Proposed data center cooling: CRAH with air chiller empirical energy calculations
For Albany New York (TMY3)

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OVERVIEW: 1) This document expands upon Section *6.5.1 "Annual energy calculations shall use the following requirements" from 2019 ASHRAE Standard 90.4 "Energy Standard for Data Centers"* (Std. 90.4), by providing a procedure and engineering calculation exemplar. This document shows how to calculate data center mechanical energy use from equipment, for an existing data center at 50% ITE load. 2) After running the Procedure at 25%, 50% , 75%, 100% ITE load, you can calculate the Annualized Mechanical Load Component (MLC) per (*Std. 90.4 Section 6.5 Maximum Annualize Mechanical Load Component)*. 3) To meet the 90.4 standard the calculated MLC must be lower than the value in Table 6.5 for your climate zone. 4) This mechanical systems model is for 4 ITE zones each served by a single computer room air handling units that utilize chilled water from a single air-cooled chiller. 5) This is the first steps of many going forward to expand controls and equipment types.

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I) CLIMATE DATA (TMY3 weather files can be obtained from http://climate.onebuilding.org/)

$OA := \text{READCSV}(\text{"NY\_ALBANY-CO-AP\_725180\_TY3A.csv"})$

Columns: Mon, Day, Hr, Db, Wb, RH, W, Dp

$OA =$

Mon	Day	Hr	Db	Wb	RH	W	Dp
"NY"	"ALBANY−CO−AP"	725180	42.75	−73.8	84	NaN	NaN
1	1	1	33.1	31	82	0	28
1	1	2	32	30.8	89	0	28.9
1	1	3	30.9	30.1	92	0	28.9
1	1	4	30	29.2	92	0	28
1	1	5	28	27.6	96	0	27
1	1	6	28	27.6	96	0	27
1	1	7	27	26.6	96	0	26.1
1	1	8	26.1	25.7	96	0	25
1	1	9	26.1	26.1	100	0	26.1
1	1	10	27	27	100	0	27
1	1	11	28	28	100	0	28
							⋮

The Maximum Annualized MLC in Table 6.5 of the 90.4 Std. is based on Climate zone. Albany is in ASHRAE Climate Zone 5A.

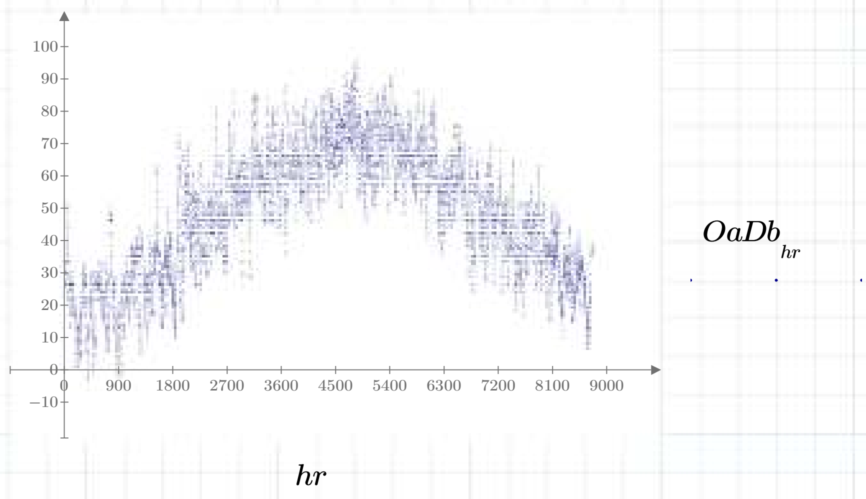
Variables from First Row

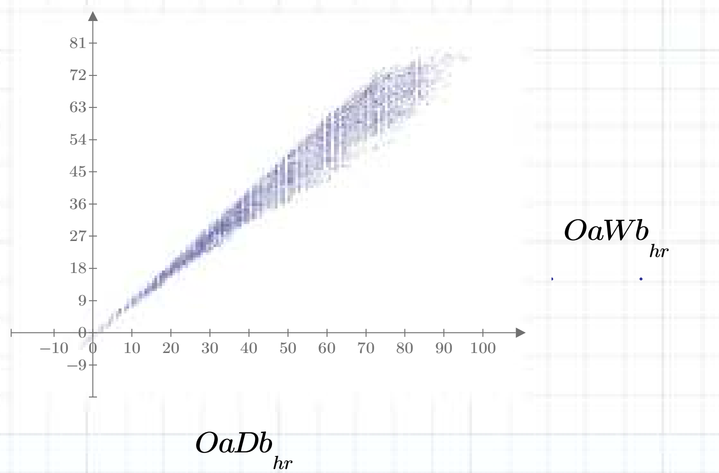
$OA_{0,0} = \text{"NY"}$ $OA_{0,1} = \text{"ALBANY−CO−AP"}$

Set Climate variables for Energy Calculations
For this air cooled chiller system only outdoor DB used

Set hrs in yr

$hr := 1..8760$ $m_{hr} := OA_{hr,0}$ $d_{hr} := OA_{hr,1}$ $h_{hr} := OA_{hr,2}$ $OaDb_{hr} := OA_{hr,3}$ $OaWb_{hr} := OA_{hr,4}$





II REFERENCE MATERIAL
1) NOMENCLATURE

Thermodynamic conventions
- Q = load or cooling capacity
- P = power
- V = volume rate
- Gpm= water volume flow rate

Zones
- Sum = sum of IT or CRAH zones or loop heat gains

Engineering design & operations
- Rated = equipment rated size and capacity at design conditions
- Avail = equipment rated size and capacity adjusted for temperature
- Ops = operating condition

Equipment
- It = Info tech (servers, storage)
- Crah= Computer room air handler
- Chill = Chiller
- Pump = pump: Sec=secondary (pumpSec), Chill=Chiller (pumpChill)

Fan = CRAH fan

Primary=Primary loop (load)

Controls
AHU(fan) **Chiller** (compressor)

dFanCtrlType: fixed or vfd chTCtrlType: chFixed or chDbReset

Pumps: fixed,vfd ---

sgCtrlType-Secondary loop cgCtrlType-chiller loop

Part load ratios
- fPlr = capacity ratio for fans vPlr = volume rate ratio for fans
- sgPlr = gpm ratio for secondary pump
- cgPlr = gpm ratio for chiller pump
- cPlr = capacity ratio for chillers

Mean = annual average value (when value varies through year)

Colors: Green=input, Red=Loads/Cap, purple=power, blue=control types, ASHRAE Std. 90.4 reference

ABC company refers to HVAC design values determined by Client/Designer

Adjustment functions
Eir = Electric input ratio (efficiency adjustment)

Cap=Capacity adjustment

Ft= function of temperature

Fplr= function of part load ratio

2) COOLING EQUIPMENT EMPIRICAL FUNCTIONS

Equipment type	Capacity Tadj	Power Tadj	Power PLRadj
a. CRAH/AHU	Treturn, Tchws,TdT (custom)		Load / Available (kW) (DOE2)
b. Chiller (DOE2)	Tchws, Tdb	Tchws, Tdb	Load / Available (kW)
c. Sec & Prim Pumps (DOE2)			Load / Rated (Gpm)

Where:

Capacity Tadj= Temp adjusted capacity
Treturn=Return air temp
Available=Temp adjusted capacity

Power Tadj= Temp adjusted power
Tchws=chilled water supply temp
Tdb=hourly outdoor dry bulb temp

