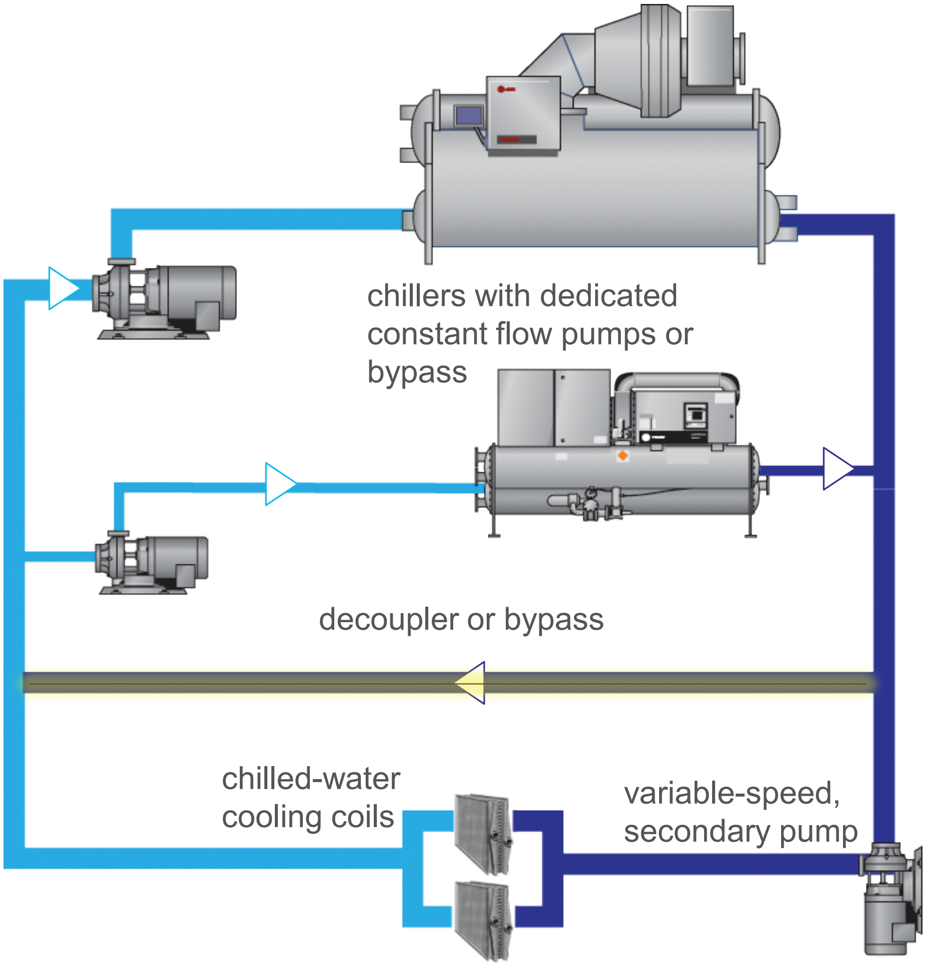
Trane Engineers Newsletter Live

State-of-the-Art Chilled-Water Systems

with Trane Engineers Susanna Hanson, Rick Heiden, Mick Schwedler, and Justin Wieman



Trane program number: APP-CMC076-EN
March 2021

Agenda

Trane *Engineers Newsletter Live* Series

State-of-the-Art Chilled-Water Systems

Abstract

When designed using today's industry guidance, chilled water systems provide building owners and operators with flexibility to meet first cost and efficiency objectives, simplify maintenance and operation, and exceed energy code minimum requirements. Design principles that right-size equipment and minimize system power draw are inherently simpler to control, and lead to high efficiency and reduced utility costs.

Presenters: Trane engineers Susanna Hanson, Rick Heiden, Mick Schwedler, and Justin Wieman

After viewing attendees will be able to:

1. Understand and use the latest industry guidance for system design
2. Recognize the versatility coil selection and fluid control offer
3. Appreciate the importance of integrated controls on successful long-term system operation
4. Apply future chiller plant designs to maximize efficiency and simplicity while minimizing first cost

Agenda

- Introduction
- Industry requirements and recommendations
- Design choices
- System control

Presenter biographies

State-of-the-Art Chilled-Water Systems

SUSANNA HANSON | SENIOR PRINCIPAL ENGINEER | TRANE

Susanna is an HVAC systems development engineer for Trane. Her specialties are chilled water systems and energy codes.

During her 23 years with the company, Susanna has served in technical roles with diverse responsibilities, from TRACE support and development, to chiller and system development. Susanna is a Certified Energy Manager who helps the company achieve its Climate Commitment. She advises product development teams on the future of energy codes. She also influences corporate sustainability projects including system optimization, energy storage systems, and energy and water savings estimates.

She speaks and writes primarily on HVAC systems, energy storage, energy codes, and systems applications. She contributed to the Encyclopedia of Energy Engineering. She is currently serving ASHRAE on the Standards committee and is a trustee of the ASHRAE Foundation. She and has presented at ASHRAE society and chapter meetings throughout the U.S., Canada and Mexico. She was a 12-year voting member of ASHRAE 90.1 and received the ASHRAE Distinguished Service Award in 2015.

RICK HEIDEN | HVAC SYSTEMS DEVELOPMENT ENGINEER | TRANE

Rick is a systems development engineer and is responsible for leading teams to develop systems and sales tools aimed at reducing the energy intensity of the world. Rick's areas of interest are in hydronic systems, split-systems, mentorship, and project management. Rick has over 25 years of experience at Trane leading compressor development for centrifugal and screw-based chiller products and holds 7 patents.

Rick is a member of ASHRAE where he holds positions on several Technical Committees, SSPC 90.1 and Standards Committee and is a recipient of the Distinguished Service Award. Rick graduated from the University of Denver with a BS in mechanical engineering.

MICK SCHWEDLER | APPLICATIONS ENGINEER | TRANE

Mick has been involved in the development, training, and support of mechanical systems for Trane since 1982. With expertise in system optimization and control (in which he holds patents), and in chilled-water system design, Mick's primary responsibility is to help designers properly apply Trane products and systems. Mick provides one-on-one support, writes technical publications, and presents seminars.

Mick is an ASHRAE Fellow and serves as President Elect on the ASHRAE Board of Directors. He is a recipient of ASHRAE's Exceptional Service, Distinguished Service and Standards Achievement Awards. He is past Chair of SSPC 90.1 and contributed to the ASHRAE GreenGuide. Mick has been active on several USGBC technical and education groups, chaired the LEED Technical Committee and served on the LEED Steering Committee. Mick earned his BSME degree from Northwestern University and his MSME from the University of Wisconsin Solar Energy Lab.

JUSTIN WIEMAN | APPLICATIONS ENGINEER | TRANE

Justin joined Trane in 2001. As an applications engineer. he partners with customers providing them system design and product knowledge to develop and deliver efficient, innovative, and sustainable designs throughout North America, Europe and the Middle East. He works with product management, product support, planning, engineering, manufacturing, and other groups where the focus is optimizing chilled-water system design and control. Justin has held a variety of key roles within Trane including technical marketing, engineering, project and product support management. Justin has also led efforts to develop and deploy a suite of Design and Analysis tools that enable engineers to effectively design HVAC systems and develop the corresponding ife cycle cost analyses, which included product management of TRACE® 700 software.

Justin earned his bachelor's degree in Chemical Engineering from the South Dakota School of Mines and Technology.

State of the Art Chilled-Water Systems

Trane Engineers Newsletter Live Series

"Trane" is a Registered Provider with The American Institute of Architects Continuing Education System. Credit earned on completion of this program will be reported to CES Records for AIA members. Certificates of Completion are available on request.

This program is registered with the AIA/CES for continuing professional education. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the AIA of any material of construction or any method or manner of handling, using, distributing, or dealing in any material or product.

Credit for viewing today's program can be applied toward LEED credential maintenance requirements.

www.USGBC.org

Visit the Registered Continuing Education Programs (RCEP) Website for individual state continuing education requirements for Professional Engineers.

www.RCEP.net

Copyrighted Materials

This presentation is protected by U.S. and international copyright laws. Reproduction, distribution, display, and use of the presentation without written permission of Trane is prohibited.

Learning Objectives

1. Summarize industry requirements for chilled water systems the different sections of Standard 90.1
2. Identify various resources for industry recommendations
3. Identify several system design choices
4. Summarize strategies for towers and pump control

Copyrighted Materials

This presentation is protected by U.S. and international copyright laws. Reproduction, distribution, display, and use of the presentation without written permission of Trane is prohibited.

