. Supply & return water and supply water temp sensors
    b. Ultrasonic flow meter
    c. Compressor run-time monitoring

2. Ice storage tank:
    a. Supply & return water temperatures
    b. Flow meter
    c. Ice level measurement system

Location of measurement probes



Temperature Sensor Calibration

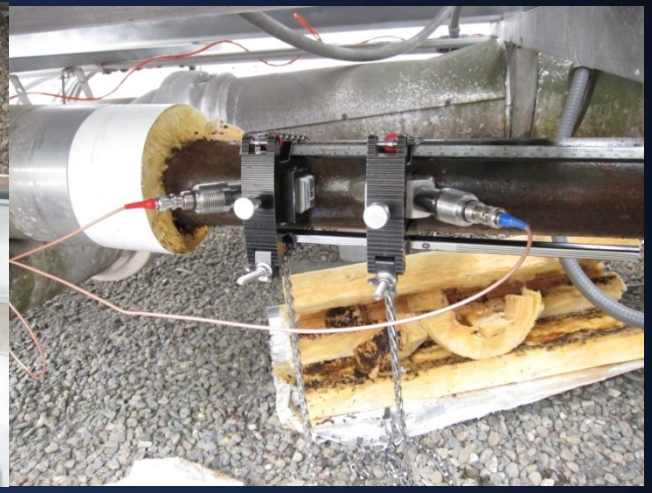
Hart Scientific 9105 dry-well temp sensor calibrator

RESULTS

Flow Measurements

Chiller Supply Water:

GE

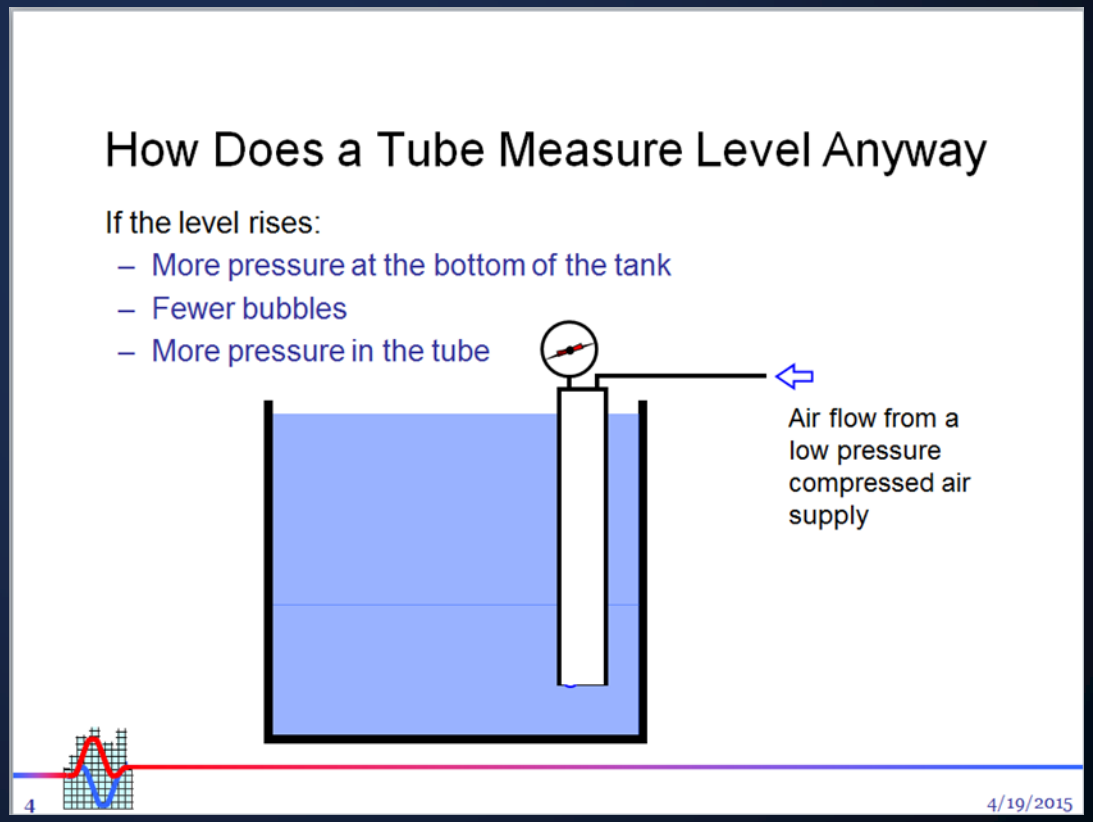


TES System:

Onicon F-1100 flow meter

Additional measurement probes, cont.

Leveload ice inventory meter

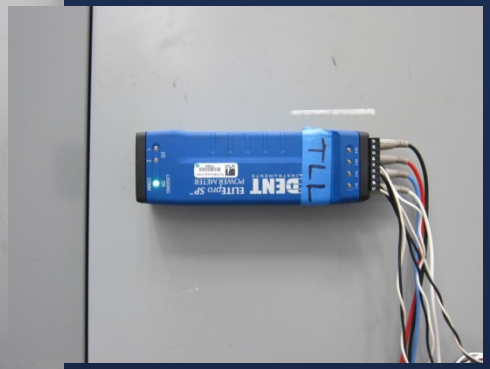


Flow Measurement Calibration Results

RESULTS

Additional measurement probes

3-phase Dent power meter



Compressor CTs

Part A: Chiller Performance Measurements

Dent Power Data

Date	Time	Avg. V	Avg. I	Avg. kW	PF	Electrical BTUH
4/29/2014	22:29:00	120.536	0	0	1	0
4/29/2014	22:30:00	120.431	0	0	1	0
4/29/2014	22:31:00	120.507	0	0	1	0
4/29/2014	22:32:00	120.618	0	0	1	0
4/29/2014	22:33:00	120.33	12.27	3.204	0.73	11,032
	22:34:00	119.023	123.59	35.919	0.82	123,469
	22:35:00	119.04	134.73	39.334	0.82	134,617
	22:36:00	119.116	129.58	37.34	0.81	127,974
	22:37:00	119.173	129.28	37.258	0.81	127,739
	22:38:00	119.362	129.82	37.469	0.81	128,476
	22:39:00	119.258	129.95	37.525	0.81	128,493
	22:40:00	119.302	130.24	37.647	0.81	128,827
	22:41:00	119.187	129.54	37.281	0.81	128,011
22:4						
22:4						
22:4						
22:4						

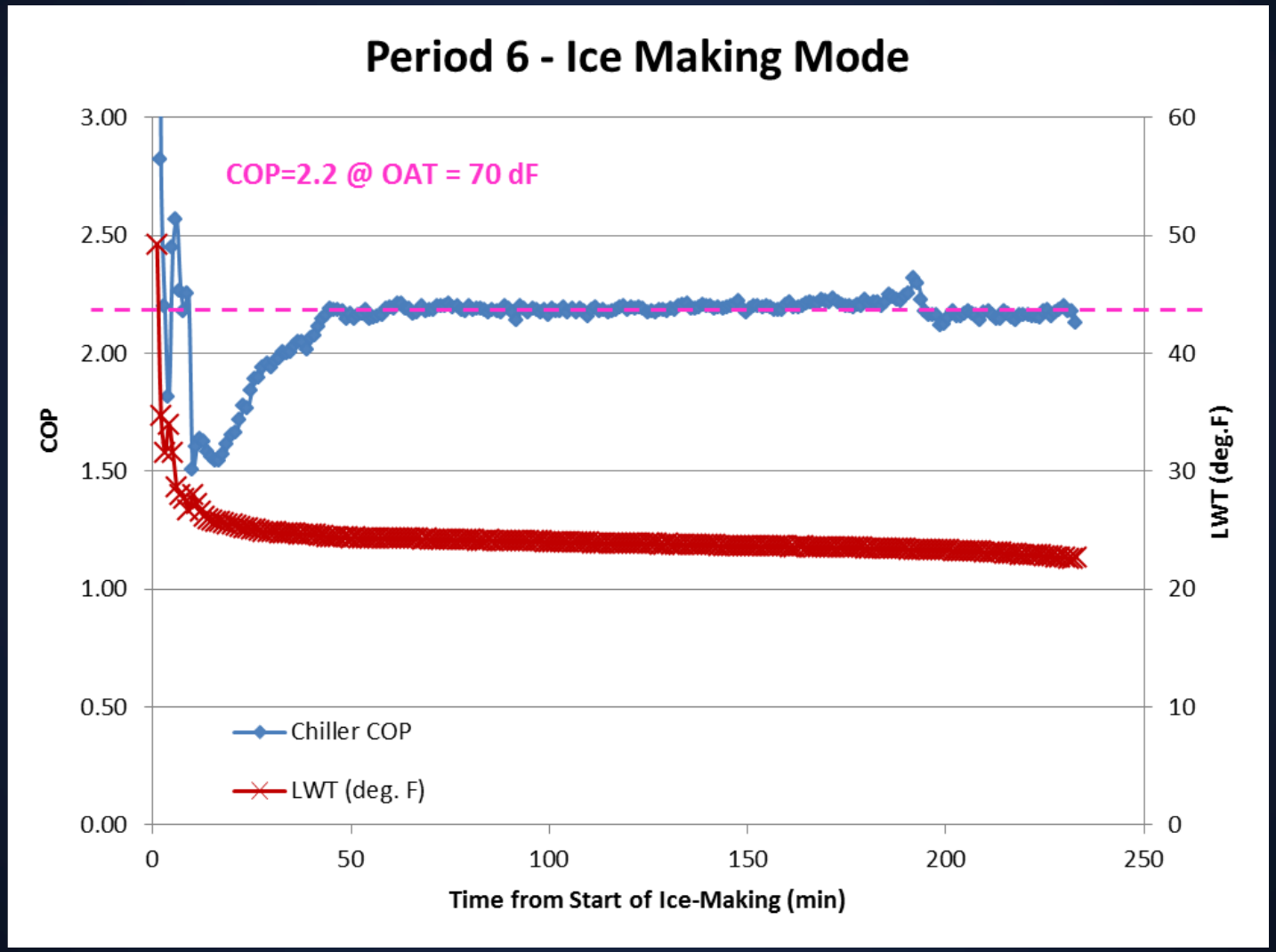
Chiller Logging Data

Date	Time	Pace Temperature Logger			Ultrasonic Flow Meter Data				Nr. comps. operating
		Leaving Water Temp	Entering Water Temp.	EWT-LWT	Date & Time	Flow (GPM)	Flow total (GPM)	Date	
4/29/2014	22:29:02	51.5	51.2	-0.4	4/29/2014 22:29	0.2	197,610	4/29/14 10:29 PM	0
4/29/2014	22:30:02	51.5	51.2	-0.3	4/29/2014 22:30	0.2	197,610	4/29/14 10:30 PM	0
4/29/2014	22:31:02	51.6	51.3	-0.3	4/29/2014 22:31	0.2	197,610	4/29/14 10:31 PM	0
4/29/2014	22:32:02	51.8	51.0	-0.8	4/29/2014 22:32	0.1	197,610	4/29/14 10:32 PM	0
4/29/2014	22:33:02	47.8	49.2	1.4	4/29/2014 22:33	102.9	197,702	4/29/14 10:33 PM	4
4/29/2014	22:34:02	34.0	41.1	7.1	4/29/2014 22:34	93.7	197,796	4/29/14 10:34 PM	4
4/29/2014	22:35:02	30.9	36.9	6.0	4/29/2014 22:35	93.3	197,892	4/29/14 10:35 PM	4
4/29/2014	22:36:02	32.9	38.2	5.3	4/29/2014 22:36	92.6	197,984	4/29/14 10:36 PM	4
4/29/2014	22:37:02	30.5	37.5	7.0	4/29/2014 22:37	92.9	198,077	4/29/14 10:37 PM	4
4/29/2014	22:38:02	27.7	35.1	7.4	4/29/2014 22:38	91.6	198,171	4/29/14 10:38 PM	4
4/29/2014	22:39:02	27.1	33.7	6.6	4/29/2014 22:39	92.5	198,262	4/29/14 10:39 PM	4
4/29/2014	22:40:02	28.7	33.2	4.5	4/29/2014 22:40	92.2	198,352	4/29/14 10:40 PM	4
4/29/2014	22:41:02	27.7	32.5	4.8	4/29/2014 22:41	90.8	198,447	4/29/14 10:41 PM	4
4/29/2014	22:42:02	27.0	31.6	4.6	4/29/2014 22:42	91.4	198,536	4/29/14 10:42 PM	4
4/29/2014	22:43:02	26.7	31.1	4.3	4/29/2014 22:43	90.8	198,627	4/29/14 10:43 PM	4
4/29/2014	22:44:02	26.4	30.7	4.3	4/29/2014 22:44	90.7	198,719	4/29/14 10:44 PM	4
4/29/2014	22:45:02	26.0	30.3	4.2	4/29/2014 22:45	90.7	198,809	4/29/14 10:45 PM	4