Power PLRadj= Part load adjusted power
TdT=Chilled water temp difference

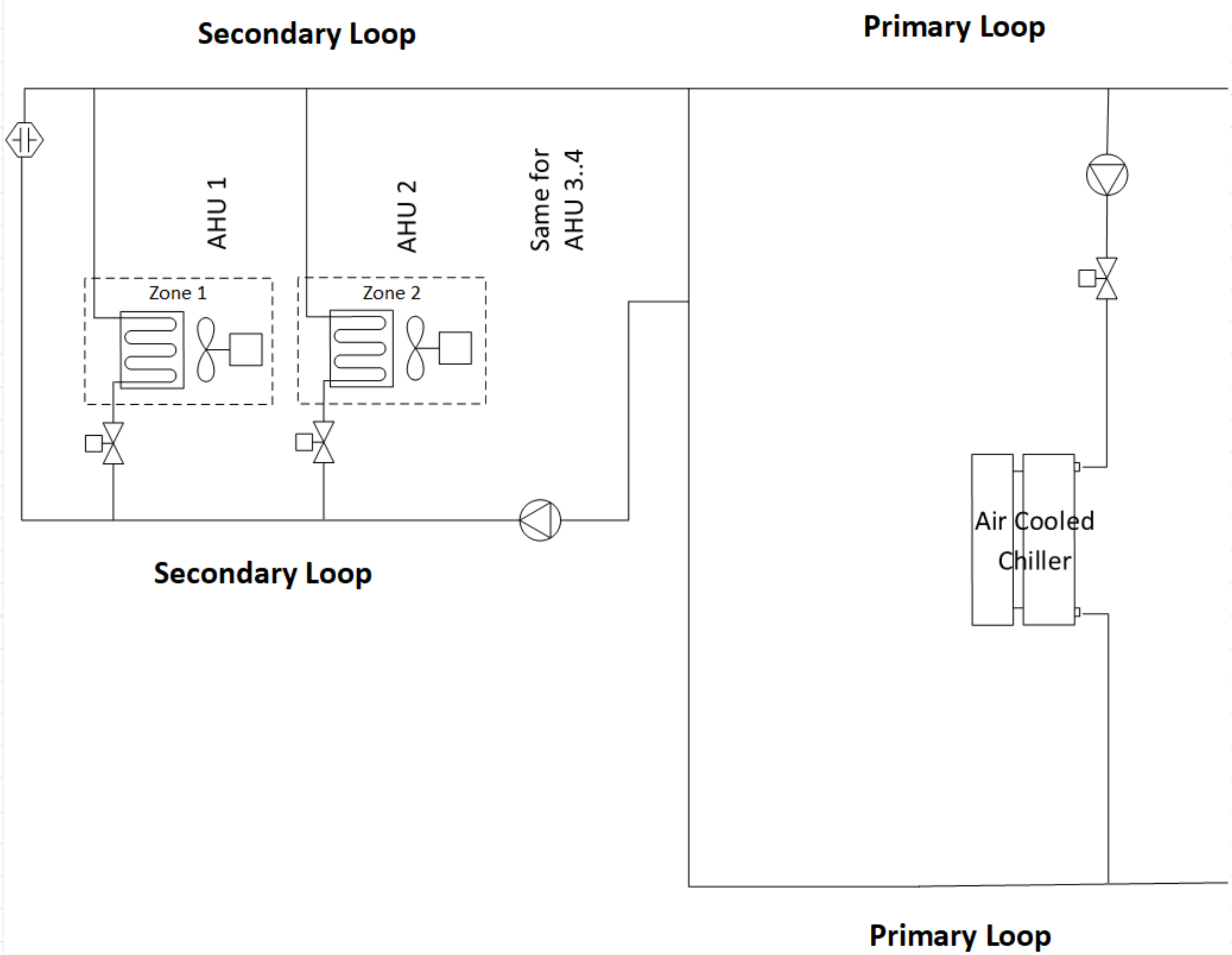
3) AIR-COOLED CHILLER COEFFICIENTS FROM EXCEL SPREADSHEET

	H	I	J	K	L	M	N
1	**Fan Power PLR**	a	b	c	d	e	f
2	Table 65 - Fan Power Part Load Adjustment - AF or BI Riding Curve	0.16310	1.59010	-0.88170	0.12810	0.0000	0.0000
3	Table 65 - Fan Power Part Load Adjustment - AF or BI Inlet Vanes	0.99770	-0.65900	0.95470	-0.29360	0.0000	0.0000
4	Table 65 - Fan Power Part Load Adjustment - FC Riding Curve	0.12240	0.61200	0.59830	-0.33340	0.0000	0.0000
5	Table 65 - Fan Power Part Load Adjustment - FC Inlet Vanes	0.30380	-0.76080	2.27290	-0.81690	0.0000	0.0000
6	Table 65 - Fan Power Part Load Adjustment - Vane Axial Variable Pitch Blades	0.16390	-0.40160	1.99090	-0.75410	0.0000	0.0000
7	Table 65 - Fan Power Part Load Adjustment - Any Fan with VSD	0.00130	0.14700	0.95060	-0.09980	0.0000	0.0000
8	Table 65 - Fan Power Part Load Adjustment - VSD with Static Pressure Reset	-0.00310	0.09910	1.02680	-0.11280	0.0000	0.0000
48	**Air cooled chiller capacity type**	a	b	c	d	e	f
49	Table 86 - Chiller Capacity Temperature Adjustment - Air Cooled - Scroll	0.400706800	0.018615400	0.000071900	0.001772900	-0.000020100	-0.000082700
50	Table 86 - Chiller Capacity Temperature Adjustment - Air Cooled - Reciprocating	0.576172900	0.020631300	0.000077600	-0.003511800	0.000003100	-0.000078600
51	Table 86 - Chiller Capacity Temperature Adjustment - Air Cooled - Screw	-0.094648990	0.038340700	-0.000092050	0.003780070	-0.000013750	-0.000154640
62	**Air cooled chiller temp efficiency type**	a	b	c	d	e	f
63	Table 89 - Chiller Efficiency Temperature Adjustment - Air Cooled - Scroll	0.99006550	-0.00584140	0.00016450	-0.00661130	0.00016800	-0.00022500
64	Table 89 - Chiller Efficiency Temperature Adjustment - Air Cooled - Reciprocating	0.66534400	-0.01383820	0.00014730	0.00712800	0.00004570	-0.00010320
65	Table 89 - Chiller Efficiency Temperature Adjustment - Air Cooled - Screw	0.13545630	0.02292940	-0.00016100	-0.00235390	0.00012990	-0.00018680
71	**Air cooled chiller Plr efficiency type**	a	b	c	d	e	f
72	Table 91 - Chiller Efficiency Part Load Adjustment - Air Cooled - Scroll	0.06369110	0.58488300	0.35280270	0.00000000	0.00000000	0.00000000
73	Table 91 - Chiller Efficiency Part Load Adjustment - Air Cooled - Reciprocating	0.11443740	0.54593340	0.34229860	0.00000000	0.00000000	0.00000000
74	Table 91 - Chiller Efficiency Part Load Adjustment - Air Cooled - Screw	0.03648720	0.73474290	0.21994740	0.00000000	0.00000000	0.00000000
98	**Pump PLR efficiency adjustment factors**	a	b	c	d	e	f
99	Table 99 - Pump Power Part Load Adjustment	0.00153030	0.00520810	1.10862420	-0.11635560	0.00000000	0.00000000

Reference extracted from: Commercial Buildings Energy Modeling Guidelines and Procedures 2010
https://comnet.org/3-building-descriptors-reference

4) HVAC SYSTEM SCHEMATIC DIAGRAM

The following simplified schematic represents the energy systems & components modeled. Simplifying energy assumptions exclude: 1) Energy for conditioning outdoor air for makeup air for ventilation units. 2) Energy for humidification / dehumidification. 3) Total cooling capacity, only sensible cooling is considered.



III) IT HEAT GAINS AND TEMPERATURE DIFFERENCES

1) The following examples are provided help establish IT inputs but are not part of the calculations.

Example 1 - IT Equipment power trends 3rd edition 2018

Workload	*yr2015*	*yr2025*
"Scientific"	32	42
"Business"	16	17
"Analytics"	15	21
"Cloud"	23	29
"Visualization"	26	32

Example 2 - My curve fit to calculate IT dT

$$dT(q) := 9.3871 \cdot \ln(1000 \cdot q) - 63.308$$

My curve fit was for 3 to 15 kW/rack workloads.
Temporary - use with caution at high kW/rack

2) Define number of zones

$zones := 0..3$ User defined number of zones

3) IT rack heat gain and temperatures

A) IT ZONE & TOTAL DESIGN/RATED Load kW

The design or rated IT is used to size ABC company AHU rated cap for each bay. QitRated used for PUE & COP calcs

$$QitRated := \begin{bmatrix} 290 \\ 580 \\ 290 \\ 580 \end{bmatrix} \qquad QitRatedSum := \sum_{zones} QitRated_{zones} = 1740$$

B) IT ZONE & TOTAL OPERATING Load kW

ABC company: Operating IT kW or
for MLC change as % QitRated

$$QitOps := \begin{bmatrix} 120 \\ 400 \\ 100 \\ 250 \end{bmatrix} \qquad QitOpsSum := \sum_{zones} QitOps_{zones} = 870$$

The rated and operating ITE loads should include ITE equipment and ITE electrical distribution segment power losses as heat gain. UPS and incoming electrical service power losses in cooled spaces are added to appropriate zone cooling load. For details Std. 90.4, Section 8.6 Design ELC

C) Std. 90.4 - ITE load set %50

$$\frac{QitOpsSum}{QitRatedSum} = 0.5$$

NOTE: IT heat gains constant for all 8760 hours

D) It inlet & outlet temps by zone

ABC company: Design IT temps or CFD based

$$Tinlet := \begin{bmatrix} 70 \\ 72 \\ 69 \\ 69 \end{bmatrix} \qquad Toutlet := \begin{bmatrix} 95 \\ 97 \\ 94 \\ 94 \end{bmatrix}$$

E) Average IT ΔT (F) by zone

$$\Delta T_{zones} := Toutlet_{zones} - Tinlet_{zones} = \begin{bmatrix} 25 \\ 25 \\ 25 \\ 25 \end{bmatrix}$$

4) HVAC air temperatures

A) HVAC supply & return temps by zone

ABC company: Design CRAH supply & return temps: estimated or CFD based

$\delta Treturn := -14$ degrade outlet temp based on level of containment

$$Tsupply := \begin{bmatrix} 67 \\ 67 \\ 66 \\ 64 \end{bmatrix} \qquad Treturn_{zones} := Toutlet_{zones} + \delta Treturn = \begin{bmatrix} 81 \\ 83 \\ 80 \\ 80 \end{bmatrix}$$

B) Average HVAC ΔT (F) by zone

$$\Delta Thvac_{zones} := Treturn_{zones} - Tsupply_{zones} = \begin{bmatrix} 14 \\ 16 \\ 14 \\ 16 \end{bmatrix}$$

IV) INDOOR HVAC: CRAH RATED AND OPERATING, CAPACITY & POWER

1) CRAH RATED CAPACITIES Input Rated HVAC cooling capacity = Design IT heat gain by zone and sum them

The rating of CRAH units is described in AHRI 1360 (Performance Rating of Computer and Data Processing Room Air Conditioners). The following tables define the rating conditions for different types of models, i.e. ceiling mount, floor mount upflow, downflow and horizontal flow (row based) systems.

AHRI STANDARD 1360 (I-P)-2017

Table 2. Indoor Return Air Temperature Standard Rating Conditions

Mounting Location	Standard Model	Cooling (Return Dry-bulb / Dew-point), °F	Humidification (Return Dry-bulb / Dew-point), °F
Ceiling Mounted Unit	Ceiling Mounted Unit–ducted	75.0 / 52.0	75.0 / 42.0
	Ceiling Mounted Unit–nonducted		
Floor Mounted Unit	Upflow Unit–nonducted	75.0 / 52.0	
	Upflow Unit–ducted	85.0 / 52.0	
	Downflow Unit	85.0 / 52.0	
	Horizontal-flow Unit	95.0 / 52.0	

Table 3. Heat Rejection / Cooling Fluid Standard Rating Conditions[1]

System Type	Fluid Condition	Test Condition
Air-cooled units	Entering outdoor ambient dry-bulb temperature, °F	95.0
Water-cooled units (typically connected to a cooling tower)[2]	Entering water temperature, °F	83.0
	Leaving water temperature, °F	95.0
	Water flow rate, gpm	N/A
Glycol-cooled units (typically connected to a common glycol loop)[3]	Entering glycol temperature, °F	104.0
	Leaving glycol temperature, °F	115.0
	Glycol flow rate, gpm	N/A
	Glycol solution concentration	40% Propylene Glycol by Volume
Chilled-water units (typically connected to a common chilled water loop)[4]	Entering water temperature, °F	50.0
	Leaving water temperature, °F	62.0

Notes:
1. All ratings are at standard atmospheric pressure.
2. For the NSenCOP calculation, add allowance for cooling tower fan(s) and heat rejection loop water pump power input in kW to the unit total input in kW = 5% of the unit net sensible capacity.
3. For the NSenCOP calculation, add allowance for dry cooler fan(s) and heat rejection loop glycol pump power input in kW to the unit total input in kW = 7.5% of the unit net sensible capacity.
4. For the NSenCOP calculation, add allowance for chilled water pump power input in kW to unit total input in kW (See Equation 1 below).