Learning Objectives

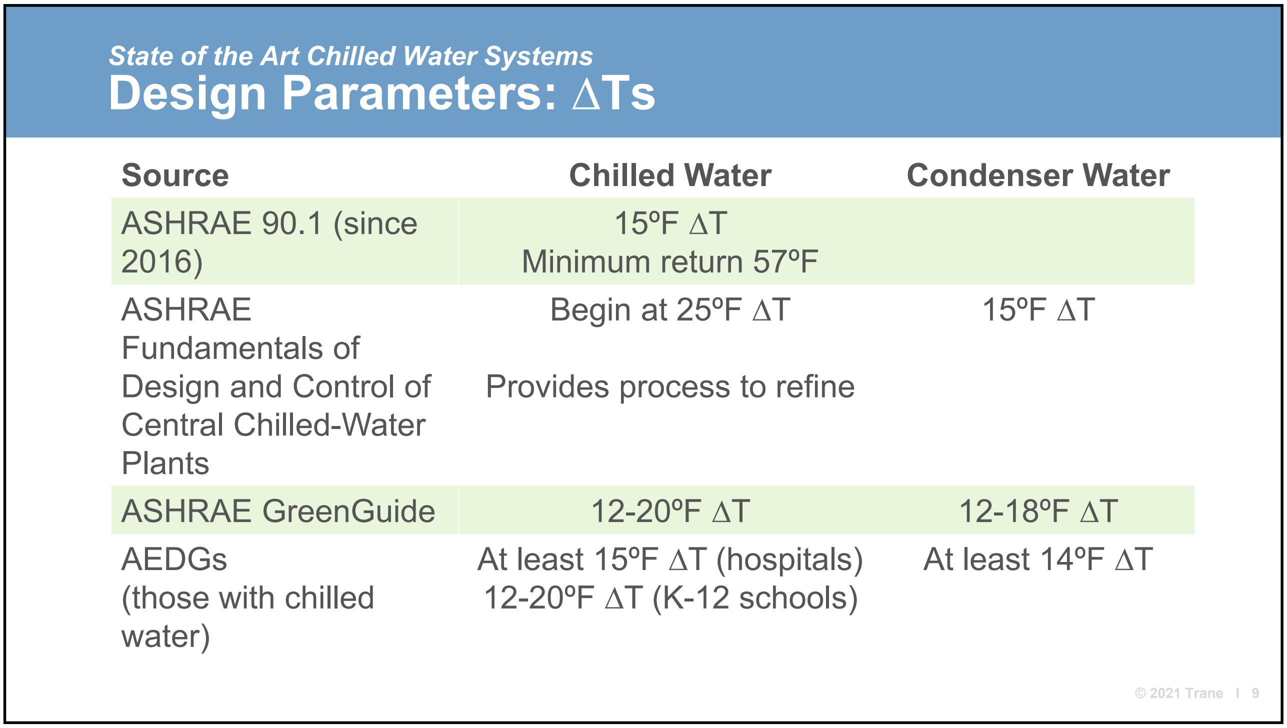
- Understand and use the latest industry guidance for system design
- Recognize the versatility coil selection and fluid control offer
- Appreciate the importance of integrated controls on successful long-term system operation
- Apply future chiller plant designs to maximize efficiency and simplicity while minimizing first cost

Industry Guidance for System Design

Chilled Water Plant Design and Control

Industry State-of-the-Art Requirements and Recommendations

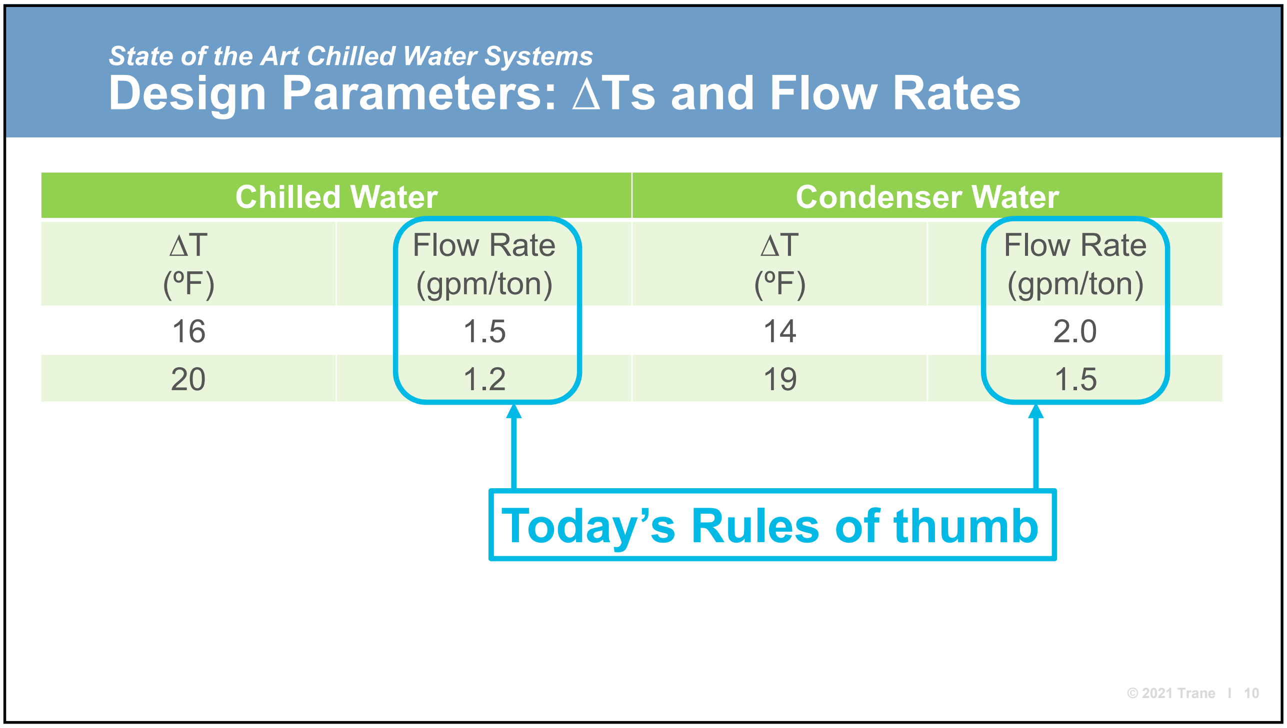
www.ashrae.org/freeaedg



State of the Art Chilled Water Systems

Design Parameters: ΔTs

Source	Chilled Water	Condenser Water
ASHRAE 90.1 (since 2016)	15ºF ΔT Minimum return 57ºF	
ASHRAE Fundamentals of Design and Control of Central Chilled-Water Plants	Begin at 25ºF ΔT Provides process to refine	15ºF ΔT
ASHRAE GreenGuide	12-20ºF ΔT	12-18ºF ΔT
AEDGs (those with chilled water)	At least 15ºF ΔT (hospitals) 12-20ºF ΔT (K-12 schools)	At least 14ºF ΔT



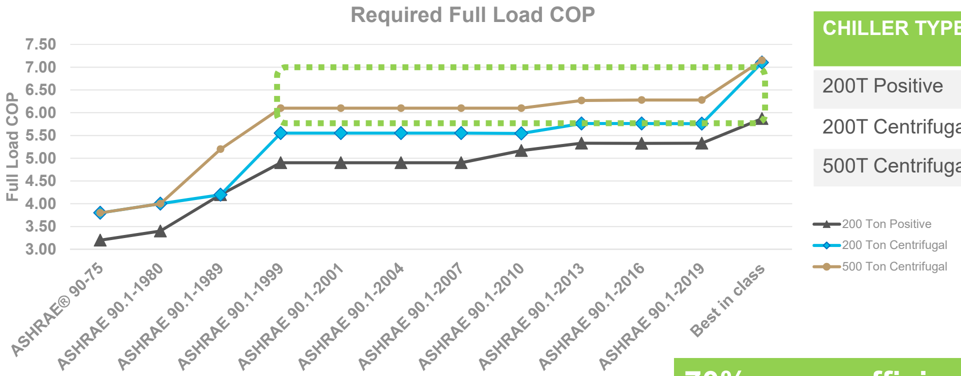
State of the Art Chilled Water Systems

Design Parameters: ΔTs and Flow Rates

Chilled Water		Condenser Water	
ΔT (ºF)	Flow Rate (gpm/ton)	ΔT (ºF)	Flow Rate (gpm/ton)
16	1.5	14	2.0
20	1.2	19	1.5

Today's Rules of thumb

Why?
Chiller efficiencies have improved by 50-70%



CHILLER TYPE	EFFICIENCY INCREASE
200T Positive	67%
200T Centrifugal	52%
500T Centrifugal	65%

70% pump efficiency = 0.7 COP

Work the most efficient part of the system, the chiller, a little harder.

Effect of Ancillary Equipment at Part Load

LOAD	PAST PRACTICE			ASHRAE GreenGuide PRACTICE		
	*Cooling Tower Fan (kW/ton)	**Condenser Water Pump (kW/ton)	Tower + Pump (kW/ton)	*Cooling Tower Fan (kW/ton)	**Condenser Water Pump (kW/ton)	Tower + Pump (kW/ton)
100%	0.053	0.057	0.11	0.036	0.019	0.05
75%	0.071	0.075	0.15	0.047	0.025	0.07
50%	0.106	0.112	0.22	0.071	0.038	0.11
25%	0.212	0.224	0.44	0.142	0.076	0.22

***Assumes cooling tower setpoint is "cold as possible"**
More on that later…

****Assumes constant speed CW pump**

Ancillary energy is extremely significant at part load conditions

State of the Art Chilled Water Systems

System Configurations

Source	Chilled Water
ASHRAE 90.1	Variable flow in many cases
ASHRAE Fundamentals of Design and Control of Central Chilled-Water Plants	Variable flow in most cases
ASHRAE GreenGuide	Variable flow
AEDGs (those with chilled water)	Variable flow *("…strongly consider variable primary flow")*

- **Variable Flow Options**
  - Variable Primary Flow (VPF)
  - Variable primary / variable secondary

Design Parameters: Chilled Water Controls

Source	Chilled Water
ASHRAE 90.1 (since 2016)	Chilled water reset OR Pump pressure optimization (PPO)
ASHRAE Fundamentals of Design and Control of Central Chilled-Water Plants	Pump pressure optimization
ASHRAE GreenGuide	Pump pressure optimization
AEDGs (those with chilled water)	Pump pressure optimization (K-12 Schools)

Design Parameters: Cooling Tower/Condenser Water Controls

Source	Cooling Tower / Condenser Water
ASHRAE 90.1 (since 2016)	VSD or “VSD-like” performance on fans 50% water flow turndown operate maximum # of cells Baseline modeled tower setpoint climate zone dependent (not optimal)
ASHRAE Fundamentals of Design and Control of Central Chilled-Water Plants	Tower efficiency ≥ 80 gpm / hp
ASHRAE GreenGuide	
AEDGs (those with chilled water)	operate maximum # of cells “…optimize chiller plus tower energy use.”