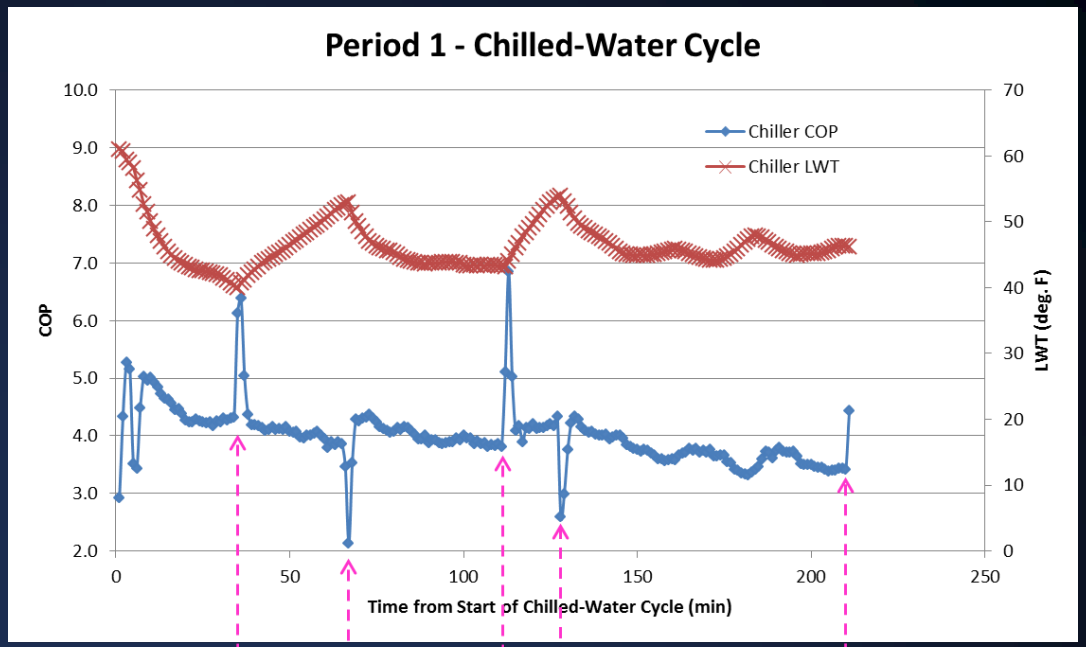
Chiller COP Analysis

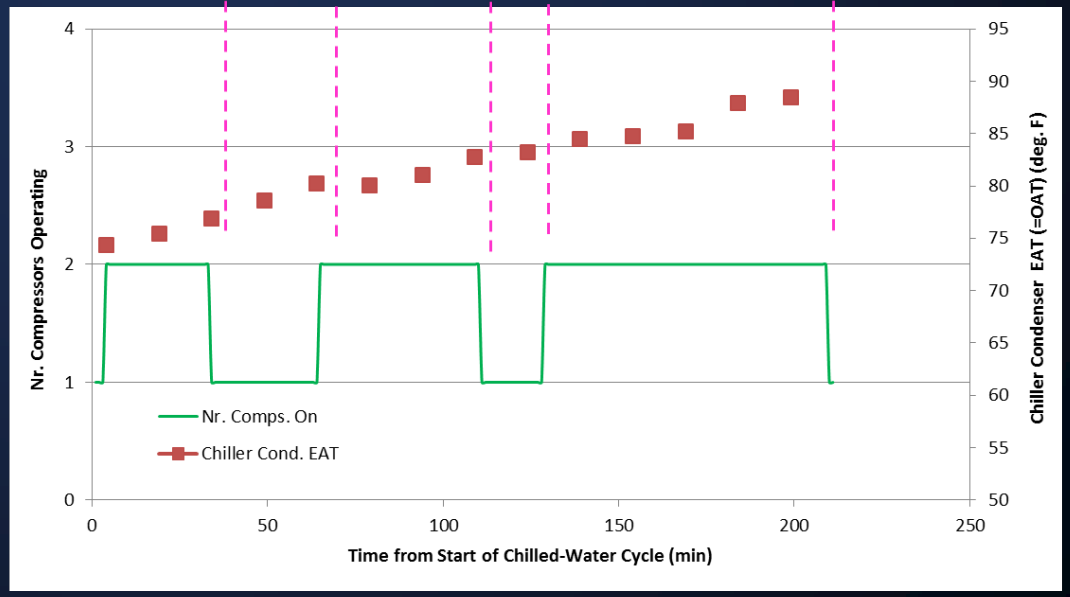
Heat absorbed by chiller		Heat Absorbed by Ice Tanks		Chiller Performance		
Q (BTUH)	Tons /hr	Btuh	Tons	kW/ton	COP	LWT
74,229	6.19			0.5	6.7	47.8
331,356	27.61			1.3	2.7	34.0
279,599	23.30			1.7	2.1	30.9
245,021	20.42	299,170	24.93	1.8	1.9	32.9
324,454	27.04			1.4	2.5	30.5
338,373	28.20			1.3	2.6	27.7
303,791	25.32			1.5	2.4	27.1
208,781	17.40			2.2	1.6	28.7
216,272	18.02	235,279	19.61	2.1	1.7	27.7
210,738	17.56			2.1	1.6	27.0
197,016	16.42			2.3	1.5	26.7
195,128	16.26			2.3	1.5	26.4
190,688	15.89			2.3	1.5	26.0
188,547	15.71	253,292	21.11	2.3	1.5	25.8
188,985	15.75			2.3	1.5	25.7
191,863	15.99			2.3	1.5	25.6
198,159	16.51			2.2	1.6	25.5
204,879	17.07			2.1	1.6	25.5
212,528	17.71	293,622	24.47	2.1	1.7	25.4