CRAH CAPACITIES

ABC company: 2 size AHU with small capacity & large capacity 2x small.
Small cool cap 990k Btus/hr

$$QcrahRated1 := \frac{990000}{3413} = 290 \qquad QcrahRated2 := \frac{2 \cdot 990000}{3413} = 580 \qquad QitOps = \begin{bmatrix} 120 \\ 400 \\ 100 \\ 250 \end{bmatrix}$$

B) CRAH ZONE & TOTAL RATED CAPACITY

ABC company: CRAH capacity sized for future design load (i.e. full occupancy is twice operating kW)

$oversize := 1.0$ Option to apply HVAC sizing factor $QcrahRated := QitRated \cdot oversize$

$$QcrahRatedSum := \sum_{zones} QcrahRated_{zones} = 1740$$

The zone rated CRAH capacities should be adequate to account for ITE equipment loads (III 3 above) and ITE electrical distribution segment losses as heat gain. UPS and incoming electrical service losses in cooled spaces may require the addition of cooling zone to serve this equipment. For details Std. 90.4 Section 8.6 Design ELC.

2) CHILLER TEMP SETPOINT CONTROL: Operating set point effects CRAH capacity as well as Chiller

A) Set CHILLER DESIGN TEMPS: Design includes constant chilled water supply temps and dT

Assumes Constant chilled water supply & return temp so dT is constant

$TchwsDes := 44$ $TchwrDes := 56$ $dTchwDes := TchwrDes - TchwsDes = 12$

3) CRAH OPERATING CAPACITY ADJUSTMENT equation and coefficients for adjusting cooling capacity for non-rated return air and supply water temps

CRAH Net Sensible Cooling Capacity (NSCC) and Efficiency adjustment functions

NSCC coeff

CRAH Rating conditions:
Treturn 85, TchwsDes 50, dTchwDes 12

$$c := \begin{bmatrix} \text{“Coefficient”} \\ -0.00218 \\ 0.043874 \\ -0.044499 \\ -0.043128 \\ 0.000366 \\ 0.000606 \\ -0.000393 \\ -0.000193 \\ -0.000187 \\ -0.00043 \end{bmatrix}$$

Net Sensible cooling capacity (NSCC) adjustment function considering return air temp, entering chilled water temp, and chilled water dT
Curvefit from Manufacturer CRAH performance data by Henry Amistadi

$$fNSCC(Edb, waterEt, waterDt) := c_1 + c_2 \cdot Edb + c_3 \cdot waterEt + c_4 \cdot waterDt + c_5 \cdot Edb \cdot waterEt + c_6 \cdot Edb \cdot waterDt + c_7 \cdot waterEt \cdot waterDt + c_8 \cdot Edb^2 + c_9 \cdot waterEt^2 + c_{10} \cdot waterDt^2$$

4) CRAH AVAILABLE & OPERATING CAPACITIES BY ZONE net sensible cooling capacity

In this model the zone IT heat gains are cooled by 2 different size CRAH units

A) CRAH CAPACITY ADJUSTMENT: Adjust cooling capacity for non-rated (off reference) return air and supply water temperatures

$$QcrahFt_{zones} := fNSCC\left(Treturn_{zones}, TchwsDes, dTchwDes\right)$$

B) CRAH AVAILABLE CAPACITY BY ZONE: Sum Available net sensible cooling capacity for plant calcs

Net sensible cooling capacity means Fan heat gain has already been subtracted from total cooling capacity

$$QcrahAvail_{zones} := QcrahRated_{zones} \cdot QcrahFt_{zones}$$

$$QcrahAvailSum := \sum_{zones} QcrahAvail_{zones}$$

$$QcrahRatedSum = 1740 \qquad QcrahAvailSum = 1875$$

C) CRAH OPERATING CAPACITY BY ZONE: Operating Cooling Capacity

Operating load is IT load which is constant through the year

$$QcrahOps_{zones} := QitOps_{zones}$$

$$QcrahOpsSum := \sum_{zones} QcrahOps_{zones} = 870 \qquad fPlr := \frac{QcrahOpsSum}{QcrahAvailSum} = 0.46$$

5) CRAH AIR FLOW AND PLR BY ZONE: Calc IT & HVAC fan CFM for constant or VFD flow

Required IT and HVAC air flow rate in cfm

A) FAN CFM FUNCTION: Fan flow in cfm as function of heat gain/capacity and temp diff (dT)

$$fVfan(Q, \Delta T) := 3.2 \cdot \frac{Q \cdot 1000}{\Delta T}$$

Rule of thumb number

$$fVfan(1, 25) = 128$$

B) IT RATED AIR FLOW LOAD Required IT air flow based on IT heat gain & dT - Informational

$$Vit_{zones} := fVfan\left(QitRated_{zones}, \Delta T_{zones}\right) = \begin{bmatrix} 37120 \\ 74240 \\ 37120 \\ 74240 \end{bmatrix}$$

C) CRAH RATED AIR FLOW

Set HVAC air flow based on AHU specs & # units operating per zone

ABC company: 2 size ACFM units. one double size of small, based on zone load

$$VcrahRated := \begin{bmatrix} 50000 \\ 100000 \\ 50000 \\ 100000 \end{bmatrix} \qquad VcrahRatedSum := \sum_{zones} VcrahRated_{zones} = 300000$$

D) CRAH OPERATING AIR FLOW

HVAC operating airflow for operating IT, and available capacity

$$VcrahOps_{zones} := fVfan\left(QcrahOps_{zones}, \Delta Thvac_{zones}\right) = \begin{bmatrix} 27429 \\ 80000 \\ 22857 \\ 50000 \end{bmatrix}$$

E) CRAH AVAILABLE AIR FLOW

Required HVAC air flow based on available capacity & HVAC dT

$$VcrahAvail_{zones} := fVfan\left(QcrahAvail_{zones}, \Delta Thvac_{zones}\right) = \begin{bmatrix} 71048 \\ 132593 \\ 68650 \\ 120138 \end{bmatrix}$$

F) CRAH OPS PLR: OPS/AVAIL BY ZONE

CFD calc cfm / Available cfm (adj for Treturn, Tchws, & dT HVAC)

Use available Plr for DOE2 correlation. HVAC dT has containment effects

$$vPlr_{zones} := \frac{VcrahOps_{zones}}{VcrahAvail_{zones}} = \begin{bmatrix} 0.39 \\ 0.6 \\ 0.33 \\ 0.42 \end{bmatrix}$$

G) Unmet hourly airflow - Rated < Operating

$$QcrahVunmet_{zones} := \text{if } VcrahAvail_{zones} < VcrahOps_{zones} \;\; \Big\| \; \text{“Negative number”} \;\; VcrahAvail_{zones} - VcrahOps_{zones} \;\; \text{else} \;\; \Big\| \; 0$$

$$\max(QcrahVunmet) = 0$$

$$\sum_{hr} \left(QcrahVunmet_{zones}\right) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

6) CRAH FAN RATED & OPERATING POWER: Calc CRAH Fan rated and operating power

A) Rated fan efficiency, Cfm, static pressure, efficiency and minimum fan fraction from ABC company specs

Supply Fan Static Pressure

Definition: Design static pressure of supply fan. Important for fan power usage & heat gain calcs

Units: Inches of water column (in. $H_2 0$)

Supply Fan Efficiency

Definition: The efficiency of the fan at design conditions

ABC company design values: Acfm 50k, TSP 3 in, BHP 37.6

Efficiency derived from BHP — BHP converted to kW

$$FanSupSP := 3.0$$

$$\frac{50000 \cdot 3}{.628 \cdot 6350} \cdot .7457 = 28.05$$

$$37.6 \cdot .7457 = 28.04$$

$$FanSupEff := .628$$

B) CRAH RATED FAN POWER BY ZONE: Detailed calc of supply fan design power in kW by zone

$$PfanRated_{zones} := \frac{\left(VcrahRated_{zones} \cdot FanSupSP\right)}{FanSupEff \cdot 6350} \cdot .7457 = \begin{bmatrix} 28 \\ 56 \\ 28 \\ 56 \end{bmatrix}$$

$$PfanRatedSum := \sum_{zones} PfanRated_{zones} = 168$$

C) CRAH OPERATING ZONE FAN POWER: Design fan power based on fan type constant or variable

i) Variable fan power speed adjustment function

For each zones, fan air flow and power are adjusted once, since zone IT load is constant for all 8760 hrs

a) Table of DOE2 fan types, fan sys num & min fan fraction

$$FanTypeData := \begin{bmatrix} \text{“AF or BI Riding Curve”} & 0 & .7 \\ \text{“AF or BI Inlet Vanes”} & 1 & .5 \\ \text{“FC Riding Curve”} & 2 & .3 \\ \text{“ FC Inlet Vanes”} & 3 & .3 \\ \text{“Vane Axial Variable Pitch Blades”} & 4 & .2 \\ \text{“Any Fan with VSD”} & 5 & .2 \\ \text{“VSD with Static Pressure Reset”} & 6 & .2 \end{bmatrix}$$

b) Select Fan system type and min plr ratio

$$Fsys := 5$$

$$FanTypeData_{Fsys,0} = \text{“Any Fan with VSD”}$$

$$minFan := FanTypeData_{Fsys,2} = 0.2$$

c) DOE2 Fan Power PLR adjustment equation and coefficients

$$\mathrm{C} := \mathrm{READEXCEL}\left(\text{“.\textbackslash MPG\_AppendixH\_ComnetDataOnly.xlsx”}, \text{“COMNET Data!H2:L8”}\right)$$

$$\mathrm{C}_{Fsys,0} = \text{“Table 65 – Fan Power Part Load Adjustment – Any Fan with VSD”}$$