Follow *Industry* Requirements and Recommendations

- ASHRAE/IESNA 90.1-2019
- ASHRAE GreenGuide
- ASHRAE Fundamentals of Design and Control of Chiller-Water Central Plants
- Advance Energy Design Guides

Design Choices

Plant Configurations

Industry Guidance Towards Zero Energy

ASHRAE Guidance

- Variable flow
- Energy model rulesets
- Recommended Delta T's

Industry guidance has set path to state of the art zero energy designs. Now how do we get there?

		System Configuration	Water flow control	CHWsec
ASHRAE ENERGY CONSUMPTION	90.1 - 2019 (IgCC / 189.1)	**PS** @ 50% flow < 30% power	Fixed and Variable	15F
	Greenguide – 5th ed	**PS and VS** VS with demand controlled pressure reset	Minimize plant energy	12-20F 0.026 kW/t
	AEDG 30% Energy – 2008	VPF	Minimize plant energy	Modelling
	AEDG 50% Energy – 2011	VPF	Minimize plant energy	Modelling
	AEDG Zero Energy - 2018	VPF w/ demand controlled pressure reset	Minimize plant energy	Modelling

Turndown

$$Turndown = \frac{Flow_{minallowed}}{Flow_{design}}$$

$$Turndown_{Chiller} = \frac{600\ gpm}{1000\ gpm} = 60\%$$

"Classic" Primary/Secondary (PS)

Characteristics

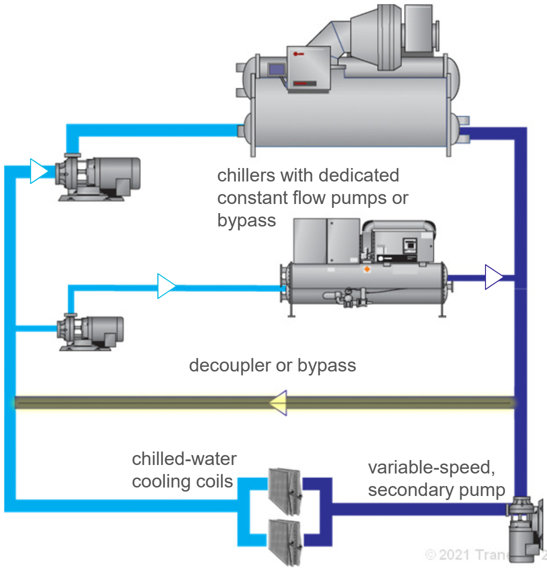
- Constant flow through chillers
- Stepped primary flow, variable secondary flow
- Easily accommodates differing chillers
- Bypass line with no control valve

Benefits

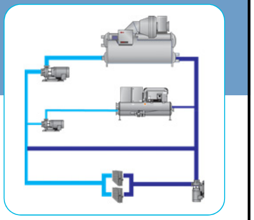
- Lower energy compared to constant flow systems
- Simple operation and control
- Easy to expand
- Can use chillers of varying size, age and capabilities

Challenges and limitations

- Unable to efficiently respond to varying secondary Delta T i.e. low Delta T syndrome
- Stepped primary flow uses more energy than variable primary flow



Chilled Water Pumping Energy (PS)



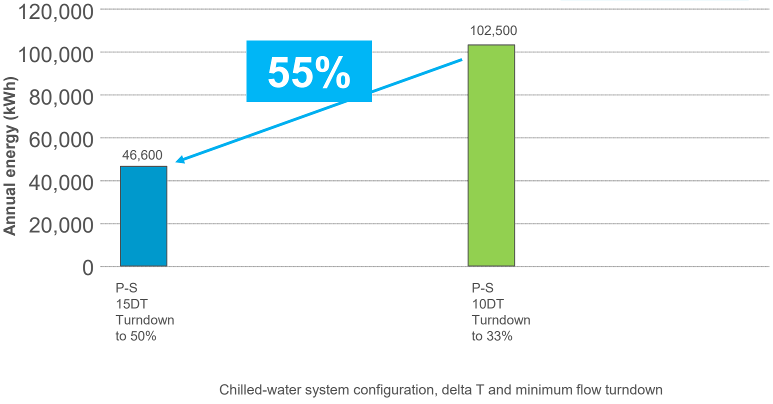
High School in St. Louis, MO
- Two Chiller 1000T Plant
- 15F DT and 10F DT designs
- Chiller turndown to 50% design

Plant Configurations

Primary stepped /secondary variable

Results
- 55% reduction in pumping energy
- 15 DT is a clear winner

Annual energy consumption-chilled-water pumping

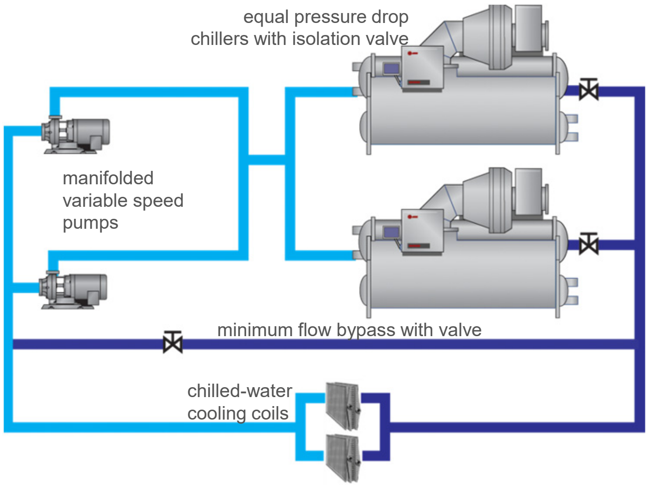


Variable Primary Flow (VPF)

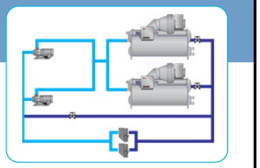
Characteristics
- Bypass line with flow control valve
- Variable flow chillers of equal size, DP, LWT and DT
- Pump speed control via remote DP or AHU valve position

Benefits
- Lower first costs and likely operating costs
- Lower pumping energy

Challenges
- Chillers must have adequate flow turndown
- More involved controls, but well understood today



PS vs VPF



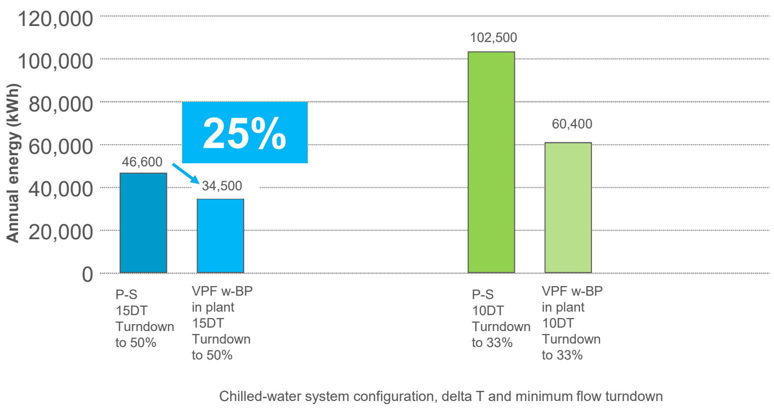
High School in St. Louis, MO
- Two Chiller 1000T Plant
- 15F DT and 10F DT designs
- Chiller turndown to 50% design

Plant Configurations

Primary stepped /secondary variable vs Variable primary flow

Results
- 25% reduction in energy
- 15 DT is a clear winner

Annual energy consumption-chilled-water pumping



Chilled Water Pumping Energy - VPF$_{50\%}$ vs VPF$_{80\%}$

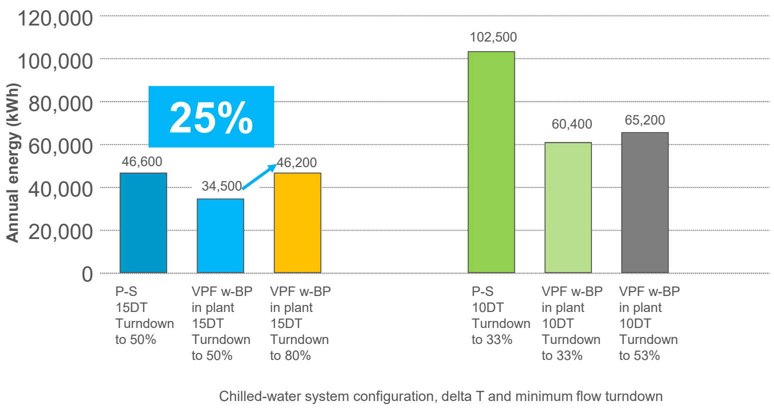
High School in St. Louis, MO
- Two Chiller 1000T Plant
- 15F DT and 10F DT designs
- Chiller turndown to 50% design vs Chiller turndown to 80% design