a) Ice Making Mode: Sample Results

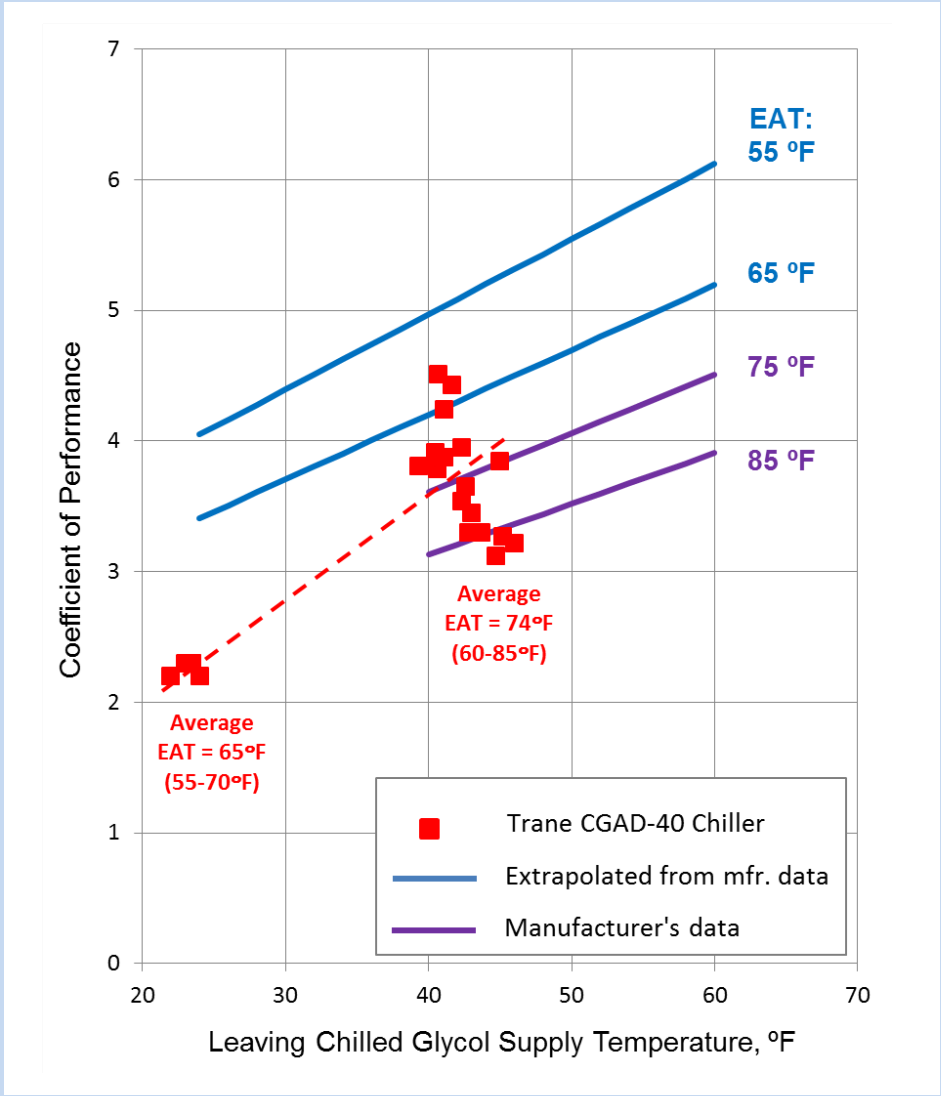


b) Chilled Water Mode: Sample Results

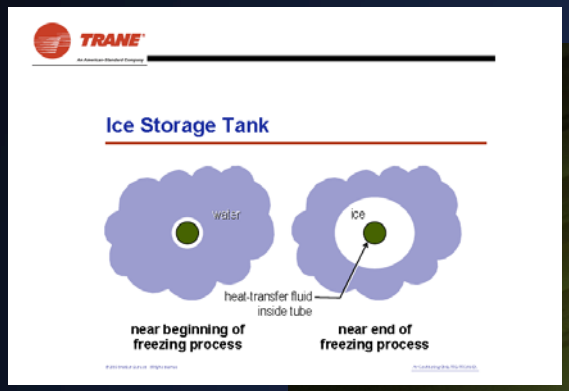


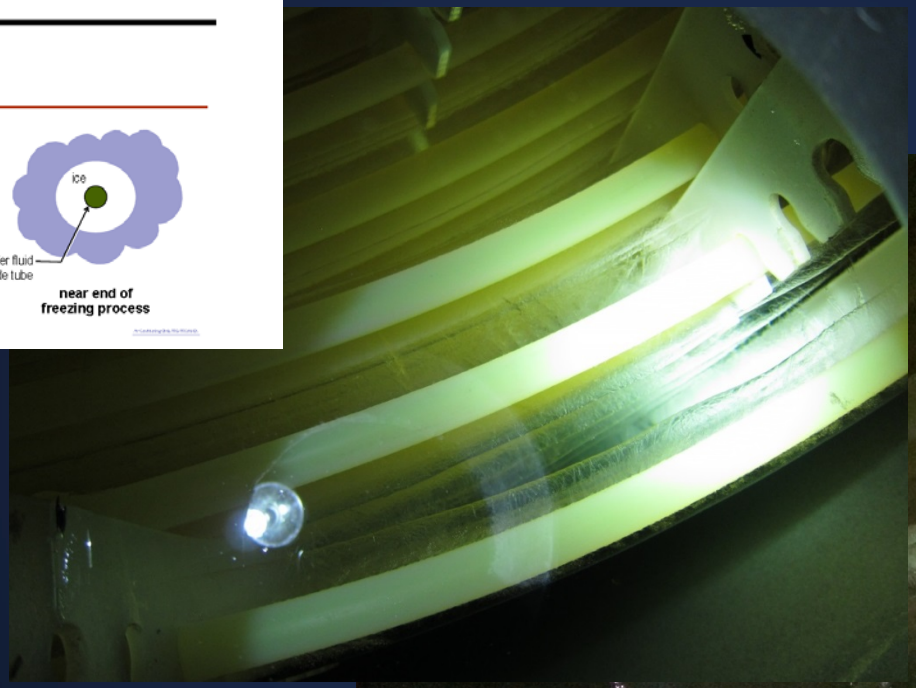


Compilation of Chiller Performance: COP



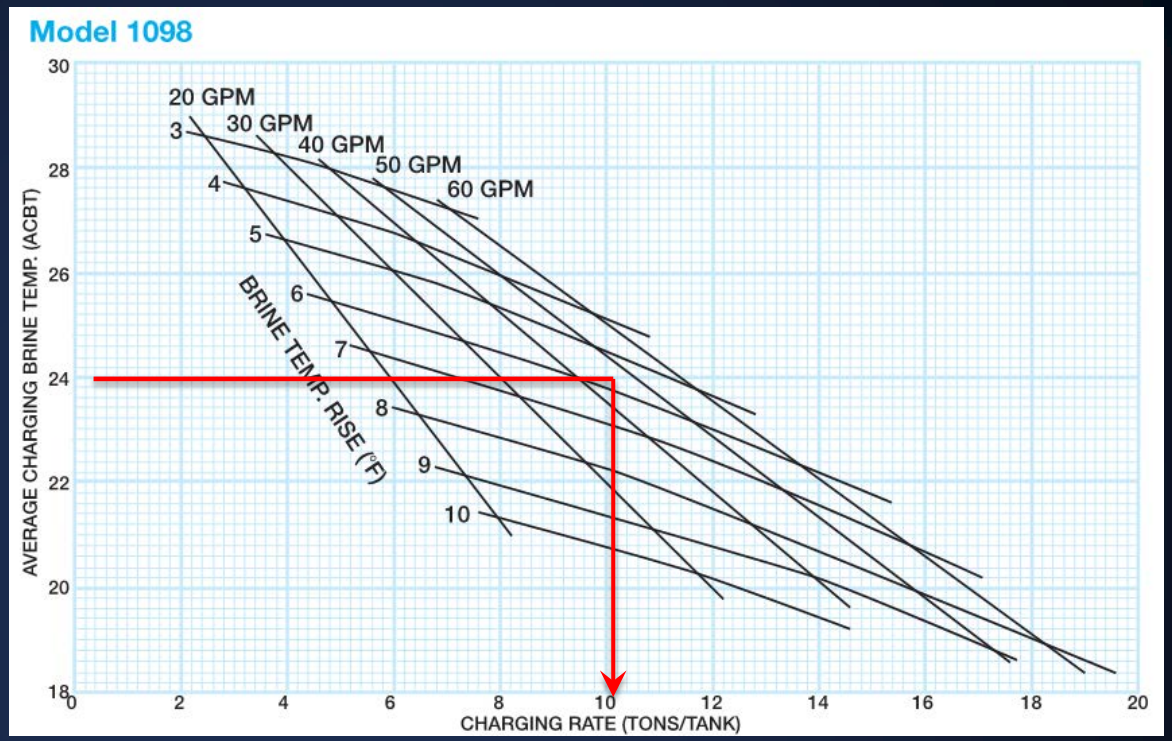
Part B: Thermal Energy Storage Performance Measurements





Calmac Ice Tank Charging Data

At 98 ton-hrs/tank capacity, charging time 9.5 hrs



10.5 tons/hr/tank

Are these charging rates from an empty tank or from onset of ice making?

Expected charging time 9.3 hrs. Actual: 8-10.5 hrs

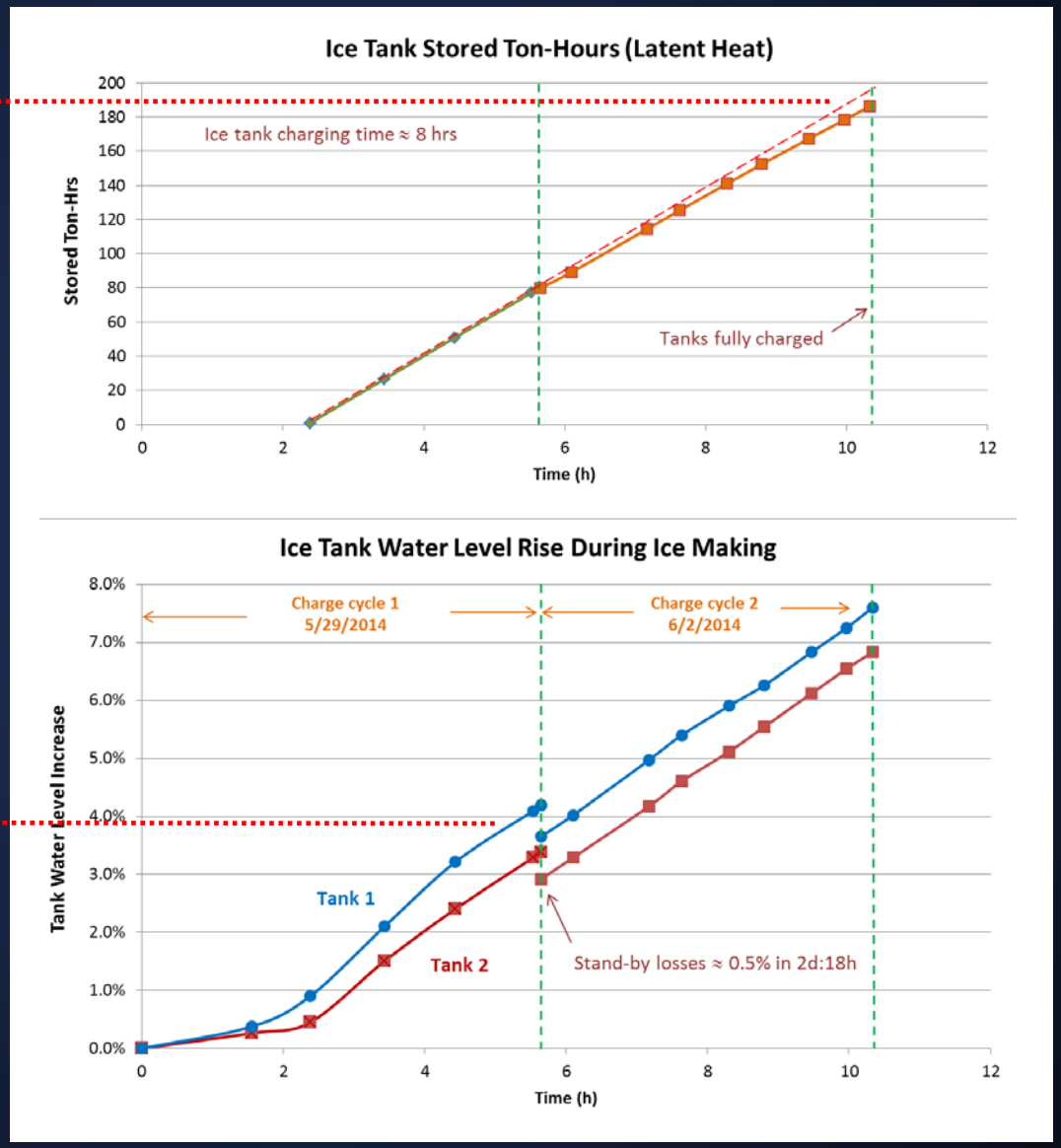
Table 1 — Minimum Charging Brine Temperature To Ice Bank For Full Charge

Average Charging Temp. F	Tons/Tank						
	3	6	9	12	15	18	21
28	25.7	25.1					
27	24.7	24.3	23.8				
26		23.4	22.9				
25		22.7	22.1	21.4			
24		22.1	21.4	20.7			
23			20.8	20.1	19.3		
22			20.1	19.5	18.6		
21			19.5	18.9	18.1	17.6	
20				18.3	17.7	17.2	
19					17.3	16.7	
18						16.1	15.8

Ice Tanks Stored Ton-Hours

Measured storage
Capacity = 190 ton-hours

Standby losses
≈ 2% day



Summary of Performance Measurements

1. Trane Chiller
   - COP ≈ 2.2 in ice-making mode
   - COP = 3.0 – 4.5 in chilled-water mode
     - *Various ambient temps*

2. Calmac Thermal Energy Storage System
   - Ice-storage capacity = 196 ton-hrs
   - Stand-by losses ≈2%/day

Good agreement with manufacturer's specs

Analysis of System Performance

1. What is the system performance vs the building's cooling needs?
2. What are the economics of operation: ice making vs chilled water?

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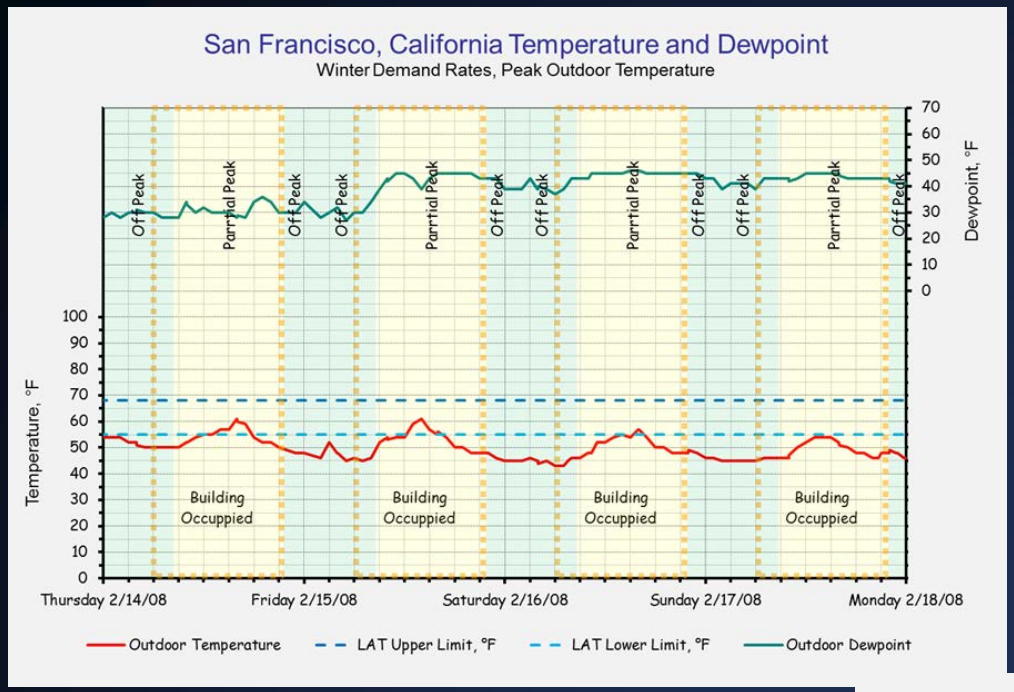
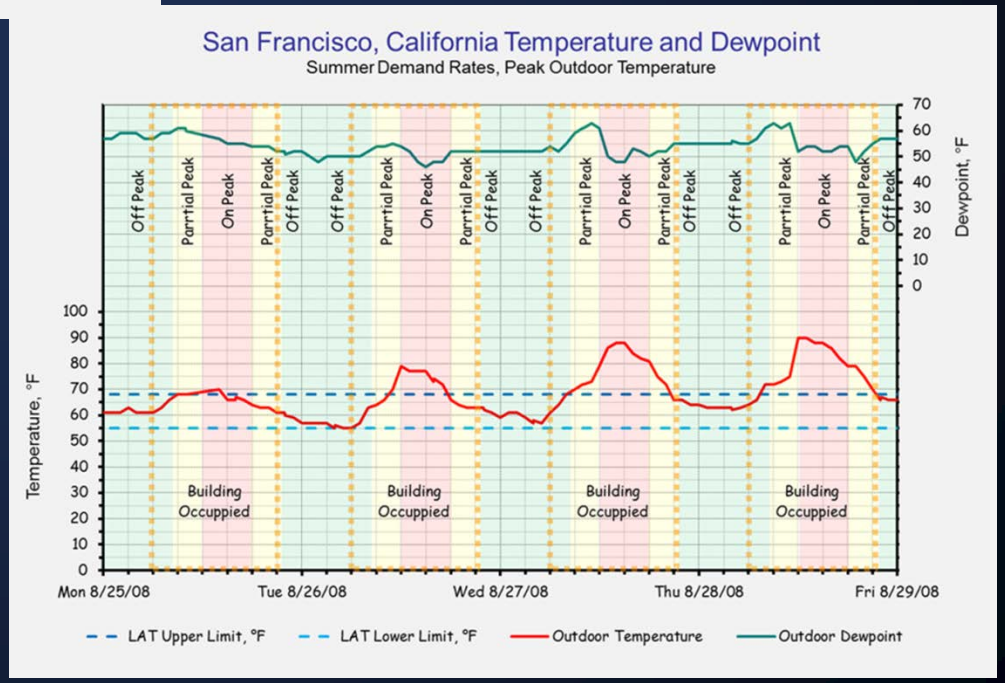
3. How can the sequences of operation be updated to improve 1. and 2.?

