Chilled Water System Optimization

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Chiller Plants: By The Numbers

Central Heating & Cooling Plant (CHCP)
• 10,000 tons
• 4 centrifugal chillers
• Primary/Secondary CHW pumps
• 5 cooling tower cells

Building Loads

40 million ton-hr/yr
12°F average ΔT
0.70 kW/ton (plant)
$0.07/kWh (average)
$2M annual cost

Thermal Energy Storage Plant (TES)
• 8,000 tons
• 4 centrifugal chillers
• Primary/Secondary CHW pumps
• 12 cooling tower cells
• 5 Mgal TES tank (40k to 50k ton-hr)
Electricity Rate

**Flat Rate**

\[
\frac{\text{Cost}}{Hr} = CX
\]

**Not Flat...**

\[
\frac{\text{Cost}}{Hr} = P_{DA,U}X_{DA,U} + C_{BR,FC}\frac{X_{BR,U}+X_{BR,HE}}{X_{BR,P}} + P_{RT,U}(X_{RT,U} - X_{DA,U}) - P_{DAM,EA}(X_{BR,U} + X_{BR,HE} - X_{BR,DP}) - P_{DCC}X_{BR,DP} + (P_{FP,CJ}X_{FP,P} - P_{DA,CJ}X_{FP,P})\frac{(X_{DA,U} - X_{BR,U})}{(X_{DAP} - X_{BR,P})}
\]
Opportunity

• Historical method of operation:
  • **Night**: Complete charging the tank
  • **Day**: Ride it out, use the tank
  • **Swing**: Turn on chillers, begin charging tank
More Opportunity
Project Goals

- System-wide approach
  - Improve the buildings (pilot and deploy)
  - Improve the plant
- Fast implementation
  - Steam-to-HW will cause changes
  - Get most savings with minimal effort
- Capital-free (or low capital)
- Collaborative partner
  - Implement and teach
  - Leverage in-house knowledge
- Fee limited by savings

ceed.ucdavis.edu/chcp
### Project Structure

**Chilled Water System**

- **Buildings**
  - UCD Energy Conservation Office (ECO)
    - Energy manager
    - Energy engineers
  - Smith Engineering building team
  - UCD Building Operators

- **Plant**
  - UCD Utilities
    - Plant operators
    - Plant management
    - Energy engineers
  - Smith Engineering plant team
  - UCD Researchers
SOLUTION – CHILLER PLANTS

• Focused around what's best for the customer.

• Maximize existing assets – The chiller you have is cheaper than the chiller you don’t have
  • Building work will reduce load, increasing capacity redundancy

• Training Training Training
  • Optimization will fail without training! Many abandoned optimization platforms out there.

• Logic is programmed into PLCs with adjustable constants – NO BLACK BOX
  • We use your programmer – Something breaks you can fix it
  • You lose the IP Network your plant still runs in near optimal

• Simple robust code
  • More important than the optimization function
    • Ex: Pump optimization – 1 to 2 or 3 is the answer
      • What happens when strainer is clogged, wear rings wear, flow meter fails, etc
      • Code will be abandoned if not robust
  • Simple is easy for new integrator to understand, complex will be commented out and start from scratch

• Complex solutions reside in PI
  • Economic dispatch
  • Load prediction
  • TES dispatch
  • Complex ML fault detection
**SOLUTION**

**Plants**
- Optimal Pump Staging
- Optimal Tower Staging
- Optimal Chiller Staging
- Optimal CHWST Reset
- Optimal DP Reset
- Optimal CW Control – Balance Tower, CW Pump, and Chiller Energy
- Optimal TES Dispatch

- Graphics clean-up
- Graphics with KPI

**Buildings**
- Optimized Air side Static Reset
- Optimized Air side SAT Reset
- Optimized AHU Economizer
- Ventilation Optimization
- Optimize Terminal Box Control
- Optimize CHW DP Reset
- Optimal HHW ST Reset
- Optimal HHW DP Reset
- Optimized Scheduling
- Optimal Start/Stop
- Optimal CHW Bridge Control
- Optimized Building DT

- Graphics clean-up
- Graphics with KPI
CHW Optimization
TRAINING, TRAINING, TRAINING

- Training is typically at the end... We start with training, before we make any changes,