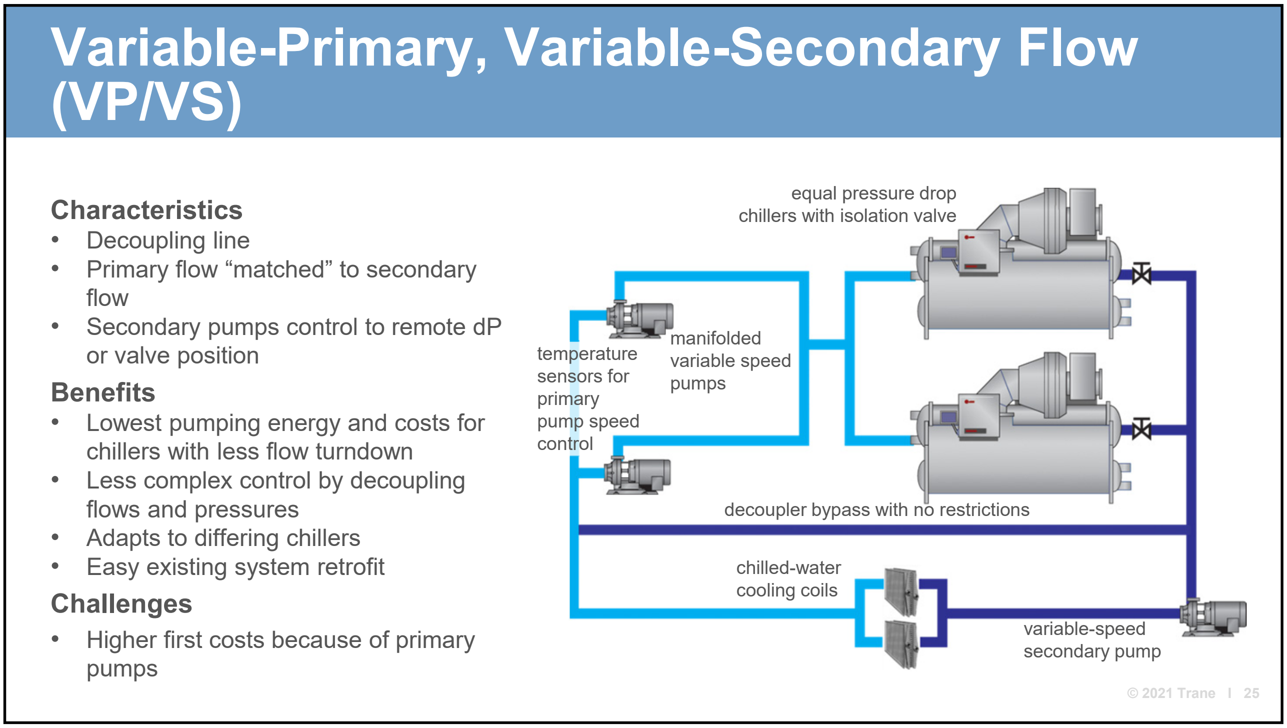
Plant Configurations

Variable primary flow

Results
- With turndown to only 80%
  - VPF looses its energy advantage
  - Control is more difficult
- 15 DT is a clear winner

Annual energy consumption-chilled-water pumping



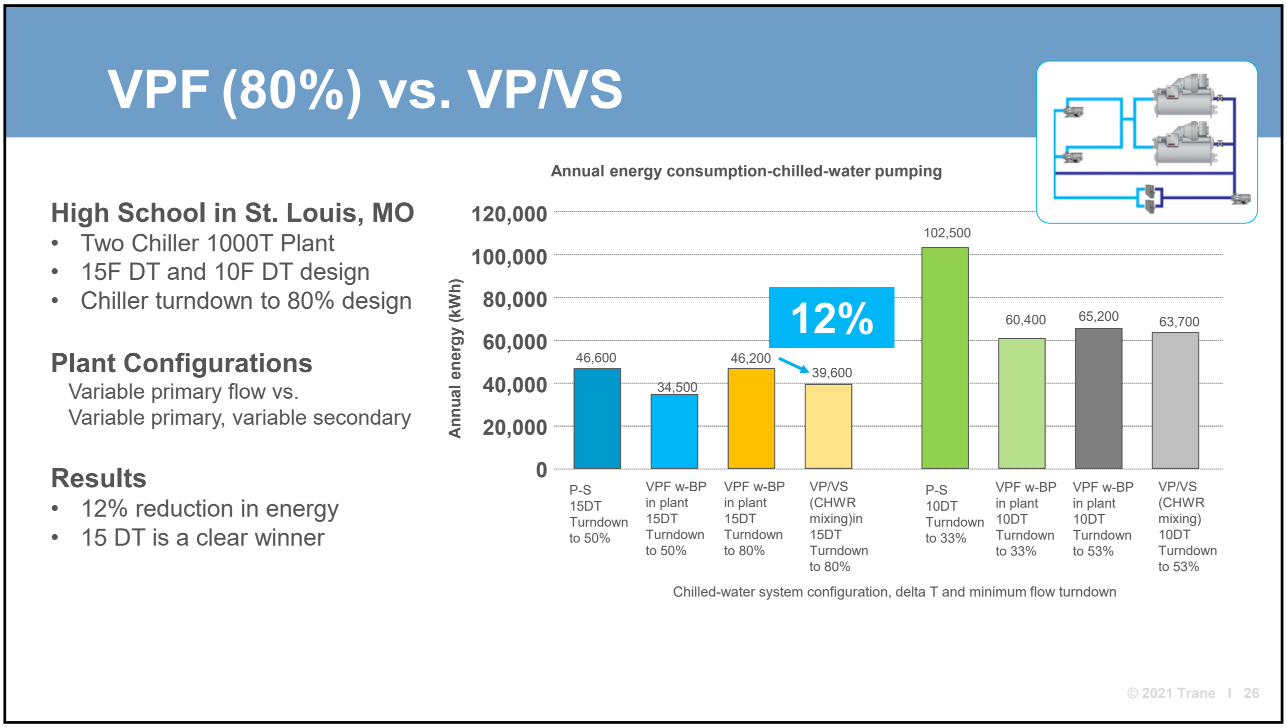


Variable-Primary, Variable-Secondary Flow (VP/VS)

Characteristics
- Decoupling line
- Primary flow “matched” to secondary flow
- Secondary pumps control to remote dP or valve position

Benefits
- Lowest pumping energy and costs for chillers with less flow turndown
- Less complex control by decoupling flows and pressures
- Adapts to differing chillers
- Easy existing system retrofit

Challenges
- Higher first costs because of primary pumps



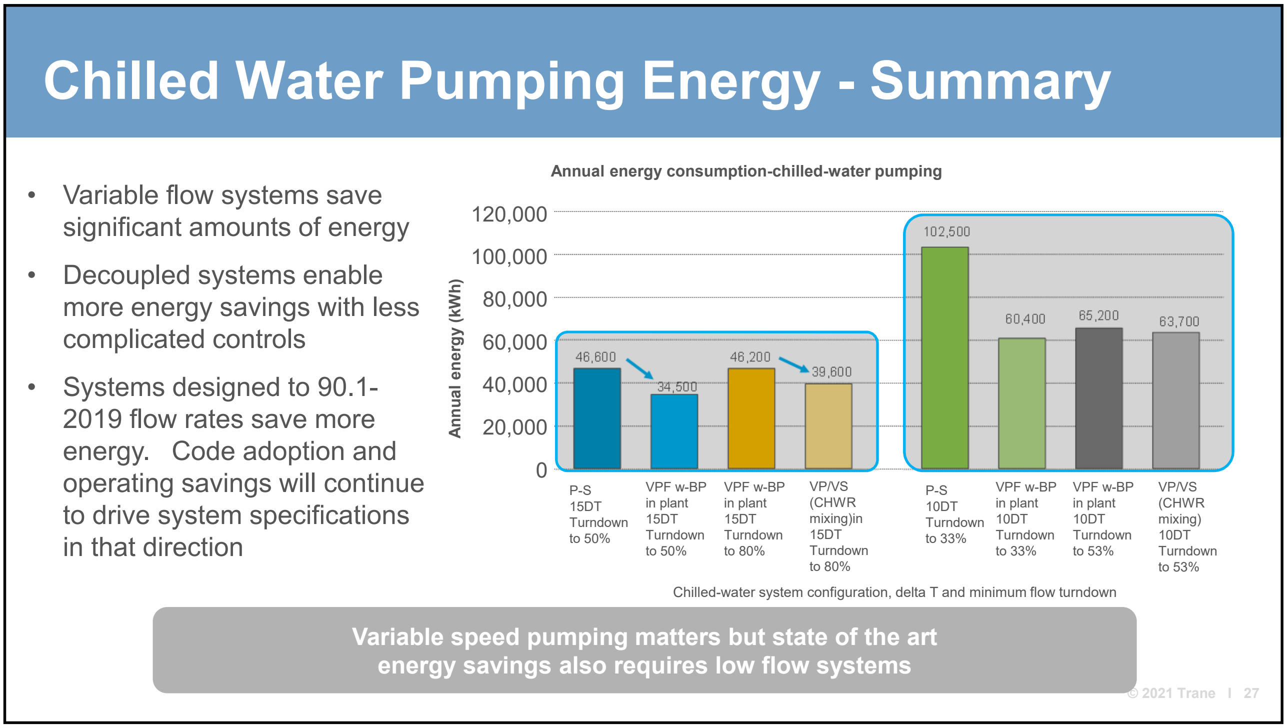
VPF (80%) vs. VP/VS

High School in St. Louis, MO
- Two Chiller 1000T Plant
- 15F DT and 10F DT design
- Chiller turndown to 80% design

Plant Configurations

Variable primary flow vs.
Variable primary, variable secondary

Results
- 12% reduction in energy
- 15 DT is a clear winner



Chilled Water Pumping Energy - Summary

- Variable flow systems save significant amounts of energy
- Decoupled systems enable more energy savings with less complicated controls
- Systems designed to 90.1-2019 flow rates save more energy.   Code adoption and operating savings will continue to drive system specifications in that direction

Variable speed pumping matters but state of the art energy savings also requires low flow systems

Design Choices

Pumps

TRANE

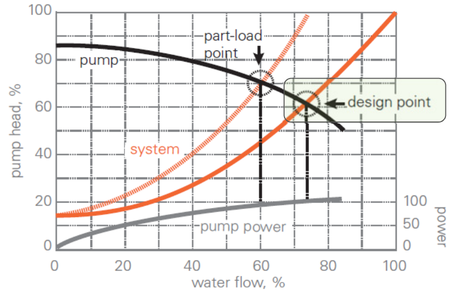
Pumping Design Choices
Pump Power

$$Pump\ kW = \frac{Flow\ x\ \Delta P\ x\ 0.746}{3960\ x\ \underbrace{Pump\ eff\ x\ Motor\ eff\ x\ Drive\ eff}_{Pump_{ww}\ eff}}$$

