Optimizing Chilled Water Plant Design & Controls

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Agenda

- Chilled Water Distribution System Selection
- Determining Optimized Sequences
- Chilled Water Pump Control
- Chilled Water Temperature and DP Setpoint Reset
- Tower Fan Speed Control
- Condenser Water Pump Control
- Chiller Staging
- Waterside Economizer Control

Primary Resources

- **Optimized Design & Control of Chilled Water Plants, ASHRAE Journal**
  - Part 1: Chilled Water Distribution System Selection
  - Part 2: Condenser Water Distribution System Design
  - Part 3: Pipe Sizing and Optimizing ΔT
  - Part 4: Chiller & Cooling Tower Selection
  - Part 5: Optimized Control Sequences
- **All are available at no charge from http://www.taylor-engineering.com/publications/articles.shtml**

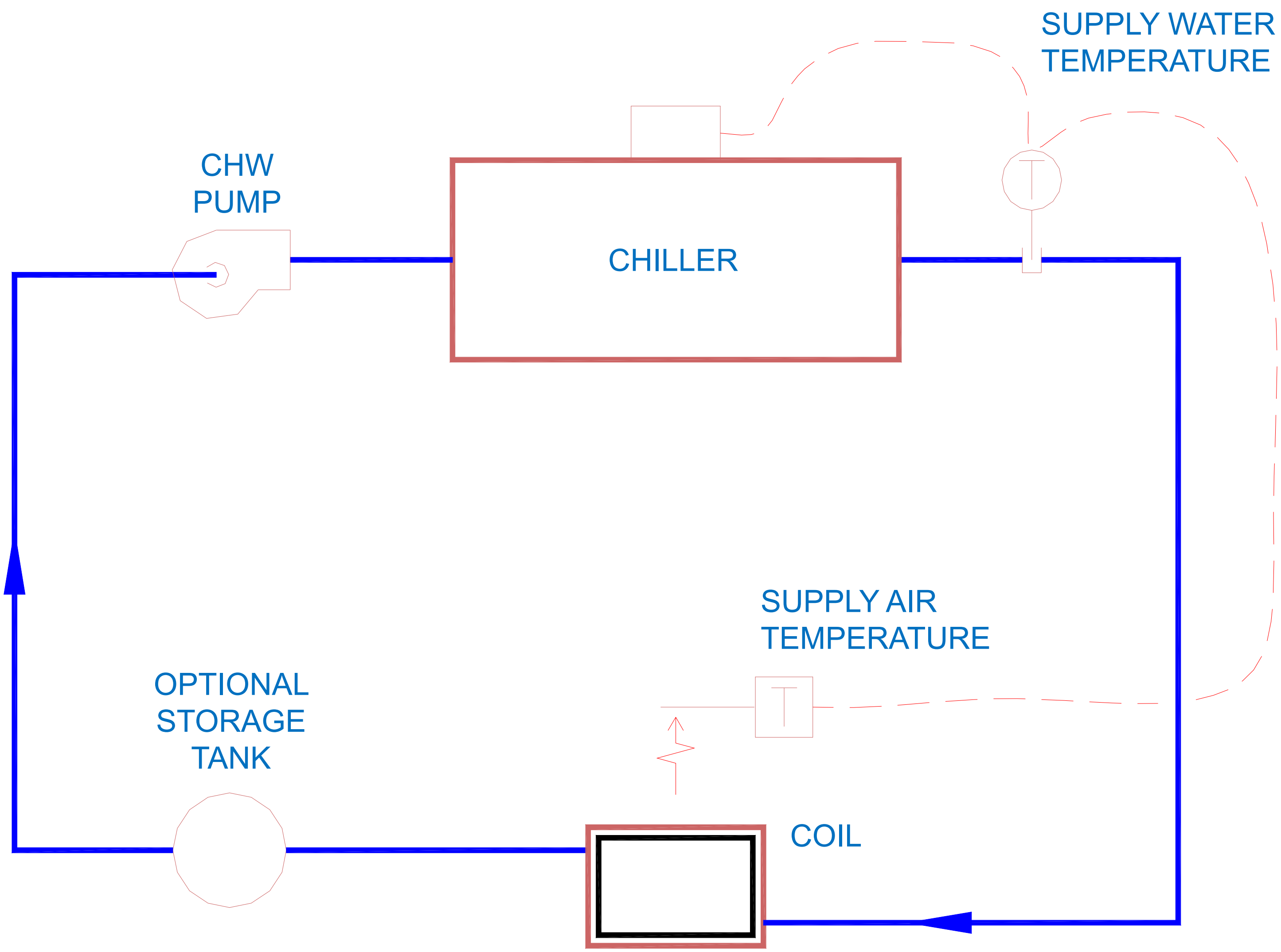
Optimizing Energy Usage

- **Chillers**
  - Type, efficiency, size, VSD
- **Cooling Towers**
  - Fan type, efficiency, approach, range, speed control, flow turndown
- **Chilled Water Pumps**
  - Arrangement, flow rate (delta-T), pressure drop, VSD
- **Condenser Water Pumps**
  - Flow rate (delta-T), pressure drop
- **Air Handling Units**
  - Coil sizing, air-side pressure drop, water-side pressure drop

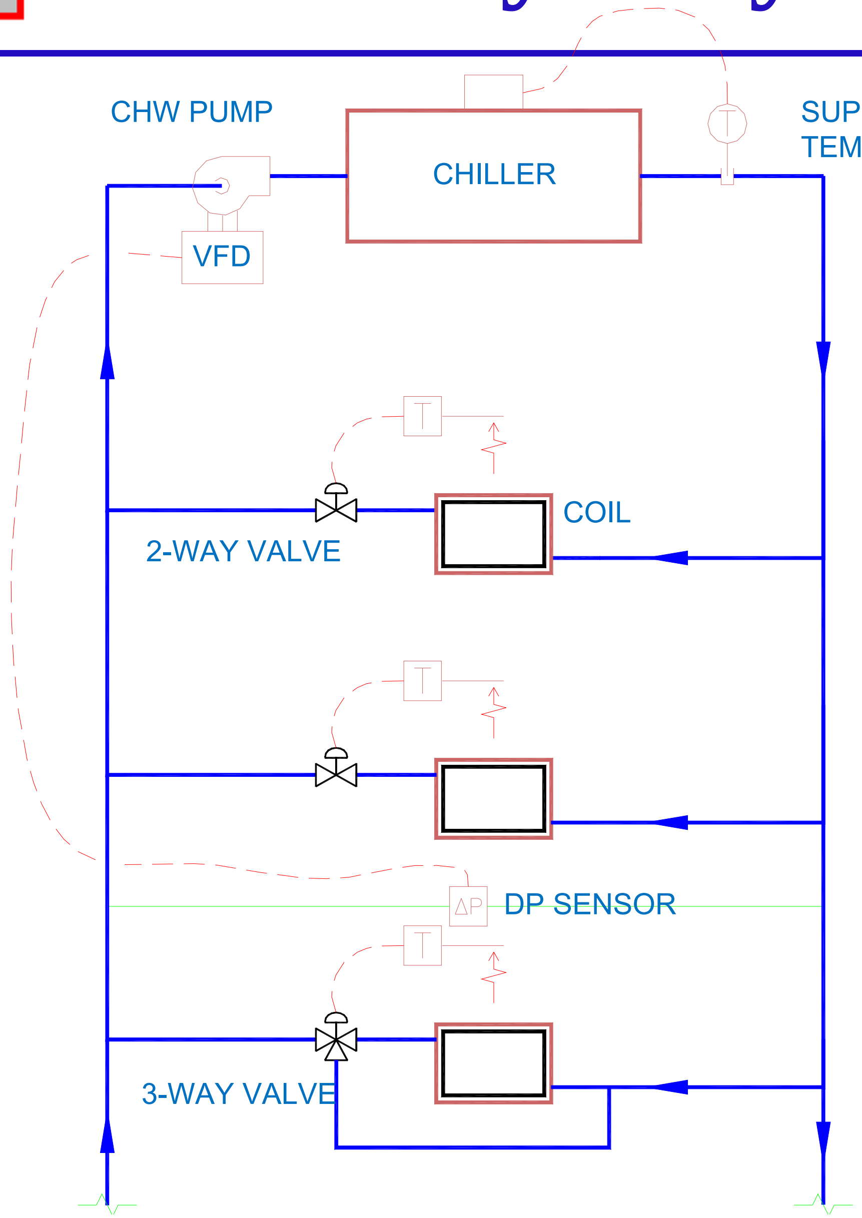
Recommended
Chilled Water Distribution Arrangement

Independent Variables			Recommended System	
Number of Coils/Loads Served	**Number of Chillers**	**Size of Coils/Loads Served**	**Control Valves**	**Distribution Type**
One	Any	Any	None	Primary-only single coil
More than one	One	Small (< ~100 gpm)	2-way and 3-way	Primary-only, single chiller
Few coils serving similar loads	More than one	Small (< ~100 gpm)	3-way	Primary-only constant flow
Many coils serving similar loads or any serving dissimilar loads	More than one	Small (< ~100 gpm)	2-way	Primary-Only or Primary-Secondary
More than one	Any	Large Campus	2-way	Primary−Distributed Secondary
More than one	Any	Large coils (> ~100 gpm)	None	Primary−Coil Secondary

Single Coil – Single Chiller



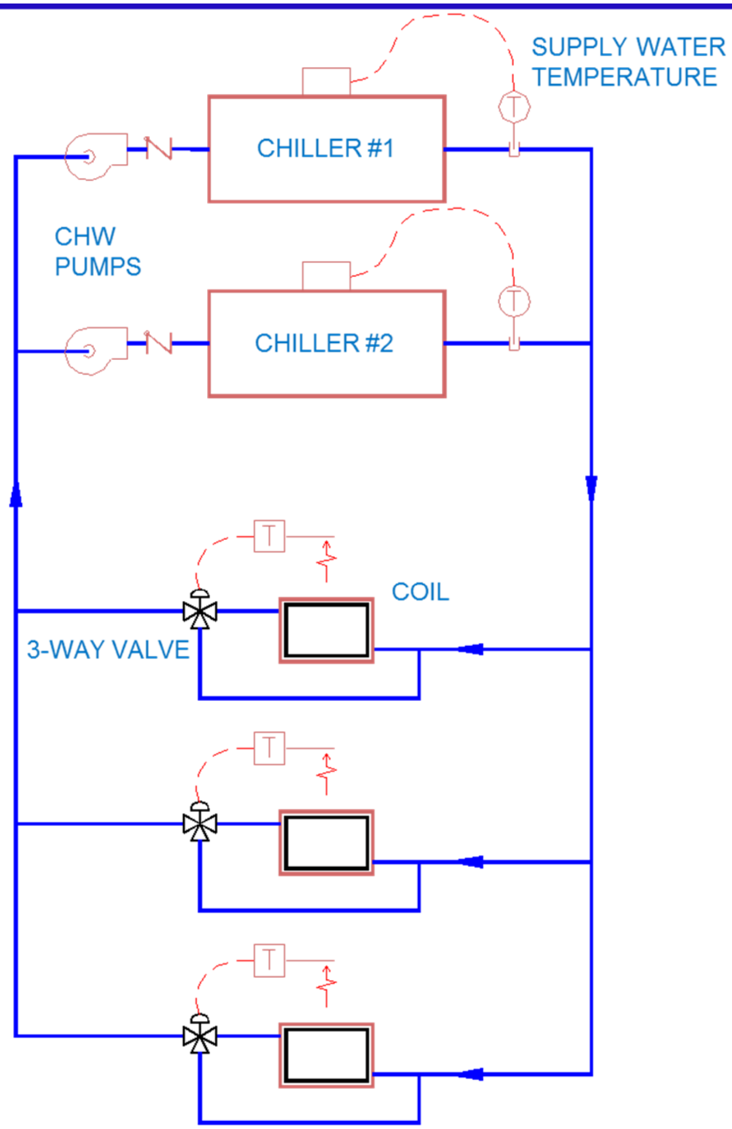
Primary-only - Single chiller



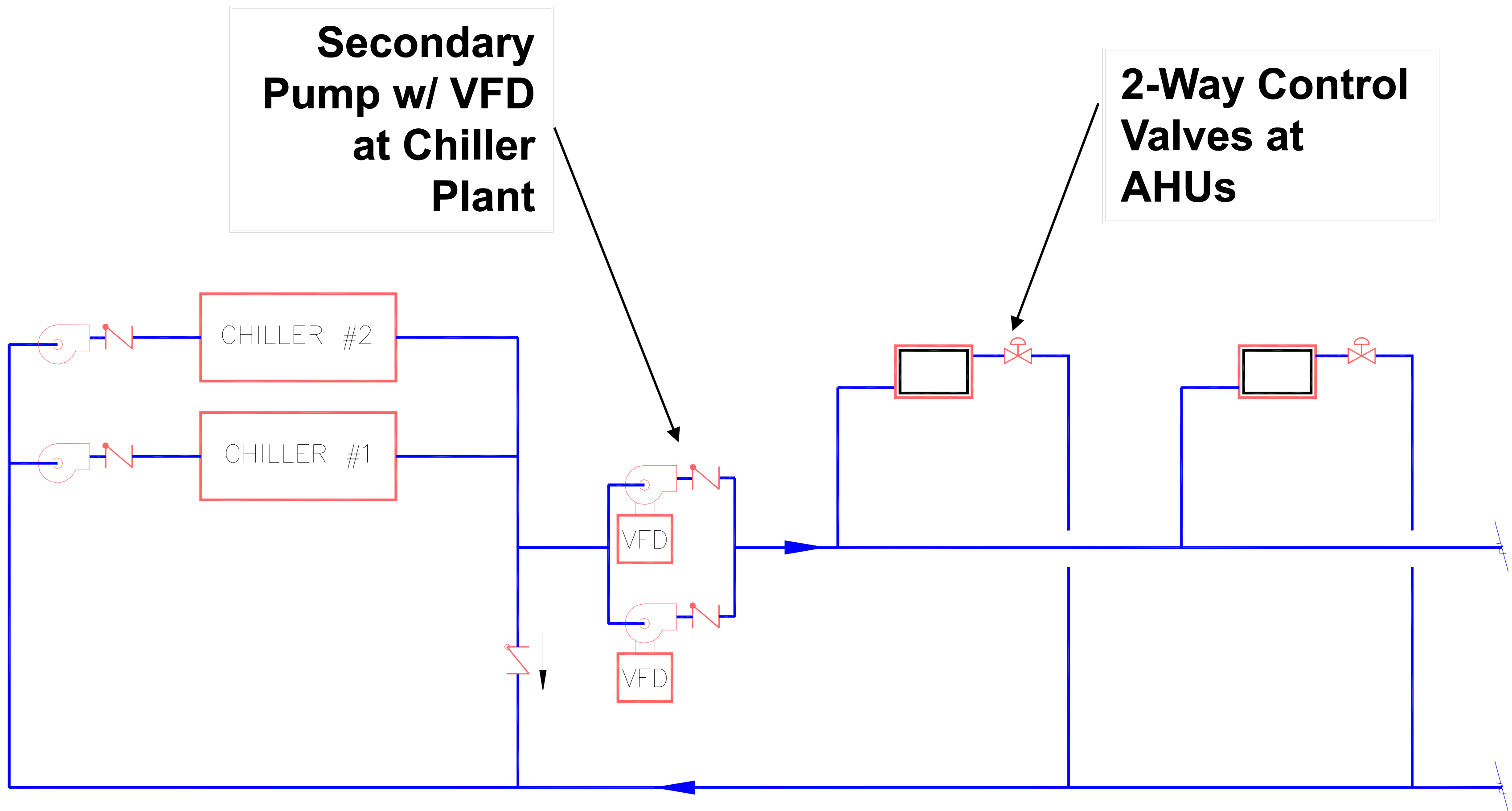
3-Way Valve

- Sized for minimum flow of chiller
- Locate at end of system
  - Engage mass
  - Retain self-balancing