Remaining analysis:

Does it make economic sense, because of demand charges, to cool the PEC with the TES system?

- Yes:
  - If it does make sense to use the TES system, is the current sequence of operation appropriate? Do we ever need to run the chiller during the day? Looks like we don't, based on ice consumption modelling for a warm, high occupancy day.
  - On cold, high occupancy days (<60F?) can cooling be achieved with OA economizer alone? Should the TES be switched off to avoid standby losses?
  - On mild days, some mechanical cooling will be necessary. How cool does it have to get before the standby losses exceed the cost of running the chiller during the day?
- No:
  - If it doesn't make sense to use the TES, recommend the TES be mothballed and the glycol removed from the system to increase energy efficiency. How much is the energy efficiency improved?



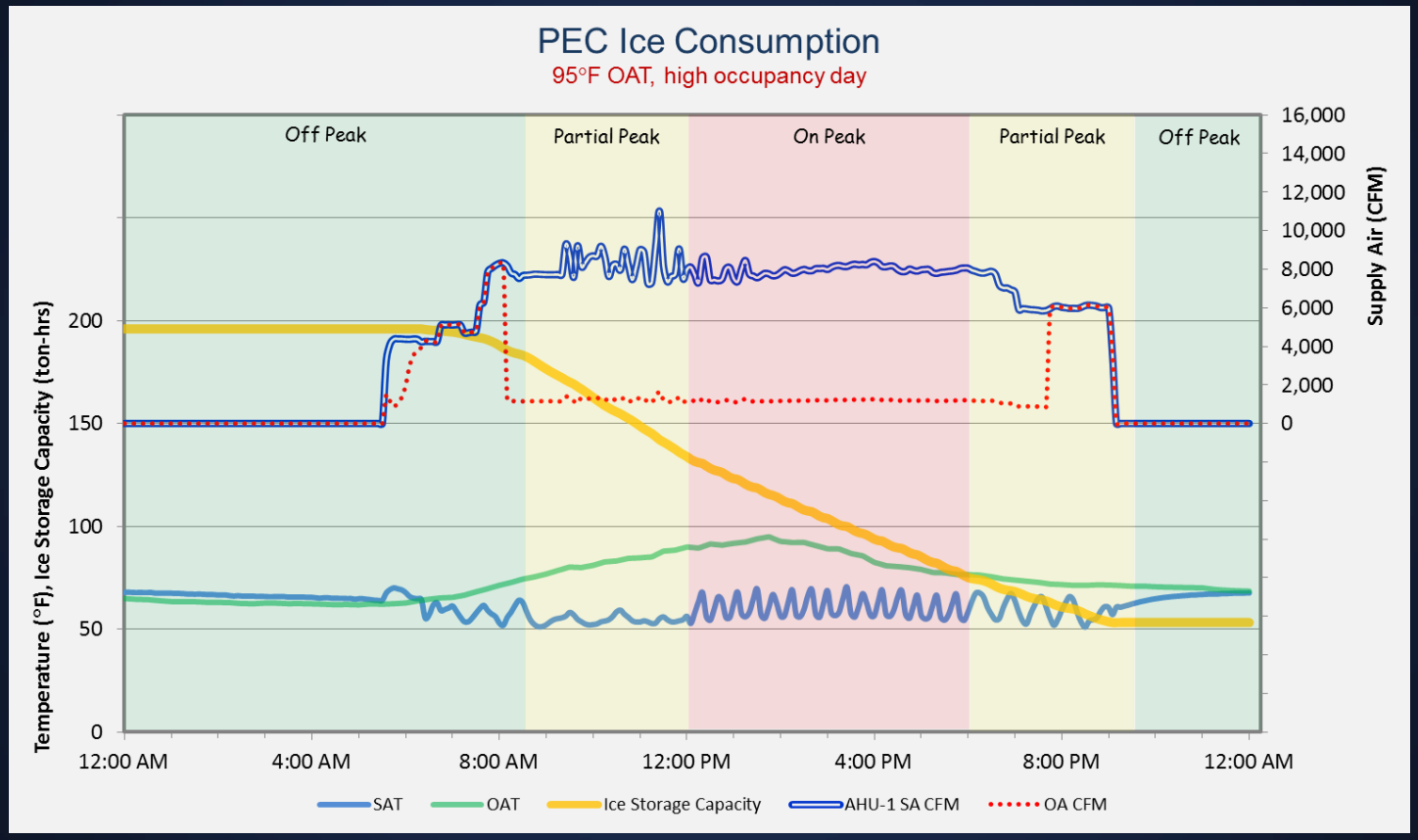


Envelope load vs occupancy load?

Setback control??

Model of Ice Consumption for Space Conditioning

- Warm San Francisco day



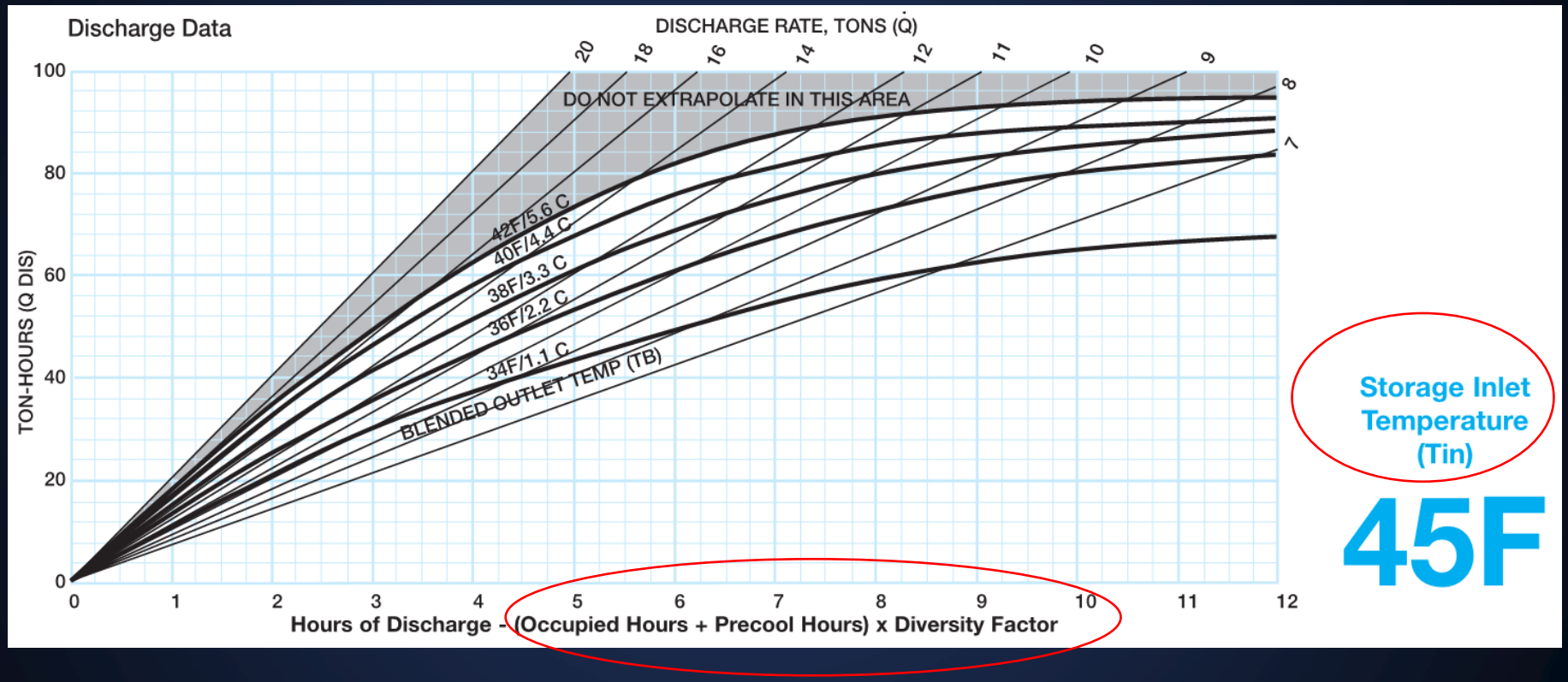
➢ Pacific Energy Center can get through day w/o chiller operation

TES Cooling Economics, May 2014

Parameter	CHW w. 45°F Brine	TES/ice w. 24°F brine
LWT	45°F	24°F
Condensing temp	75°F	55-70°F
COP	3.75	2.3
Nr. comps	2	4
Measured tonnage output:	22.0	24.5
kW/ton of cooling	0.94	1.53
Energy cost/ton (P/PP/OP)	$0.17/$0.16/$0.14	$0.22
PEC AHU-1 mechanical cooling load	Peak: 781.5 ton-hrs P-peak: 479.1 ton-hrs O-peak: 39.5 ton-hrs	O-peak: 1,300.1 ton-hrs
Peak power, kW	20.6	37.5
Demand charge	$303.63	$528.42
Total energy used, kWh:	**1,222**	**1,989**
Cooling costs:	**$520.64**	**$813.60**

Ice Tank Discharge Data

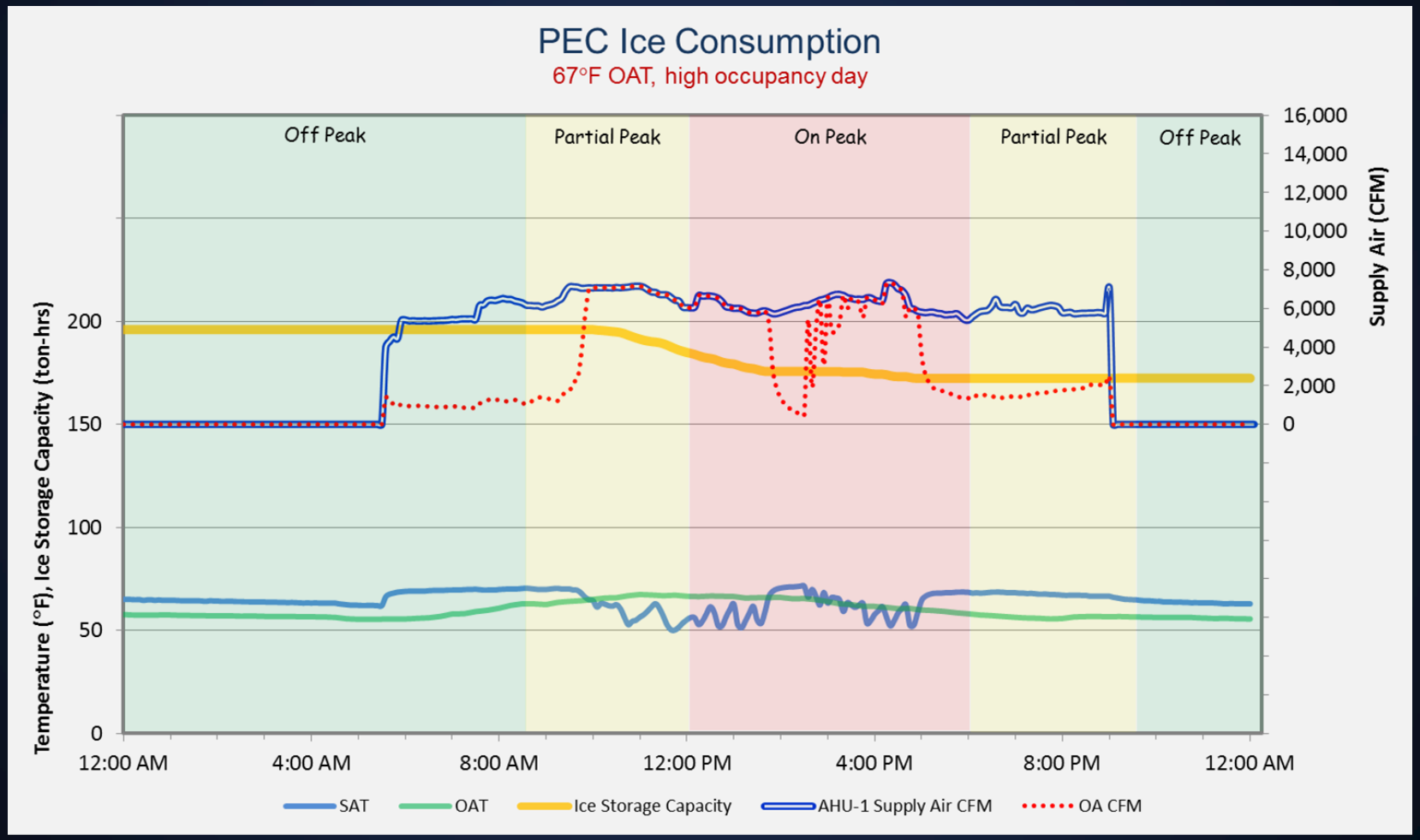
- Can get about 14 tons/hr for 5.5 hrs per tank, or total of 28 tons/hr for 5.5 hrs
- Or can get a total of about 16 tons/hr (2 tanks) for 12 hours. 16 tons per hour is a little less than the peak cooling load on the warm day (≈18.8? Tons/hr)