Below excel cell ranges access coefficient for functions. In Section II 3) coefficient values can be looked up

$$FanFplr(gPlr) := \left\| \begin{array}{l} Coeff \leftarrow \mathrm{READEXCEL}\left(\text{“.\textbackslash MPG\_AppendixH\_ComnetDataOnly.xlsx”}, \text{“COMNET Data!H2:L8”}\right) \\ a \leftarrow Coeff_{Fsys,1} \\ b \leftarrow Coeff_{Fsys,2} \\ c \leftarrow Coeff_{Fsys,3} \\ d \leftarrow Coeff_{Fsys,4} \\ FanFplr \leftarrow \left(a + b \cdot gPlr + c \cdot gPlr^2 + d \cdot gPlr^3\right) \end{array} \right.$$

d) Fan Power PLR adjustment factor

$$fEirFplr_{zones} := \max\left(FanFplr\left(vPlr_{zones}\right), minFan\right) = \begin{bmatrix} 0.2 \\ 0.41 \\ 0.2 \\ 0.22 \end{bmatrix}$$

ii) CRAH FAN SPEED CONTROL

Set fan control type

$fixed := 0 \quad vfd := 1 \qquad dFanCtrlType := vfd$

iii) CRAH FAN OPERATING POWER

a) CRAH HOURLY OPERATING ZONE FAN POWER: using DOE2 correlation & OPS/Available PLR

$$PfanOps_{zones} := \text{if } dFanCtrlType = fixed$$
$$\quad PfanOps_{zones} \leftarrow PfanRated_{zones}$$
$$\text{else if } dFanCtrlType = vfd$$
$$\quad PfanOps_{zones} \leftarrow PfanRated_{zones} \cdot fEirFplr_{zones}$$

Operating fan power kW

$$PfanOps = \begin{bmatrix} 6 \\ 23 \\ 6 \\ 12 \end{bmatrix}$$

iv) SUM CRAH HOURLY OPERATING FAN POWER BY ZONE

$$PfanOpsSum := \sum_{zones} PfanOps_{zones} = 47$$

V) SECONDARY PUMP RATED & OPERATING POWER Secondary constant or variable speed pumping

Pump Design Flow (GPM)
Definition: The flow rate of the pump at design conditions. This is derived from the load, and the design supply and return temperatures.
Units: gpm or gpm/ton for condenser and primary chilled water pumps
Baseline:
-The dT on evaporator side of chillers is 12 F (56 F less 44 F) equates to a flow of 2 gpm/ton.
-The flow for secondary chilled water pumps varies with cooling demand, due to two-way valves at the coils. The flow for primary chilled water loops is constant.
NOTE for CRAH use the water dT to calc chiller Gpm

1) SECONDARY PUMP RATED GPM & POWER: ABC company secondary pump design data

ABC company Design: 3 pumps only one operates. 1150 gpm, 75ft TDH, 40HP motor 80% eff. Static pressure setpoint

A) SECONDARY PUMP RATED GPM and design values:

$GpmSecRated := 1150 \qquad HeadSec := 75 \qquad EffSec := .8$

B) SECONDARY PUMP RATED POWER

$$PpumpSecRated := \frac{GpmSecRated \cdot HeadSec}{EffSec} \cdot \frac{.643}{1000} = 69$$

2) SECONDARY PUMP OPERATING GPM: Constant or Variable speed

A) SET SECONDARY PUMP SPEED CONTROL TYPE: Set pump speed type and Calc Gpm based on constant or variable speed

Set the pump flow type

$fixed := 0 \qquad vfd := 1 \qquad sgCtrlType := vfd$

B) SECONDARY PUMP OPERATING GPM: Calc GPM based on constant or variable speed mode

```
GpmCrahOps :=  if sgCtrlType = fixed
                  "use design pump gpm"
                  Gpm ← GpmSecRated
               else if sgCtrlType = vfd
                  "Calc gpm from load & dT"
                  Gpm ← (QcrahOpsSum · 3413) / (500 · dTchwDes)
               Gpm
```

$= 495$

$GpmSecRated = 1150$

500 btu/gal-F-hr = 8.341 lb/gal * 1.0 btu/lb-F * 60 min/hr

3) SECONDARY PUMP OPERATING PLR: Secondary variable speed Pump Power Adjusted for Part Load Ratio

$$sgPlr := \frac{GpmCrahOps}{GpmSecRated} = 0.43$$

4) PUMP OPERATING PLR equation: Pump Power Adjusted for Part Load Ratio (Used by all pumps)

DOE2 Pump Power Part Load Adjustment

$$C := \text{READEXCEL}\left(\text{“.\\MPG\_AppendixH\_ComnetDataOnly.xlsx”}, \text{“COMNET Data!H99:L99”}\right)$$

$$C_{0,0} = \text{“Table 99 – Pump Power Part Load Adjustment”}$$

$$pumpFplr(gPlr) := \left\| \begin{array}{l} Coeff \leftarrow \text{READEXCEL}\left(\text{“.\\MPG\_AppendixH\_ComnetDataOnly.xlsx”}, \text{“COMNET Data!H99:L99”}\right) \\ a \leftarrow Coeff_{0,1} \\ b \leftarrow Coeff_{0,2} \\ c \leftarrow Coeff_{0,3} \\ d \leftarrow Coeff_{0,4} \\ pumpFplr \leftarrow \left(a + b \cdot gPlr + c \cdot gPlr^2 + d \cdot gPlr^3\right) \end{array} \right.$$

5) HOURLY SECONDARY CHILLED WATER PUMP OPERATING POWER

Secondary chilled water pump speed varies seasonally with chiller supply temp and dTemp and is based on constant IT load

$$PpumpSecOps := PpumpSecRated \cdot pumpFplr(sgPlr) = 14$$

VI) HOURLY SECONDARY LOOP RATED & OPERATING LOAD
includes available AHU capacity, Fan power and Secondary pump power

Add secondary water loop pump and fan heat gain to secondary load

1) HOURLY SECONDARY LOOP RATED LOAD: Design / Rated secondary loop heat gain

Used to calculate constant chiller water pump power

$$QsecRatedLoad := QcrahRatedSum + PfanRatedSum + PpumpSecRated = 1978$$

2) HOURLY SECONDARY LOOP OPERATE LOAD: Operating secondary loop heat gain

Used to calculate variable chiller water pump power

Fan power effected by Tchws & dTchw, Sec pump power effected by dTchw

$$QsecOpsLoad := QcrahOpsSum + PfanOpsSum + PpumpSecOps = 931$$

3) Consider cooling load in relation to CRAH capacity.

Unmet hour load - capacity is less than load

$$QcrahUnmet := \text{if } QcrahAvailSum < QitOpsSum \;\; \| \; \text{“Negative number”} \;\; \| \; QcrahAvailSum - QitOpsSum \;\; \text{else} \;\; \| \; 0$$

$$\max(QcrahUnmet) = 0$$

$$\sum(QcrahUnmet) = ?$$

------------------------END SECONDARY CALCULATIONS------------------------

VII) DESIGN CALCULATIONS

Part 1 - Input in the secondary section above

1) IT RATED LOAD: IT DESIGN COOLING LOAD

$QitRatedSum = 1740$ $\sum_{zones} Vit_{zones} = 222720$

2) CRAH RATED & AVAILABLE CAPACITY: CRAH DESIGN CAPACITY

$QcrahRatedSum = 1740$ $QcrahAvailSum = 1875$ $VcrahRatedSum = 300000$

3) SECONDARY PUMP RATED POWER

$GpmSecRated = 1150$ $HeadSec = 75$ $EffSec = 0.8$ $PpumpSecRated = 69$

4) PRIMARY CHILLER WATER LOOP DESIGN

A) CHILLER CONTROL TEMPS: CHILLER DESIGN CONDITIONS for seasonal chilled water supply set point and dTemp

$TchwsDes = 44$ $dTchwDes = 12$ $TchwrDes = 56$

Part 2 - New design inputs for chillers

B) PRIMARY CHILLED WATER PUMP RATED POWER

ABC company chiller pump specs 1200 gpm, 50ft head, 85% overall efficiency (incl: pump, motor, Vfd)

$GpmChillRated := 1200$ $HeadChill := 50$ $EffChill := .85$ $PpumpChillRated := \frac{GpmChillRated \cdot HeadChill}{EffChill} \cdot \frac{.643}{1000} = 45$

C) CHILLER RATED LOAD: RATED COOL LOAD FOR evaporator side of CHILLER includes secondary loop + chiller loop pump

Consider cooling load in relation to Chiller capacity. Use load if oversized. Use capacity if undersized.