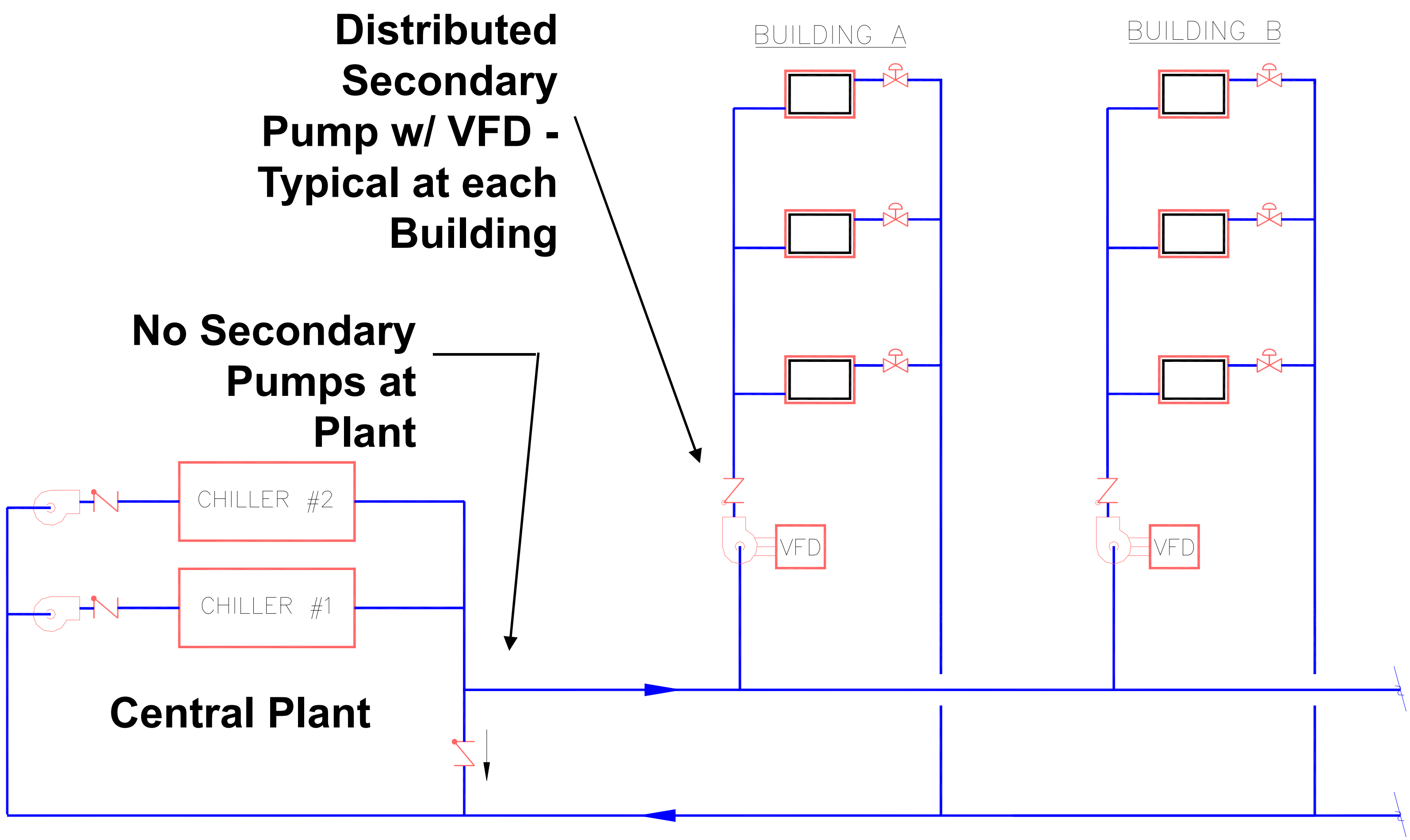
Primary-only Constant Flow



Primary/Secondary



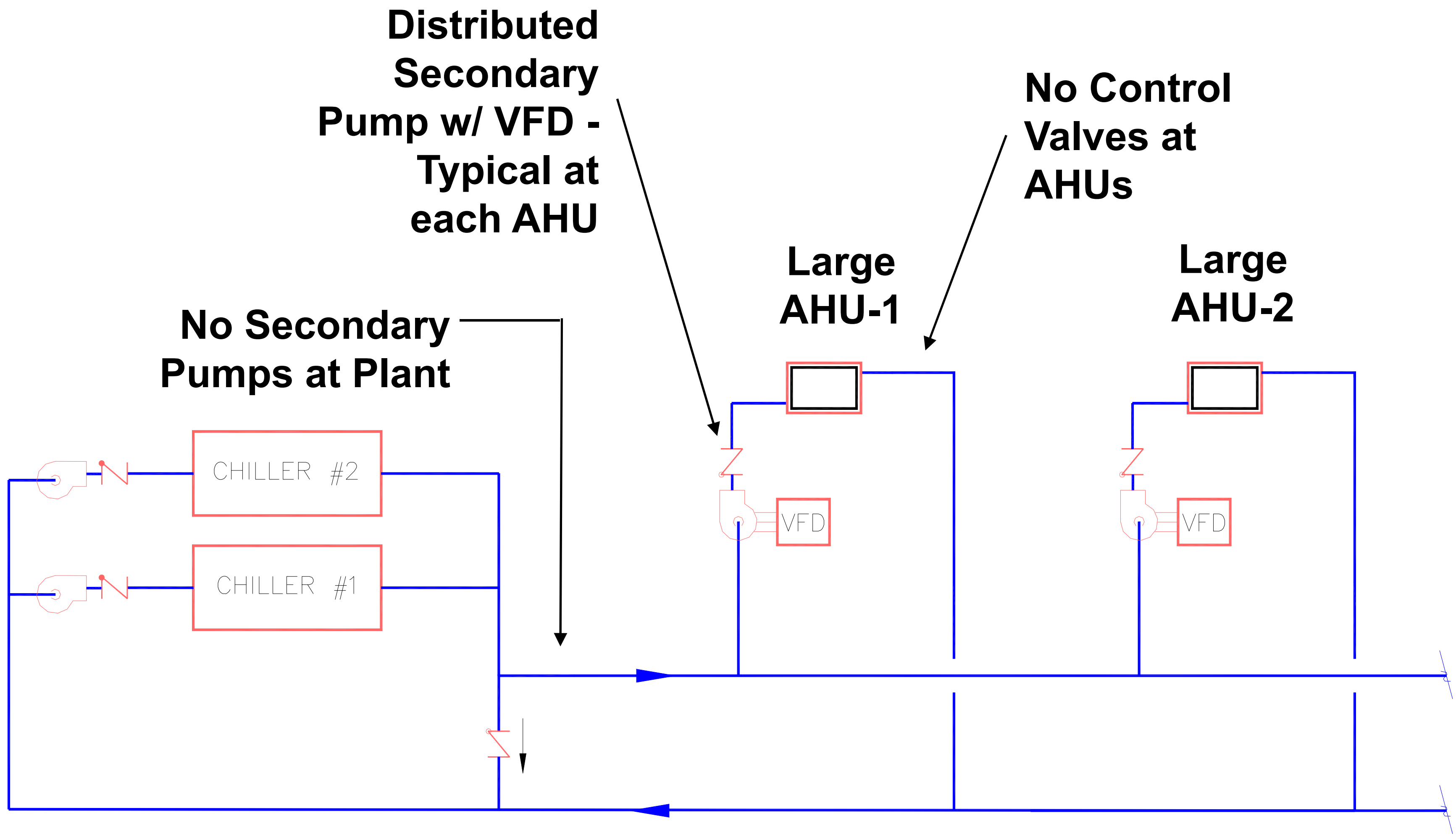
Primary/Distributed Secondary



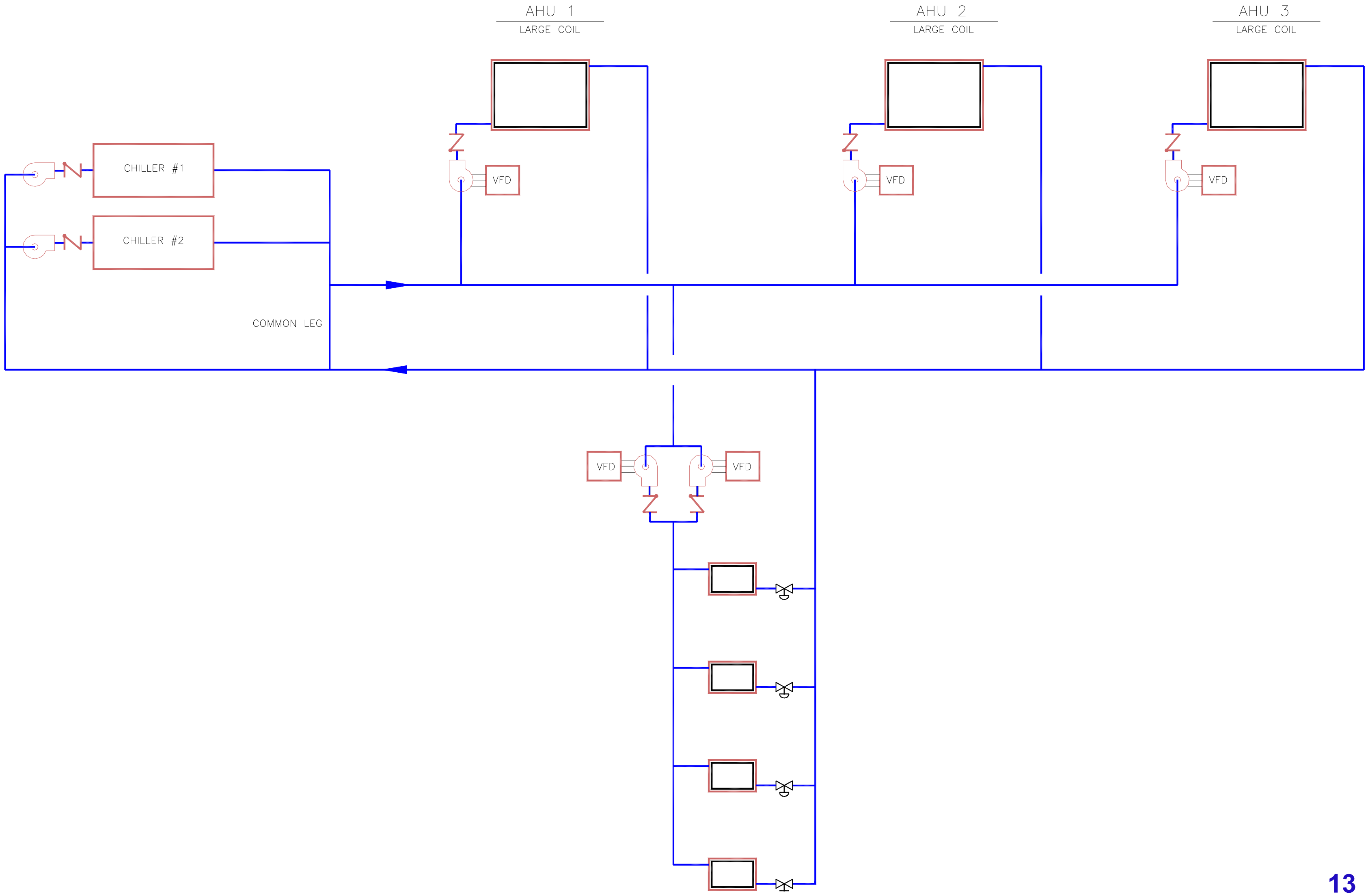
Distributed P/S versus Conventional P/S or P/S/T

- **Advantages**
  - Reduced Pump HP - Each Pump Sized for Head From Building to Plant
  - Self-balancing
  - No Over-pressurized Valves at Buildings Near Plant
  - Reduced Pump Energy, Particularly When One or More Buildings Are off Line
  - No Expensive, Complex Bridge Connections Used in P/S/T Systems
  - Similar or Lower First Costs
- **Disadvantages (vs. P/S)**
  - Pump room needed at building
  - Higher expansion tank pre-charge and size

Primary/Coil Secondary



Hybrid systems



Advantages of VFD Coil Pumps versus Conventional P/S system

- **Reduced Pump HP**
  - Each pump sized for head from coil to plant
  - Eliminated 10 feet or so for control valves
- **Self-balancing**
  - No need for or advantages to balancing valves, reverse return
- **Lower Pump Energy**
  - No minimum DP setpoint
  - Pump efficiency constant
- **Better Control**
  - Smoother flow control - no valve hysteresis
  - No valve over-pressurization problems
- **Usually Lower First Costs Due to Eliminated Control Valves, Reduced Pump and VFD HP**

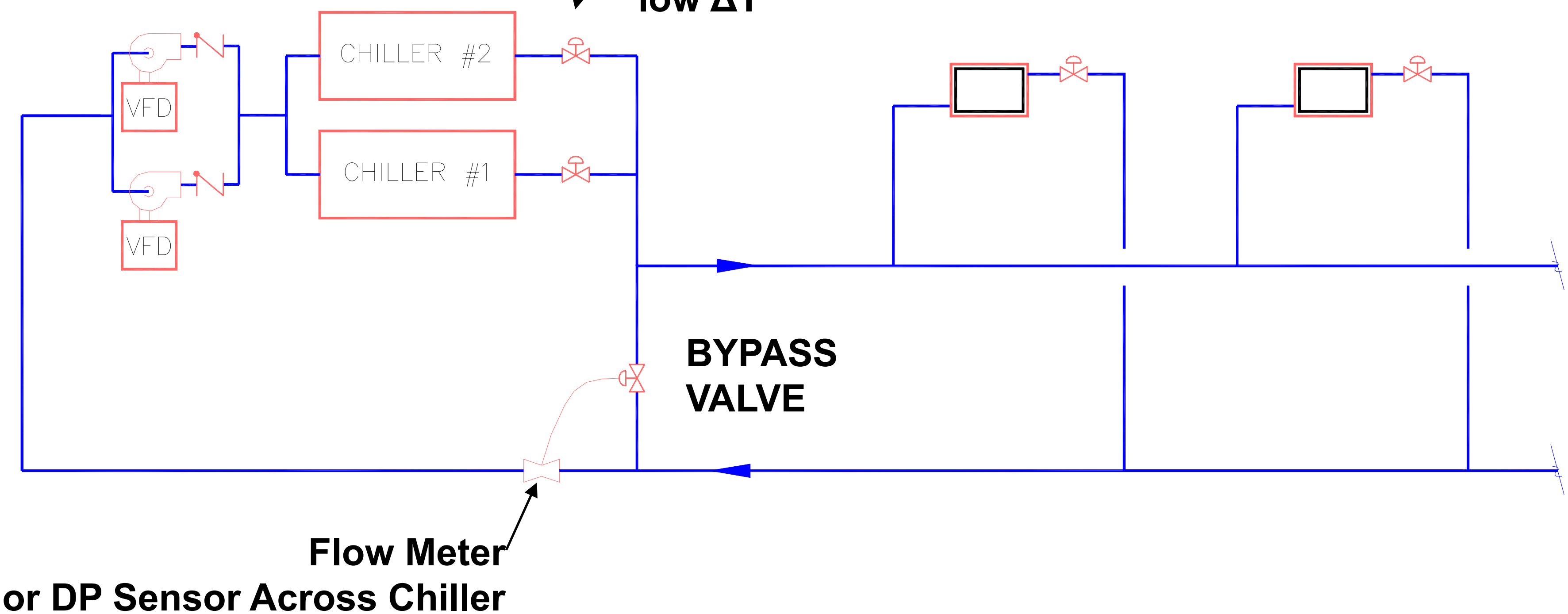
Disadvantages of VFD Coil Pumps versus conventional P/S system

- **Cannot Tap into Distribution System without Pump**
  - May be problem with small coils (low flow, high head pump)
- **Possible Reduced Redundancy/Reliability unless Duplex Coil Pumps are Added**
- **Possible Low Load Temperature Fluctuations**
  - Minimum speed on pump motor
  - May need to cycle pump at very low loads

Primary-only System

Headered Pumps & Auto Isolation Valves Preferred to Dedicated Pumps:

- **Allows slow staging**
- **Allows 1 pump/2 chiller operation**
- **Allows 2 pump/1 chiller operation if there is low ΔT**

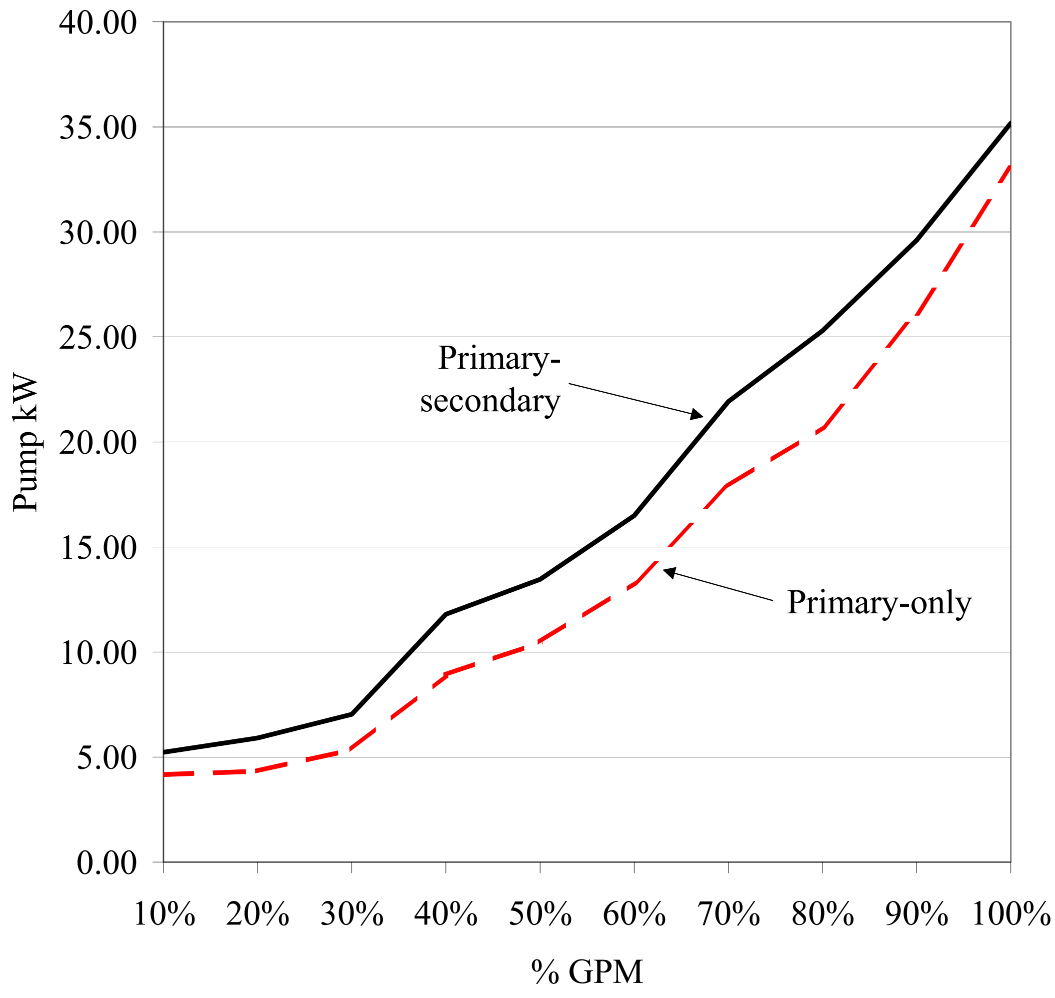


Advantages of primary-only versus primary/secondary system

- **Lower First Costs**
- **Less Plant Space Required**
- **Reduced Pump HP**
  - Reduced pressure drop due to fewer pump connections, less piping
  - Higher efficiency pumps (unless more expensive reduced speed pumps used on primary side)
- **Lower Pump Energy**
  - Reduced connected HP
  - “Cube Law” savings due to VFD and variable flow through both primary and secondary circuit

Pump Energy

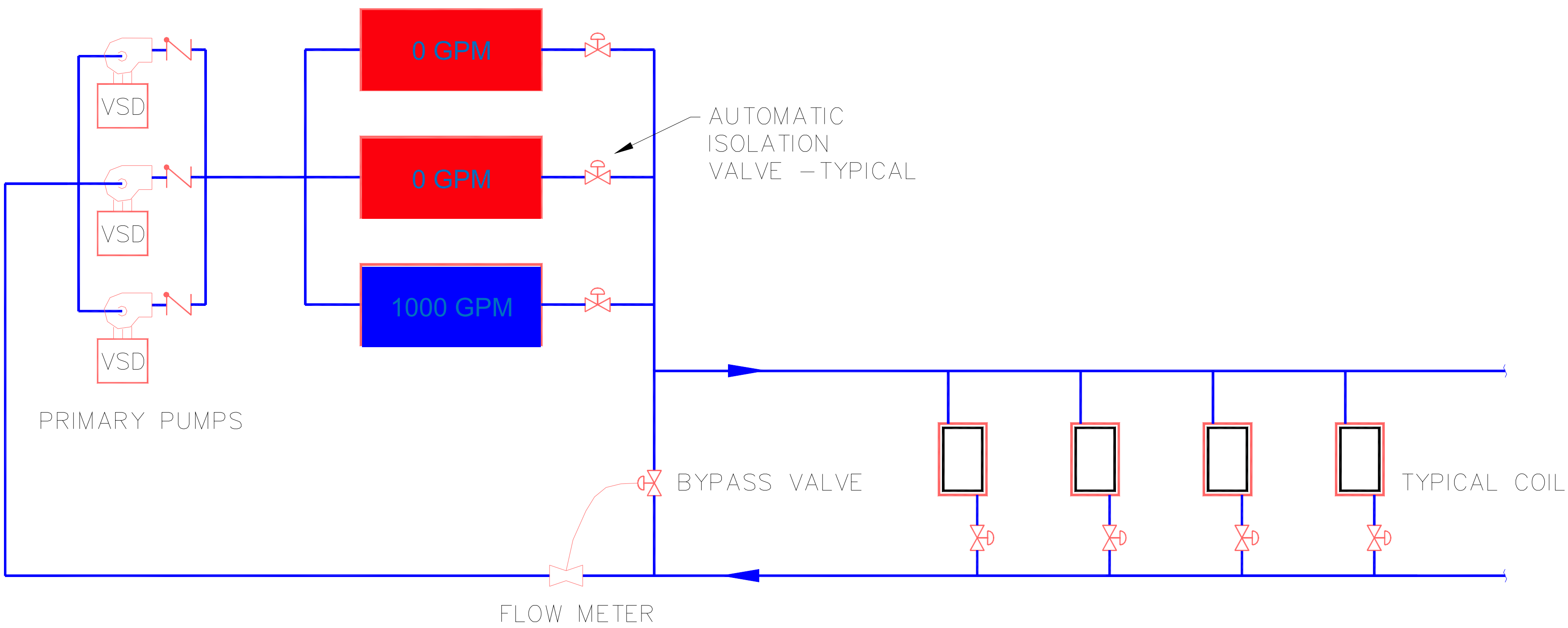
Primary vs. Primary/Secondary (3-chiller plant)



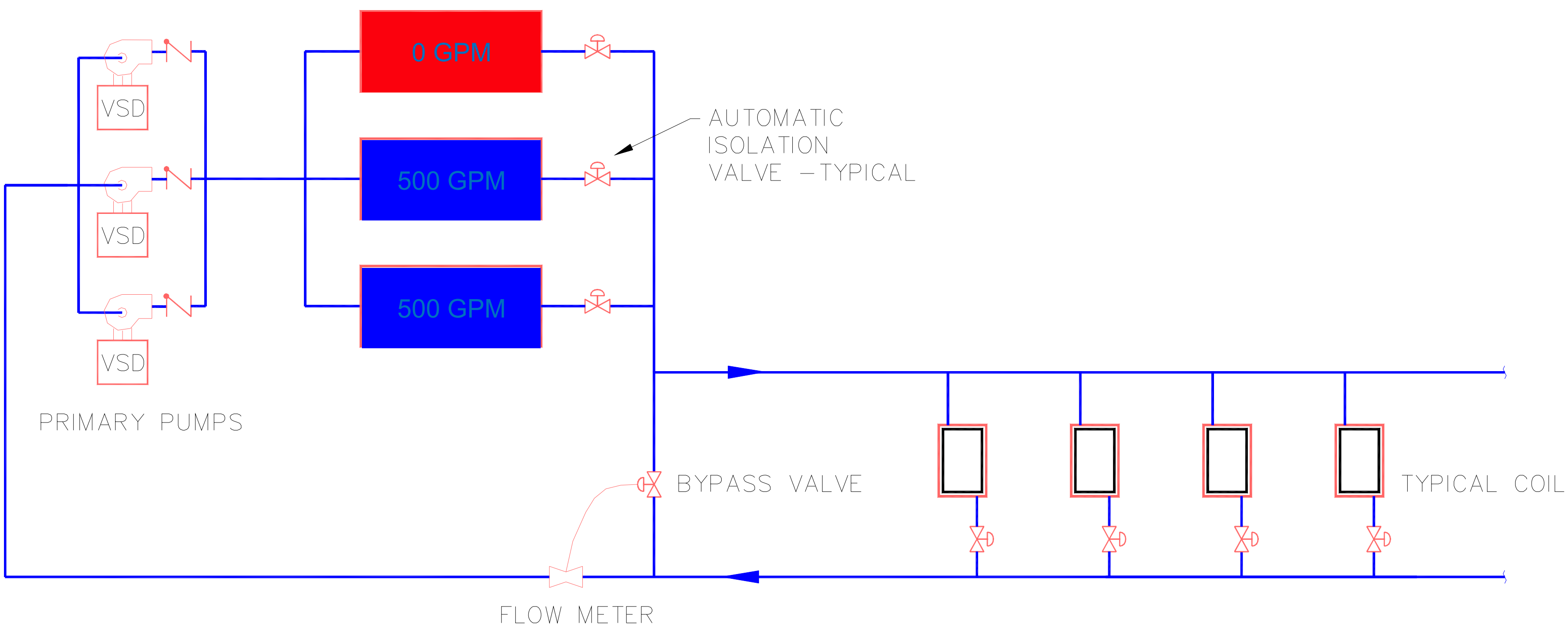
Disadvantages of primary-only versus primary/secondary system