Spare Slides

Model of Ice Consumption for Space Conditioning

- "Normal" San Francisco day



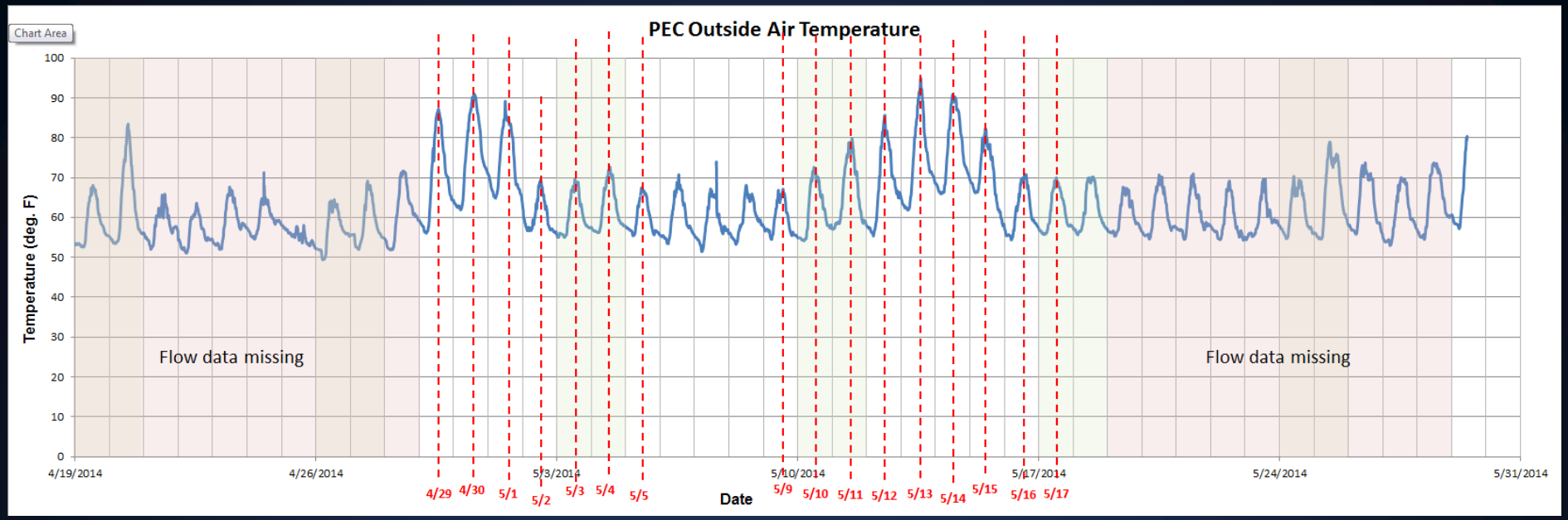
Cooling loads:

- Envelope
- Ventilation
- Occupants
- Equipment – all electrical power in building

- Total building (sensible only?) load you can see from the AHU-1
- CFM and delta-T across coil data.
    - Minimum ventilation?

- Need to map sequences of operation…

1. Cool day? Want to show that don't need
2. Normal day?
   - On most days can get by on OA economizer free cooling + small amount of mechanical cooling
     - Need a graph of how much cooling actually provided by economizer vs mechanical cooling
   - Don't make ice at all – cost of standby losses?
   - Precooling?
   - AHU-1 operates between 55 to 70dF SAT…
3. Warm day
   - Only need to run chiller during off peak hours
   - Make ice at night…but cheaper to run chiller…what about the demand charge?
   - Ice vs chilled water?



5_6_14 Chiller COP Calcs MAIN backup/OAT Temp

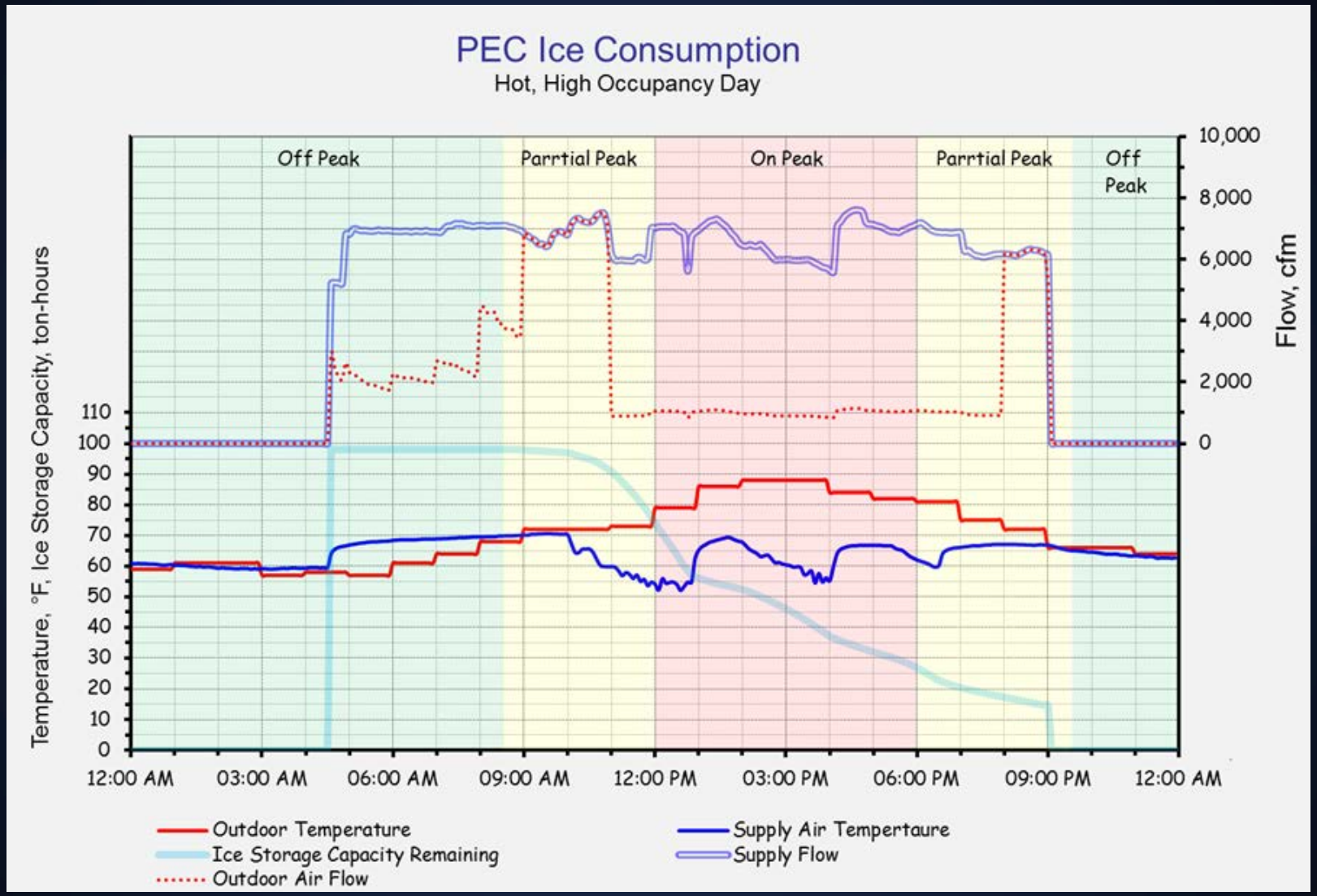

PEC Ice Consumption
Hot, High Occupancy Day
Off Peak
Parrtial Peak
On Peak
Parrtial Peak
Off Peak
Temperature, °F, Ice Storage Capacity, ton-hours
Flow, cfm
110
100
90
80
70
60
50
40
30
20
10
0
10,000
8,000
6,000
4,000
2,000
0
12:00 AM
03:00 AM
06:00 AM
09:00 AM
12:00 PM
03:00 PM
06:00 PM
09:00 PM
12:00 AM
Outdoor Temperature
Ice Storage Capacity Remaining
Outdoor Air Flow
Supply Air Tempertaure
Supply Flow

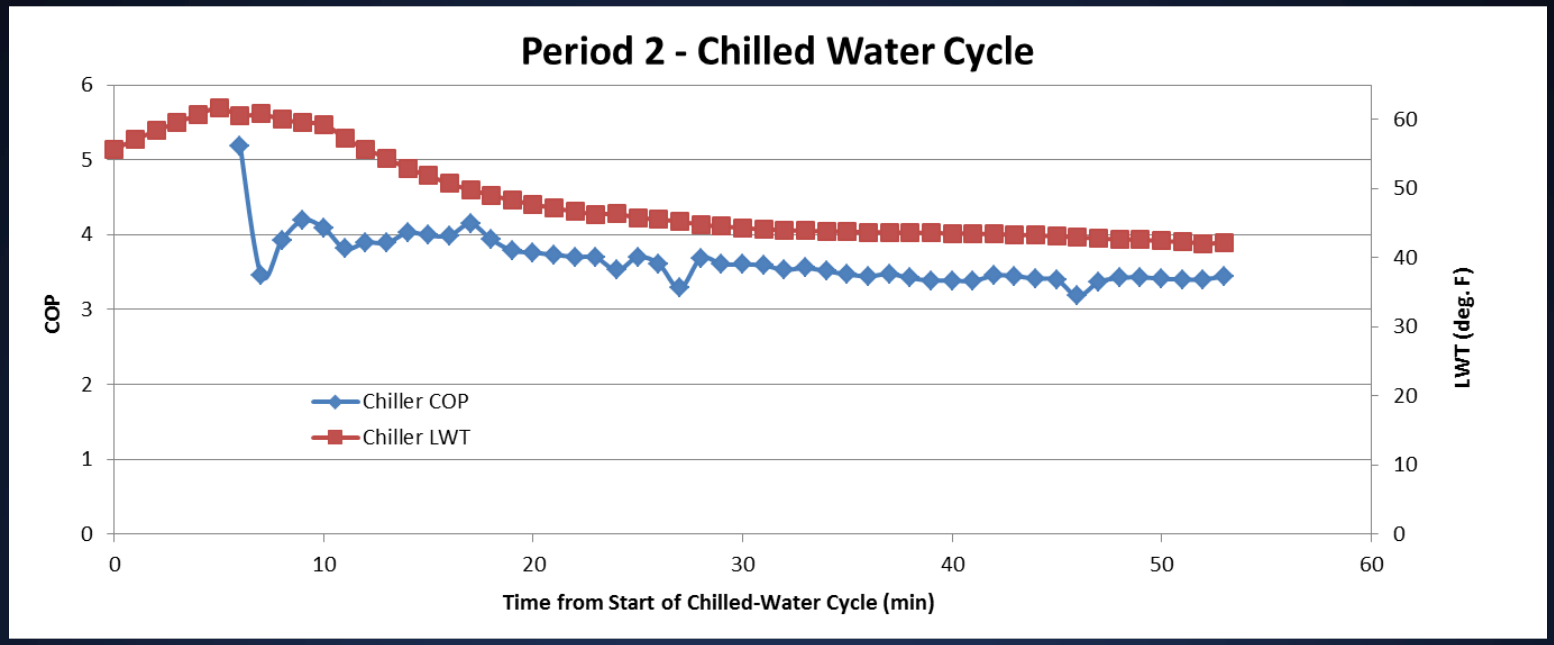
Table 3: Original control sequence vs new control sequence:

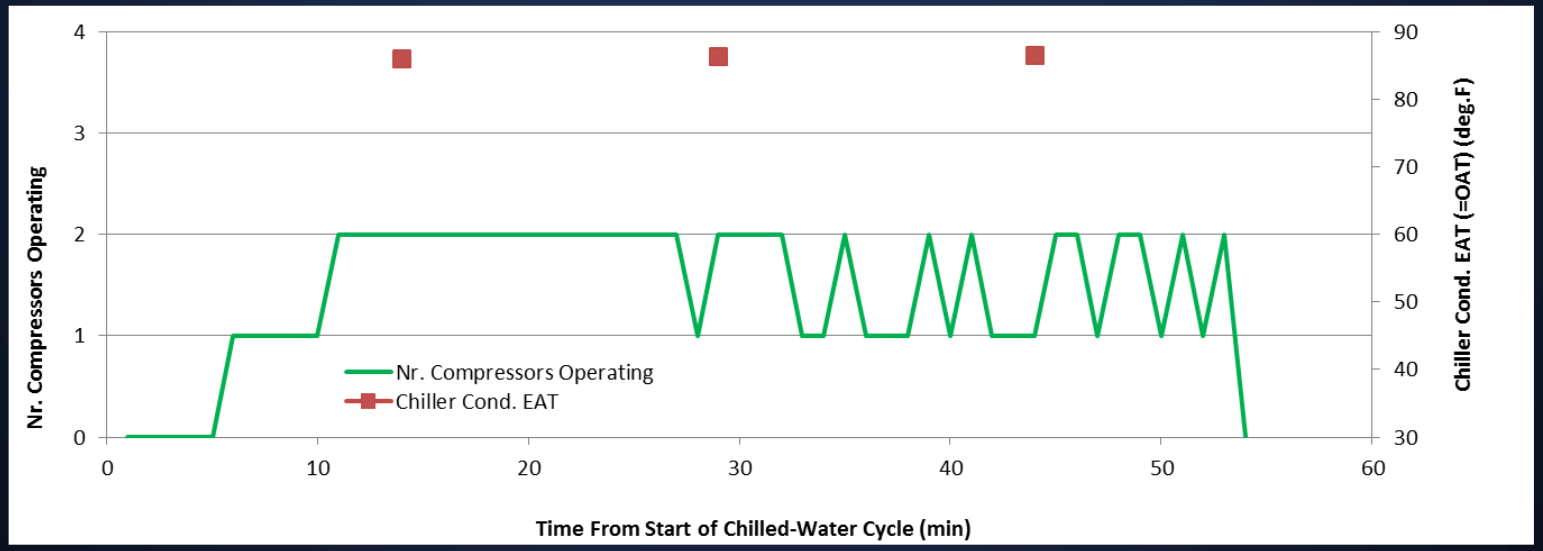
- All operating modes
- Ability to measure ice level accurately.
- 4 different ice storage sequence

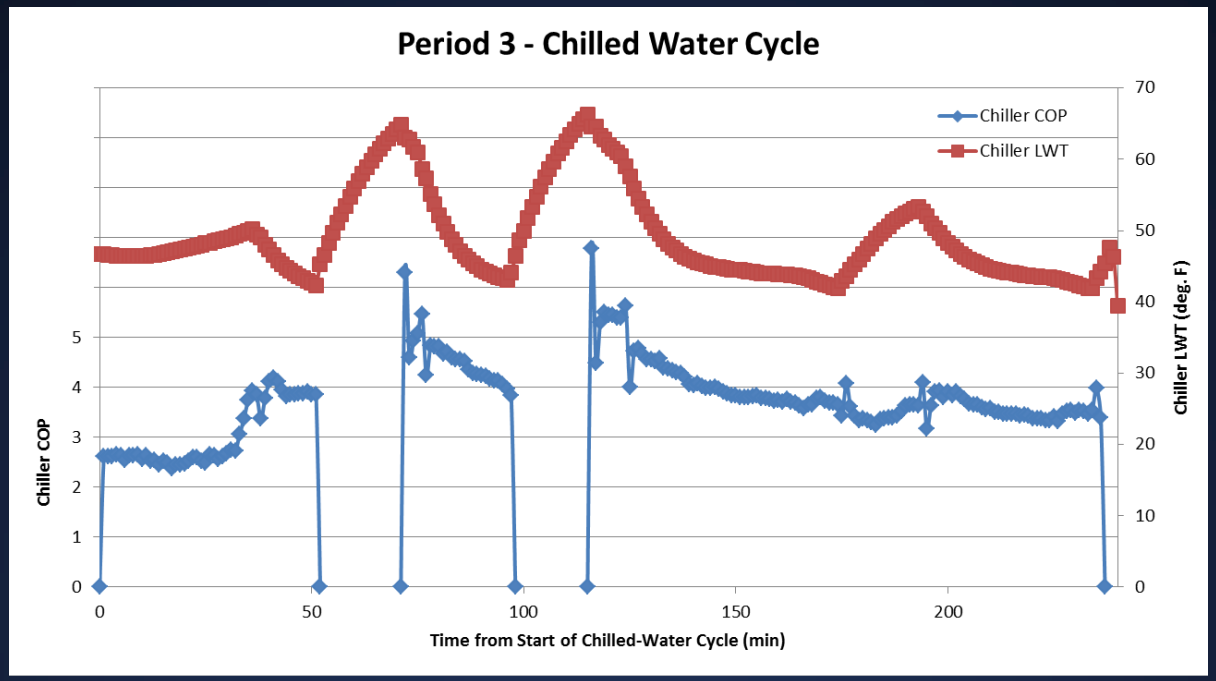
HAAKON

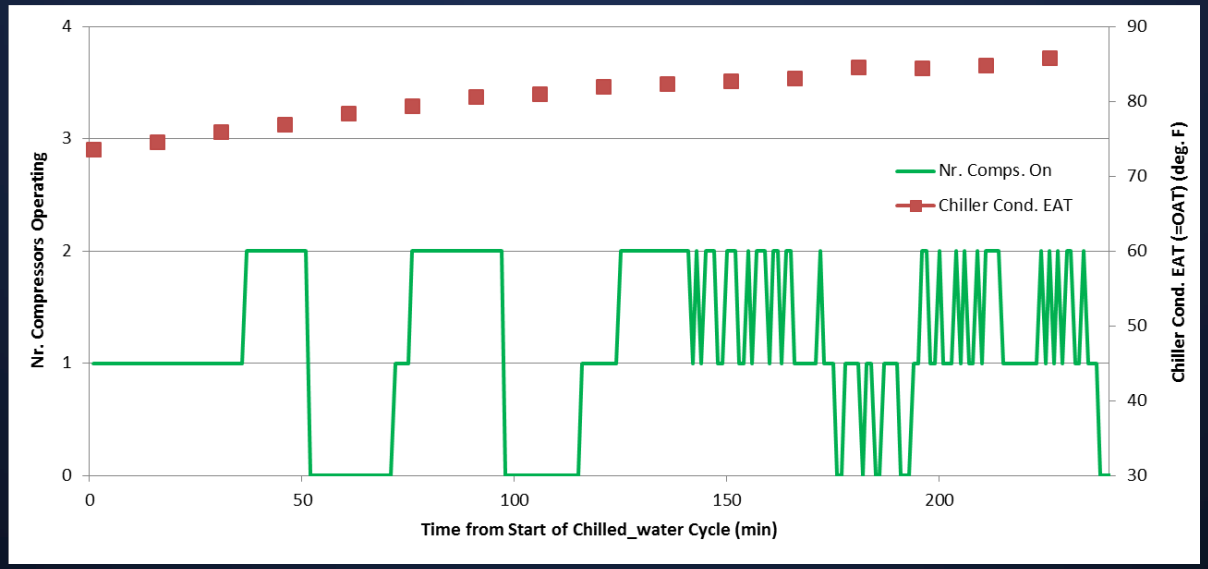
CHILL WATER

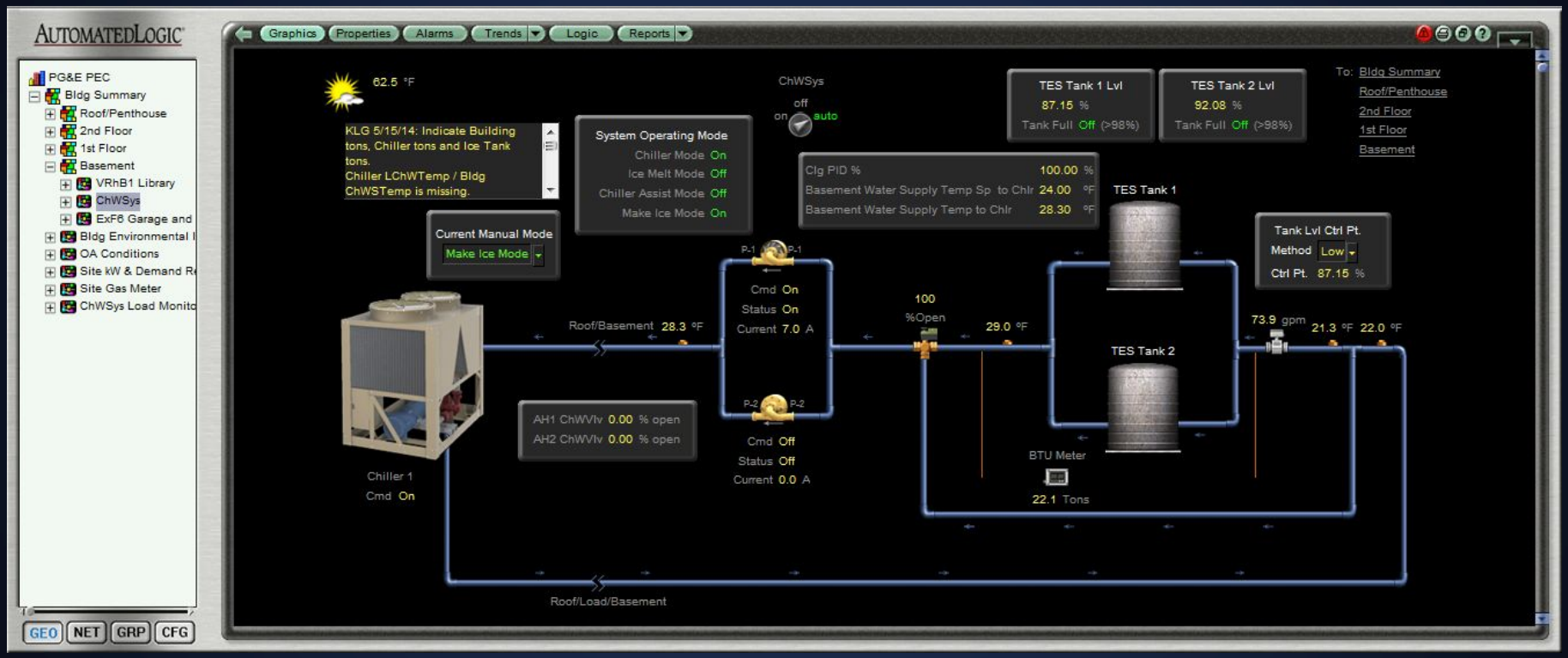
CALMAC


Period 2 - Chilled Water Cycle
COP
LWT (deg. F)
Chiller COP
Chiller LWT
Time from Start of Chilled-Water Cycle (min)
0
1
2
3
4
5
6
0
10
20
30
40
50
60


Nr. Compressors Operating
Chiller Cond. EAT (=OAT) (deg.F)
Nr. Compressors Operating
Chiller Cond. EAT
Time From Start of Chilled-Water Cycle (min)
0
1
2
3
4
30
40
50
60
70
80
90
0
10
20
30
40
50
60