Pumping Design Choices
DOE and ASHRAE 90.1- 2019 Requirements

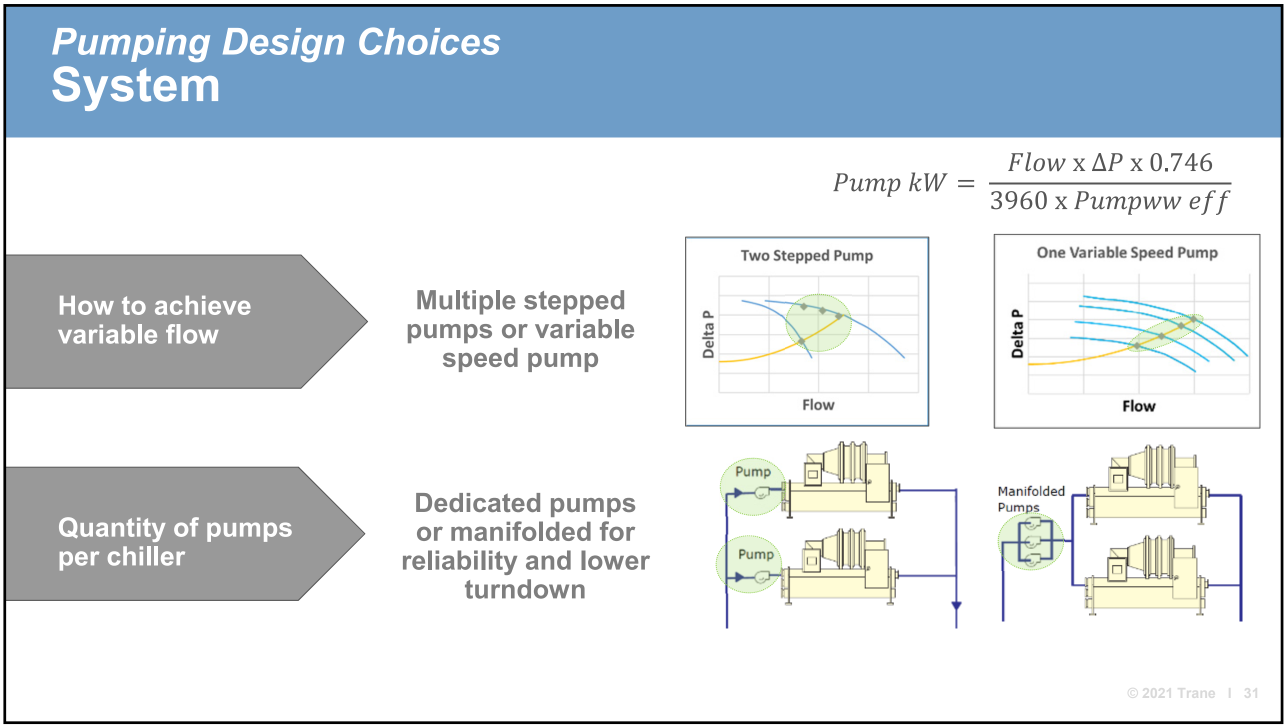
$$Pump\ kW = \frac{Flow\ x\ \Delta P\ x\ 0.746}{3960\ x\ Pumpww\ eff}$$

$$PEI = \frac{Pump\ Energy\ Rating}{Pump\ Energy\ Rating\ _{STD}}$$



Category	Requirements	Agency
Pump Energy	Pump Energy Index (PEI) $\leq$ 1.0 Constant load PEI_{CL} and Variable load PEI_{VL}	ASHRAE 90.1 per DOE 10 CFR 429 & 431
Control	No more than 30% design power at 50% design flow	ASHRAE 90.1, 6.5.4
System Energy	Chilled water pumping less than 22 W/gpm **	ASHRAE 90.1, Appendix G

** **Baseline building pumping energy budget for primary / secondary system**



Pumping Design Choices
System

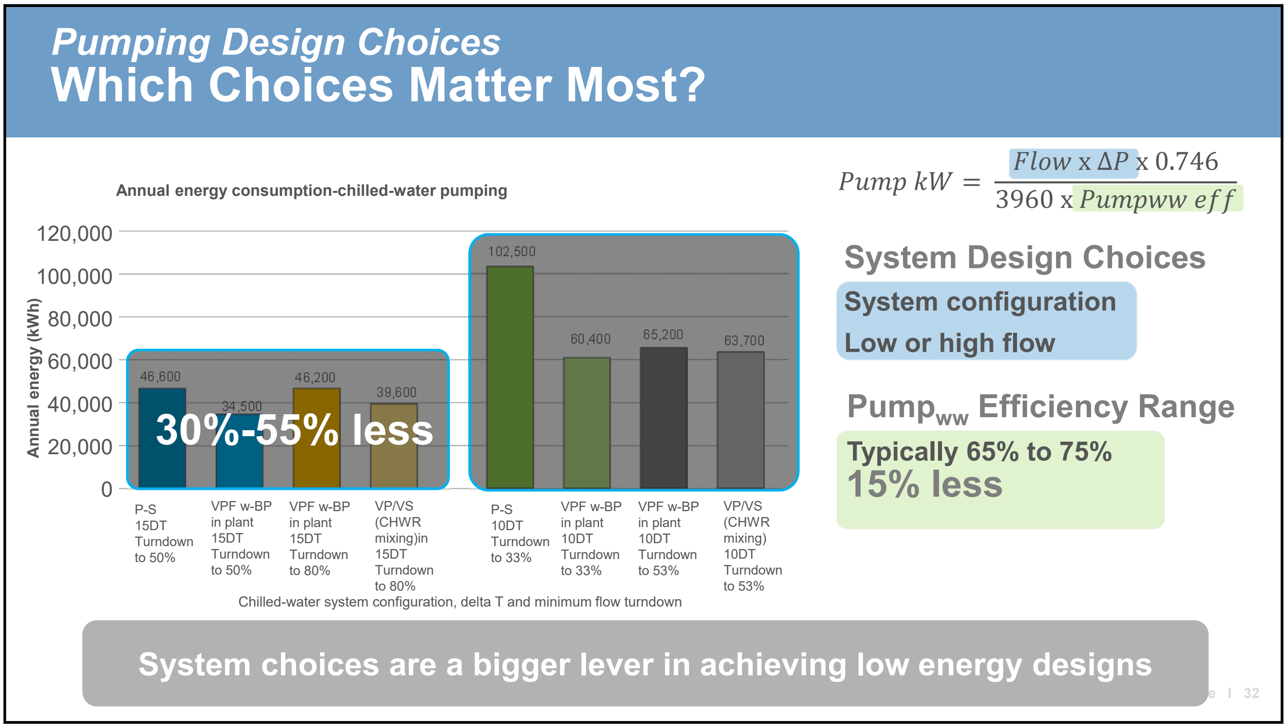
$$Pump\ kW = \frac{Flow \times \Delta P \times 0.746}{3960 \times Pumpww\ eff}$$

How to achieve variable flow

Multiple stepped pumps or variable speed pump

Quantity of pumps per chiller

Dedicated pumps or manifolded for reliability and lower turndown



Pumping Design Choices
Which Choices Matter Most?

$$Pump\ kW = \frac{Flow \times \Delta P \times 0.746}{3960 \times Pumpww\ eff}$$

Annual energy consumption-chilled-water pumping

Chilled-water system configuration, delta T and minimum flow turndown

System Design Choices

System configuration

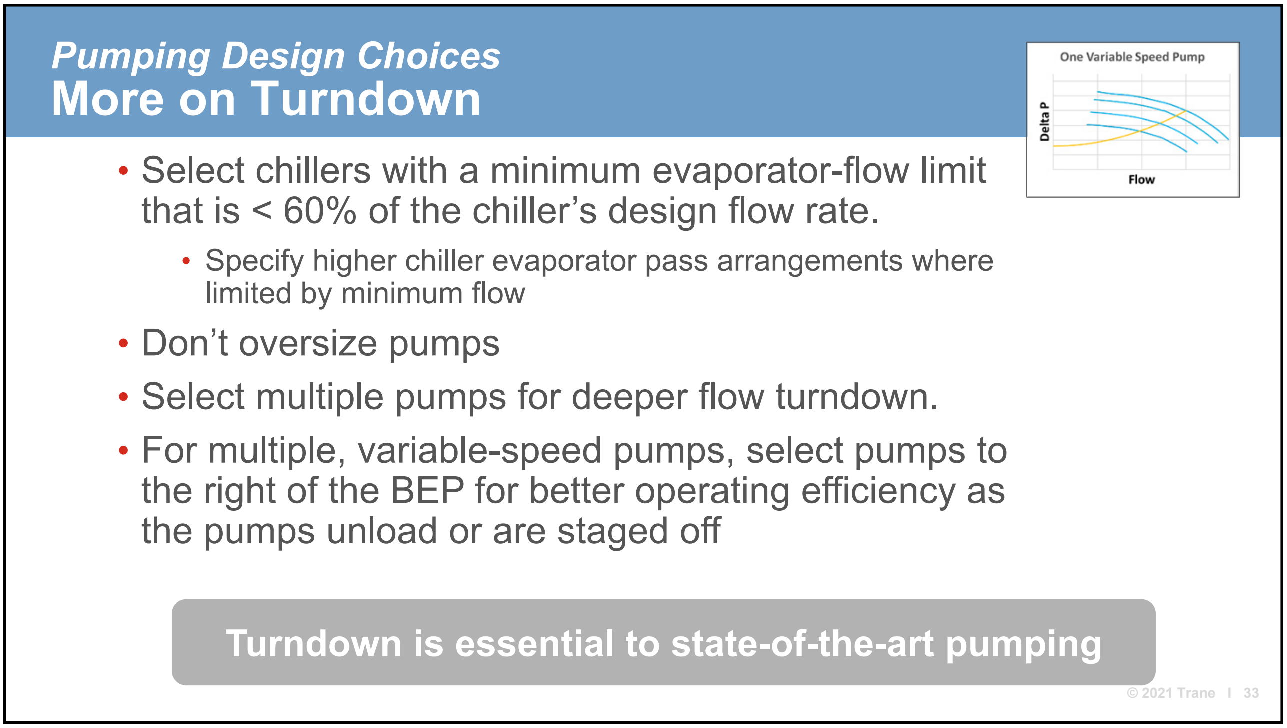
Low or high flow

Pump$_{ww}$ Efficiency Range

Typically 65% to 75%

15% less

System choices are a bigger lever in achieving low energy designs



Pumping Design Choices
More on Turndown

- Select chillers with a minimum evaporator-flow limit that is < 60% of the chiller's design flow rate.
  - Specify higher chiller evaporator pass arrangements where limited by minimum flow
- Don't oversize pumps
- Select multiple pumps for deeper flow turndown.
- For multiple, variable-speed pumps, select pumps to the right of the BEP for better operating efficiency as the pumps unload or are staged off