- **Failure of Bypass Control**
  - Not as fail-safe - what if valve or controls fail?
  - Must avoid abrupt flow shut-off (e.g. valves interlocked with AHUs all timed to stop at same time)
  - Must be well tuned to avoid chiller short-cycling
- **Flow Fluctuation when Staging Chillers On**
  - Flow drops through operating chillers
  - Possible chiller trips, even evaporator freeze-up
  - Must first reduce demand on operating chillers and/or slowly increase flow through starting chiller; causes temporary high CHWS temperatures
- **(Problems above are seldom an issue with very large plants, e.g. more than 3 chillers)**

Primary-only System Staging



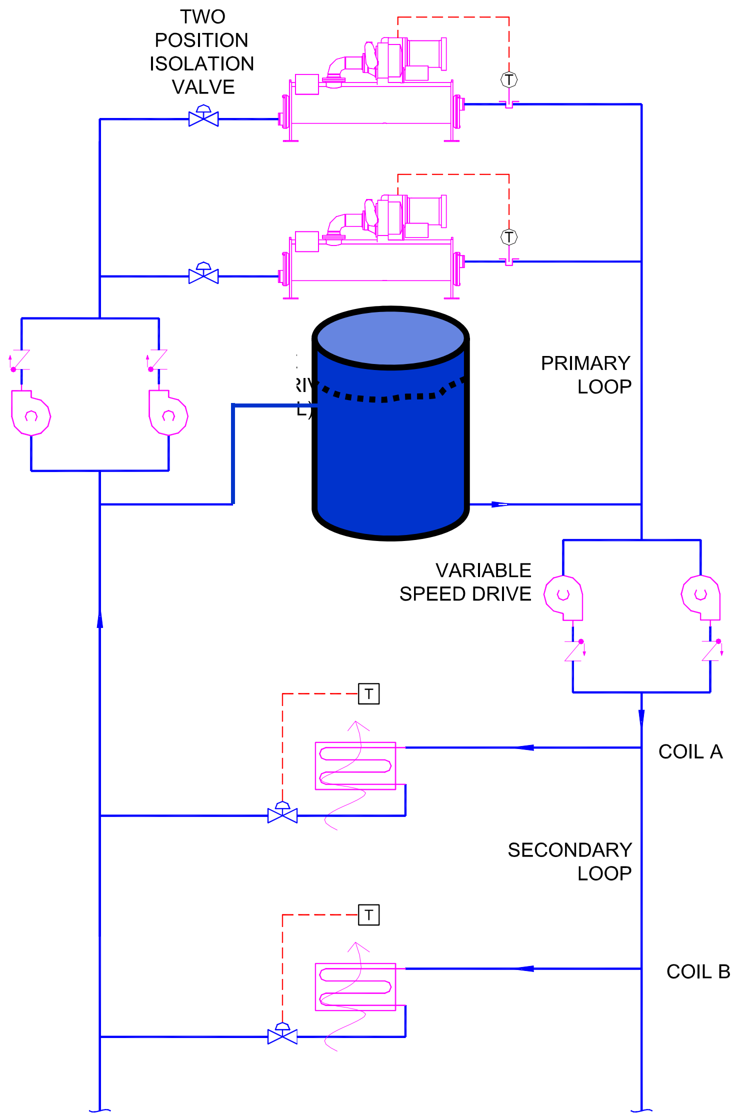
Primary-only System Staging



Variable Flow

Primary/Secondary with CHW Storage

- **Advantages**
  - Peak shaving
  - Simplifies chiller staging
  - Provides back-up for chiller failure
  - Secondary water source for fire department
  - Secondary water source for cooling towers
- **Disadvantages**
  - Installed cost
  - Space



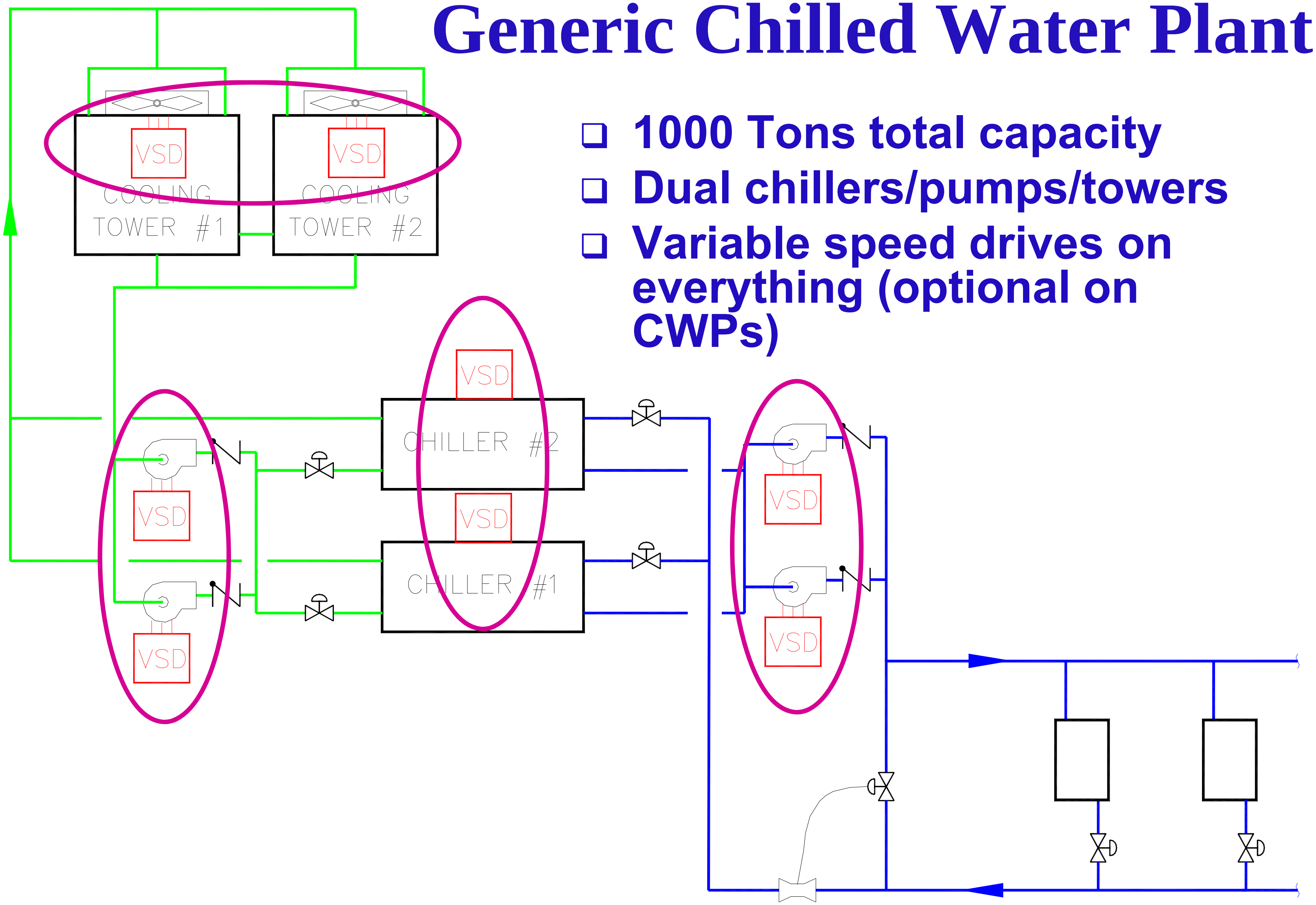
Primary-only vs. Primary/Secondary

- **Use Primary-only Systems for:**
  - Plants with many chillers (more than three) and with fairly high base loads where the need for bypass is minimal or nil and flow fluctuations during staging are small due to the large number of chillers; and
  - Plants where design engineers and future on-site operators understand the complexity of the controls and the need to maintain them.
- **Otherwise Use Primary-secondary**
  - Also for plants with CHW storage

Optimizing Control Sequences

Generic Chilled Water Plant

- 1000 Tons total capacity
- Dual chillers/pumps/towers
- Variable speed drives on everything (optional on CWPs)



Optimum Sequences

- **All plants are different**
  - Tower efficiency, approach
  - Chiller efficiency, unloading control
  - Pump efficiency, head, unloading control
  - Number of chillers, pumps, towers
- **Too many independent variables**
  - CT fan speed
  - Chiller staging
  - CW pump speed
- **What is the optimum control sequence for a given plant?**
- **Can sequences be generalized to apply to any plant based on plant design parameters?**

Equipment Models

- **Chillers**
  - Hydeman et al, Regression Based Electric Chiller Model
  - Multi-point calibration using zero-tolerance manufacturer's data
- **Towers**
  - DOE-2.2 model calibrated using manufacturer's data
- **Pumps**
  - Multiple piping sections $\Delta P = C * GPM^{1.8}$
  - Pump efficiency from regression of manufacturer's data
- **VFD and motor efficiency**
  - Part load curves from manufacturer's data

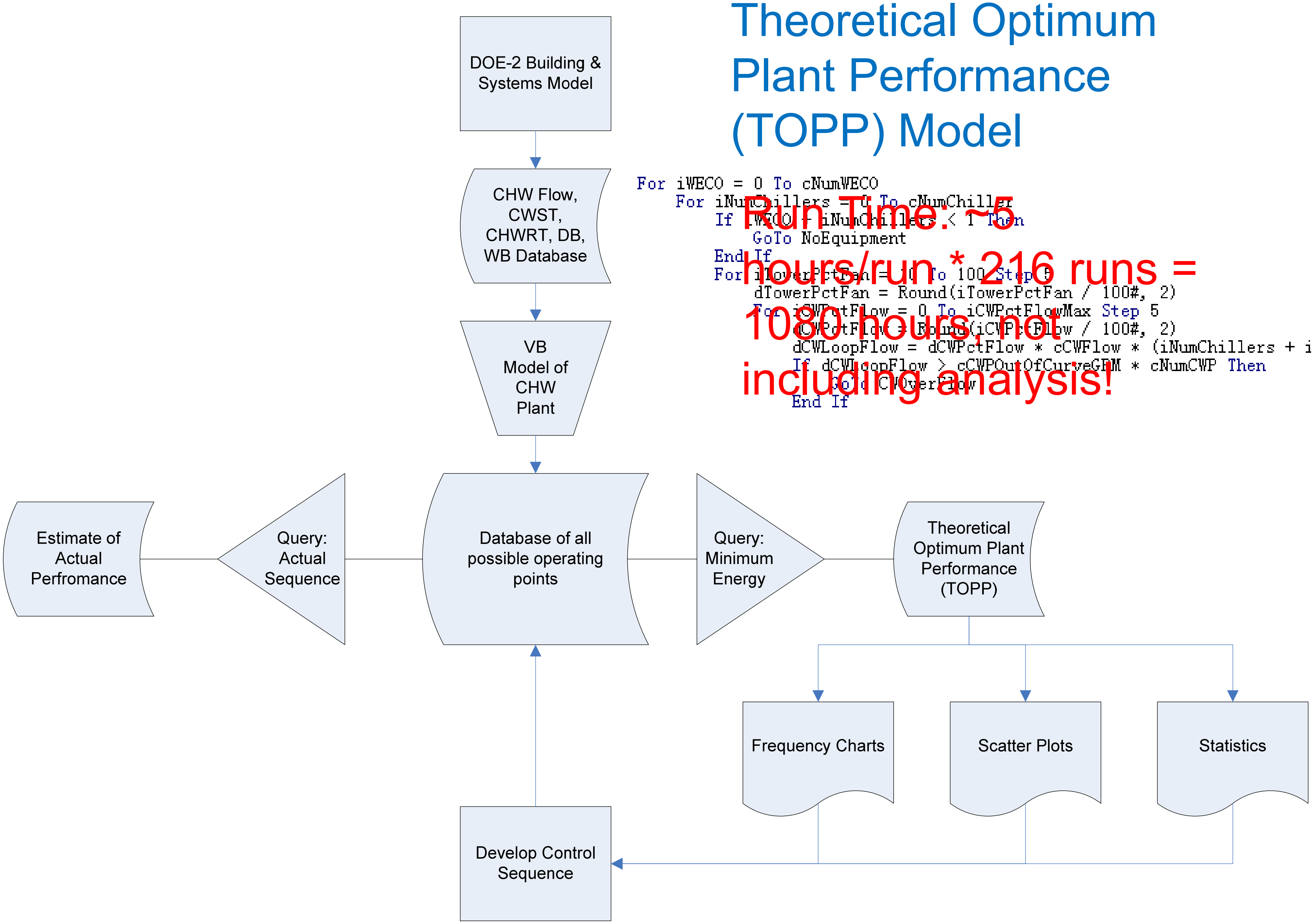
Generic Plant Design Options

- **Plant**
  - Office building
  - Peak Load = 900 ton
  - Two chillers each 500 ton
  - Two CW pumps & towers
  - Two CHW pumps
  - All variable speed
- **Climate:**
  - 3C: Oakland
  - 4B: Albuquerque
  - 5C: Chicago
- **Chillers:**
  - A: two stage R-123 hermetic
  - B: one stage R-134a open drive
- **Tower Approach**
  - -A: 3 ~ 5F
  - -B: 5 ~ 7F
  - -C: 7 ~ 10F
  - -D: 9 ~ 12F
- **Tower Range:**
  - -1: 9F
  - -2: 12F
  - -3: 15F
- **Tower Efficiency**
  - H: ~90 gpm/hp
  - M: ~70 gpm/hp
  - L: ~50 gpm/hp

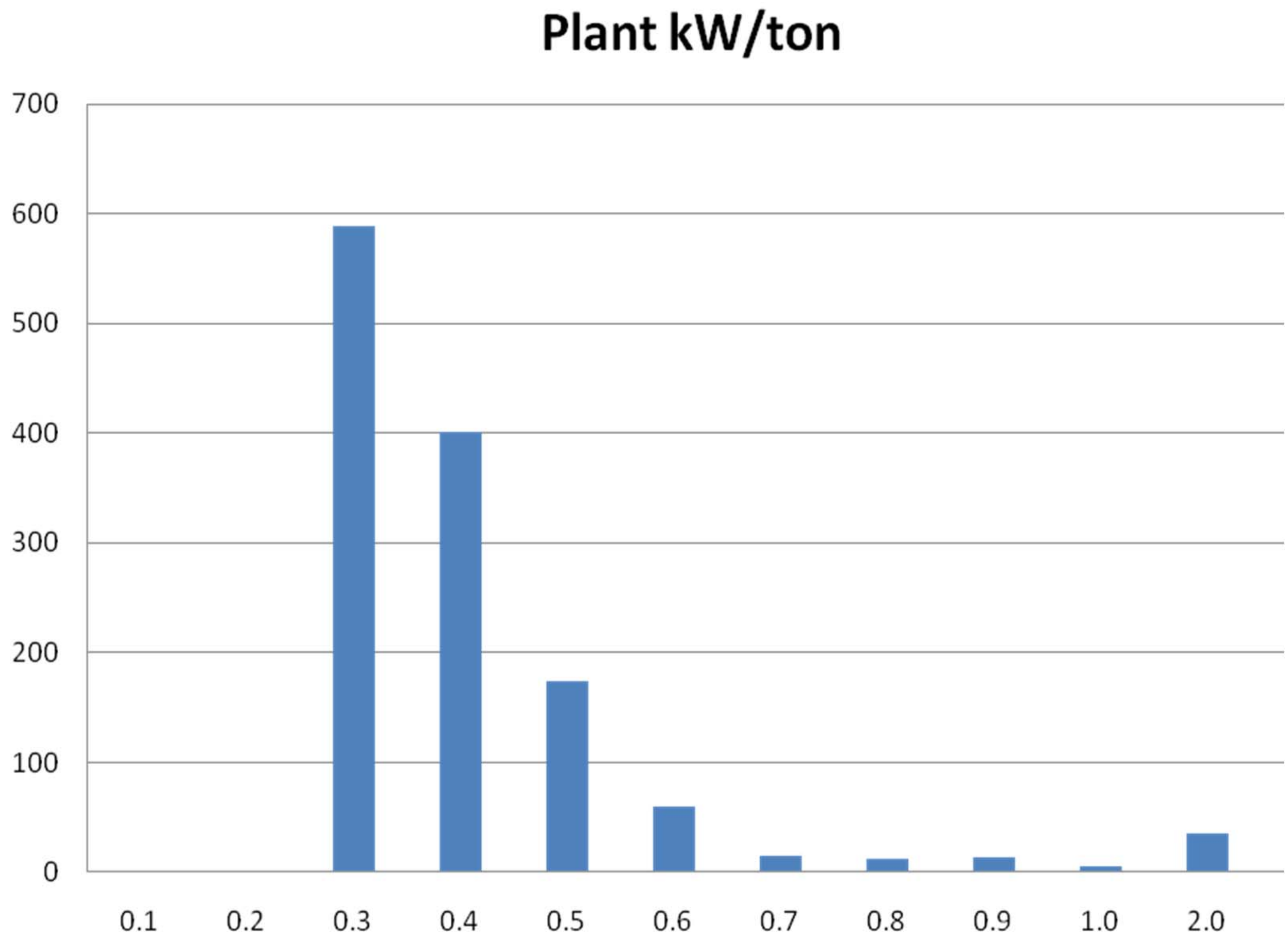
Theoretical Optimum Plant Performance (TOPP) Model

```
For iWECO = 0 To cNumWECO
    For iNumChillers = 0 To cNumChiller
        If iWECO + iNumChillers < 1 Then
            GoTo NoEquipment
        End If
        For iTowerPctFan = 10 To 100 Step 5
            dTowerPctFan = Round(iTowerPctFan / 100#, 2)
            For iCWPctFlow = 0 To iCWPctFlowMax Step 5
                dCWPctFlow = Round(iCWPctFlow / 100#, 2)
                dCWLoopFlow = dCWPctFlow * cCWFlow * (iNumChillers + i
                If dCWLoopFlow > cCWPOutOfCurveGPM * cNumCWP Then
                    GoTo CWOverFlow
                End If
```

Run Time: ~5 hours/run * 216 runs = 1080 hours, not including analysis!