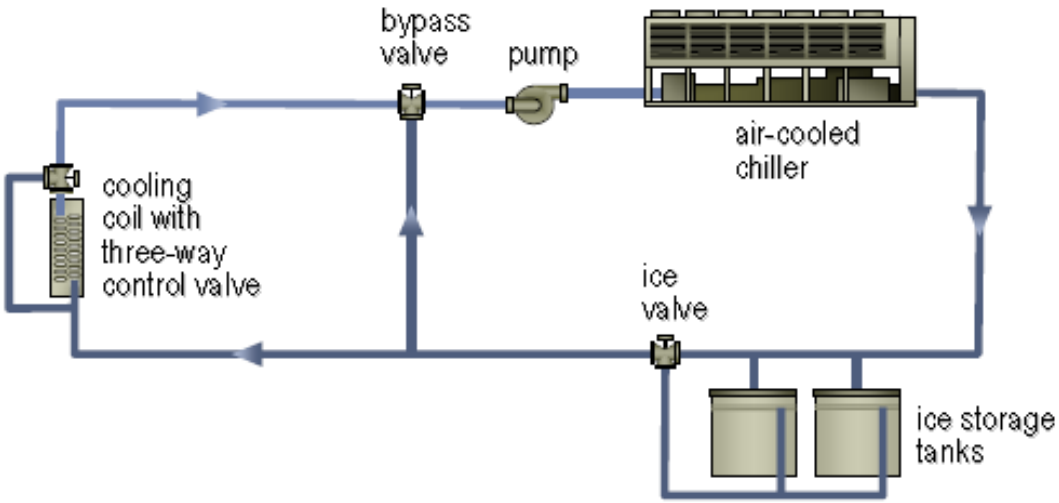

Period 3 - Chilled Water Cycle
Chiller COP
Chiller LWT
Chiller COP
Chiller LWT (deg. F)
Time from Start of Chilled-Water Cycle (min)
0
1
2
3
4
5
0
10
20
30
40
50
60
70
0
50
100
150
200


Nr. Comps. On
Chiller Cond. EAT
Nr. Compressors Operating
Chiller Cond. EAT (=OAT) (deg. F)
Time from Start of Chilled_water Cycle (min)
0
1
2
3
4
30
40
50
60
70
80
90
0
50
100
150
200

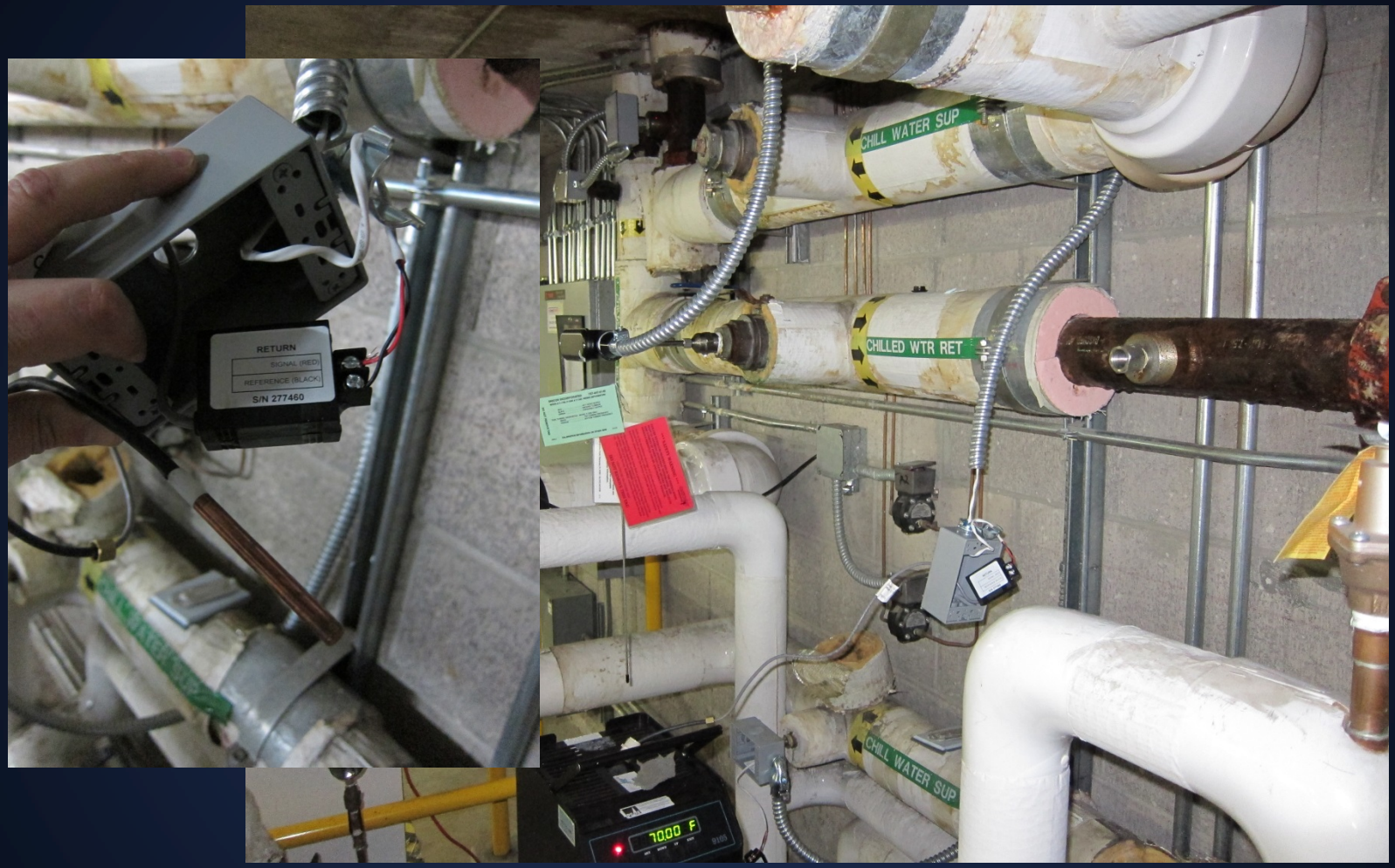

AUTOMATEDLOGIC
PG&E PEC
Bldg Summary
Roof/Penthouse
2nd Floor
1st Floor
Basement
VRhB1 Library
ChWSys
ExF6 Garage and
Bldg Environmental I
OA Conditions
Site kW & Demand R
Site Gas Meter
ChWSys Load Monito
GEO
NET
GRP
CFG
Graphics
Properties
Alarms
Trends
Logic
Reports
62.5 °F
KLG 5/15/14: Indicate Building tons, Chiller tons and Ice Tank tons.
Chiller LChWTemp / Bldg ChWSTemp is missing.
Current Manual Mode
Make Ice Mode
System Operating Mode
Chiller Mode On
Ice Melt Mode Off
Chiller Assist Mode Off
Make Ice Mode On
ChWSys
off
on
auto
Clg PID % 100.00 %
Basement Water Supply Temp Sp to Chlr 24.00 °F
Basement Water Supply Temp to Chlr 28.30 °F
TES Tank 1 Lvl
87.15 %
Tank Full Off (>98%)
TES Tank 2 Lvl
92.08 %
Tank Full Off (>98%)
To: Bldg Summary
Roof/Penthouse
2nd Floor
1st Floor
Basement
TES Tank 1
TES Tank 2
Tank Lvl Ctrl Pt.
Method Low
Ctrl Pt. 87.15 %
P-1
Cmd On
Status On
Current 7.0 A
P-2
Cmd Off
Status Off
Current 0.0 A
Roof/Basement 28.3 °F
100
%Open
29.0 °F
73.9 gpm
21.3 °F
22.0 °F
AH1 ChWVlv 0.00 % open
AH2 ChWVlv 0.00 % open
Chiller 1
Cmd On
BTU Meter
22.1 Tons
Roof/Load/Basement

TRANE
An American-Standard Company

Small Air-Cooled System



- Sizing of system
- AHU size and cooling capacity llkkklkl
- Type of AC system?
- Description of system
- Pressure drop through chiller
- History of TES storage system
- Control options
- Basic sequence of operation:


RETURN
SIGNAL (RED)
REFERENCE (BLACK)
S/N 277460
CHILL WATER SUP
CHILLED WTR RET
CHILL WATER SUP
70.00 F
RUN

CALMAC

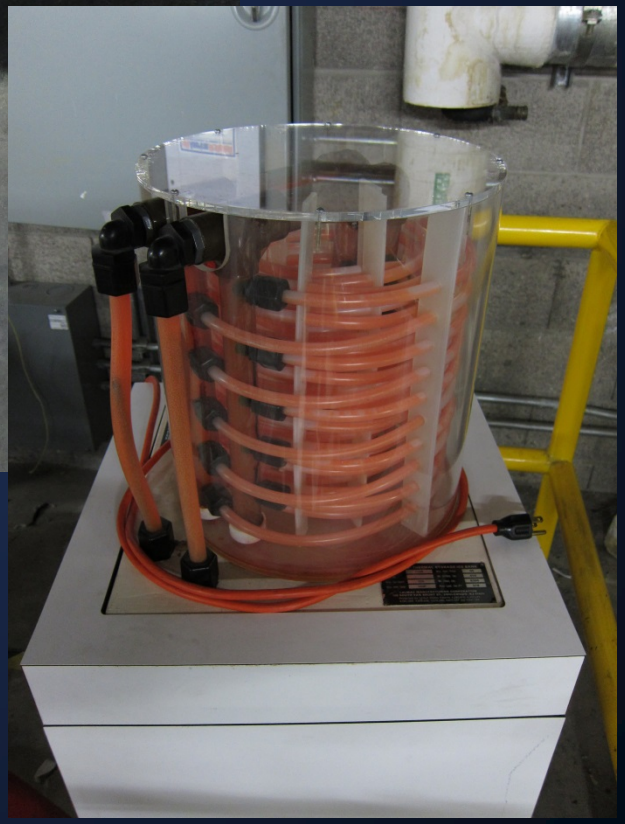
CALMAC
HOUR SERVICE
-351-7578

CHILL WATER SUP
CHILL WATER SUP
CHILLED WTR RET
49

CHILL WATER
CHILLED WTR RET
50
44
45

CHILLED WTR RET
CHILL WATER
48
47

LEVLOAD® THERMAL STORAGE ICE BANK
Model No. 1098
Serial No. 70139
Nom. Ton-Hours 115
Max. Inlet Temp. 100F
Max. Oper. Press. 90
Wt. Unfilled, Lbs. 1060
Wt. Filled, Lbs. 9940
Floor Load, Lbs./Ft² 230
CALMAC
CALMAC MANUFACTURING CORPORATION
101 W. SHEFFIELD AVE., ENGLEWOOD, NJ 07631
Protected by United States Patents 4,294,078; 4,403,645
4,565,069; 4,609,838; 4,615,390; 4,671,347 and 4,687,569



AHRI Chiller Rating Conditions

AHRI 550/590-2011

Standard:

- Evaporator: LWT = 44°F, flow rate = 2.4 GPM/ton
- Air cooled condenser entering temp = 95°F
- 100% load – achieved how?

IPLV:

- All loads, evaporator LWT: 44°F
- Air-cooled condenser:
  - 100% load, EDB, °F: 95
  - 75% load, EDB, °F: 80
  - 50% load, EDB, °F: 65
  - 25% load, EDB, °F: 55

What about rating under ice production conditions? Chiller efficiency goes down with decreasing evaporator temperatures. Calmac assumes 35% reduction at a LWT = 28°F instead of 44°F.

PEC Rate Schedule

A-10 TOU Secondary (Table B) Customers with high electric use and medium to high load factors generally benefit under Schedule A-10 TOU. Part of customer's bill varies according to the customer's maximum monthly electric demand.	$4.59959 per meter per day	$0.98563 per meter per day	**Summer**	$13.36	Peak	$0.16506	$0.90	($2.60)	($0.00702)	$0.17437
					Part-Peak	$0.15784			($0.00702)	
					Off-Peak	$0.13588			($0.00702)	
			Winter	$6.26	Part-Peak	$0.12044		-	-	
					Off-Peak	$0.10161				
A-10 TOU Primary (Table B) Customers with high electric use and medium to high load factors generally benefit under Schedule A-10 TOU. Part of customer's bill varies according to the customer's maximum monthly electric demand.			**Summer**	$12.61	Peak	$0.15271	$0.90	($2.46)	($0.00800)	$0.15914
					Part-Peak	$0.14756			($0.00800)	
					Off-Peak	$0.12785			($0.00800)	
			Winter	$6.48	Part-Peak	$0.11342		-	-	
					Off-Peak	$0.09800				
A-10 TOU Transmission (Table B) Customers with high electric use and medium to high load factors generally benefit under Schedule A-10 TOU. Part of customer's bill varies according to the customer's maximum monthly electric demand.			**Summer**	$8.94	Peak	$0.12759	$0.90	($2.73)	($0.00861)	$0.12812
					Part-Peak	$0.12288			($0.00861)	
					Off-Peak	$0.10505			($0.00861)	
			Winter	$4.84	Part-Peak	$0.09981		-	-	
					Off-Peak	$0.08566				

A-10 (Table A) Customers with high electric use and medium to high load factors generally benefit under Schedule A-10. Part of a customer's bill varies according to the customer's maximum monthly electric demand.	$4.59959 per meter per day	$0.98563 per meter per day		**Secondary**	**Primary**	**Transmission**		**0.13741**	**Primary**	**Transmission**				
			Summer	$13.36	$12.61	$8.94		$0.14911	$0.13939	$0.11550	-	-	-	$0.17423
			Winter	$6.26	$6.48	$4.84		$0.11077	$0.10552	$0.09255	-	-	-	

[1/]Peak Day Pricing (PDP) (Consecutive Day and Four-Hour Event Option). All Usage During PDP Event. See specific tariff for further details.