Benefits:
1. Learn from operators
2. Builds Trust
3. Reduces Fear
4. Opens Lines of communication
5. Operators become part of the team

- Success without training is very low
LOW ENTERING CW TEMPERATURE

- ECWT must be above 70°F
  - Safe, but not optimal
  - Wastes enormous amounts of energy in the US
- Simple leaving CW must be 15°F above CHW supply
  - 45°F CHWST
  - LCWT must = 60°F
  - CWST ~ 55°F @ 5°FΔT

When running...
- The chiller can run steady state with very cold entering tower water. It is important to maintain a minimum 3 psid (20.7 kPaD) pressure differential as shown in Figure 2. The 3 psid (20.7 kPaD) minimum at all loads is nominally equivalent to a 15°F differential between leaving chilled water temperature and leaving condenser water temperature. For example, a chiller running at 40°F chilled water could operate with an entering condenser water temperature below 50°F, as long as the leaving condenser water temperature is greater than or equal to 55°F. If you have chillers with older controls, refer to previous revisions of this bulletin for pressure differential minimums.

Figure 2. Minimum condenser-evaporator refrigerant pressure differential
Strategies

• Optimal Pump Staging
• Optimal CHWST Reset (Drives chiller lift/power more than pump)
• Optimal DP Reset

\[
Power \ (HP) = \frac{Flow \ (GPM) \times Head \ (Ft)}{3,960 \times \eta}
\]
LARGE CAMPUS CHILLED WATER PUMP

\[ HP = \frac{\text{Flow} \times \text{Head}}{3960 \times \eta} \]

1. Flow: Campus dictates \(\Delta T\) and thus flow

2. Head: Too many valves to poll to perform DP reset; therefore hydraulically remote DPT determines pump head

3. \(\eta\) can never be greater than pump+motor+VFD BEP ~80%
PRINCETON CHW PUMP OPTIMIZATION
3 CHW Pumps

TDH: 135’
Total FLOW: 7,863 GPM
Ƞ: 56%
Total kW: 375
4 CHW Pumps

P-1 (On)

TDH: 133' FLOW: 1965 GPM η : 76%

P-2 (On)

TDH: 133' FLOW: 1965 GPM η : 76%

P-3 (On)

TDH: 133' FLOW: 1965 GPM η : 76%

P-4 (On)

TDH: 133' FLOW: 1965 GPM η : 76%

Total FLOW: 7,863 GPM
η: 76%

Total kW: 259
kW Reduction: 115
### Campus TES CHW Distribution Pumps – (4) 400hp Pumps

<table>
<thead>
<tr>
<th></th>
<th>Pre-Optimization</th>
<th>Cx and Operator Training</th>
<th>Stable Optimized Operation</th>
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<tbody>
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<td>Peak (kW)</td>
<td>609</td>
<td>350</td>
<td>215</td>
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<tr>
<td>Kwh Per day</td>
<td>7,701</td>
<td>4,583</td>
<td>2,525</td>
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</table>

![Graph showing power consumption over time](image-url)
CHW PUMP OPTIMIZATION

- Stage up at 1.8 and 2.8
  - Dwell timer set-point linear reset
    - X.8 = 2,000 Sec
    - X.99 = 20 Sec
- Stage down at 1.25 and 2.25
  - Dwell timer set-point linear reset
    - X.2 = 2,000 Sec
    - X.01 = 60 Sec
- If pumps speed reaches 90% stage up.

Pumps shall stage on and off based on the following formula.

\[
\text{Recommended Number of Pumps} = A + B \times \text{Flow} + C \times \text{Head} + D \times \text{Flow}^2 + E \times \text{Head}^2 + F \times \text{Flow} \times \text{Head}
\]

<p>| | | | | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>A</td>
<td>1.23100000000</td>
<td></td>
<td></td>
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<tr>
<td>B</td>
<td>0.00019400000</td>
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<td>C</td>
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<td>D</td>
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<td>E</td>
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</tr>
<tr>
<td>F</td>
<td>0.00000080000</td>
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</tbody>
</table>
4.7 PUMP OPERATION TO THE RIGHT OR LEFT OF THE BEST EFFICIENCY POINT (B.E.P.)

The impeller is subjected to axial and radial forces. The level of the radial force depends on the pressure within the casing and is taken up by the drive shaft bearings.