TOPP Plant Energy: Oakland



Determining Sequences

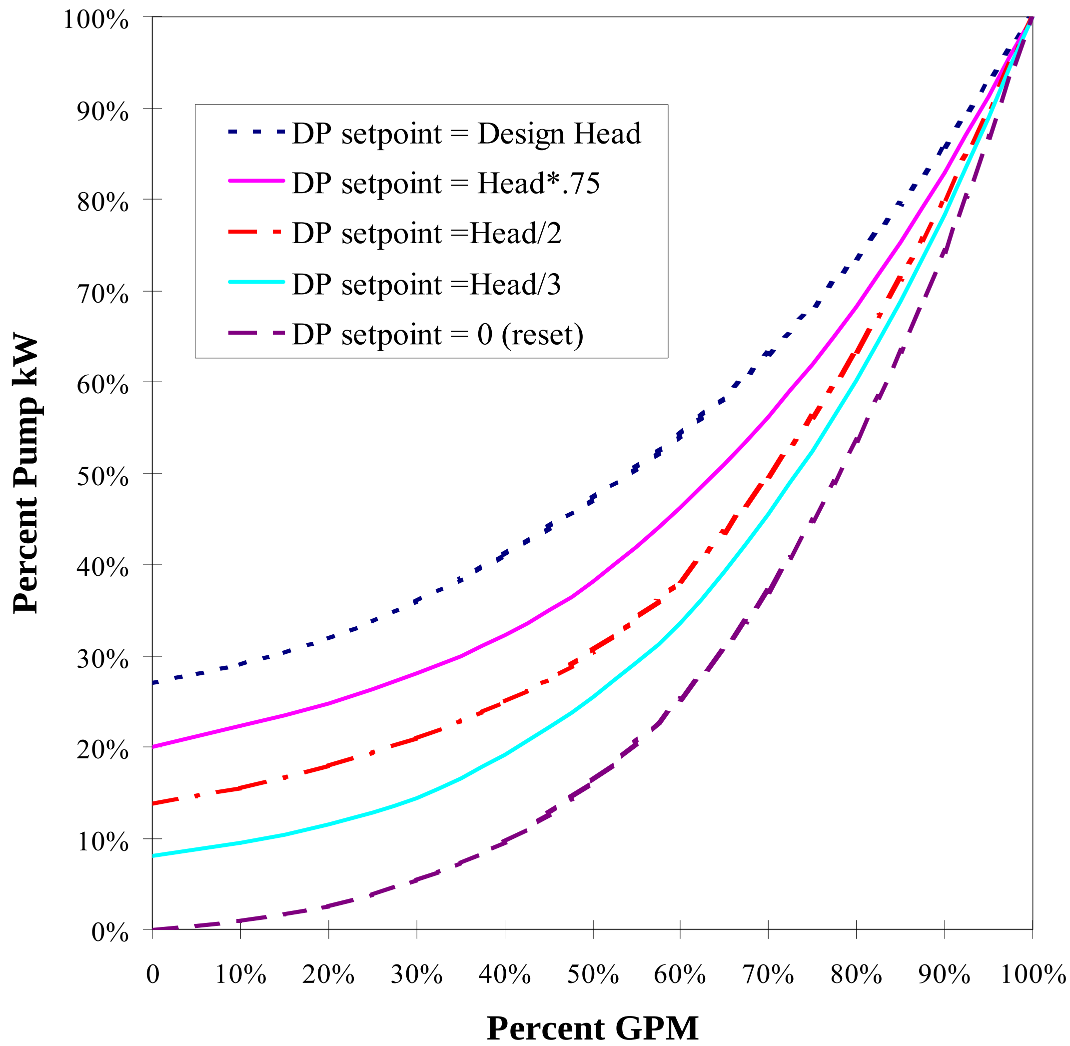
- Plot TOPP results vs. various independent variables to see if there are trends
- Once independent variables are selected, determine correlations
- Test the sequence using the models to see how close they are to the TOPP

Chilled Water Pumps

Controlling CHW Pumps

- **Primary-only and Secondary CHW Pumps**
  - Control speed by differential pressure measured as far out in system as possible and/or reset setpoint by valve demand
  - Stage pumps by differential pressure PID loop speed signal:
    - Start lag pump at 90% speed
    - Stop lag pump at 40% speed
    - For large HP pumps, determine flow and speed setpoints with detailed energy analysis

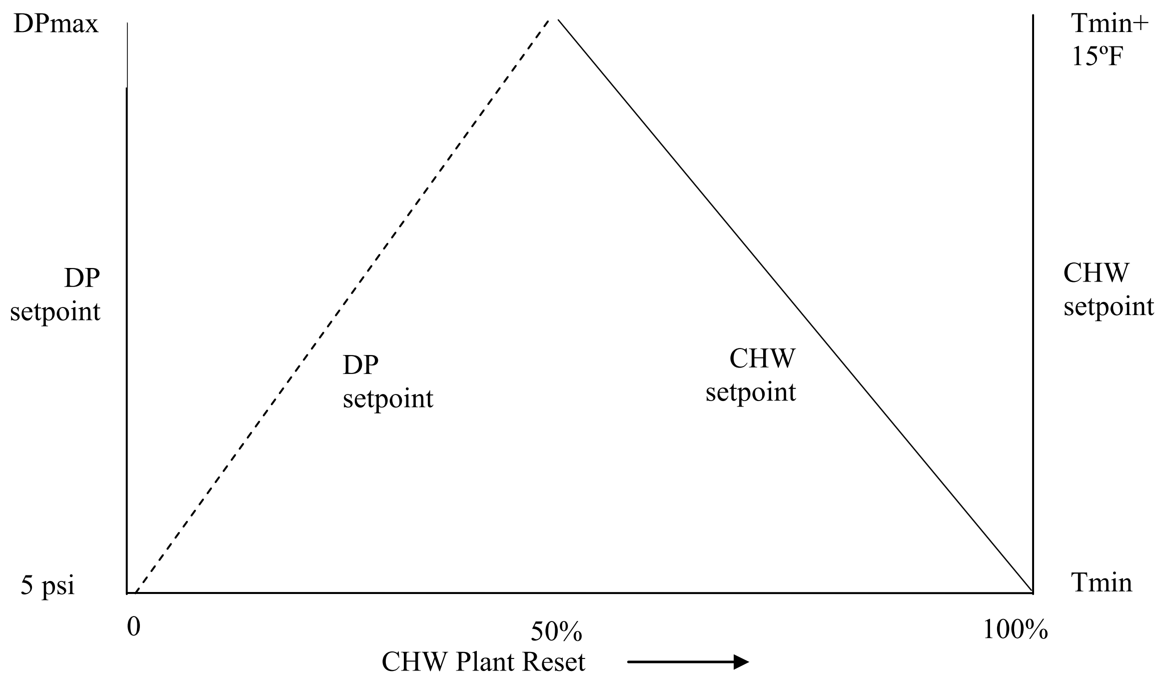
VSD Pump Power vs. Setpoint



Chilled Water Setpoint Reset

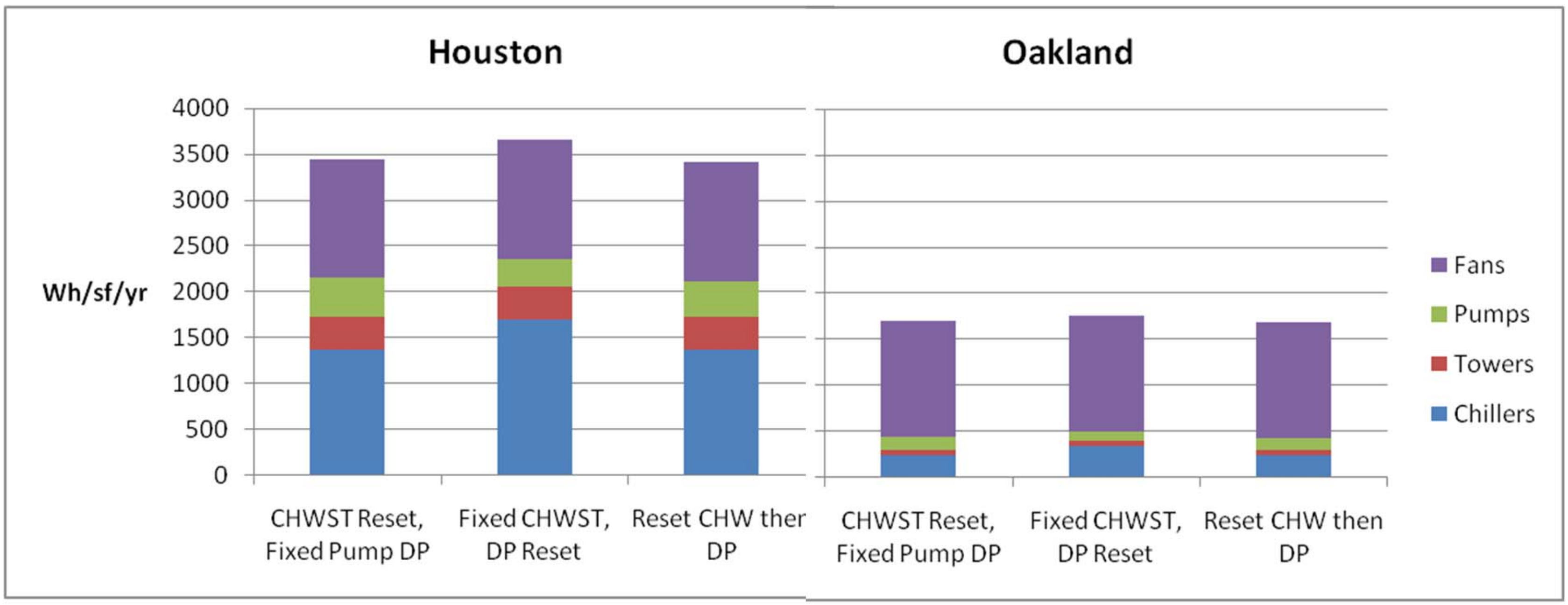
- **Reset Impacts**
  - Resetting CHWST upwards reduces chiller energy but will increase pump energy in VSD variable flow systems
  - Dehumidification
    - Reset with “open” or indirect control loops (e.g. OAT) can starve coils and reduce dehumidification
    - Reset by control valve position will never hurt dehumidification − humidity of supply determined almost entirely by supply air temperature setpoint, not CHWST
- **Recommendations**
  - Reset from control valve position using Trim & Respond logic
  - For variable flow systems with VSDs
    - Reset of CHWST and VSD differential pressure setpoint must be sequenced − not independent like VAV systems since control valves are pressure-dependent
    - Sequence reset of CHWST and DP − next slide…

CHWST/DP Setpoint Reset for VSD CHW System



- Back off on CHWST first
- Then back off on DP setpoint first
- Reverse this for constant speed chillers

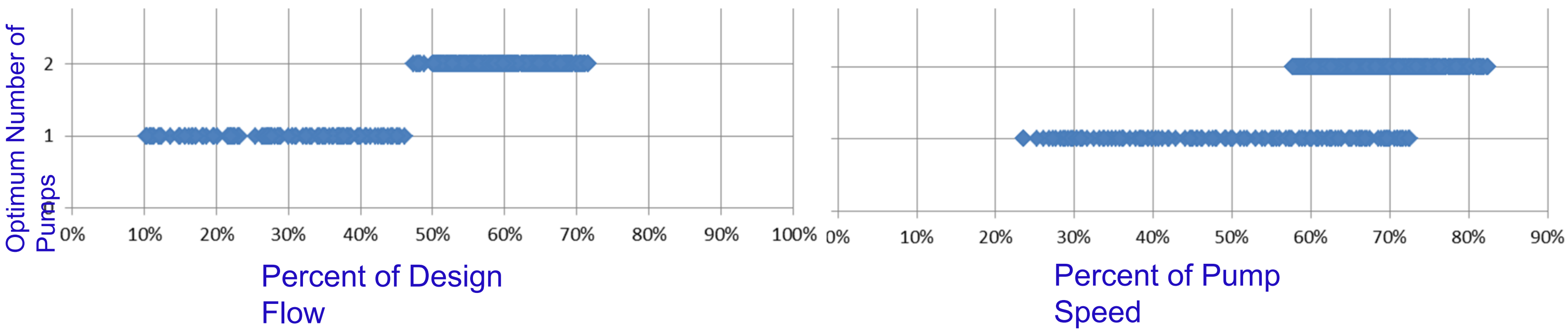
CHW vs. DP Setpoint Reset



Plant with 150 ft CHW pump head, variable speed chillers

CHW Pump Staging

TOPP Model Results

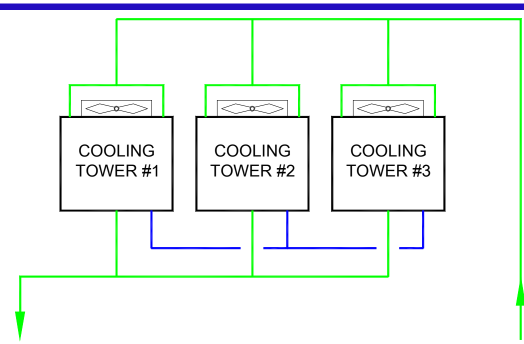


One Pump: CHWFR <47%
Two Pumps: CHWFR >47%
Time delays to prevent short-cycling

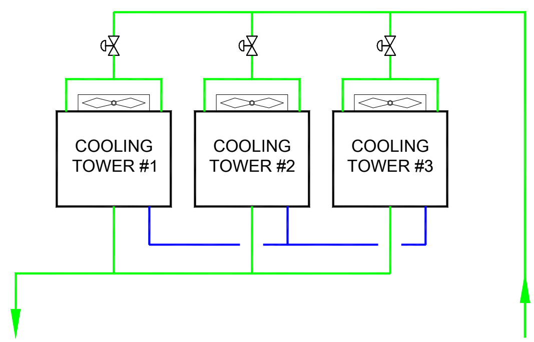
Cooling Towers

Tower Isolation Options

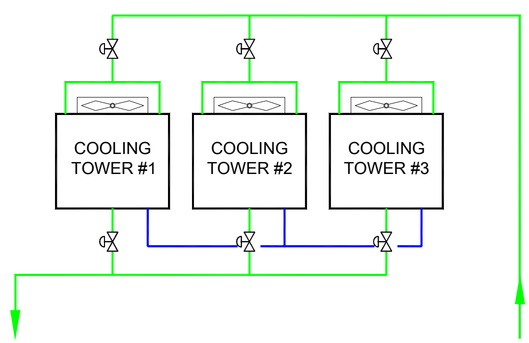
1. **Select tower weir dams & nozzles to allow one pump to serve all towers**
   - Always most efficient
   - Almost always least expensive
   - Usually possible with 2 or 3 cells



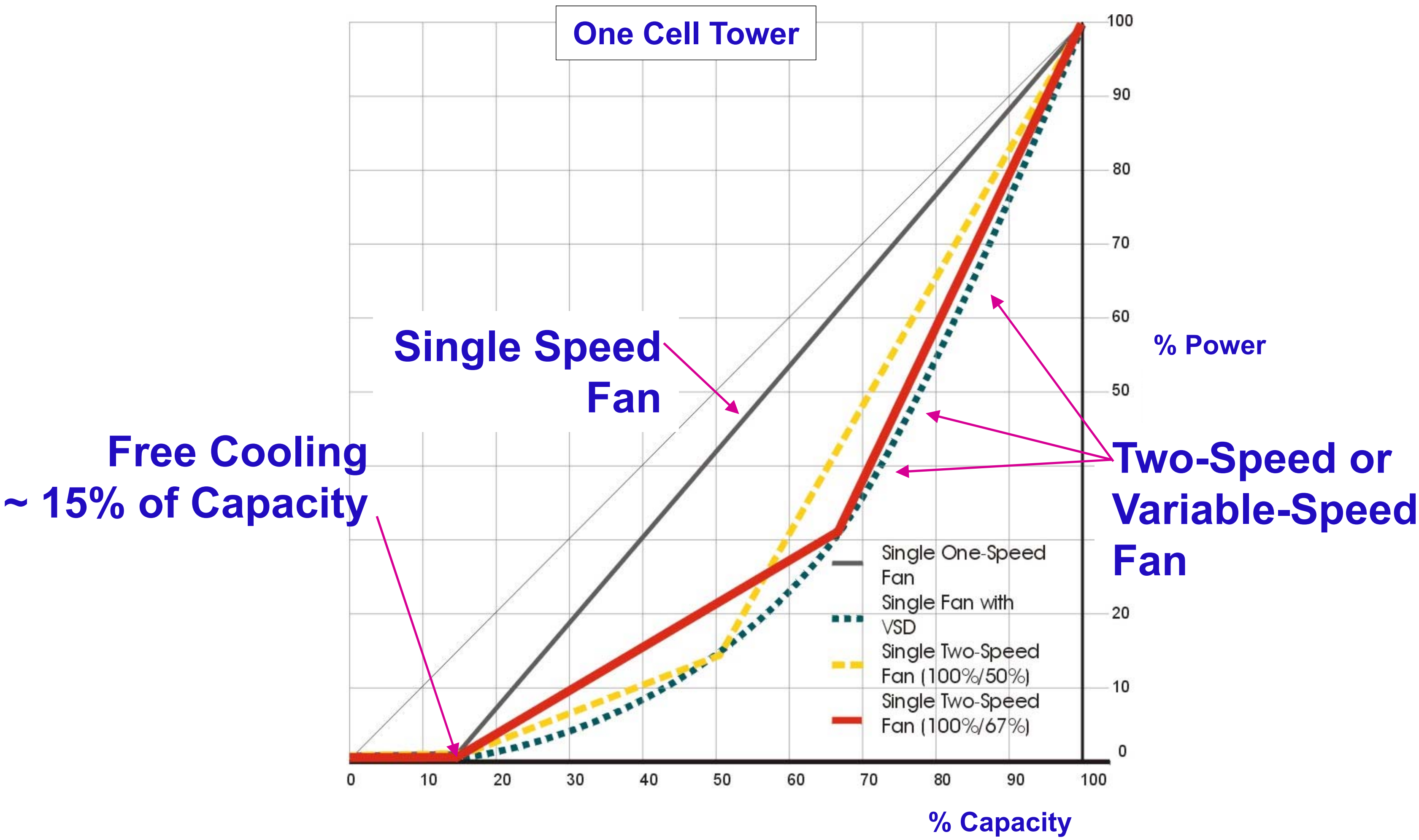
2. **Install isolation valves on supply lines only**
   - Need to oversize equalizers



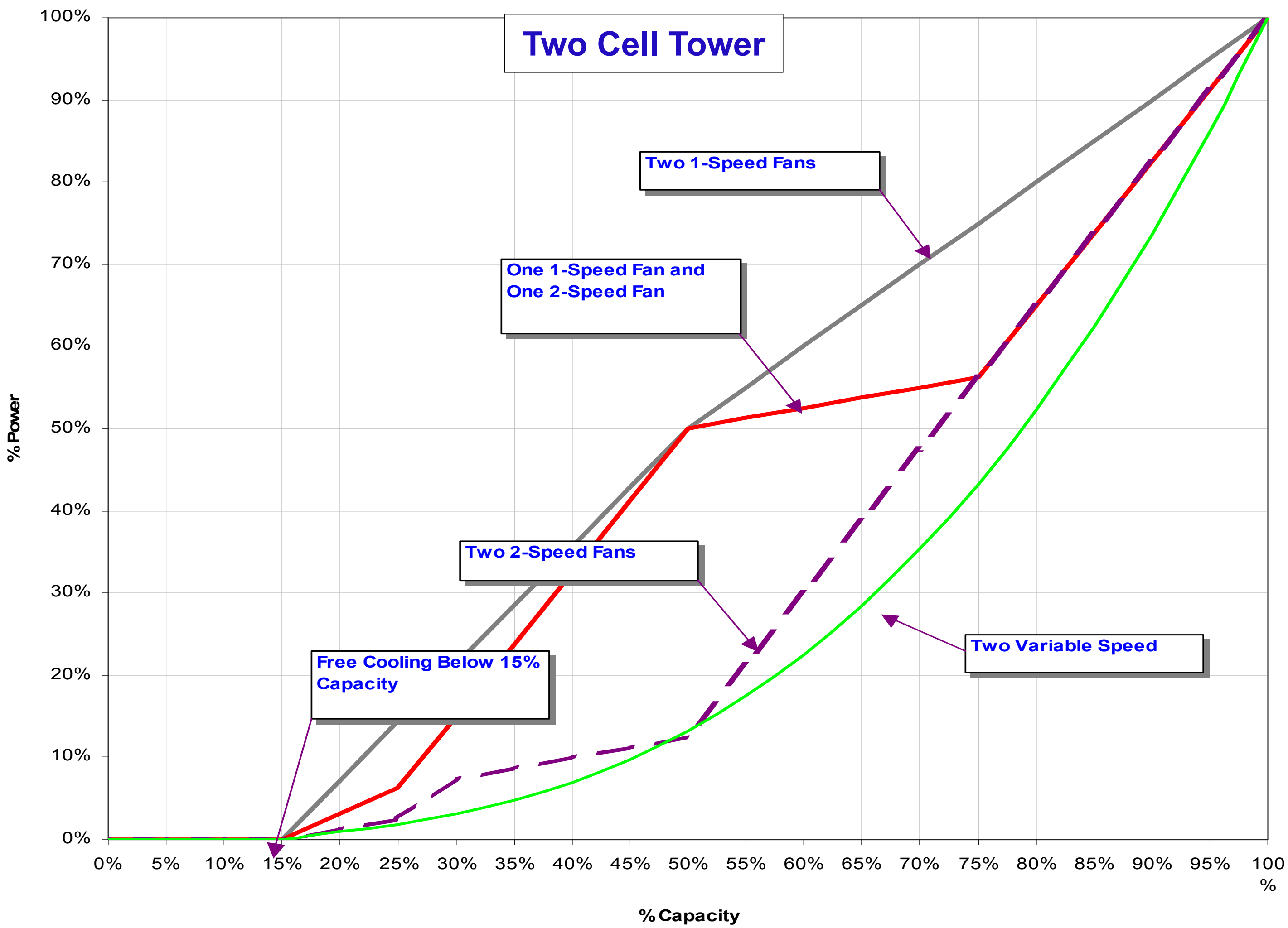
3. **Install isolation valves on both supply & return**
   - Usually most expensive
   - Easiest to design
   - Valve sequencing issues and possible failure