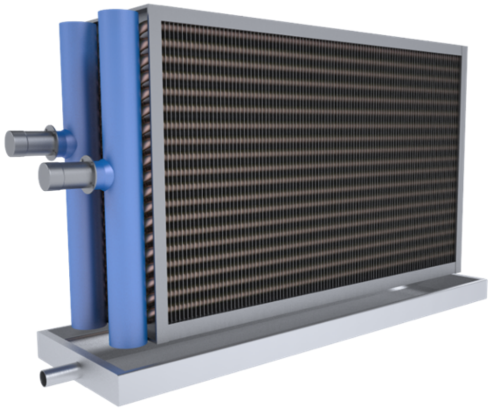
Turndown is essential to state-of-the-art pumping

Design Choices

Coils-valves

Myths about Coils

- They are selected for a certain delta T



Cooling Coils – Reselecting Existing

MBH	**504**	**504**
WTR	**10° F**	**16° F**
GPM/Ton	**2.4**	**1.5**
EWT	**44° F**	**41° F**
LWT	**54° F**	**57° F**
GPM	**101**	**63.0**

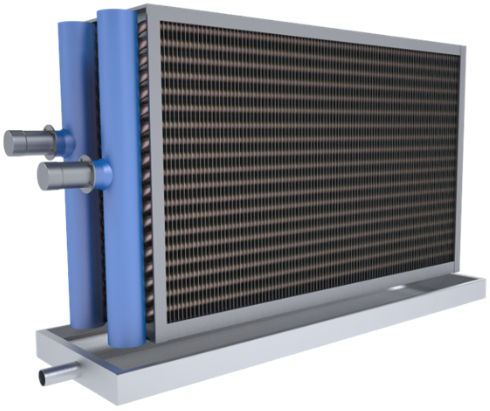
GPM reduction of 37.5%

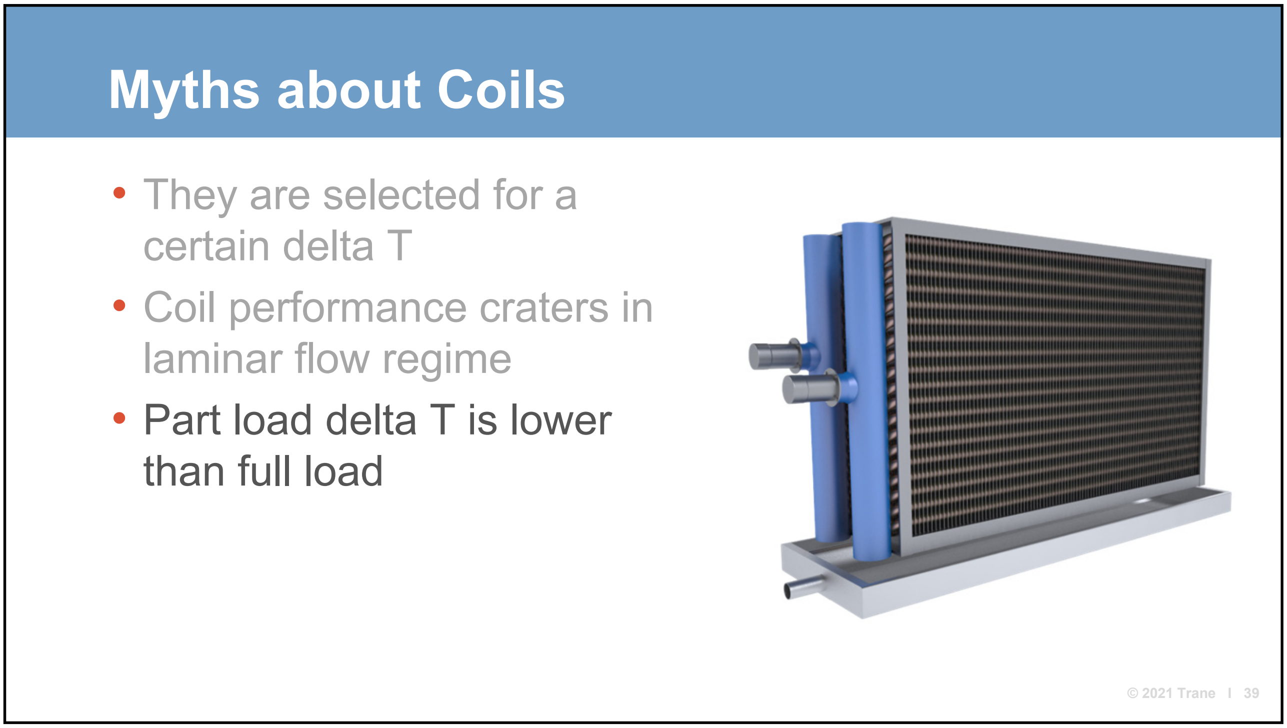
New Coil Selection

	Lowest Cost	Typical	Lowest Energy
entering water temp, °F	42	42	42
leaving water temp, °F	57	57	57
water ΔT, °F	15	15	15
tube diameter, in.	3/8	1/2	5/8
rows	6	6	6
fin density, fins/ft	114	159	133
fin design	high cap	high cap	high eff
turbulators	yes	no	yes
water flow rate, gpm	40	40	40
water velocity, ft/sec	2.7	2.8	2.1
water pressure drop, ft. H_2O	11.2	4.7	5.2
air pressure drop, in. H_2O	0.81	0.95	0.71
cost of coil	**base - 30%**	**base**	**base + 15%**

Myths about Coils

- They are selected for a certain delta T
- Coil performance craters in laminar flow regime

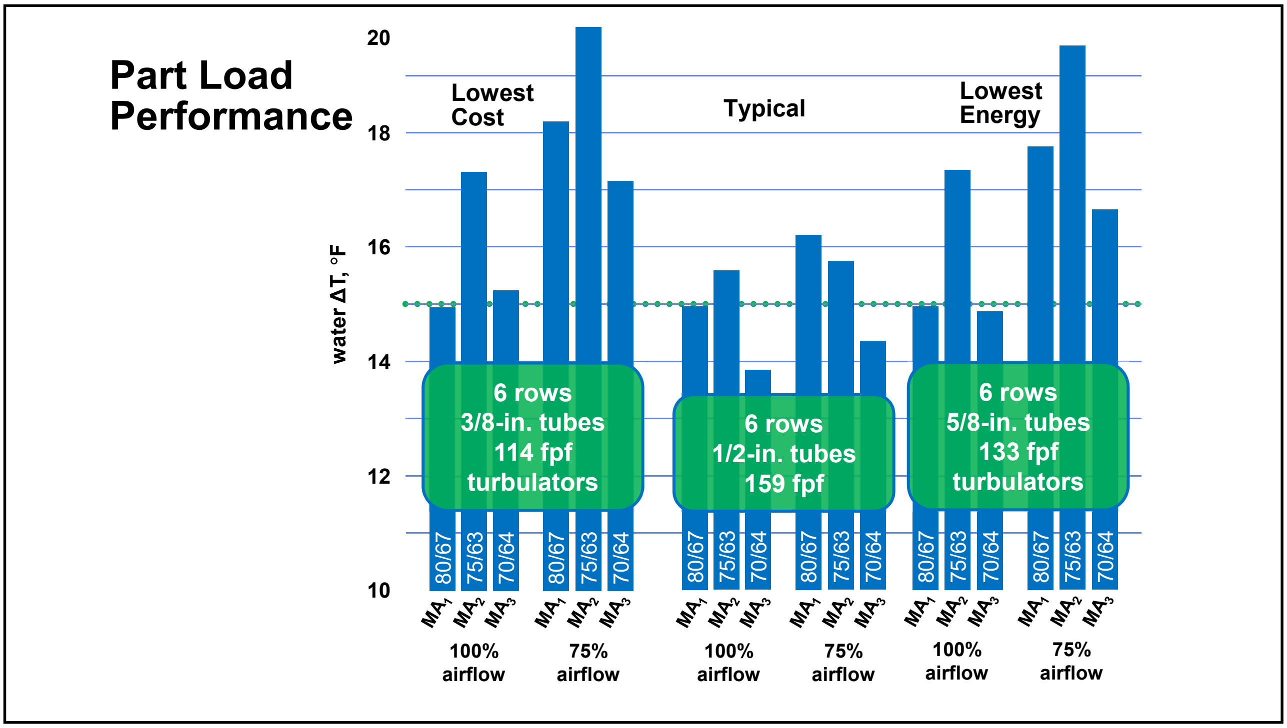




Myths about Coils

- They are selected for a certain delta T
- Coil performance craters in laminar flow regime
- Part load delta T is lower than full load