What are the consequences of operating to the right or left of the B.E.P.?

To the right of the B.E.P., or at high flows
Operating at the far right of the curve, near run-out point of the pump (point B, Figure 4-4) should be avoided. As flow increases, so does the N.P.S.H. required, and therefore cavitation is more likely to occur.

To the left of the B.E.P. or at low flows
Operation of centrifugal pumps at reduced capacity leads to a number of unfavorable results that may take place separately or simultaneously, and should be anticipated and circumvented. Some of these are:

- **Operating at less than best efficiency**
  On occasion, reduced flows may be required by the process. This can be accommodated by a variable speed drive, or by using several pumps. One or more pumps can then be shut down to provide the reduced flow.

- **Higher bearing load**
  If a pump is of a single volute design, it will be subjected to higher radial thrust, which will increase the load on the radial bearing. Therefore, the bearing life would be expected to diminish.

- **Temperature rise**
  As capacity is reduced, the temperature of the pumped liquid increases. To avoid exceeding permissible limits, a minimum flow by-pass is required.

- **Internal re-circulation**
  At certain flows below the best efficiency, all centrifugal pumps are subjected to internal re-circulation, in both the suction and the discharge area of the impeller. This can cause hydraulic surging and damage to the impeller metal, similar to that caused by classic cavitation, but taking place in a different area of the impeller.

There is also a net radial force whose level depends on the pressure level within the casing, and also on the position of the operating point with respect to the B.E.P.. This force increases rapidly the further away the operating point (see Figure 4-15) gets from the B.E.P. of the pump (for more information see reference 16).
DP RESET – HEAD REDUCTION

CHW Pump DP Control

10 psid

VFD

80%

Speed

40%

Chiller

50%

60%

70%

Chiller

CHW Pump DP Control – with DP Reset

4 psid

VFD

45%

Speed

70%

80%

90%

Chiller
Strategies

- Limit flow through decoupler
- Optimize Load on chiller
DECOUPLER
CONSTANT SPEED PRIMARY PUMPING

Chiller
Load

Primary Pump
Secondary Pump

40 F
50 F
10,000 GPM
50 F

0 GPM
40 F

10,000 GPM

40 F
40 F
40 F

UCDAVIS FACILITIES
SMITH ENGINEERING
DECOUPLER
CONSTANT SPEED PRIMARY PUMPING

Chiller
50 F

Primary Pump
7,500 GPM
40 F

Secondary Pump
40 F

VFD
0 GPM
40 F

Load
50 F

40 F

7,500 GPM
TOWERS

vapor pressure = 23.8 torr

liquid H₂O at 25°C

small surface area

large surface area
CW OPTIMIZATION – COUNTERFLOW

Cooling Towers

- Fan on High Speed
- Falling Water
- Water Channeling in Fill
- Reduced Flow Rate
CW OPTIMIZATION – CROSSFLOW

Cooling Towers

Fan Affinity Law

Fan Power varies with x^3 of flow

50 HP at ½ speed = 6.25 HP
Open Valve, leave open except the event a cell fan in not functional

Requires Programming
PUMP TOWER INTERCONNECT - C-PLANT

Program to keep valves open

Requires Programming
Chillers
CHCP CWST OPTIMIZATION

CWST SP = A - B * % Tower Load + C * WB
Max Value = 83F
Min Value = Chiller CHWST + 15F or 55F, whichever is greater
A = X
B = Y
C = Z
A, B, C – TO BE DETERMINED
# TES CW PUMP ISSUES

All pumps except CP-4 are short on flow. Needs further investigation (TESTING).