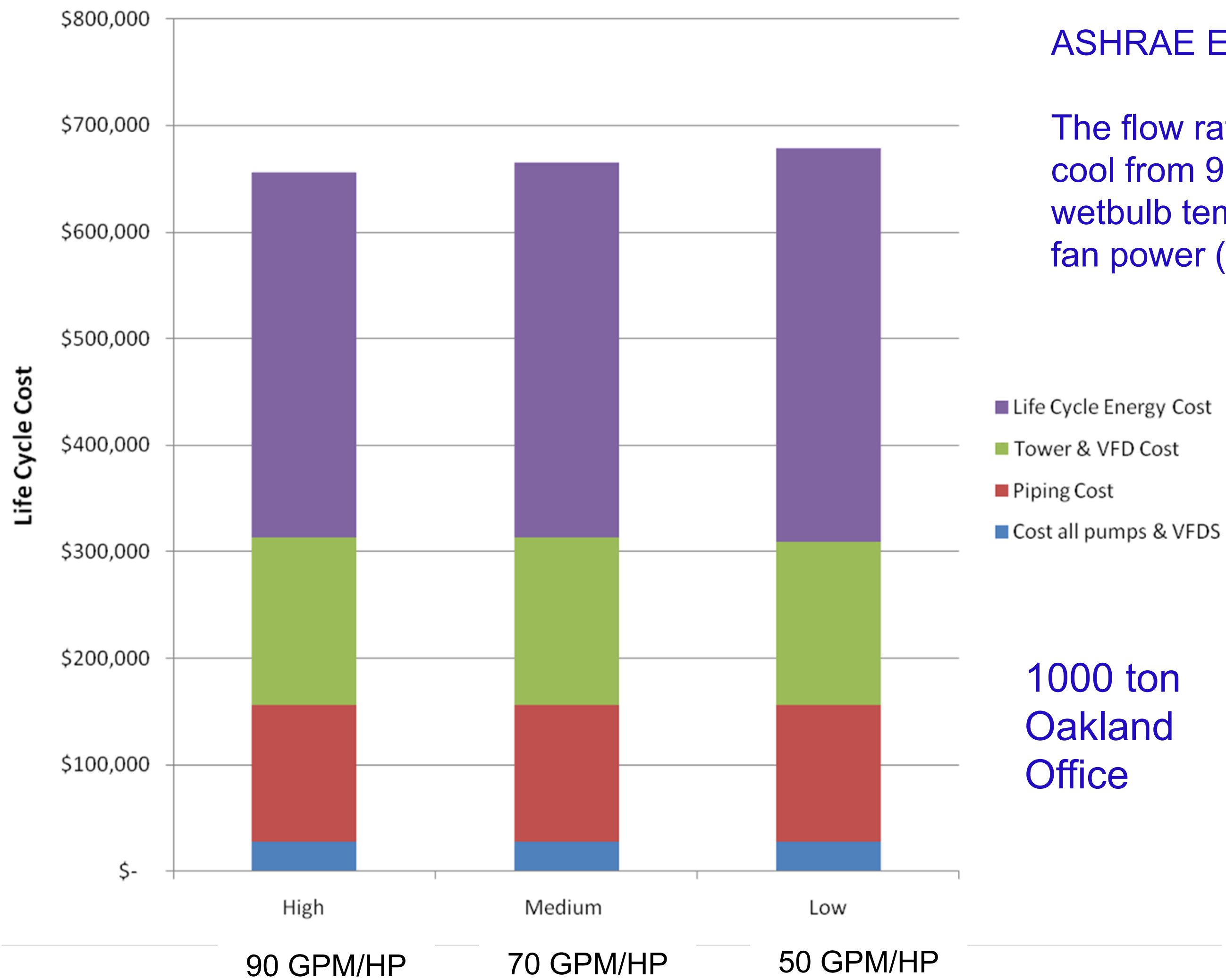
Tower Fan Control



Tower Fan Control



Tower Efficiency LCC

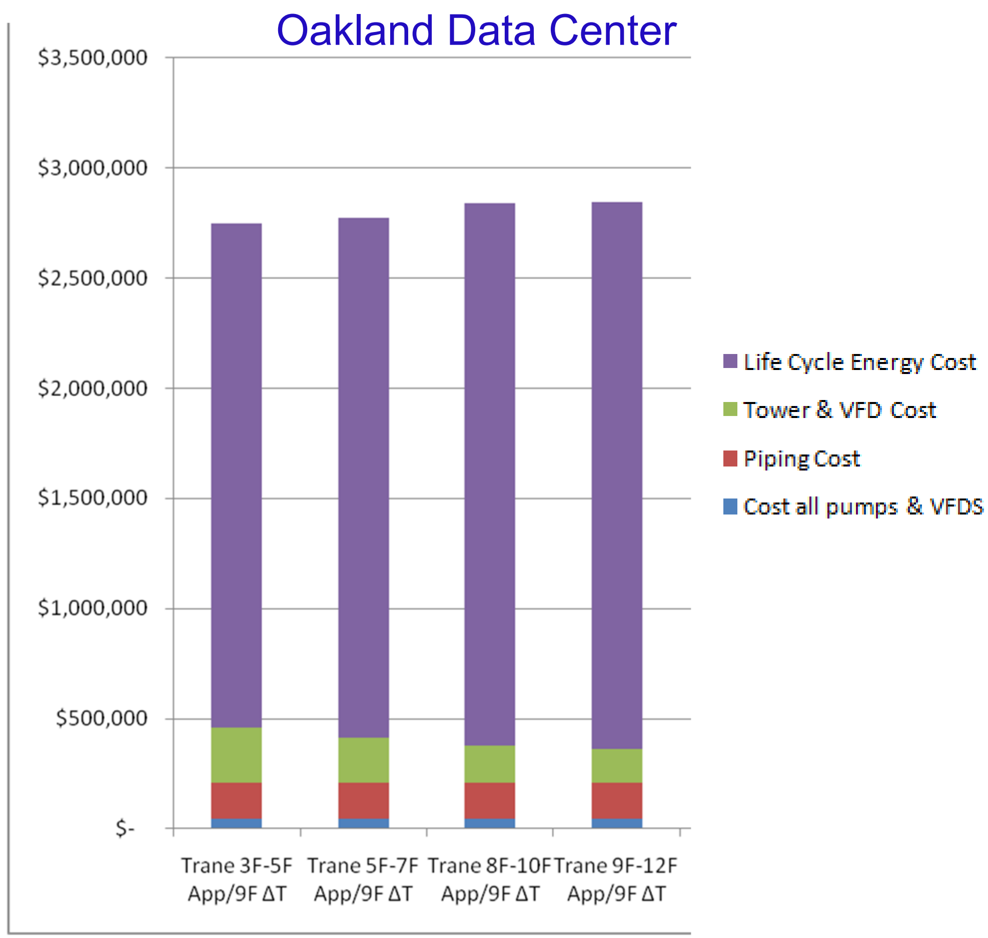


ASHRAE Efficiency:

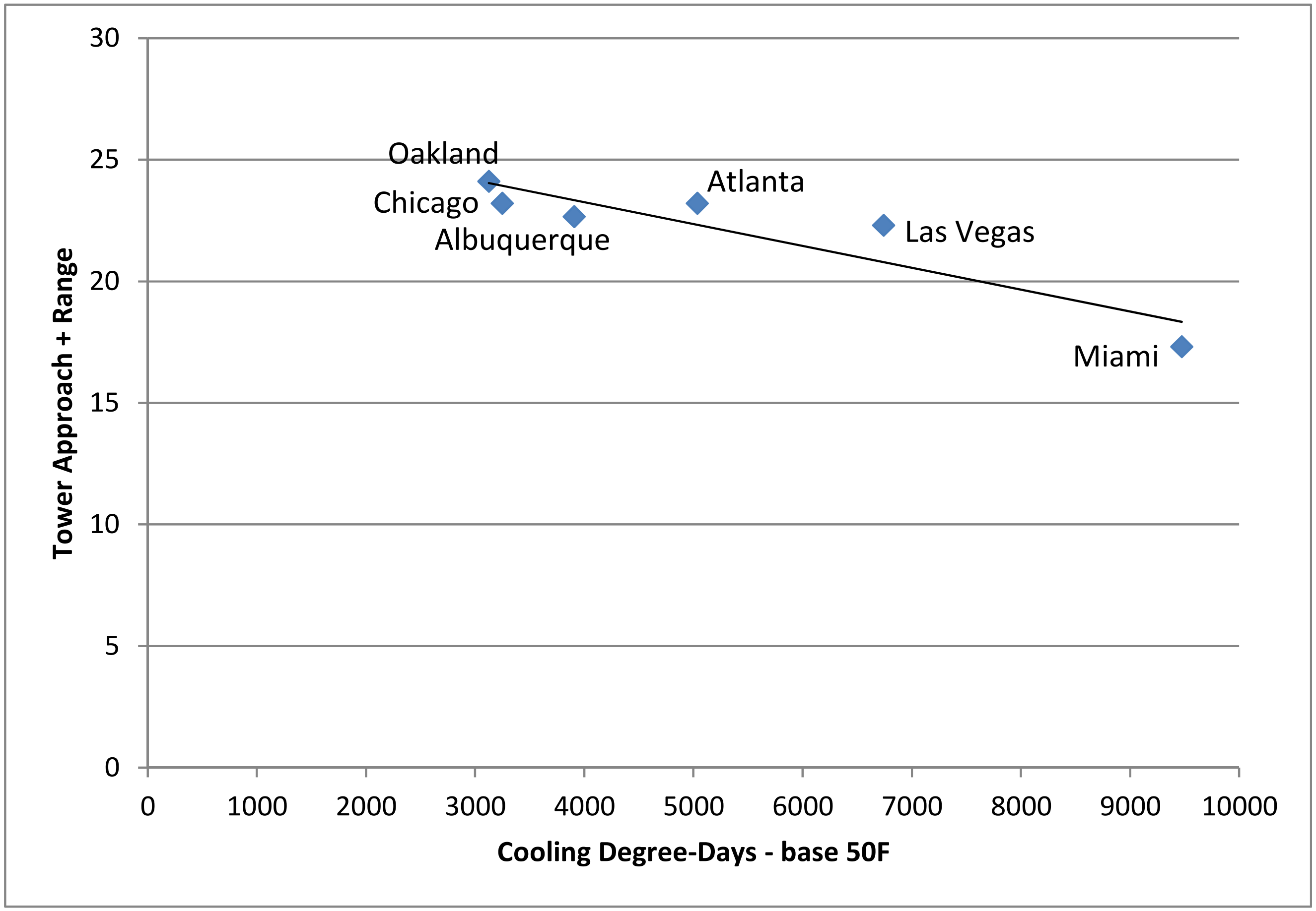
The flow rate the tower can cool from 95F to 85F at 75F wetbulb temperature divided by fan power (GPM/HP)

1000 ton Oakland Office

Tower Approach



Optimum Approach Temperature

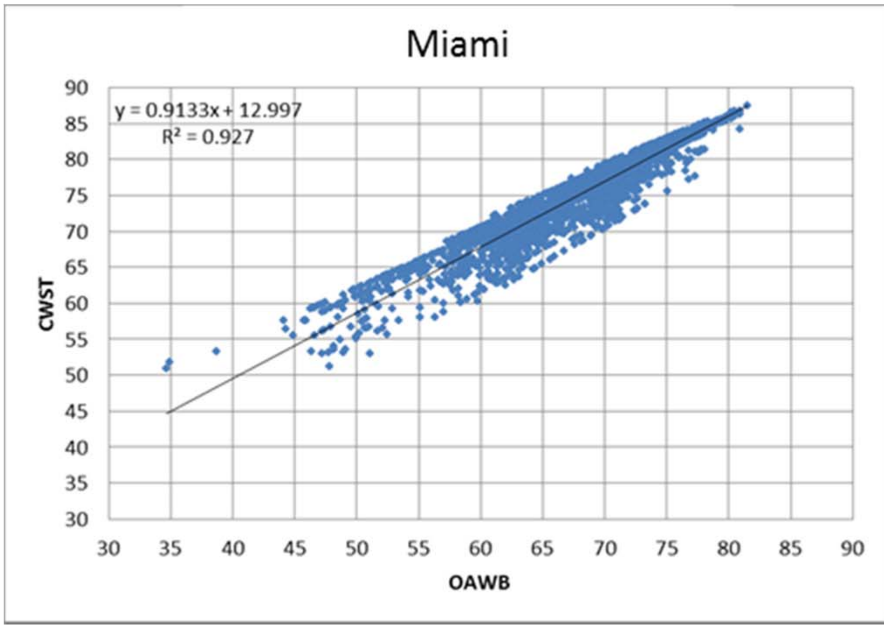


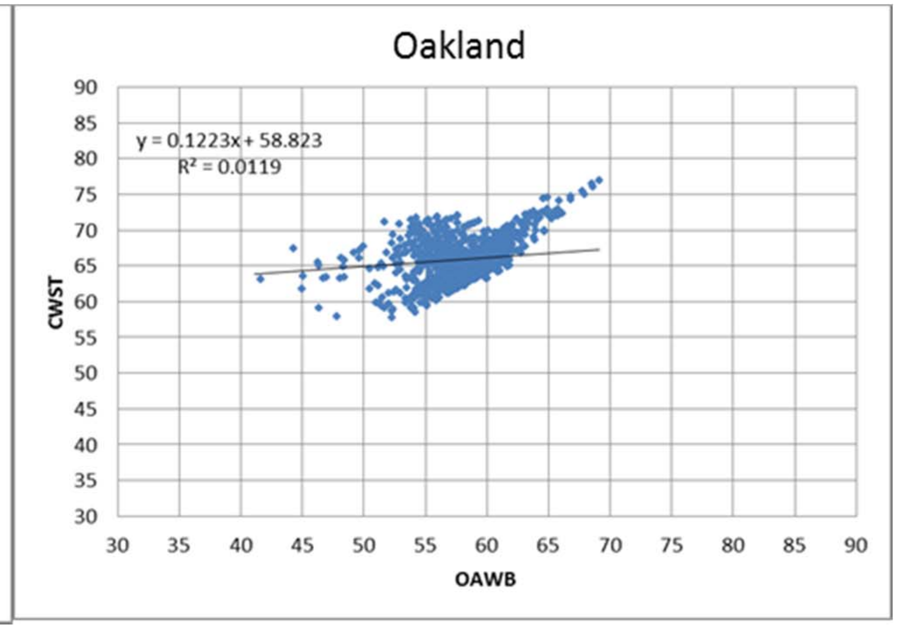
$$T_A = 27 - \Delta T_{CW} - 0.001 CDD_{50}$$

Tower Efficiency Guidelines

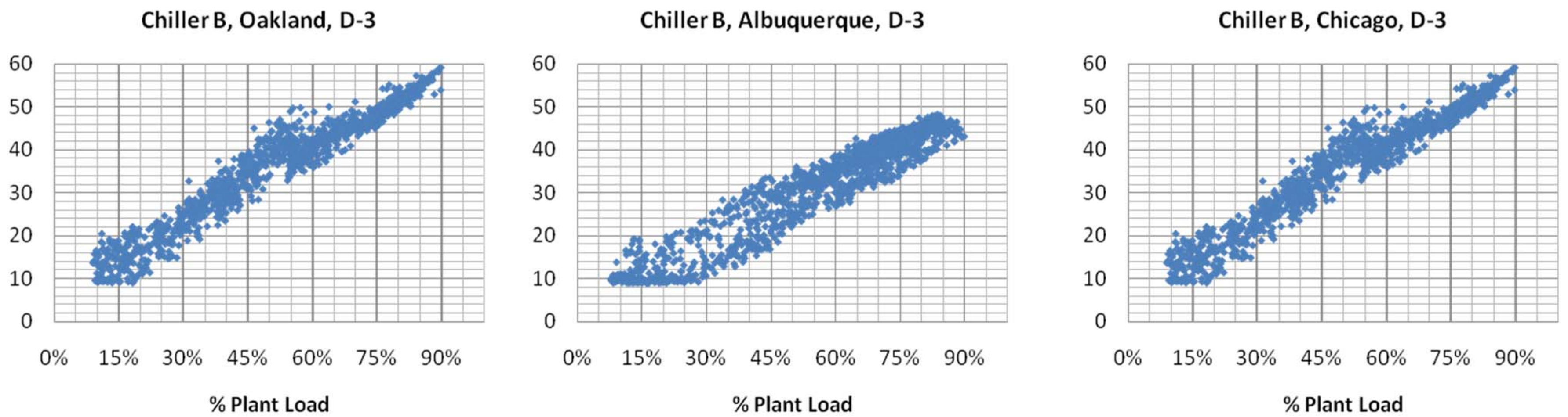
- **Use Propeller Fans**
  - Avoid centrifugal except where high static needed
  - Consider low-noise propeller blade option and high efficiency tower where low sound power is required
- **Efficiency**
  - Minimum 80 gpm/hp for commercial occupancies
  - Minimum 100 gpm/hp for 24/7 plants (data centers)
- **Approach**
  - Commercial occupancies: See previous slide
    - 8°F to 9°F for Bay Area
  - 24/7 plants (data centers): 3°F

Reset by Wetbulb Temperature?