$QchillRatedLoad := QsecRatedLoad + PpumpChillRated$

D) CHILLER RATED COMPRESSOR CAPACITY AND POWER

Use ABC company design data: Capacity 600 tons and motor Power 362 kW
Convert capacity from tons to kW

$QchillRated := \frac{600 \cdot 12000}{3413} = 2110$ $PchillRated := 362$

VIII) HOURLY CHILLER PUMP OPERATING POWER

HOURLY CHILLER GPM: **Chiller pump operated to exceed secondary pump gpm**

A) CHILLER SPEED CONTROL TYPE: Set pump speed type

$fixed := 0 \quad vfd := 1 \qquad cgCtrlType := fixed$

B) CHILLER PUMP OPERATING GPM: Calc Tower GPM based on constant or variable speed type

$$GpmChillOps := \left\| \begin{array}{l} \text{if } cgCtrlType = fixed \\ \quad \left\| \begin{array}{l} \text{“use design pump gpm”} \\ Gpm \leftarrow GpmChillRated \end{array} \right. \\ \text{else if } cgCtrlType = vfd \\ \quad \left\| \begin{array}{l} \text{“Calc gpm from load \& dT”} \\ Gpm \leftarrow \dfrac{(QsecOpsLoad) \cdot 3413}{500 \cdot dTchwDes} \end{array} \right. \\ Gpm \end{array} \right. = 1200 \qquad GpmChillRated = 1200$$

500 btu/gal-F-hr = 8.341 lb/gal * 1.0 btu/lb-F * 60 min/hr

C) CHILLER PUMP OPERATING PLR: Chiller Pump Power Adjusted for gpm Part Load Ratio

$$cgPlr := \frac{GpmChillOps}{GpmChillRated} = 1$$

D) HOURLY CHILLER PUMP OPERATING POWER

$$PpumpChillOps := PpumpChillRated \cdot pumpFplr(cgPlr) = 45$$

IX) HOURLY CHILLER OPERATING LOAD
Chiller evaporator side cooling load - Add chilled water pump

$$QchillOpsLoad := QsecOpsLoad + PpumpChillOps$$

X) HOURLY CHILLER OPERATING CAPACITY AND POWER:
Chiller capacity and power use for operation at varying temperatures

1) Overview

Chiller Type

Vapor compression chillers operate on the reverse-Rankine cycle, using mechanical energy to compress the refrigerant, and include:

-Reciprocating – uses pistons for compression

-Screw – uses two counter rotating screws for compression

-Scroll – uses two interlocking spirals or scrolls to perform the compression

-Centrifugal – uses rotating impeller blades to compress the air

Chiller Rated Capacity

Definition: The **cooling capacity of a piece of cooling equipment at rated conditions**.

Units: Btu/h or tons or kW MW

Input Restrictions: If unmet load hours are greater than 300, the chiller may have to be made larger.

Baseline Rules: Determine loads for baseline building and oversize by 15%.

Chiller Rated Efficiency

Definition The **Coefficient of Performance (COP) at ARI rated conditions**.

Baseline Rules With the ***ASHRAE Standard 90.1*** baseline, use the minimum values of efficiency

Table 4. Standard Rating Conditions

Operating Category	Conditions	Cooling Mode Evaporator[2]			Cooling Mode Heat Rejection Heat Exchanger: Tower (Water Conditions)[3]			Heat/Recovery (Water Conditions)[4]		Evaporatively-cooled Entering Temperature[5, 7]		Air-cooled (AC) Entering Temperature[5, 7]		Without Condenser: Air-cooled Refrigerant Temperature		Water & Evaporatively Cooled Refrigerant Temperature	
		Entering Temperature, °F	Leaving Temperature, °F	Flow Rate, gpm/ton	Entering Temperature, °F	Leaving Temperature, °F	Flow Rate, gpm/ton	Entering Temperature, °F	Leaving Temperature, °F	Dry-Bulb, °F	Wet-Bulb, °F	Dry-Bulb, °F	Wet-Bulb, °F	SDT, °F	LIQ, °F	SDT, °F	LIQ, °F
All Cooling	Standard	54.00	44.00	Note - 8	85.00	94.30	Note - 10	--	--	95.00	75.00	95.00	--	125.00	105.00	105.00	98.00
AC Heat Pump High Heating[6]	Low	--	105.00	Note - 1	--	--	--	--	--	--	--	47.00	43.00	--	--	--	--
	Medium	--	120.00	Note - 1	--	--	--	--	--	--	--	47.00	43.00	--	--	--	--
	High	--	140.00	Note - 1	--	--	--	--	--	--	--	47.00	43.00	--	--	--	--
AC Heat Pump Low Heating[6]	Low	--	105.00	Note - 1	--	--	--	--	--	--	--	17.00	15.00	--	--	--	--
	Medium	--	120.00	Note - 1	--	--	--	--	--	--	--	17.00	15.00	--	--	--	--
	High	--	140.00	Note - 1	--	--	--	--	--	--	--	17.00	15.00	--	--	--	--
Water Cooled Heating	Low	--	44.00	Note - 8	--	--	--	95.00	105.00	--	--	--	--	--	--	--	--
	Medium	--	44.00	Note - 8	--	--	--	105.00	120.00	--	--	--	--	--	--	--	--
	High	--	44.00	Note - 8	--	--	--	120.00	140.00	--	--	--	--	--	--	--	--
	Boost	--	65.00	Note - 8	--	--	--	120.00	140.00	--	--	--	--	--	--	--	--
Heat Recovery	Low	--	44.00	Note - 8	75.00	--	Note - 9	95.00	105.00	40.00	38.00	40.00	38.00	--	--	--	--
	Medium	--	44.00	Note - 8	75.00	--	Note - 9	105.00	120.00	40.00	38.00	40.00	38.00	--	--	--	--
	Hot Water 1	--	44.00	Note - 8	75.00	--	Note - 9	90.00	140.00	40.00	38.00	40.00	38.00	--	--	--	--
	Hot Water 2	--	44.00	Note - 8	75.00	--	Note - 9	120.00	140.00	40.00	38.00	40.00	38.00	--	--	--	--

Notes:

1. The water flow rate used for the heating tests of reverse cycle air to water heat pumps shall be the flow rate determined during the cooling test.
2. The rating Fouling Factor Allowance for the cooling mode evaporator or the heating Condenser for AC reversible cycles shall be R_{foul} = 0.000100 h·ft²·°F/Btu.
3. The rating Fouling Factor Allowance for tower heat exchangers shall be R_{foul} = 0.000250 h·ft²·°F/Btu.
4. The rating Fouling Factor Allowance for heating and heat recovery heat exchangers shall be R_{foul} = 0.000100 h·ft²·°F/Btu for closed loop and R_{foul} = 0.000250 h·ft²·°F/Btu for open loop systems.
5. Evaporatively cooled Condensers and Air-Cooled Condensers shall be rated with a Fouling Factor Allowance of zero, R_{foul} = 0.000 h·ft²·°F/Btu.
6. A reversible cycle is assumed where the cooling mode evaporator becomes the condenser circuit in the heating mode.
7. Air-cooled & evaporatively-cooled unit ratings are at standard atmospheric condition (sea level). Measured test data will be corrected to an atmospheric pressure of 14.696 psia per Appendix C.
8. Rated water flow is determined by the water temperatures at the rated Cooling Capacity.
9. Rated water flow is determined by the water temperatures at the rated Capacity and rated efficiency.

For data centers refer to All Cooling row

2) CHILLER UNLOADING CONTROL: Set minimum unloading ratio based on chiller type

Definition The minimum unloading capacity of a chiller expressed as a fraction of the rated capacity.
Below this level the chiller must cycle to meet the load.

A) Select chiller type

$scroll := 0 \quad recip := 1 \quad screw := 2 \quad centifugal := 3$

Select chiller type

$sys := recip$

B) Set unloading ratio based on chiller type

$$UnloadTable := \begin{bmatrix} \text{“Scroll”} & .25 \\ \text{“Reciprocating”} & .25 \\ \text{“Screw”} & .15 \\ \text{“Centrifugal”} & .1 \end{bmatrix}$$

$UnloadTable_{sys,0} = \text{“Reciprocating”}$

$minPlr := UnloadTable_{sys,1} = 0.25$

3) HOURLY CHILLER AVAILABLE CAPACITY TEMPERATURE ADJUSTMENT

A curve that represent the available total cooling capacity as a function of evaporator and condenser conditions and other operating conditions.

Condenser Type

Definition: The type of condenser for a chiller. The choices are:

- Air-cooled chillers use air to cool the condenser coils.
- Water-cooled chillers use cold water to cool the condenser and additionally need either a cooling tower or a local source of cold water.
- Evaporatively-cooled chillers are similar to air-cooled chillers, except they use a water mist to cool the condenser coil which makes them more efficient.

A) Chiller capacity adjustment function based on supply and outdoor or condenser temperature

Where:

$Q_{chillAvail}$ Available cooling capacity at present evaporator and condenser conditions (MBH)
T_{chws} The chilled water supply temperature (°F) rated temp 44F leaving evap temp
t_{odb} The outside air dry-bulb temperature (°F) rated temp 95F entering outdoor air DB temp
$Q_{chillRatedLoad}$ Rated capacity at AHRI 550 conditions (MBH)
Note: If an air-cooled unit employs an evaporative condenser, t_{odb} is the effective dry bulb temperature of the air leaving the evaporative cooling unit

$C := \text{READEXCEL}(\text{".\MPG\_AppendixH\_ComnetDataOnly.xlsx"}, \text{"COMNET Data!H49:N51"})$

$C_{sys,0} = \text{"Table 86 – Chiller Capacity Temperature Adjustment – Air Cooled – Reciprocating"}$

$$CapFt_{hr} := \begin{array}{l} Tchws \leftarrow TchwsDes \\ Todb \leftarrow OaDb_{hr} \\ Coeff \leftarrow \text{READEXCEL}(\text{".\MPG\_AppendixH\_ComnetDataOnly.xlsx"}, \text{"COMNET Data!H49:N51"}) \\ a \leftarrow Coeff_{sys,1} \\ b \leftarrow Coeff_{sys,2} \\ c \leftarrow Coeff_{sys,3} \\ d \leftarrow Coeff_{sys,4} \\ e \leftarrow Coeff_{sys,5} \\ f \leftarrow Coeff_{sys,6} \\ CapFt_{hr} \leftarrow (a + b \cdot Tchws + c \cdot Tchws^2 + d \cdot Todb + e \cdot Todb^2 + f \cdot Tchws \cdot Todb) \end{array}$$

AHRI 550 rated temp conditions:

44F Leaving evap temp

95F outdoor dry bulb

$\text{mean}(CapFt) = 1.31$

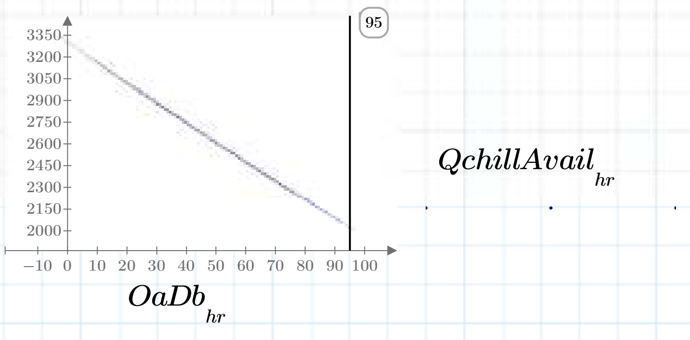
$\text{max}(CapFt) = 1.65$

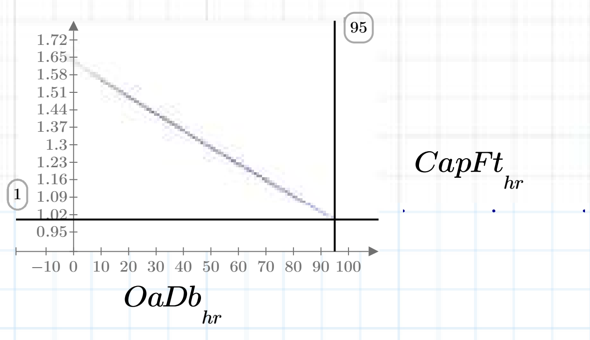
4) HOURLY CHILLER AVAILABLE CAPACITY: Available cooling capacity for evaporator & condenser temps

A) Available Capacity for range of outdoor temperatures in Albany NY. Maintain minimum unloading capacity

$$QchillAvail_{hr} := \max(QchillRatedLoad \cdot CapFt_{hr}, QchillRatedLoad \cdot minPlr)$$

$\text{mean}(QchillAvail) = 2643$ $\text{max}(QchillAvail) = 3347$ $QchillRatedLoad = 2023$ $QchillOpsLoad = 976$





B) Unmet hour load - capacity is less than load

$$QchillUnmet_{hr} := \text{if } QchillAvail_{hr} < QchillOpsLoad \;\; \left\| \begin{array}{l} \text{“Negative number”} \\ QchillAvail_{hr} - QchillOpsLoad \end{array} \right. \;\; \text{else} \;\; \left\| 0 \right.$$

$$\sum QchillUnmet = 0$$

$$\frac{\left| \sum QchillUnmet \right|}{QchillOpsLoad} = 0$$

$$QchillOpsLoad = 976$$

5) HOURLY CHILLER TEMP POWER ADJUSTMENT: Hourly Chiller Power Temperature Efficiency Adjustment

Definition: A curve or group of curves that varies the cooling efficiency of an electric chiller as a function of evaporator conditions, condenser conditions and part-load ratio. The default curves are given as follows.

Where:

- PLR - Part load ratio based on available capacity (not rated capacity)
- Qoperating - Present load on chiller (Btu/h)
- QchillAvail - Chiller available capacity at present evaporator and condenser conditions (Btu/h)
- Tchws - The chilled water supply temperature (°F)
- Tdb - The outside air dry-bulb temperature (°F)
- **Prated - Rated power draw at ARI conditions (kW)**
- Poperating - Power draw at specified operating conditions (kW)

Note: If an air-cooled chiller employs an evaporative condenser, todb is the effective dry-bulb temperature of the air leaving the evaporative cooling unit.

A) CHILLER POWER TEMP ADJUSTMENT FUNCTION

$C := \text{READEXCEL}(\text{".\\MPG\_AppendixH\_ComnetDataOnly.xlsx"}, \text{"COMNET Data!H63:N65"})$

$C_{sys,0} = \text{"Table 89 – Chiller Efficiency Temperature Adjustment – Air Cooled – Reciprocating"}$

$$EirFt_{hr} := \left| \begin{array}{l} Tchws \leftarrow TchwsDes \\ Todb \leftarrow OaDb_{hr} \\ Coeff \leftarrow \text{READEXCEL}(\text{".\\MPG\_AppendixH\_ComnetDataOnly.xlsx"}, \text{"COMNET Data!H63:N65"}) \\ a \leftarrow Coeff_{sys,1} \\ b \leftarrow Coeff_{sys,2} \\ c \leftarrow Coeff_{sys,3} \\ d \leftarrow Coeff_{sys,4} \\ e \leftarrow Coeff_{sys,5} \\ f \leftarrow Coeff_{sys,6} \\ EirFt_{hr} \leftarrow (a + b \cdot Tchws + c \cdot Tchws^2 + d \cdot Todb + e \cdot Todb^2 + f \cdot Tchws \cdot Todb) \end{array} \right.$$

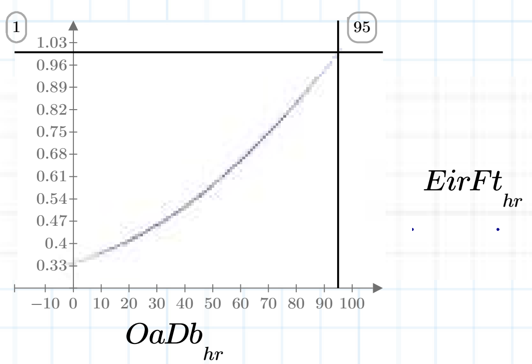
AHRI 550 rated temp conditions:

44F Leaving evap temp

95F Outdoor dry bub

B) CHILLER POWER TEMP ADJUSTMENT: Electric input ratio, function of CHWS & CWS temperature (EirFt) for adjusting chiller power for non-rated design temps

Air cooled



6) HOURLY CHILLER POWER PLR ADJUSTMENT

A) HOURLY CHILLER LOAD PLR: Cooling capacity part load ratio

$$cPlr_{hr} := \max\left(\frac{QchillOpsLoad}{QchillAvail_{hr}}, minPlr\right)$$

$$\text{mean}(cPlr) = 0.37$$
$$\max(cPlr) = 0.49$$

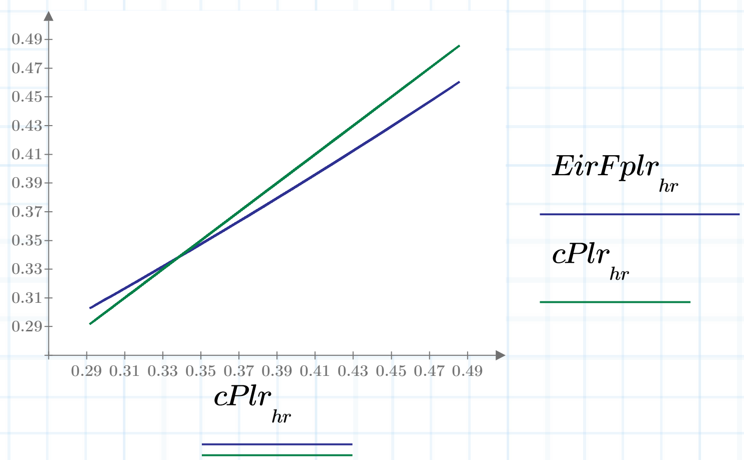
QchillOpsLoad is hourly sum of zone, fan adjusted, heat gains
If Plr < false part load ratio, PLR is set to false load ratio

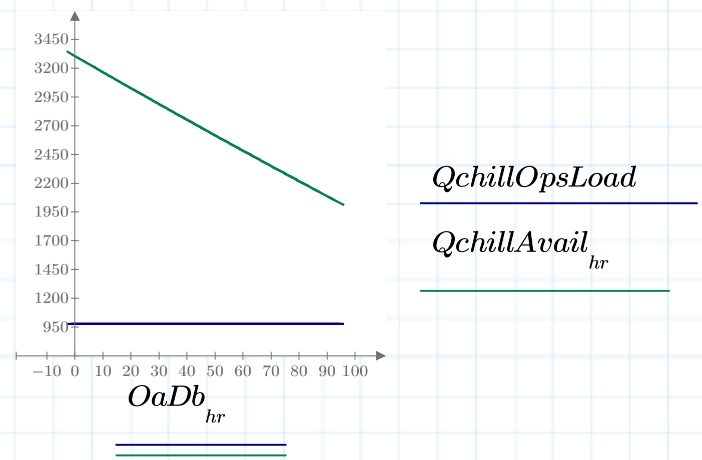
B) CHILLER POWER PLR ADJUSTMENT: Electric input ratio, function of PLR (EirFplr) for adjusting power based on Part load ratio

$$C := \text{READEXCEL}(\text{“.\textbackslash MPG\_AppendixH\_ComnetDataOnly.xlsx”}, \text{“COMNET Data!H72:N74”})$$

$$C_{sys,0} = \text{“Table 91 – Chiller Efficiency Part Load Adjustment – Air Cooled – Reciprocating”}$$

$$EirFplr_{hr} := \left\| \begin{array}{l} Coeff \leftarrow \text{READEXCEL}(\text{“.\textbackslash MPG\_AppendixH\_ComnetDataOnly.xlsx”}, \text{“COMNET Data!H72:N74”}) \\ a \leftarrow Coeff_{sys,1} \\ b \leftarrow Coeff_{sys,2} \\ c \leftarrow Coeff_{sys,3} \\ EirFplr_{hr} \leftarrow \left(a + b \cdot cPlr_{hr} + c \cdot cPlr_{hr}^{\ 2}\right) \end{array} \right.$$





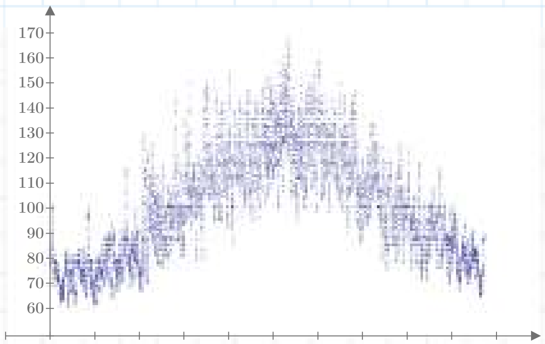
7) HOURLY CHILLER OPERATING COMPRESSOR POWER

A) Chiller power with compressor

$$PchillOps_{hr} := PchillRated \cdot EirFplr_{hr} \cdot EirFt_{hr} \cdot CapFt_{hr}$$

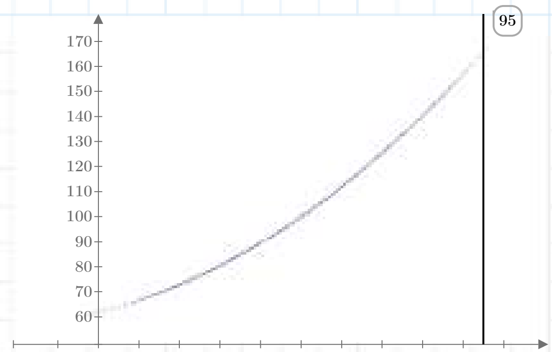
B) Hourly chiller power use and PLR vs outdoor temp