<table>
<thead>
<tr>
<th>Pump ID</th>
<th>CP-1</th>
<th>CP-2</th>
<th>CP-3</th>
<th>CP-4</th>
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<tr>
<td>Condenser Water Design Flow Rate</td>
<td>GPM</td>
<td>6,000</td>
<td>6,000</td>
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<td>Condenser Water Actual Flow Rate</td>
<td>GPM</td>
<td>5,501</td>
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<tr>
<td>Percent Deficit or Surplus</td>
<td>%</td>
<td>-9.1%</td>
<td>-6.5%</td>
<td>-5.4%</td>
</tr>
</tbody>
</table>
• Pump has a small amount of damage, most likely worn wear rings. Pump requires rebuild.
• Pump is low on flow due to poor performance, but more importantly a flow restriction on the CW return.
CH-1&2 CW
Reduce kW as much as possible 6PM-8PM

<table>
<thead>
<tr>
<th></th>
<th>kW/Ton</th>
<th>$/MWh</th>
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<tr>
<td>Max</td>
<td>1.1</td>
<td>$70</td>
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<tr>
<td>Min</td>
<td>0.65</td>
<td>$20</td>
</tr>
<tr>
<td>Max/Min</td>
<td>1.69</td>
<td>3.5</td>
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</tbody>
</table>

$ = 10,000 Tons * 1.1kW/Ton * $0.02 = $220

$ = 10,000 Tons * 0.65kW/Ton * $0.07 = $455
Leaving 30-40% Capacity in the tank

Peak Tonnage ~16,000 Tons

Total Plant Capacity = 18,000 Tons
N+1 Capacity = 17,000 Tons

Probabilistic Failure Analysis Looks Even Better

Cost of Fear?
TES - SENSIBLE – VS – LATENT TES

- Sensible is better for the following reasons
  - No toxic ethylene glycol and glycol management
  - No dedicated TES chillers
  - No energy penalty to generate TES
  - No Chiller surge at high CW water temps – lower lift
  - Less equipment to buy and maintain
  - Can Partial Charge – Latent cannot partial charge
  - Less complicated
  - **Latent has a max discharge rate whereas sensible does not – Most important**

- For these reasons any new TES plant is sensible except for those sites which don’t have the space. The last 15 years has seen many more ton-hrs of sensible installed than latent. The only benefit of Ice is the space, all else is negative. Use ice storage when space is a concern.

- **Site already has sensible**
TES TANK - IMPROVED DT

- Roughly 40,000 Ton-hrs
- Every degree of DT is about 3,300 Ton-Hrs of additional storage with the existing system
  - Increased by
    - Storing colder
    - Warmer CHWR
    - Increased storage volume
CHILLED WATER STORAGE CAPACITY

- **4.8M Gallons**
- **40,000 ton-hrs**
- **39/51 degF CHWS/R**
- **12 degF DT**

- **62F**
- **24F DT**

- **4.8M Gallons**
- **80,000 ton-hrs**
- **38/60 degF CHWS/RT**
- **24 degF DT**
1. **1,000 Ton-hrs of storage reduce the peak by 0.65 MW**
   - Assumes shedable generation is at 0.65 kw/ton. Which is reasonable.
   - Assumes the system can discharge the entire 1,000 Tons in one hour. Which we can with sensible storage.
1. 1,000 Ton-hrs of storage reduce the peak by 0.65 MW -
   - Assumes shedable generation is at 0.65 kw/ton. Which is reasonable.
   - Assumes the system can discharge the entire 1,000 Tons in one hour. Which we can with sensible storage.
Traditional non-linear regression analysis allows 2D M&V normalization

Machine learning allows for limitless dimensional normalization and prediction
CHILLER SCREEN (IN PROGRESS)
### CHILLER SCREEN (IN PROGRESS)

#### Parameters

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<tr>
<th>Parameter</th>
<th>CH-2A</th>
<th>CH-1B</th>
<th>CH-1A</th>
<th>CH-2B</th>
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Building Optimization
Robert Mondavi Institute