“Lift” (CWRT-CHWST) vs. %Load



Lift Reset Best Fit for Offices

Wetbulb reset best for data centers since load does not vary

Tower Control

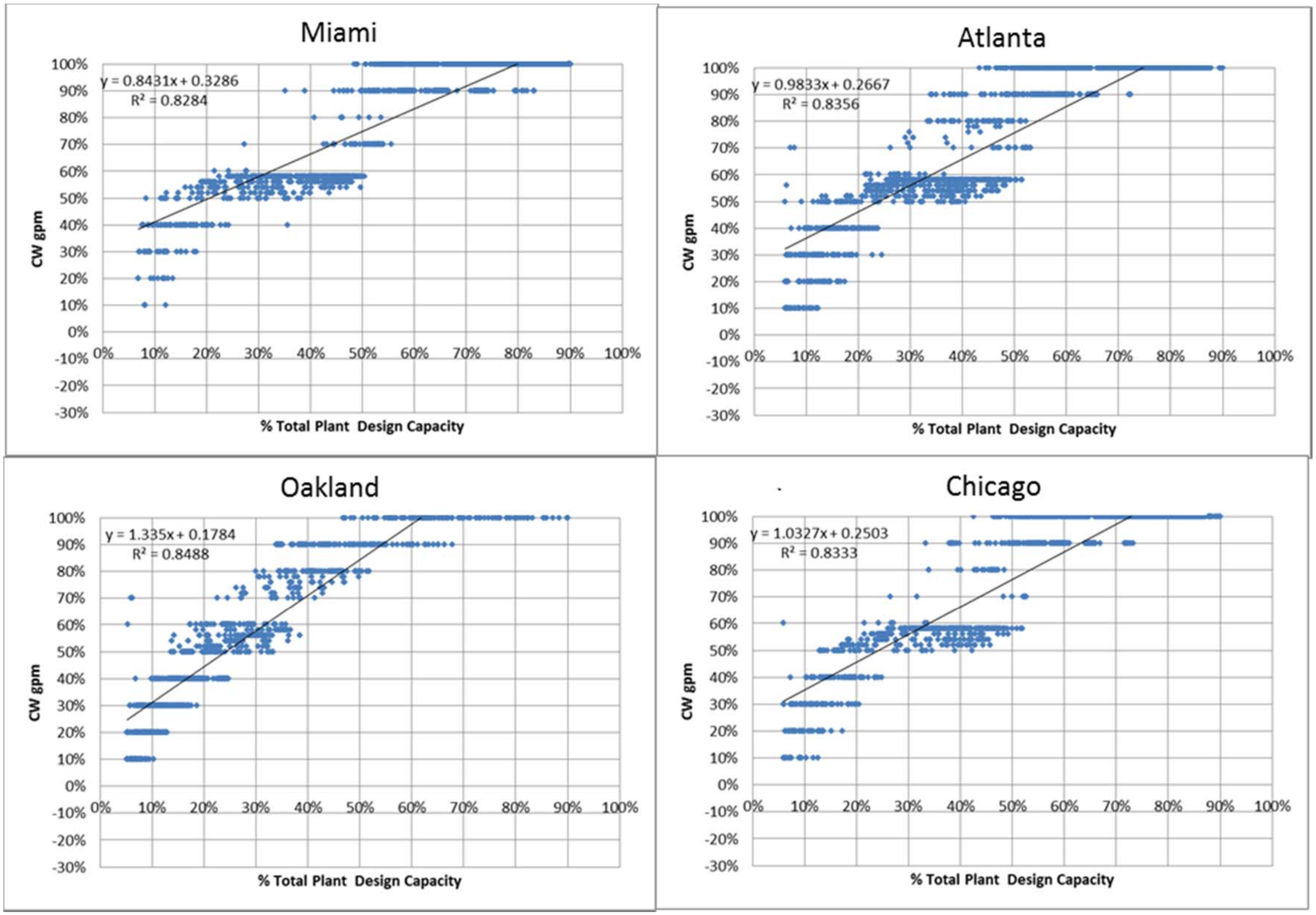
- LIFT = A*PlantLoadRatio + B
  - Bounded by minimum LIFT at minimum PLR (from manufacturer) and maximum LIFT (design lift)
  - CWRT setpoint = LIFT + CHWST
  - Control CT fans to maintain **CWRT**
- A and B coefficients
  - Best optimized by modeling
  - Rough estimate:
    - LIFTd= design lift = CWRTdesign – CHWSTdesign
    - LIFTm= Minimum lift at minimum load
    - A = (LIFTd – LIFTm)/0.7
    - B = LIFTd - A

Condenser Water Pump

CW pump Control

- **Constant speed CW pumps**
  - Stage along with chillers
- **Variable speed CW pumps?**

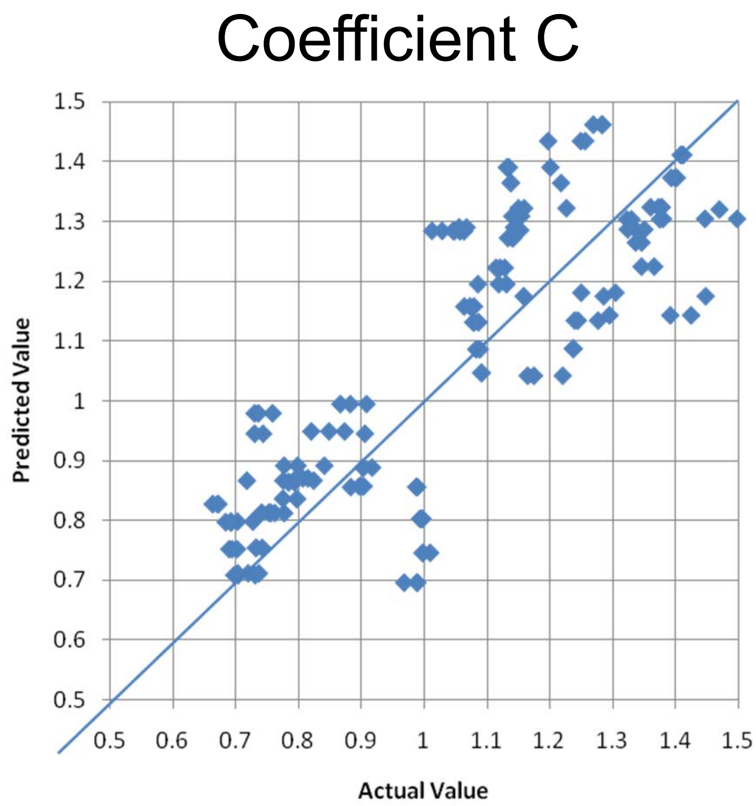
%CW Loop Flow vs. %Plant Load

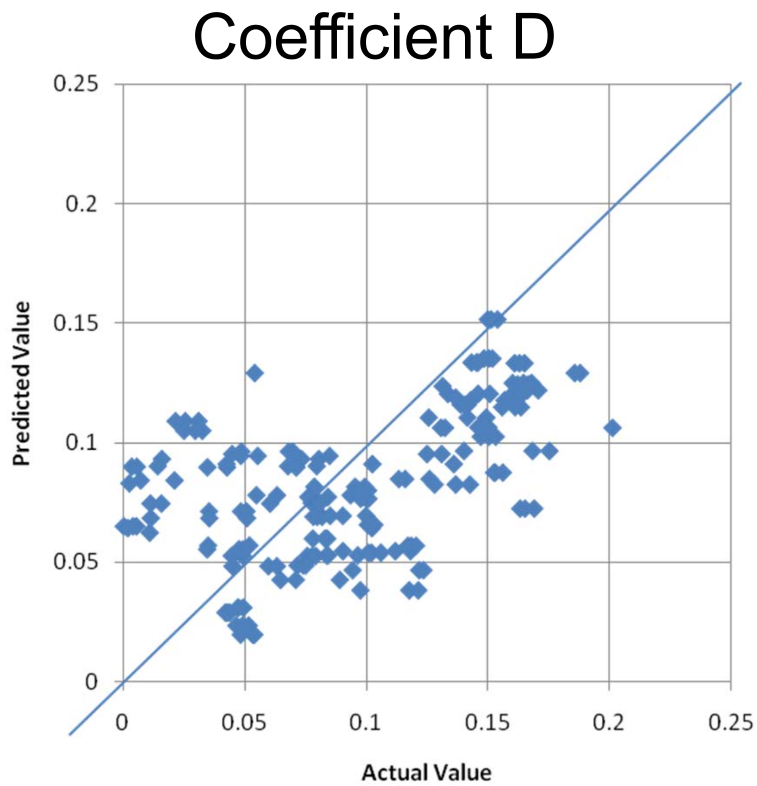


VSD CWP Control Logic

- **Pump speed control**
  - CWFR = C*PLR + D
  - CWFSP = CWFR*CWDF
  - Control speed to maintain CW flow at setpoint
- **Staging**
  - Same logic as CHW pumps
- **Disadvantages**
  - Requires flow meter
  - C and D coefficients only optimized by simulation

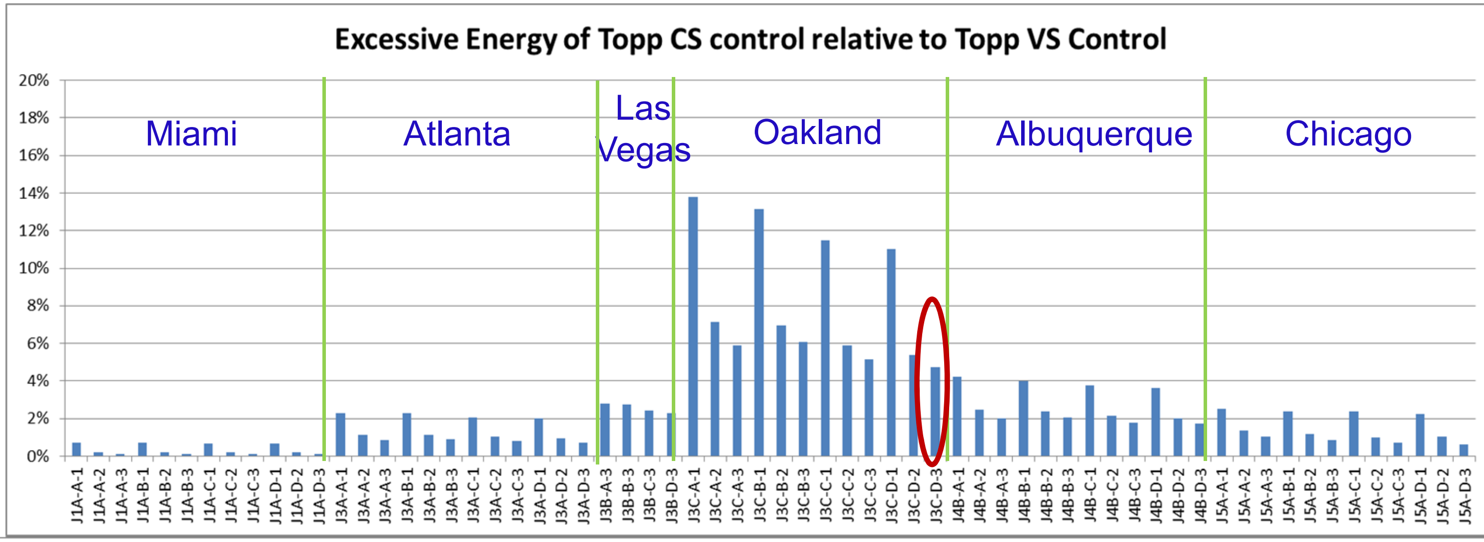
CWLoopFlowRatio = C*PlantLoadRatio + D

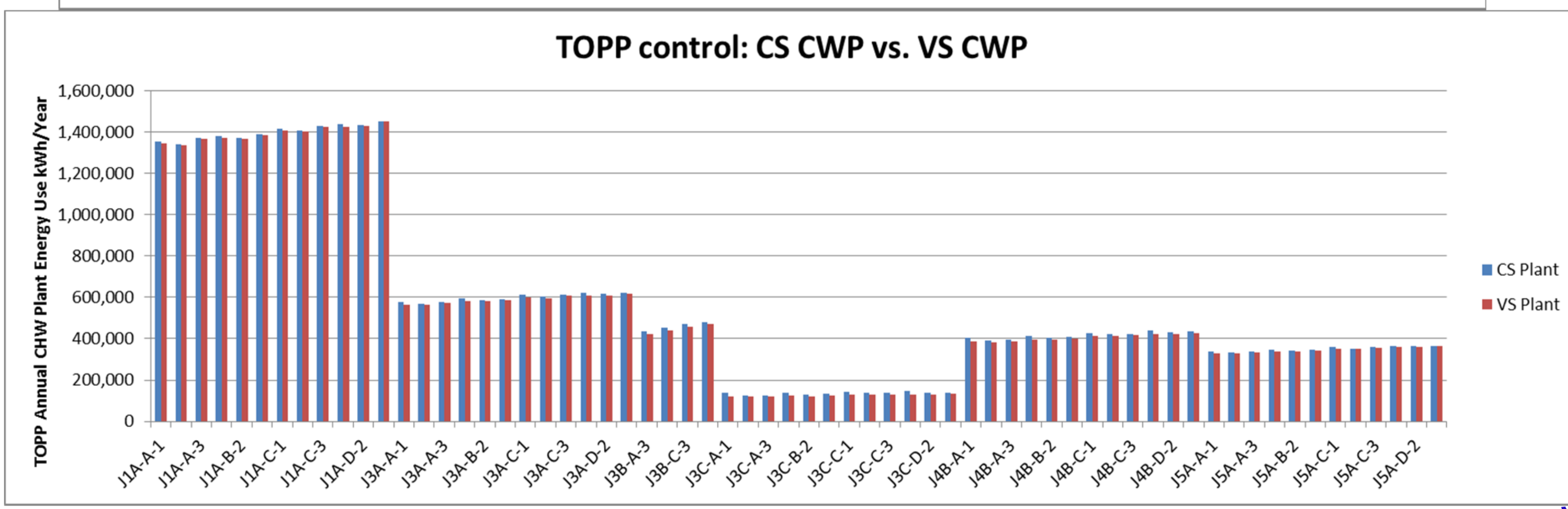




C = -0.0000811 * CDD55 + -0.01293 * WB + 3.486 * NPLV + -0.02476 * APPROACH + 0.07400 * RANGE
D = -0.797 + 2.282 * IPLV + 0.002196 * APPROACH + -0.00795 * RANGE

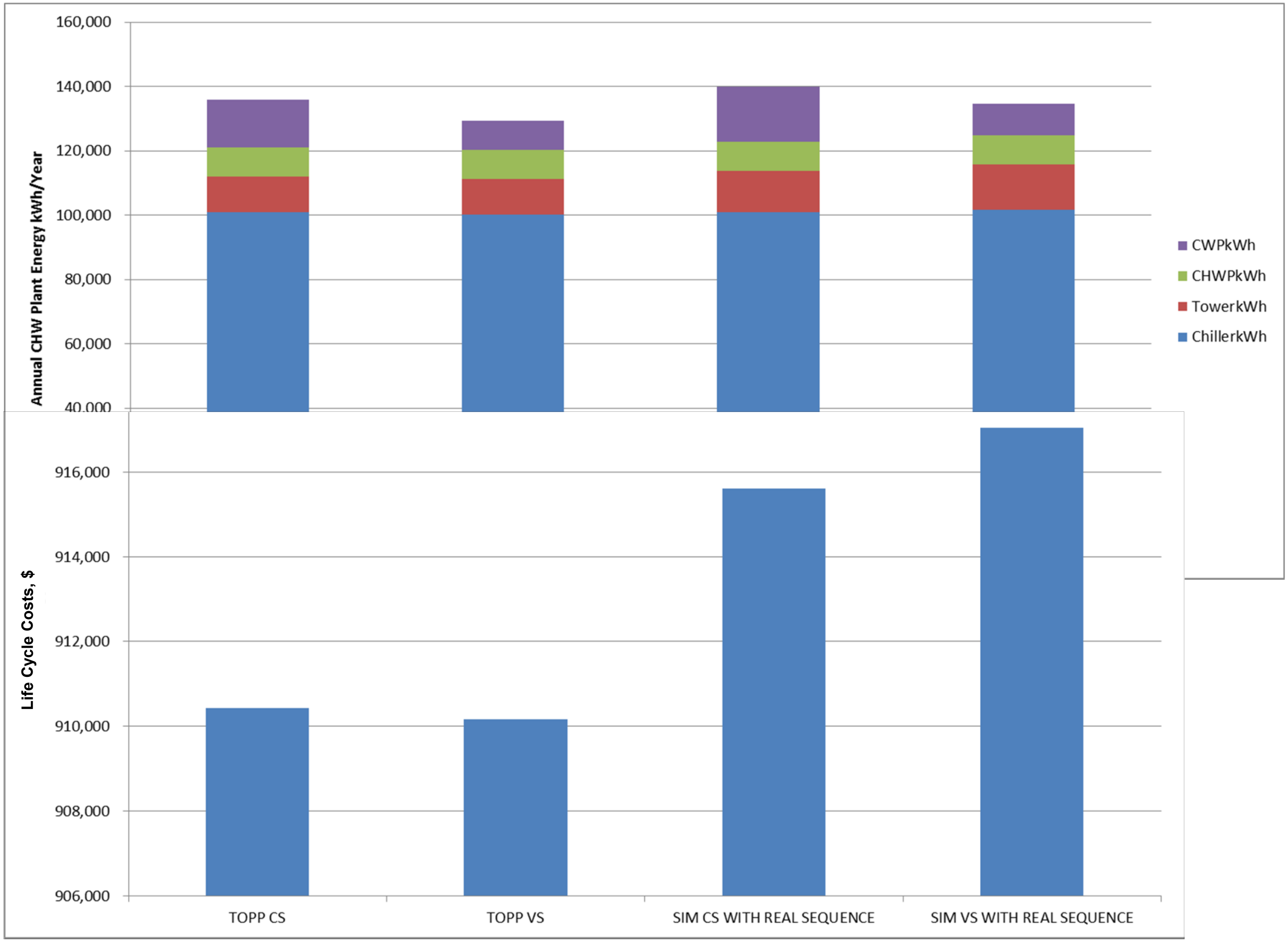
Even Optimum Savings are Small





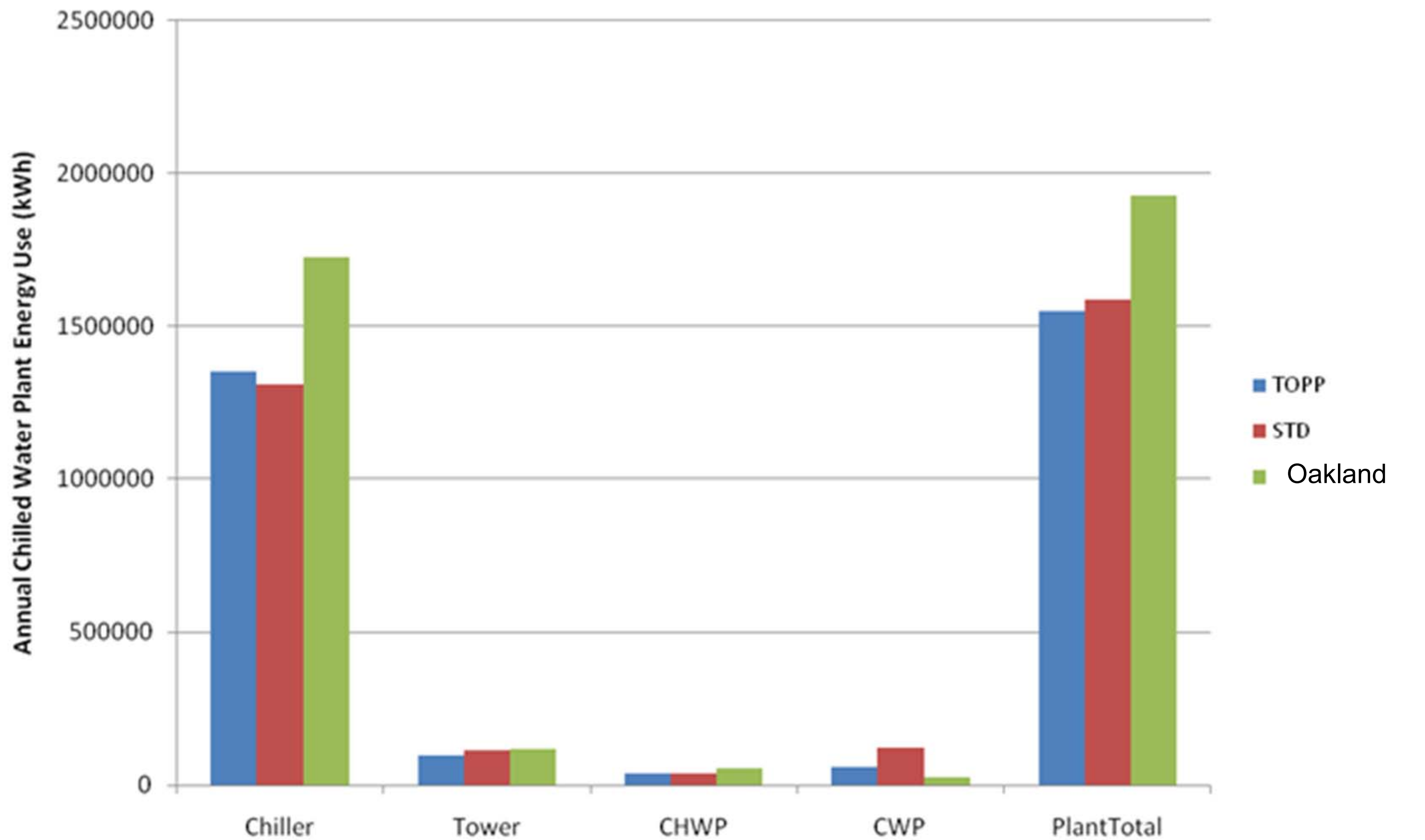
Answer: VFDs on CWPs are Not Cost Effective

for Office Buildings

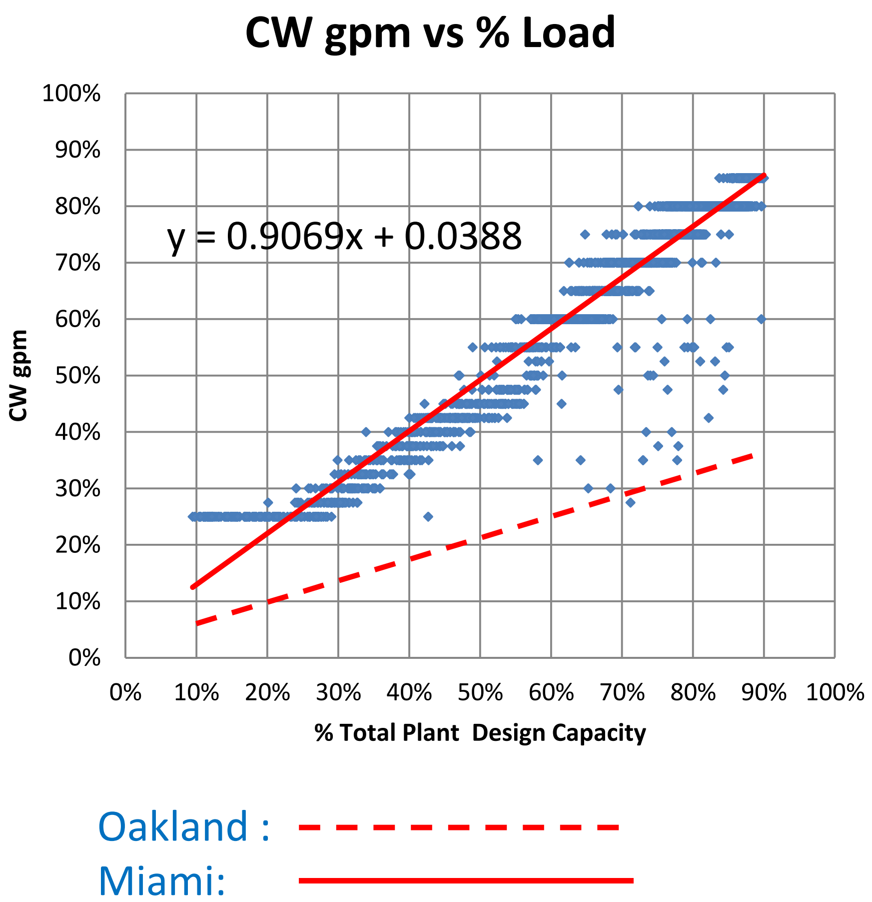


Energy Use May Increase!