© 2021 Trane I 39



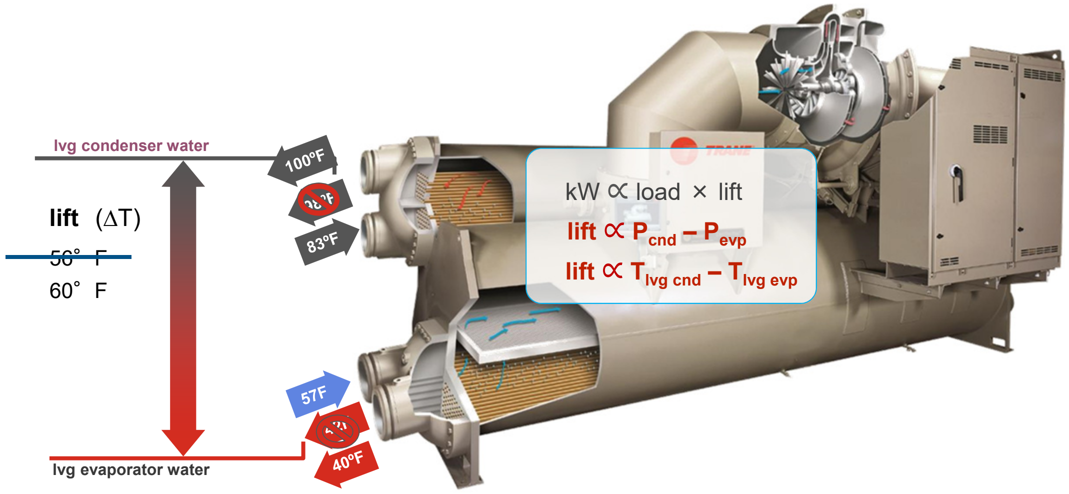
Part Load Performance

Chilled Water Pump (800 tons)

Flow rate	**1920 gpm**	**1200 gpm**
Pump head	**110 feet**	**49 feet**
Pump efficiency	**80 %**	**80 %**
Motor efficiency	**95 %**	**95 %**
Pump power	**52 kW**	**16 kW**

In this installation:
a 37.5% reduction in flow =
nearly 70% reduction in chilled water pumping energy consumption

Selecting Future Proof Chillers

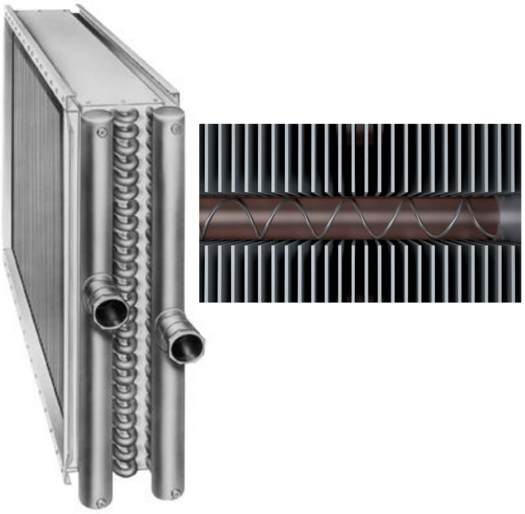


$\text{kW} \propto \text{load} \times \text{lift}$

$\textbf{lift} \propto P_{\text{cnd}} - P_{\text{evp}}$

$\textbf{lift} \propto T_{\text{lvg cnd}} - T_{\text{lvg evp}}$

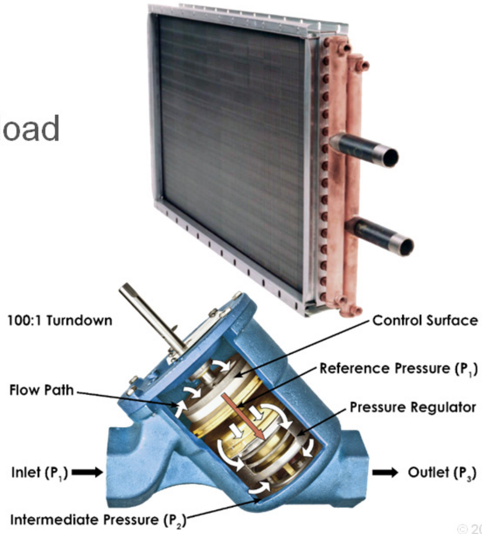
Cooling Cool Performance

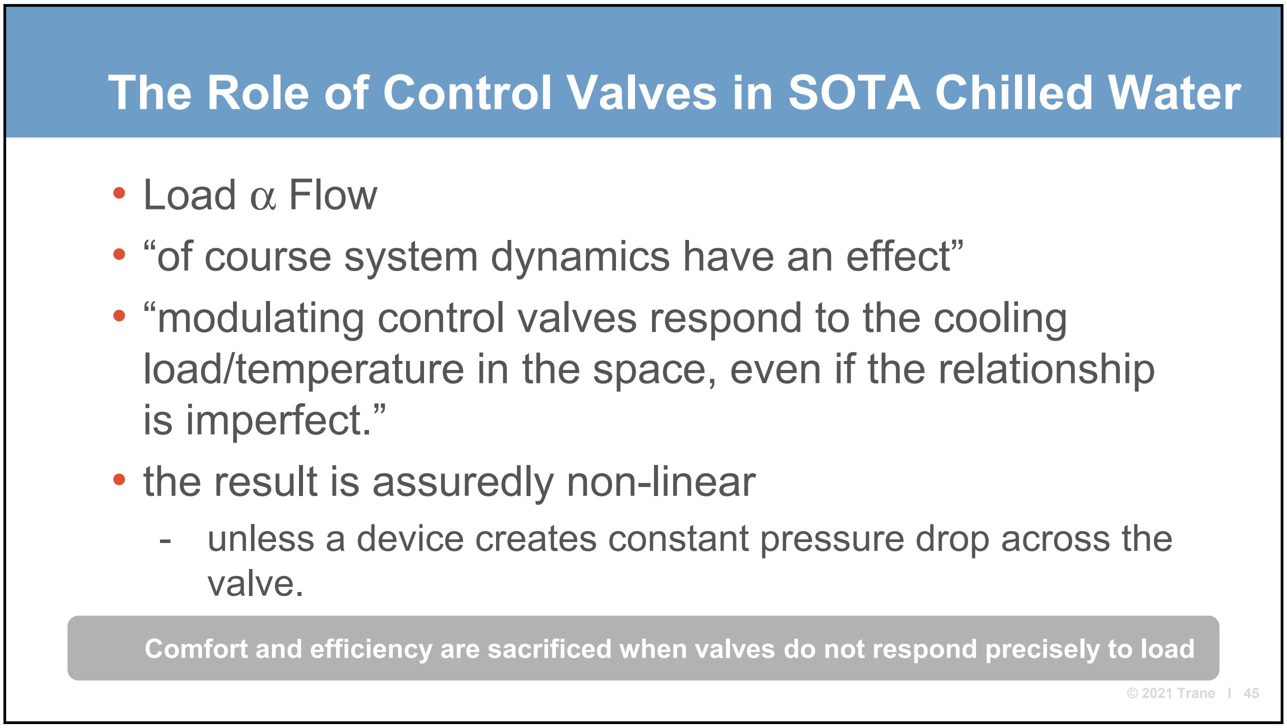


- New chilled water coils should use turbulators
- Existing chilled water coils should get colder water
- Part load delta T should be Higher than full load

Design Delta T and Greater is Achievable

1. AHRI certified coil selections
2. AHU set point limits
3. Chilled water reset only at part load
4. Pressure boosting – no tertiary “mixing”
5. Properly selected, high quality control valves

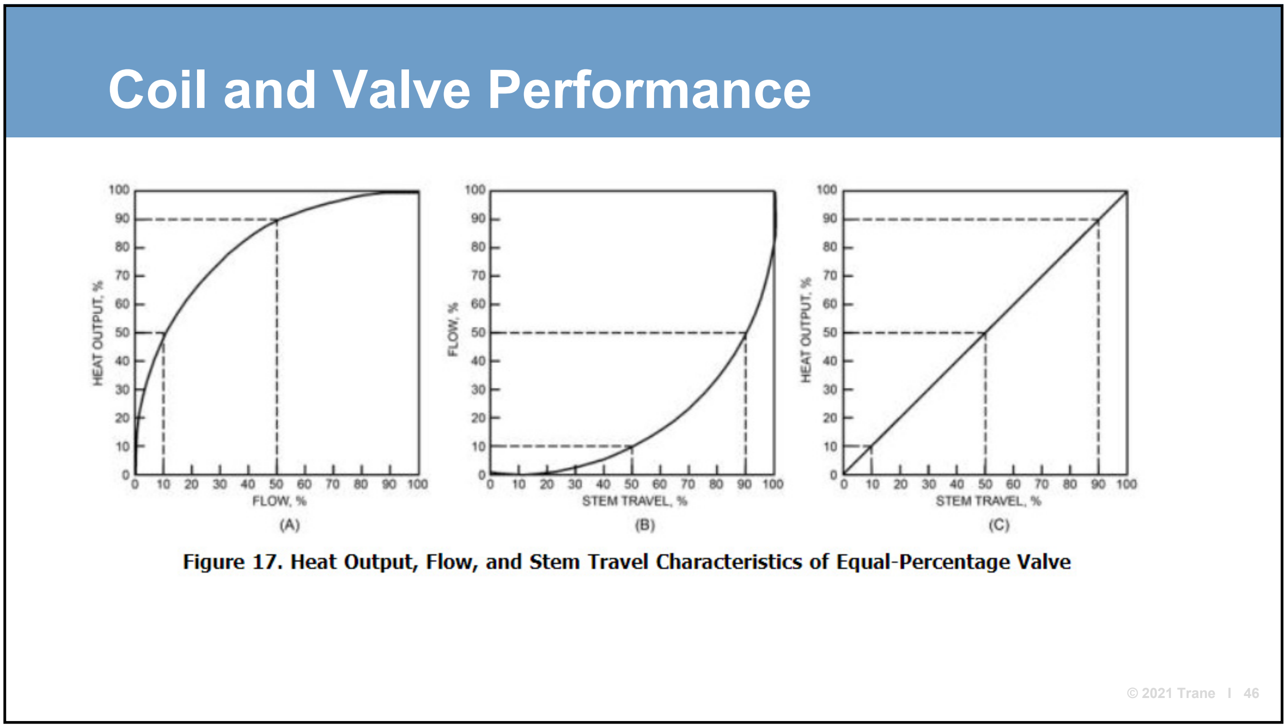




The Role of Control Valves in SOTA Chilled Water

- Load α Flow
- “of course system dynamics have an effect”
- “modulating control valves respond to the cooling load/temperature in the space, even if the relationship is imperfect.”
- the result is assuredly non-linear
  - unless a device creates constant pressure drop across the valve.