Jess S. Jackson Sustainable Winery Building

Teaching and Research Winery

August A. Busch III Brewing and Food Science Laboratory

California Processing Tomato Industry Pilot Plant

Good Life Garden

Viticulture and Enology Teaching Vineyard

Robert Mondavi Institute Sensory

Robert Mondavi Institute North

Robert Mondavi Institute South
<table>
<thead>
<tr>
<th>AIR HANDLER</th>
<th>SUPPLY AIR SET POINT</th>
<th>SUPPLY AIR TEMPERATURE</th>
<th>HEATING COIL VALVE OR MIX AIR DAMPER</th>
<th>COOLING COIL VALVE</th>
<th>SUPPLY FAN RETURN FAN</th>
<th>AVG RM TEMP</th>
<th>SUPPLY STATIC PRESSURE</th>
<th>SMOKE DETECTOR</th>
<th>Reset</th>
<th>SP Culprit</th>
<th>SP Max Term</th>
<th>SAT Culprit</th>
<th>SAT Max Term</th>
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<tbody>
<tr>
<td>AHU 4-1</td>
<td>NORMAL 55.0 DEG F</td>
<td>NORMAL 55.2 DEG F</td>
<td>NORMAL 0 %</td>
<td>NORMAL ON</td>
<td>NORMAL 72.7 DEG F</td>
<td>NORMAL 1.59 in WC</td>
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<td>RESET</td>
<td>14</td>
<td>76</td>
<td>6</td>
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<td>NORMAL 56.0 DEG F</td>
<td>NORMAL 0 %</td>
<td>NORMAL ON</td>
<td>NORMAL 72.0 DEG F</td>
<td>NORMAL 1.96 in WC</td>
<td>NORMAL OFF</td>
<td>RESET</td>
<td>15</td>
<td>97</td>
<td>16</td>
<td>56</td>
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</tr>
<tr>
<td>AHU 4-3</td>
<td>NORMAL 62.3 DEG F</td>
<td>NORMAL 56.0 DEG F</td>
<td>NORMAL 0 %</td>
<td>NORMAL ON</td>
<td>NORMAL 71.2 DEG F</td>
<td>NORMAL 1.60 in WC</td>
<td>NORMAL OFF</td>
<td>RESET</td>
<td>14</td>
<td>100</td>
<td>9</td>
<td>100</td>
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</tr>
<tr>
<td>AHU 4-4</td>
<td>NORMAL 55.0 DEG F</td>
<td>NORMAL 55.8 DEG F</td>
<td>NORMAL 0 %</td>
<td>NORMAL ON</td>
<td>NORMAL 69.3 DEG F</td>
<td>NORMAL 1.17 in WC</td>
<td>NORMAL OFF</td>
<td>RESET</td>
<td>31</td>
<td>78</td>
<td>3</td>
<td>100</td>
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</tr>
<tr>
<td>AHU 4-5</td>
<td>NORMAL 65.0 DEG F</td>
<td>NORMAL 57.8 DEG F</td>
<td>NORMAL 0 %</td>
<td>NORMAL ON</td>
<td>NORMAL 73.1 DEG F</td>
<td>NORMAL 0.79 in WC</td>
<td>NORMAL OFF</td>
<td>RESET</td>
<td>22</td>
<td>96</td>
<td>12</td>
<td>66</td>
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</tr>
<tr>
<td>AHU 4-6</td>
<td>NORMAL 60.8 DEG F</td>
<td>NORMAL 55.5 DEG F</td>
<td>NORMAL 0 %</td>
<td>NORMAL ON</td>
<td>NORMAL 72.6 DEG F</td>
<td>NORMAL 0.80 in WC</td>
<td>NORMAL OFF</td>
<td>RESET</td>
<td>19</td>
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<td>100</td>
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</tr>
<tr>
<td>AHU 3-1</td>
<td>NORMAL 56.5 DEG F</td>
<td>NORMAL 56.8 DEG F</td>
<td>NORMAL 0 %</td>
<td>NORMAL ON</td>
<td>NORMAL 71.8 DEG F</td>
<td>NORMAL 0.50 in WC</td>
<td>NORMAL OFF</td>
<td>RESET</td>
<td>8</td>
<td>81</td>
<td>17</td>
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</tbody>
</table>

OAT: 73.6 DEG F, OAH: 37.14 % RH
20% CFM savings of 100% OA (CHW, Steam, Fan savings).

- 2459, 2611, 2612, 2627 Lab Room Controller (LRC)

Currently at 7.2 ACH (but requires manual calc to determine this)

Does not control to temperature deadband

Displays and controls down to min ACH setpoint (6 ACH)

No reheat, less CFM

Allow for day and night space temp deadband
BUILDING M&V SCREEN
Key Take-Aways

• Chilled water optimization through buildings and plant changes
• Plant:
  • Utilize the equipment already owned
  • Understand the rate
  • Use TES to advantage, not to disadvantage
• Buildings:
  • Successful pilot of changes that can be applied at other buildings
• Collaborative partners
• Project funded by savings
• Consultant fee tied to savings goals