Performance in Miami using C and D optimized for Oakland



Miami


CW gpm vs % Load
y = 0.9069x + 0.0388
CW gpm
% Total Plant Design Capacity
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Oakland :
Miami:

Recommendations

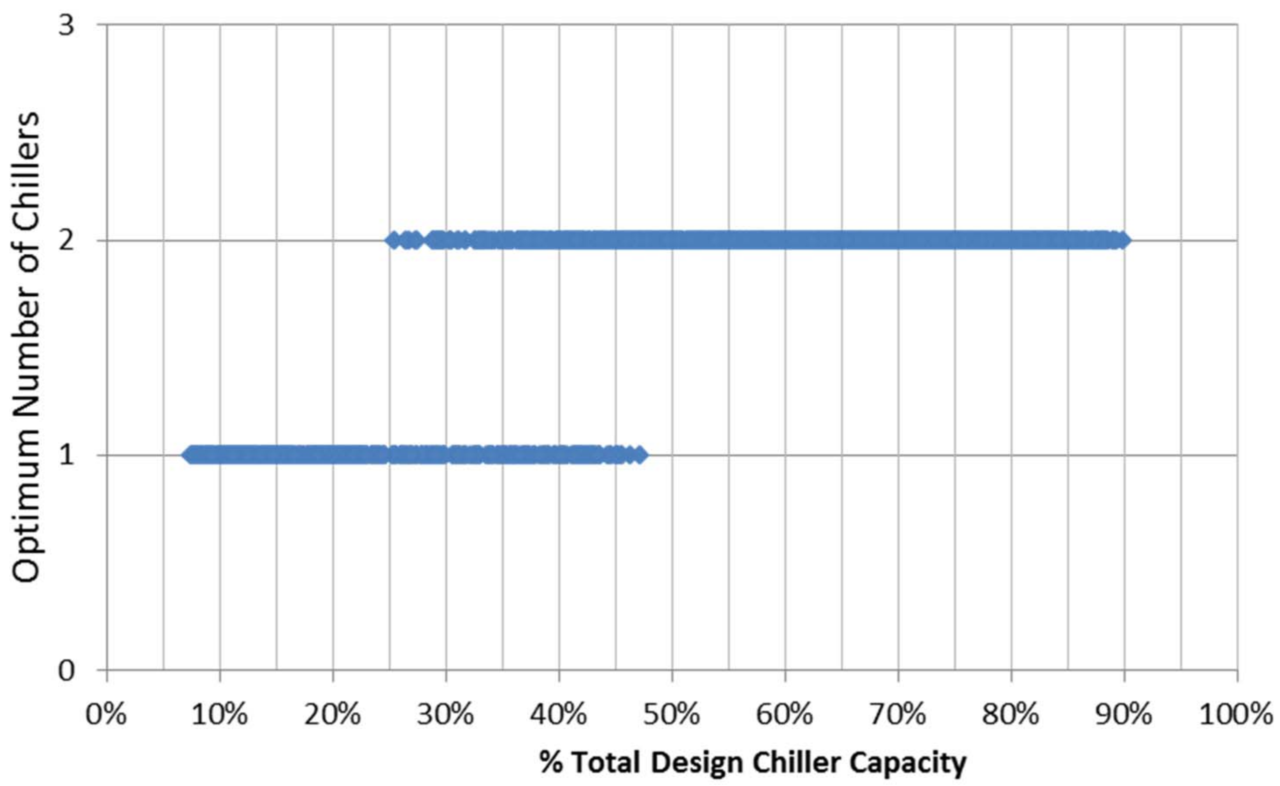
- **For offices etc., use constant speed pumps**
- **For data centers and other 24/7 plants**
  - Use VFDs
  - Determine C and D coefficients through modeling
    - Other logic may increase energy usage

Chiller Staging

Staging Fixed Speed Chillers

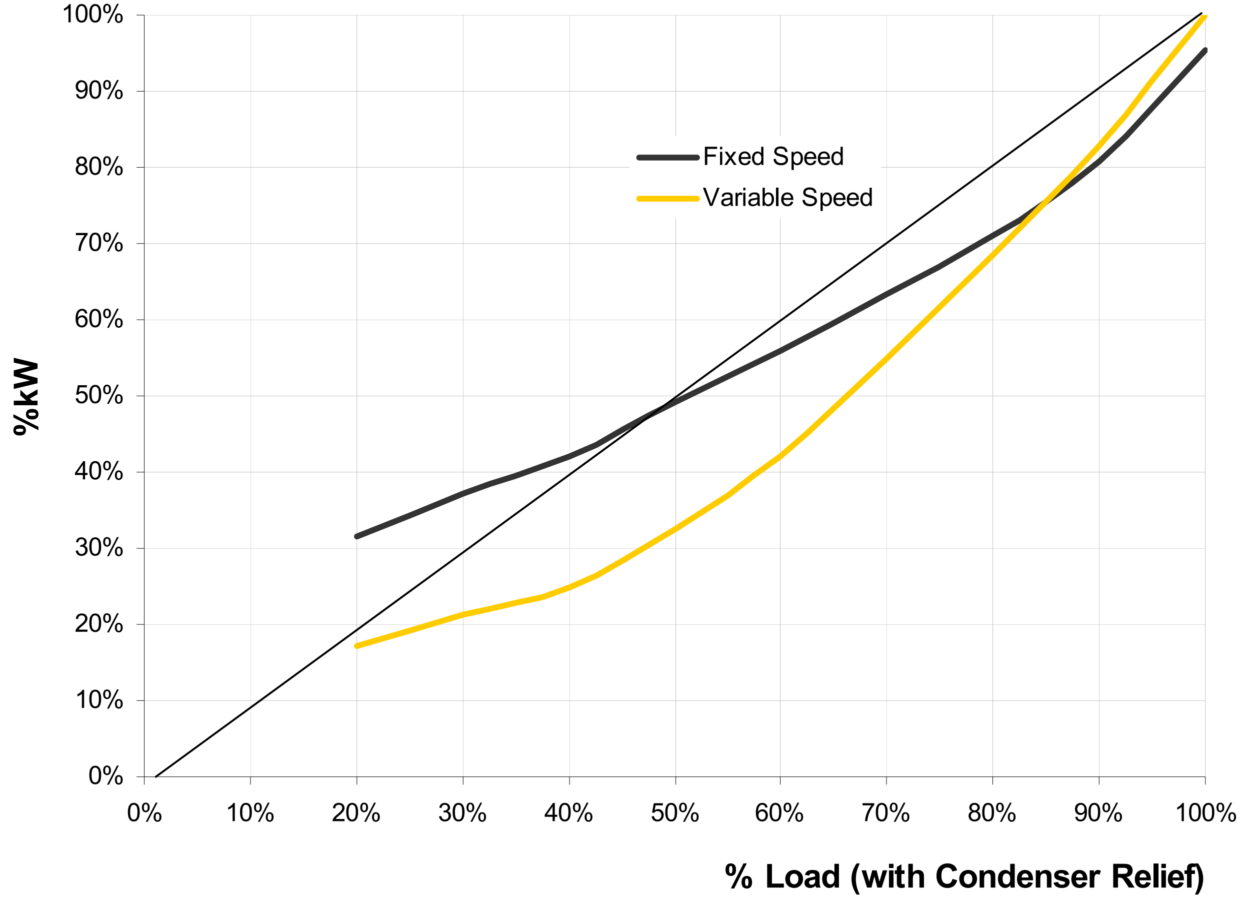
- **Fixed Speed Chillers**
  - Operate no more chillers than required to meet the load
  - Stage on when operating chillers maxed out as indicated by measured load (GPM, ΔT), CHWST, flow, or other load indicator.
  - For primary-secondary systems w/o check valve in the common, start chiller to ensure Primary-flow > Secondary-flow
  - Stage off when measured load/flow indicates load is less than operating capacity less one chiller – be conservative to prevent short cycling

Staging Variable Speed Chillers

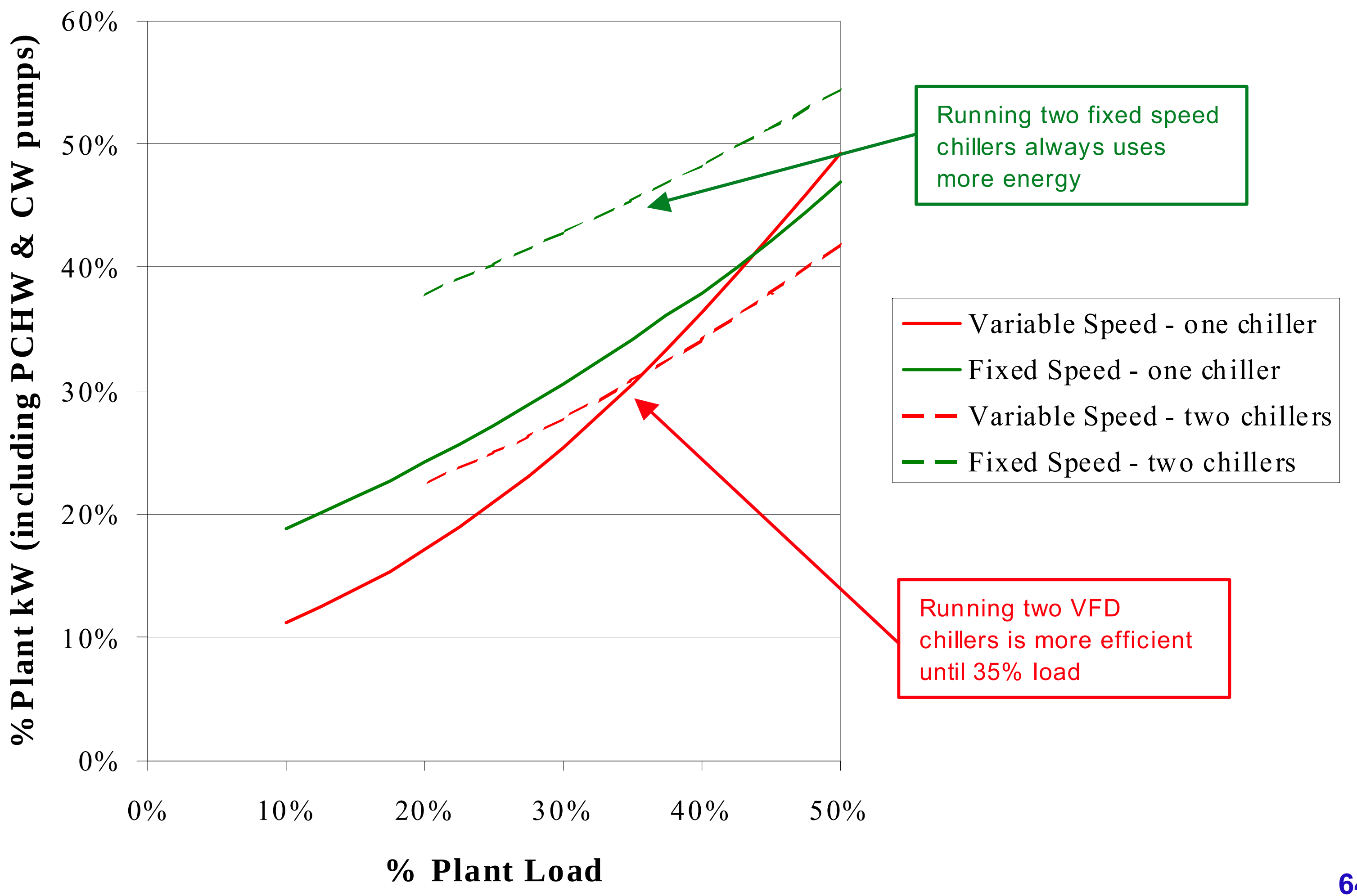


Part Load Chiller Performance

w/ Zero ARI Tolerance



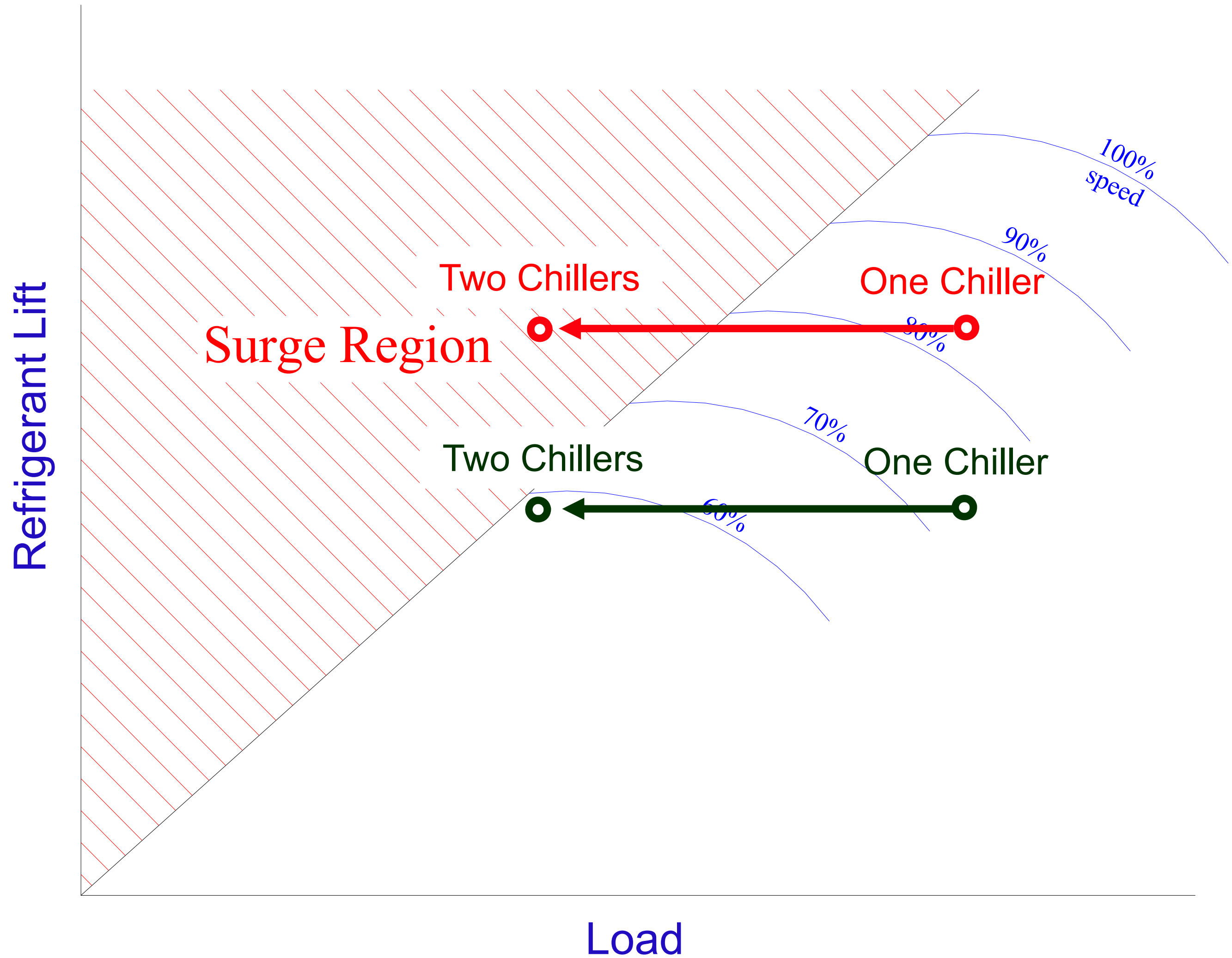
Two-Chiller Plant Performance at Low Load



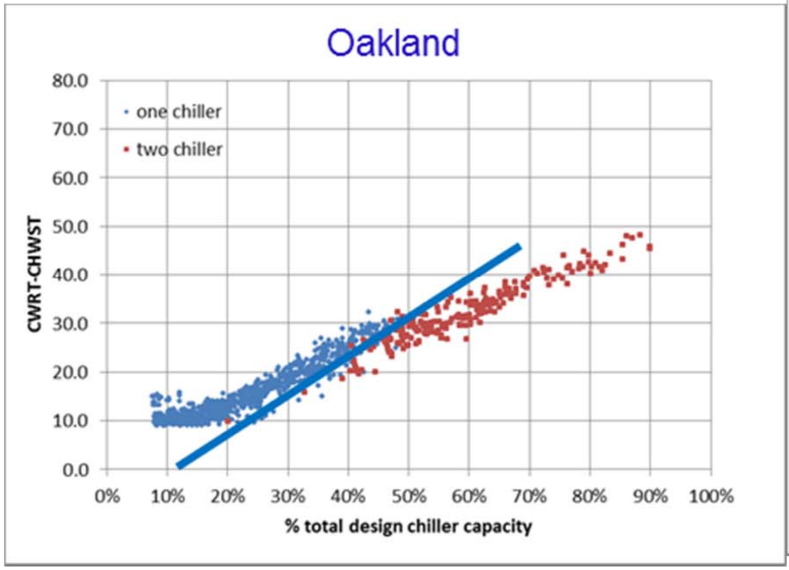
Cautionary Note

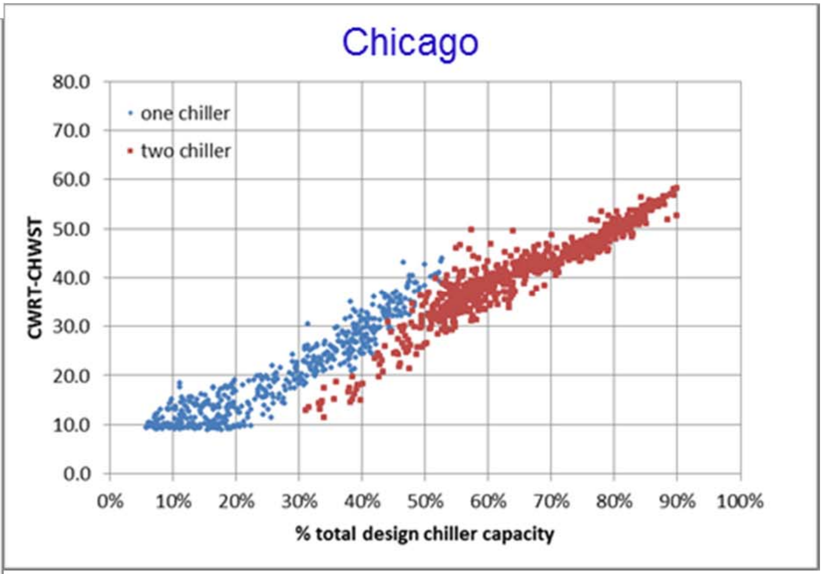
- **Staging logic must limit possibility for surge operation for centrifugal chillers**
- **Some variable speed chillers don't dynamically measure surge conditions**
  - You will lose some of the savings with primary-only variable flow systems because minimum speed may have to be increased to avoid surge
  - You may have premature tripping due to onset of surge otherwise
  - This is only an issue with variable evaporator flow systems (like primary-only variable flow)