Hourly chiller power use



$PchillOps_{hr}$

hr



$PchillOps_{hr}$

$OaDb_{hr}$

XII) ANNUAL COOLING ENERGY & EFFICIENCY

Monthly Loads: $mon := 1..12$

Daily Loads: $day := 1..364$

Hourly Loads: $hr := 1..8760$

Day of the year: $dayOfYr_{hr} := \text{floor}\left(\frac{hr}{24}\right)$

Weather file order month, day of month, hour of day

month of year: $m_{hr} := OA_{hr,0}$

day of month: $d_{hr} := OA_{hr,1}$

hour of day: $h_{hr} := OA_{hr,2}$

1) Total hourly, daily & monthly IT heat gain / cooling load (kW)

IT loads used by MLC and COP efficiency metrics

$Qhr_{hr} := QitOpsSum$

$Qyr := \sum_{hr} Qhr_{hr}$

$Qmon_{mon} := \sum_{hr} QitOpsSum \cdot (mon = m_{hr})$

$Qday_{day} := \sum_{hr} QitOpsSum \cdot (day = dayOfYr_{hr})$

2) Total hourly, daily & monthly power uses (kW)

A) Hourly & Yearly Total Cooling Power

$$Ecool_{hr} := PfanOpsSum + PpumpSecOps + PchillOps_{hr} + PpumpChillOps$$

$$EcoolYr := \sum_{hr} Ecool_{hr} = 1812840$$

B) Sum total power monthly and daily

$$EcoolMon_{mon} := \sum_{hr} Ecool_{hr} \cdot \left(mon = m_{hr}\right) \qquad EcoolDay_{day} := \sum_{hr} Ecool_{hr} \cdot \left(day = dayOfYr_{hr}\right)$$

3) Hourly, daily, monthly & Yearly Mechanical Load Component - MLC@50%

EcoolYr is the Mechanical Energy at 50% of IT design load (Mech_Energy50% as per Std. 90.4 Section 6.5) and is Not annualized MLC. *The MLCs for other times are not part of the Std. 90.4 but are useful as efficiency metrics.*

$$MLCyr := \frac{EcoolYr}{Qyr} = 0.24 \qquad MLCmon_{mon} := \frac{EcoolMon_{mon}}{Qmon_{mon}} \qquad MLCday_{day} := \frac{EcoolDay_{day}}{Qday_{day}} \qquad MLC_{hr} := \frac{Ecool_{hr}}{Qhr_{hr}}$$

4) Calculating ASHRAE Annual Mechanical Load Component (MLC):

This calculation procedure used 50% IT load. By changing a single vector (QitOps) this procedure can calculate annual mechanical energy (EcoolYr) at 25%, 75%, & 100% IT loads (Qyr) . With the results of the 4 runs you can calculate annual MLC according to Std. 90.4 Section 6.5 as follows:

Annual MLC = [EcoolYr @25% + **EcoolYr @50%** + EcoolYr @75% + EcoolYr @100%]

[Qyr @25% + **Qyr @50%** + Qyr @75% + Qyr @100%]

5) Monthly cooling only electric utility costs (IT not included)

energy use $/kwh

$$EcostMon := \begin{bmatrix} 0 \\ .0752 \\ .0752 \\ .0752 \\ .0752 \\ .0752 \\ .0752 \\ .0752 \\ .0752 \\ .0752 \\ .0752 \\ .0752 \\ \vdots \end{bmatrix} \quad EcoolMon = \begin{bmatrix} 0 \\ 133327 \\ 123182 \\ 144038 \\ 147870 \\ 163195 \\ 162483 \\ 174820 \\ 171621 \\ 158769 \\ 153674 \\ 141402 \\ \vdots \end{bmatrix} \quad EcoolMonCost_{mon} := EcoolMon_{mon} \cdot EcostMon_{mon} = \begin{bmatrix} 10026 \\ 9263 \\ 10832 \\ 11120 \\ 12272 \\ 12219 \\ 13146 \\ 12906 \\ 11939 \\ 11556 \\ 10633 \\ 10412 \end{bmatrix}$$

Annual energy cost in dollars $AnnEcoolCost := \sum_{mon} EcoolMonCost_{mon} = 136326$

XIII) SUPPLEMENTAL SYSTEMS AND COMPONENT ENERGY USE CALCULATIONS & GRAPHS

1) Optional System and Component Energy Use Calculations (kW)

A) Secondary Loop Cooling Power (PfanOpsSum*8760 = AHU Fan Energy from Std. 90.4 Section 6.5)

$EcoolSec_{hr} := PfanOpsSum + PpumpSecOps$ $AnnEcoolSec := \sum_{hr} EcoolSec_{hr} = 531212$

B) Chiller Loop Cooling Power (Sum(PchillOps) = Cooling Energy + Heat Rejection Fan Energy from Std. 90.4 Section 6.5)

$EcoolChill_{hr} := PchillOps_{hr} + PpumpChillOps$ $AnnEcoolChill := \sum_{hr} EcoolChill_{hr} = 1281628$

C) Pumps Power (AnnEcoolPumps = Pump Energy from Std. 90.4 Section 6.5)

a) Pumps Power

$EcoolPumps_{hr} := PpumpSecOps + PpumpChillOps$ $AnnEcoolPumps := \sum_{hr} EcoolPumps_{hr} = 518541$

b) Secondary pump energy fraction

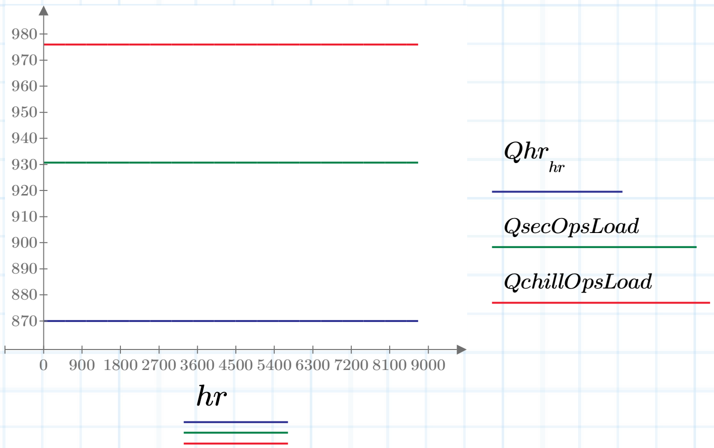
$$\frac{PpumpSecOps}{PfanOpsSum + PpumpSecOps} = 23\%$$

c) Primary pump energy fraction

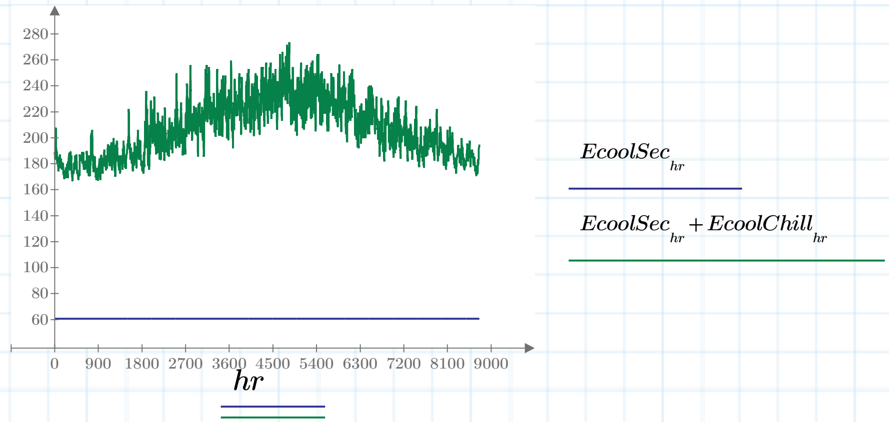
$$\frac{\sum_{hr} PpumpChillOps}{\sum_{hr} \left(PchillOps_{hr} + PpumpChillOps\right)} = 31\%$$

2) Hourly Secondary, Primary and Condenser Cooling Loads and Power (kW)

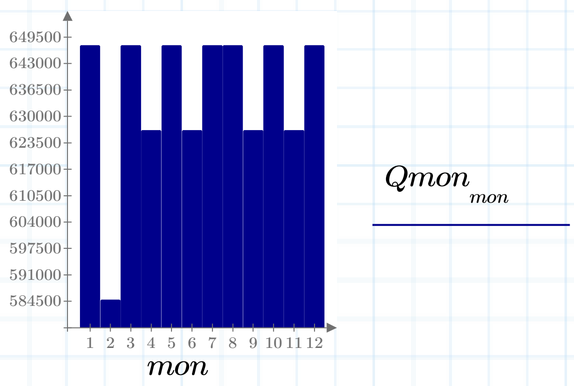
Additive cooling loads for IT, secondary & primary loops

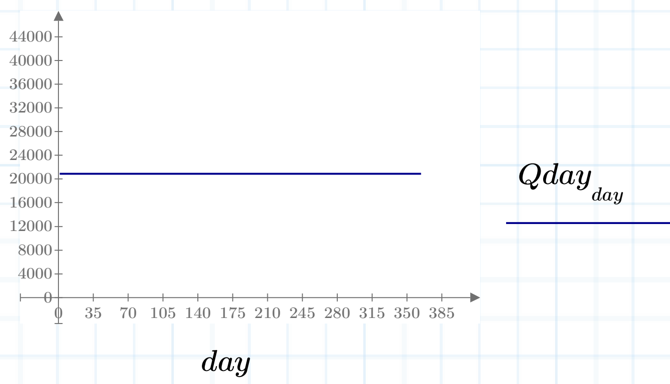


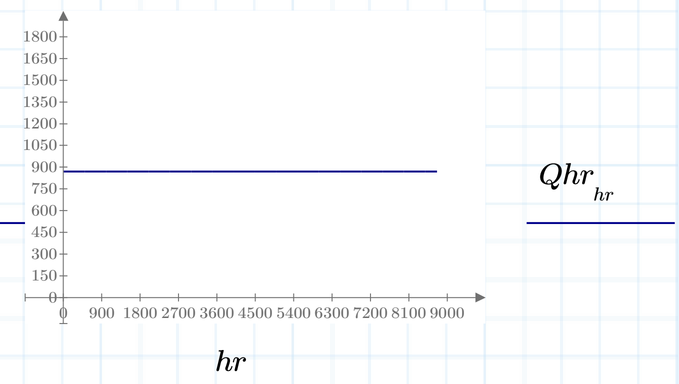
Additive cooling power for secondary & chiller loops including pumps