[2/]Peak Day Pricing (PDP) (Consecutive Day and Four-Hour Event Option). See specific tariff for further details.

[3/]Based on estimated forecast. Average rates provided only for general reference, and individual customer's average rate will depend on its applicable kW, kWh, and TOU data.

Summer Season (May-October):

Peak Hours: 12:00 noon to 6:00 pm, Monday-Friday (except holidays)

Partial-Peak Hours: 8:30 am to 12:00 noon AND 6:00 pm to 9:30 pm, Monday-Friday (except holidays)

Off-Peak Hours: 9:30 pm to 8:30 am, Monday-Friday; All day Saturday, Sunday and holidays

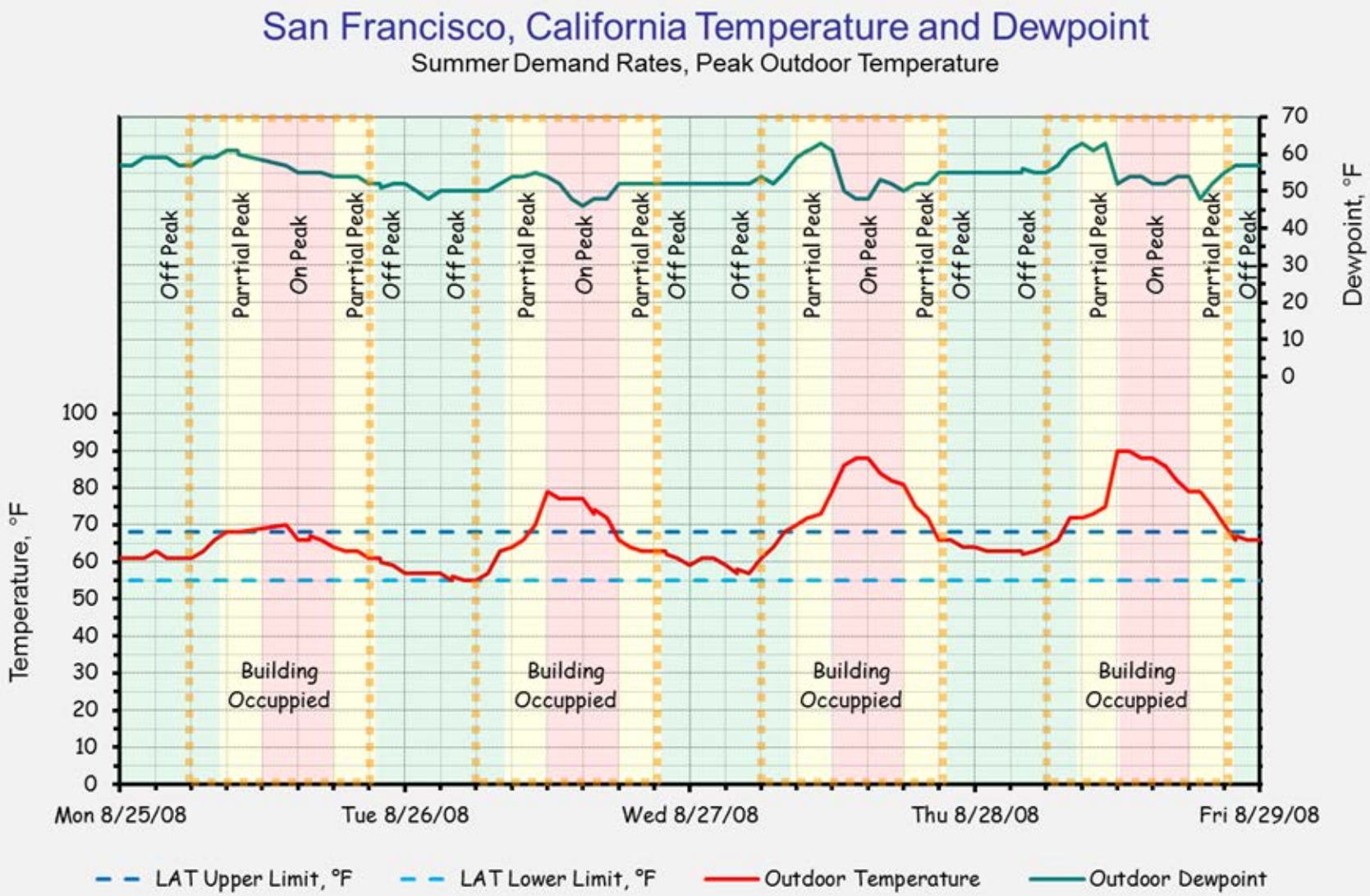
Winter Season (November-April):

Partial-Peak Hours: 8:30 am to 9:30 pm, Monday-Friday (except holidays)

Off-Peak Hours: 9:30 pm to 8:30 am, Monday-Friday (except holidays); All day Saturday, Sunday and holidays

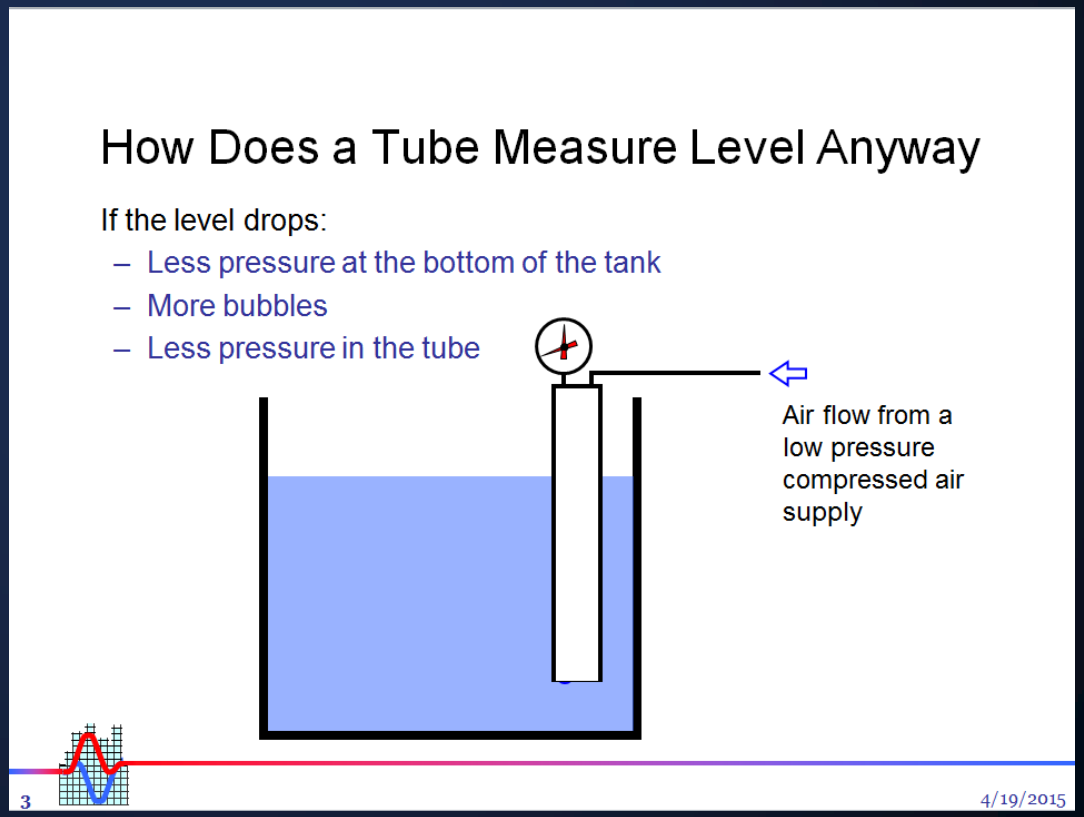
This table provided for comparative purposes only. See current tariffs for full information regarding rates, application, eligibility and additional options.

Souce file: Chiller Performance v1. xls


San Francisco, California Temperature and Dewpoint
Summer Demand Rates, Peak Outdoor Temperature
Temperature, °F
Dewpoint, °F
Off Peak
Parrtial Peak
On Peak
Building Occuppied
Mon 8/25/08
Tue 8/26/08
Wed 8/27/08
Thu 8/28/08
Fri 8/29/08
LAT Upper Limit, °F
LAT Lower Limit, °F
Outdoor Temperature
Outdoor Dewpoint

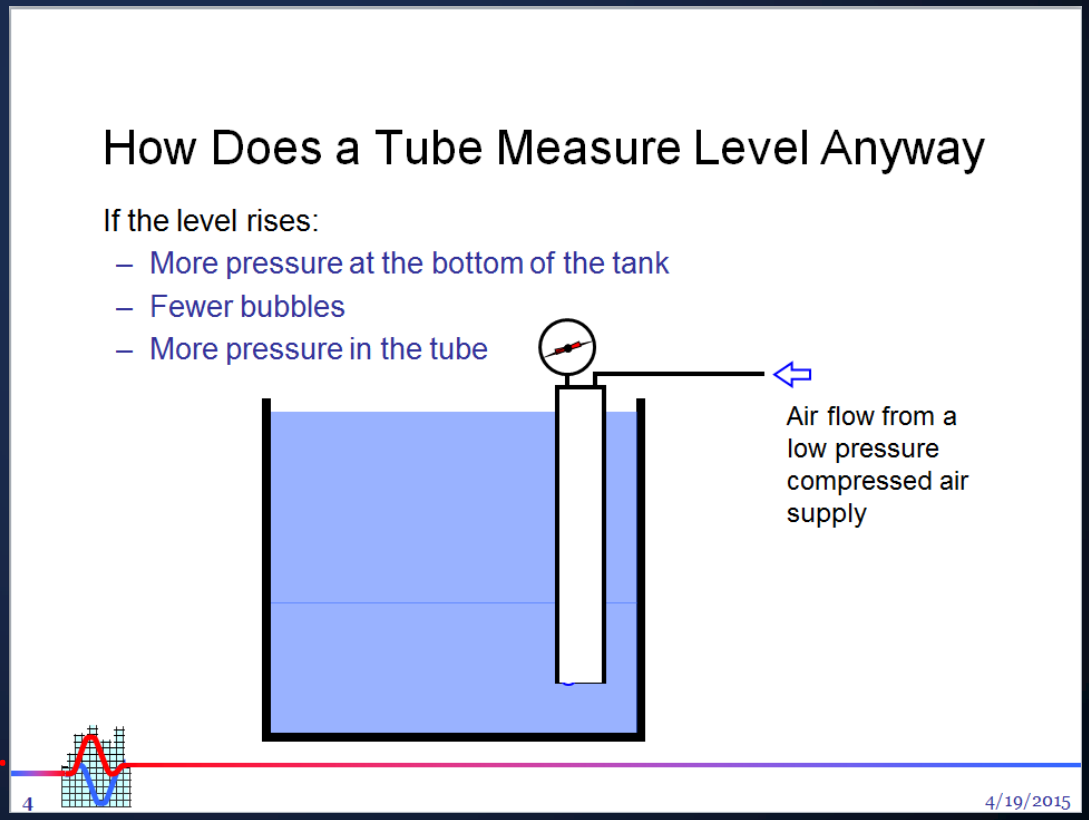
Additional measurement probes, cont.

Leveload ice inventory meter



Additional measurement probes, cont.

Leveload ice inventory meter



Data to show inability of ice inventory meter to accurately measure ice level…