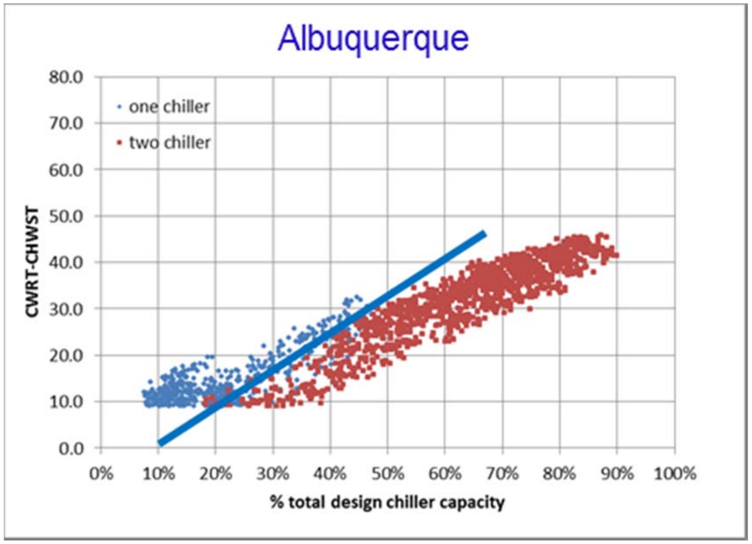
Staging & Surge



Correlation with Lift & Load







Generic Control Sequences

All-variable speed plant

$$SPLR = E(T_{CWR} - T_{CHWS}) + F$$

Stage	Chillers on	Nominal Capacity	Stage up to next stage if either:		Stage down to lower stage if:
0	All off	0	–	Any Chiller Plant Requests and OAT>LOT and schedule is active	–
2	Lead chiller	50%	for 15 minutes load greater than SPLR	CHW Plant Reset = 100 for 15 minutes, and load greater than 30%	No Chiller Plant Requests for 5 minutes or OAT<(LOT-5F) or schedule is inactive
3	Both chillers	100%	–	–	for 15 minutes load less than SPLR

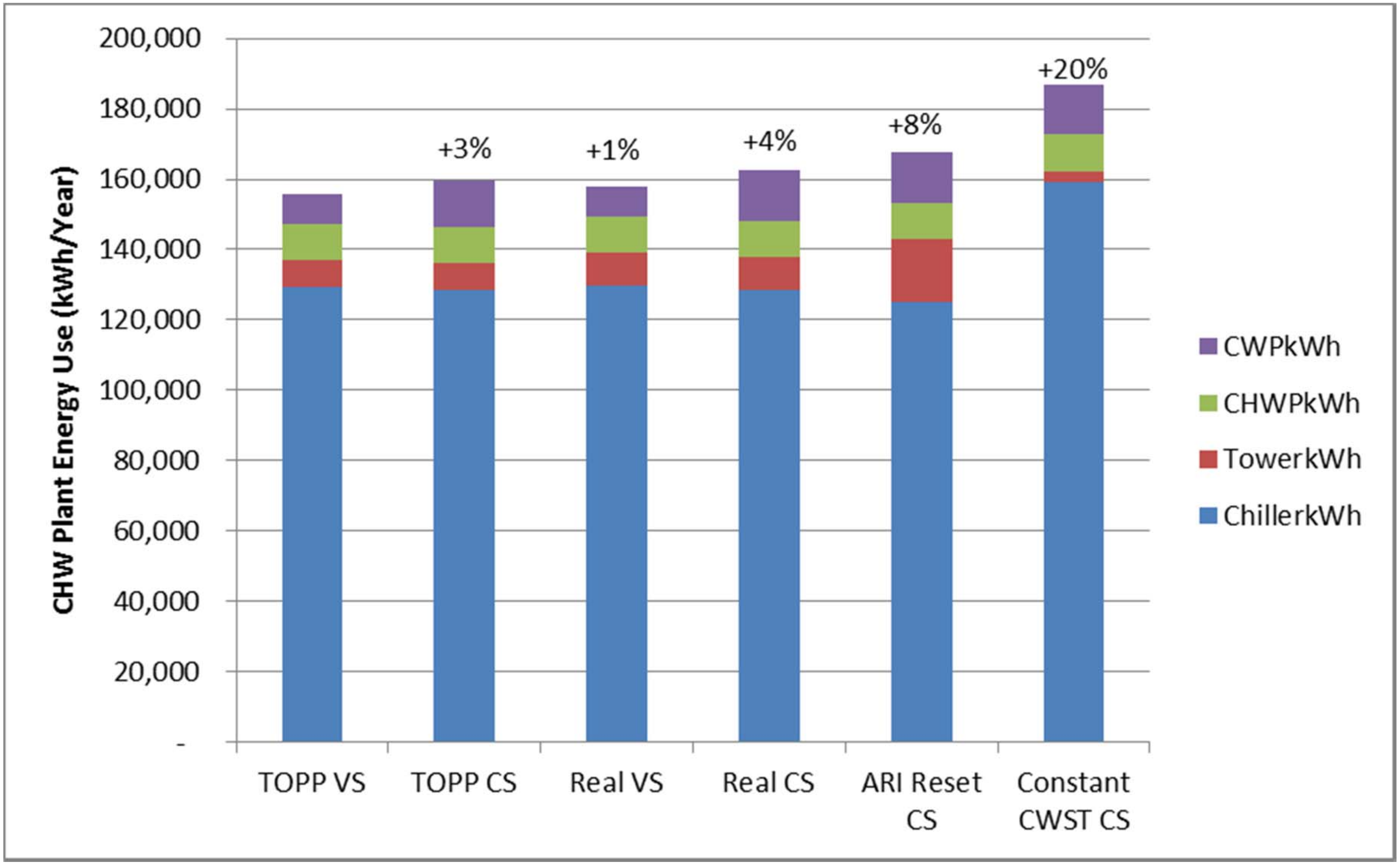
Determining E and F

- **TE Correlations**
  - E = 0.057 - 0.000569*WB - 0.0645*IPLV - 0.000233*APPROACH - 0.000402*RANGE + 0.0399*KW/TON
  - F = -1.06 + 0.0145*WB + 2.16*IPLV + 0.0068*APPROACH + 0.0117*RANGE - 1.33*KW/TON
- **Need to test for reasonableness**
- **Default values**
  - E=0.004 and F = 0.30

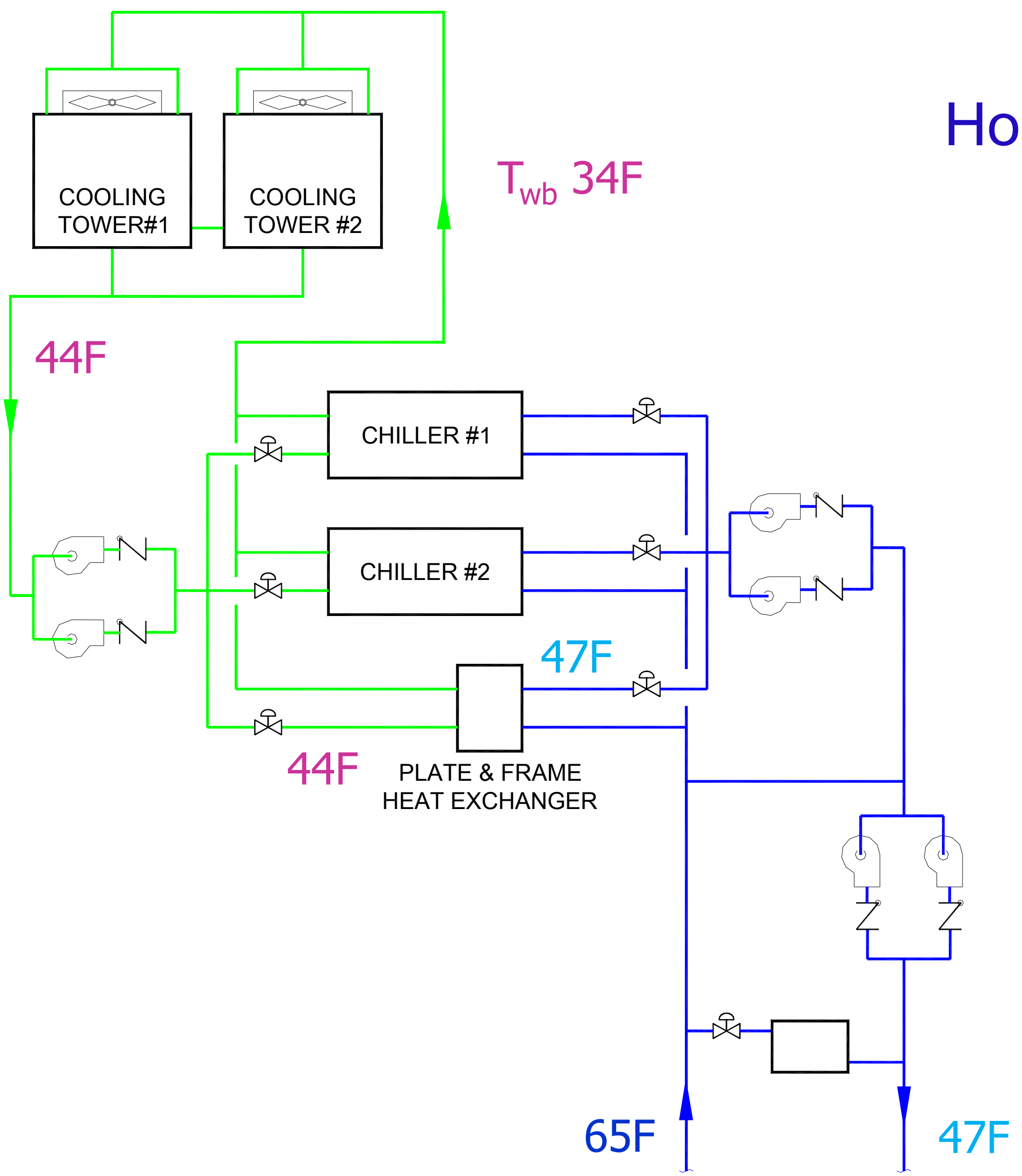
Example

- **Oakland office building**
- **All variable speed plant**
- **TOPP model coefficients**
  - A = 47, B =5.2
  - C = 1.3, D = 0.13
  - E = 0.009, F = 0.21

TOPP vs. Real Sequences



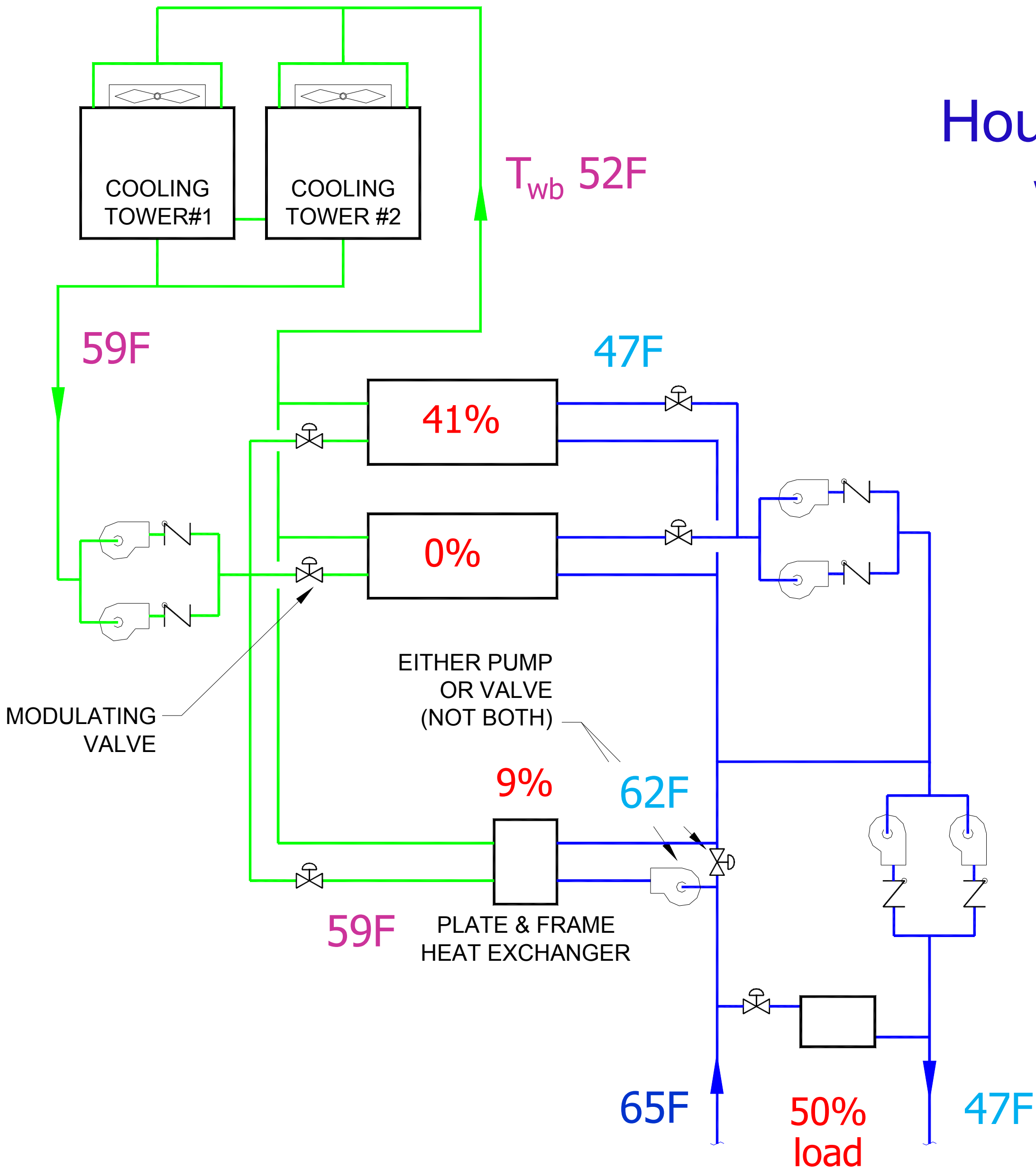
Waterside Economizers



Hours in SF Bay Area with T_{wb} <= 34F??

10 hrs/yr

Non-Integrated Economizer

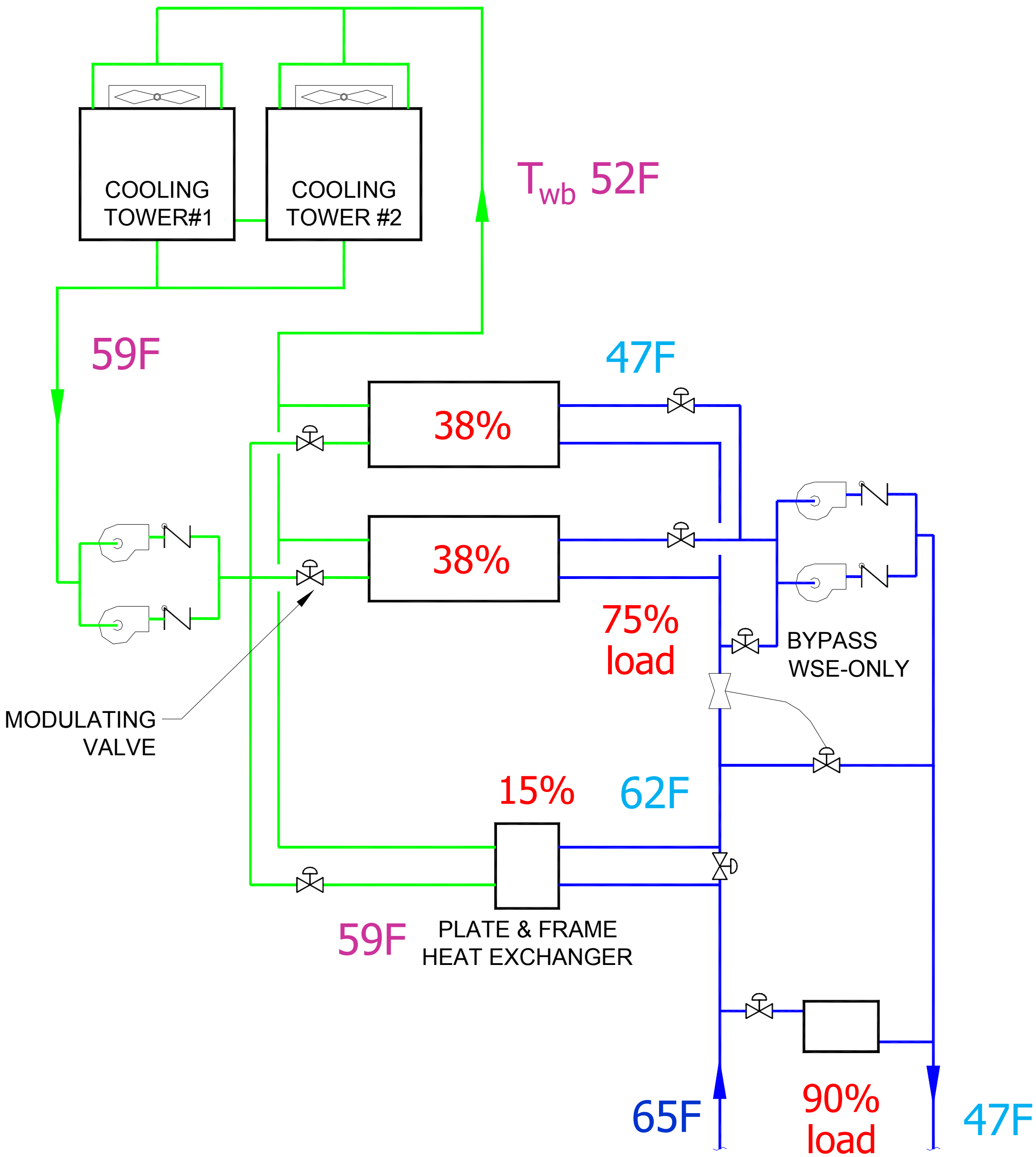


Hours in SF Bay Area with T_{wb} <= 52F??

4000 hrs/yr

Integrated Economizer

Primary/Secondary



Integrated Economizer

Primary Only

Integrated WSE Control Sequences

- **Run all air handlers, including redundant units with variable speed drives**
- **Reset CHWST setpoint based on valve demand**
- **Enable WSE if CHWRT > predicted HXLWT + 2**
  - Predicted HXLWT = Ambient wetbulb + HX_Approach + Tower_Approach
    - HX_Approach = Design HX approach * %HX-Load
    - Tower_Approach = Design Tower approach for office type occupancies
      = Adjust based on WBT from manufacturer's data for data center– see slide 5
- **Disable WSE if HXLWT > CHWRT - 2**
- **Disable chiller(s) when HXLWT ≤ CHWST setpoint**
- **Enable chiller(s) when CHWST > setpoint**
- **Run as many tower cells as minimum flow will allow**
- **Tower speed:**
  - When WSE is disabled control speed "normally"
  - When WSE and chiller(s) are enabled run 95% speed
  - When chiller is disabled control speed to maintain CHWST setpoint

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Summary

- **In this seminar, you have learned how to**
  - Select optimum chilled water distribution system
  - Optimally control
    - Chilled Water Pumps
    - Chilled Water Temperature and DP Setpoint Reset
    - Tower Fans
    - Condenser Water Pumps
    - Chiller Staging
    - Waterside Economizers

Questions