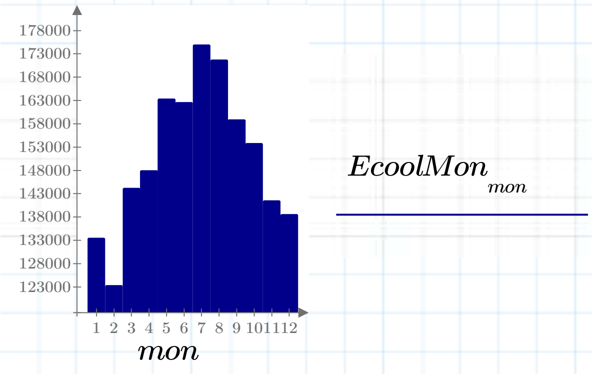
3) Monthly, daily and hourly LOAD Graphs (kW)

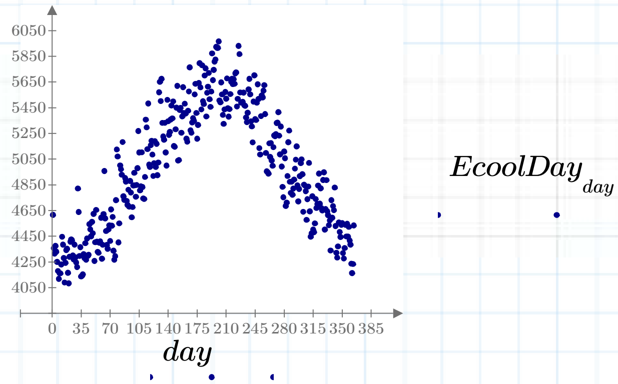


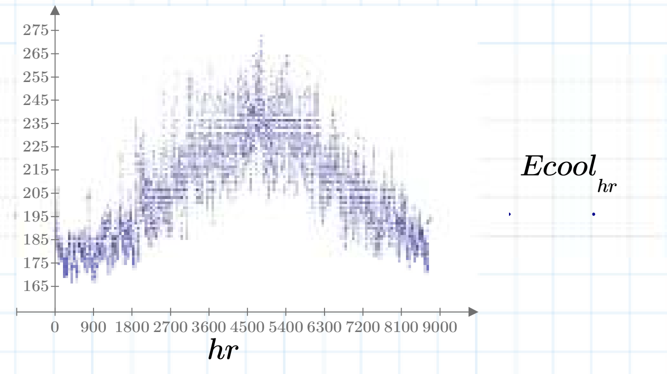




4) Monthly, daily and hourly POWER Graphs (kW)

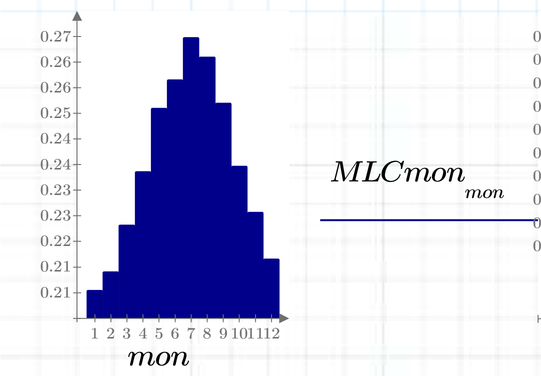


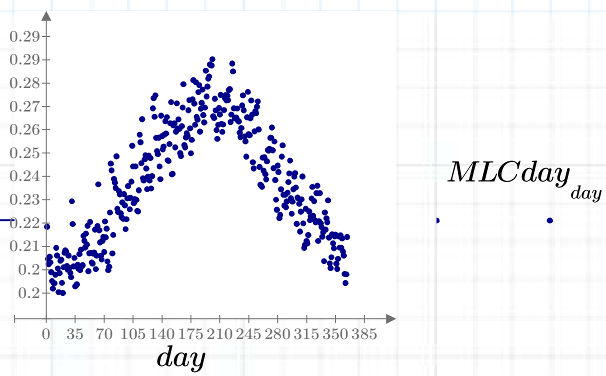


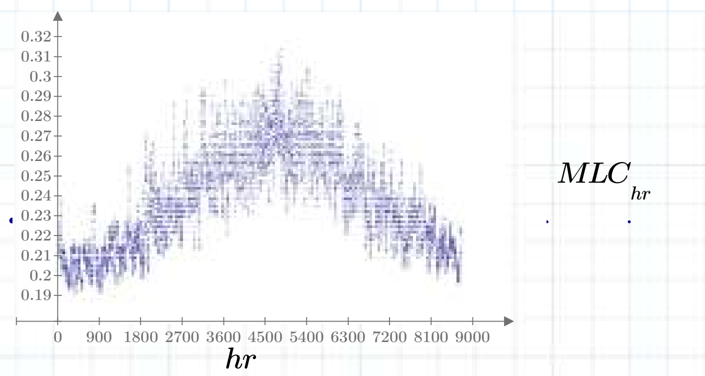


5) Monthly, daily & hourly MLC at 50% IT load EFFICIENCY Graphs

A) Monthly, Daily & Hourly MLC Efficiency Values







XIV) HOURLY LOADS, CAPACITIES & POWER DETAILS BY LOOP all Capacity, Loads & Power in kW

IT & CRAH - Operating--Design/Rated--

IT heat gains - IT design and current operating

$QitOps = \begin{bmatrix} 120 \\ 400 \\ 100 \\ 250 \end{bmatrix}$ $QitOpsSum = 870$ kW

$QitRated = \begin{bmatrix} 290 \\ 580 \\ 290 \\ 580 \end{bmatrix}$ $QitRatedSum = 1740$ kW

Net CRAH capacity (is tot-fan power) adjusted for RAT, CHWST, CHWdT

$QcrahOpsSum = 870$

$fPlr = 0.46$

$QcrahVunmet_{zones} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$

$QcrahRatedSum = 1740$ $QcrahAvailSum = 1875$

$Treturn = \begin{bmatrix} 81 \\ 83 \\ 80 \\ 80 \end{bmatrix}$ $TchwsDes = 44$ $dTchwDes = 12$

$QcrahFt_{zones} = \begin{bmatrix} 1.07 \\ 1.14 \\ 1.04 \\ 1.04 \end{bmatrix}$

CRAH fan power based on fan type variable or constant

Plr Ops/Avail

$PfanOpsSum = 47$

$PfanRatedSum = 168$

$VcrahAvail = \begin{bmatrix} 71048 \\ 132593 \\ 68650 \\ 120138 \end{bmatrix}$

$VcrahRated = \begin{bmatrix} 50000 \\ 100000 \\ 50000 \\ 100000 \end{bmatrix}$

$vPlr = \begin{bmatrix} 0.39 \\ 0.6 \\ 0.33 \\ 0.42 \end{bmatrix}$

$PfanOps = \begin{bmatrix} 6 \\ 23 \\ 6 \\ 12 \end{bmatrix}$

$PfanRated = \begin{bmatrix} 28 \\ 56 \\ 28 \\ 56 \end{bmatrix}$

Pumps - Operating---Design/Rated---

Secondary loop PUMP power based on variable speed operating conditions

$PpumpSecOps = 14$

$GpmCrahOps = 495$

$sgPlr = 0.43$

$pumpFplr(sgPlr) = 0.2$

$PpumpSecRated = 69$

$GpmSecRated = 1150$

Secondary loop LOAD including CRAH fan & secondary pump power

$QsecOpsLoad = 931$

$QcrahOpsSum = 870$

$QitOpsSum = 870$

$PfanOpsSum = 47$

$PpumpSecOps = 14$

$QsecRatedLoad = 1978$

$QcrahAvailSum = 1875$

$QitRatedSum = 1740$

$PfanRatedSum = 168$

$PpumpSecRated = 69$

Chiller loop PUMP power

$PpumpChillOps = 45$

$GpmChillOps = 1200$

$cgPlr = 1$

$pumpFplr(cgPlr) = 1$

$PpumpChillRated = 45$

$GpmChillRated = 1200$

Combined operating PUMP power and energy

$\mathrm{mean}(EcoolPumps) = 59$ $AnnEcoolPumps = 518541$

Chiller - Operating--Design/Rated--

LOAD to Chiller including secondary loop load & chiller loop pumps (chiller evaporator load)

$QchillOpsLoad = 976$

$QsecOpsLoad = 931$

$PpumpChillOps = 45$

$QcrahOpsSum = 870$

$QitOpsSum = 870$

$QchillRatedLoad = 2023$

$QsecRatedLoad = 1978$

$PpumpChillRated = 45$

$QcrahAvailSum = 1875$

$QitRatedSum = 1740$

Chiller cooling CAPACITY

$QchillOpsLoad = 976$

$\sum QchillUnmet = 0$

$QchillRated = 2110$

$\text{mean}(QchillAvail) = 2643$

$\text{mean}(CapFt) = 1.31$

$QchillRatedLoad = 2023$

$\max(QchillAvail) = 3347$

$\max(CapFt) = 1.65$

Chiller COMPRESSOR power

$\text{mean}(PchillOps) = 101$

$\text{mean}(CapFt) = 1.31$

$\text{mean}(EirFt) = 0.59$

$\text{mean}(cPlr) = 0.37$

$\text{mean}(EirFplr) = 0.37$

$\max(PchillOps) = 168$

$\max(CapFt) = 1.65$

$\max(EirFt) = 1.01$

$\max(cPlr) = 0.49$

$\max(EirFplr) = 0.46$

$PchillRated = 362$