Comfort and efficiency are sacrificed when valves do not respond precisely to load

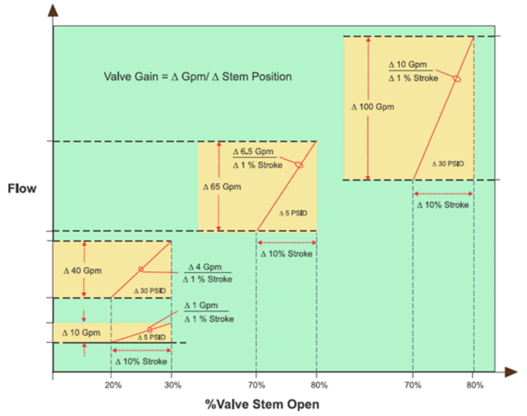


Coil and Valve Performance

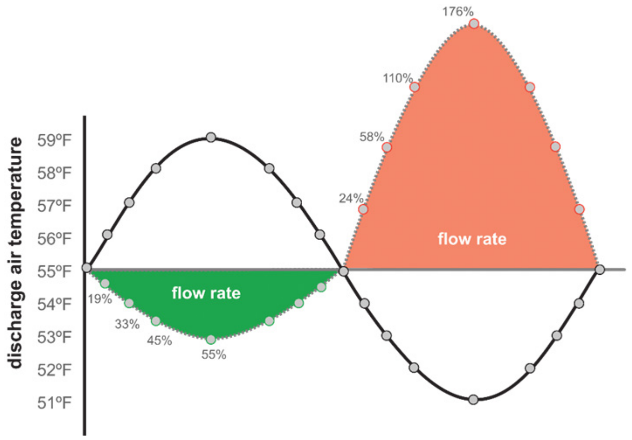
Figure 17. Heat Output, Flow, and Stem Travel Characteristics of Equal-Percentage Valve

Pressure Dependent Control

Pressure Dependent Control Valve Gain

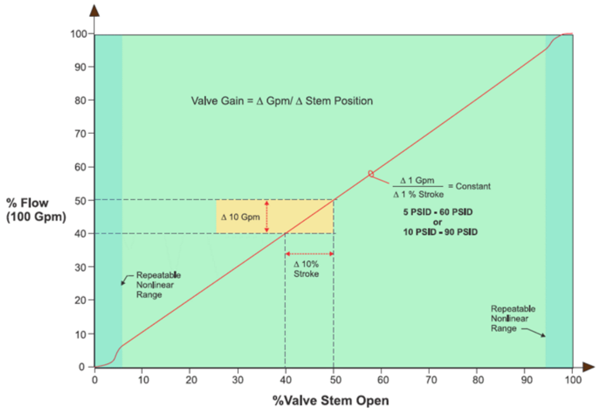


Process Gain of Pressure Dependent Control Valves changes by on order of magnitude with stem position and with pressure differential.



Pressure-Independent Control

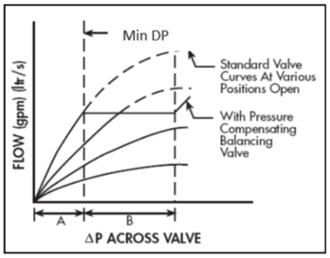
Pressure Independent Control Valve Gain vs. Stem Position

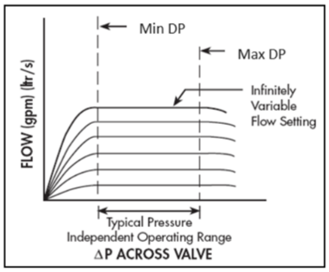


Process Gain of Pressure Independent Control Valves is constant over >85% of stem travel and pressure differential (5 - 60 Psid or 10 - 90 Psid).

- No hunting
  - Increased reliability
  - Increased comfort

Flow versus Pressure Relationship – PD versus PI





- Decreased energy consumption
  - Chiller capacity restored
  - Pipe capacity restored
  - Lower flow rates, pump energy
- Requires valve position for pump control (ΔP is close to constant)

How to Get Good Valve Performance

- Account for system interactions
  - Know where each valve is in the system
- Estimate the loads within reason
  - Determine valve Cv, flow, authority
- Successfully hand off to a team of
  - Installers
  - Controls contractors
  - System balancers, and
  - Commissioning agents
- Or…specify better control valves

Design Choices

Chillers & cooling towers

State-of-the-Art Chilled Water Systems

Chillers

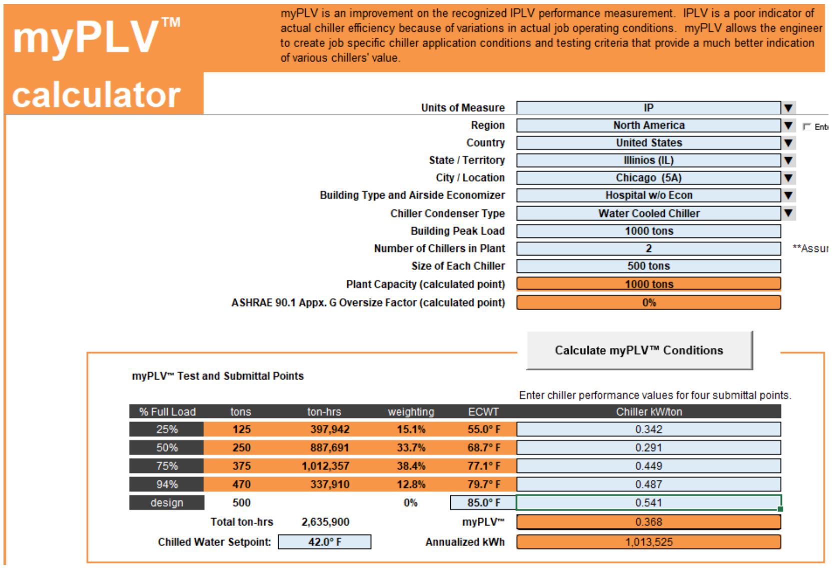
Key Attributes:

- Reliability
- Efficiency
- Lowest Emissions

State-of-the-Art Chilled Water Systems
Chiller Operating Points

Building specific inputs

- Location
- Building Type
- Plant Tonnage



myPLV™ calculator

myPLV is an improvement on the recognized IPLV performance measurement. IPLV is a poor indicator of actual chiller efficiency because of variations in actual job operating conditions. myPLV allows the engineer to create job specific chiller application conditions and testing criteria that provide a much better indication of various chillers' value.

Units of Measure	IP ▼
Region	North America ▼ ☐ Ent
Country	United States ▼
State / Territory	Illinios (IL) ▼
City / Location	Chicago (5A) ▼
Building Type and Airside Economizer	Hospital w/o Econ ▼
Chiller Condenser Type	Water Cooled Chiller ▼
Building Peak Load	1000 tons
Number of Chillers in Plant	2 **Assur
Size of Each Chiller	500 tons
Plant Capacity (calculated point)	1000 tons
ASHRAE 90.1 Appx. G Oversize Factor (calculated point)	0%

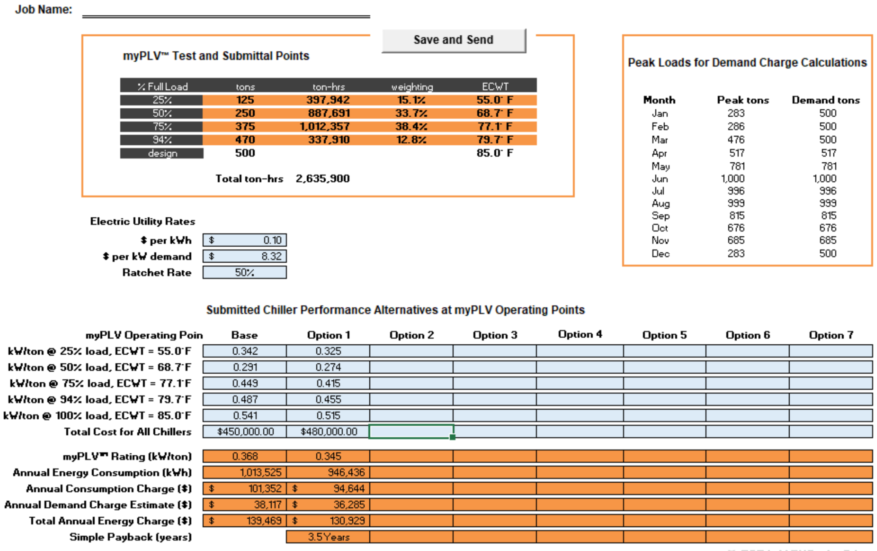
myPLV™ Test and Submittal Points

Enter chiller performance values for four submittal points.

% Full Load	tons	ton-hrs	weighting	ECWT	Chiller kW/ton
25%	125	397,942	15.1%	55.0° F	0.342
50%	250	887,691	33.7%	68.7° F	0.291
75%	375	1,012,357	38.4%	77.1° F	0.449
94%	470	337,910	12.8%	79.7° F	0.487
design	500		0%	85.0° F	0.541
	Total ton-hrs	2,635,900		myPLV™	0.368
Chilled Water Setpoint:	42.0° F			Annualized kWh	1,013,525

State-of-the-Art Chilled Water Systems
Chiller Evaluation

- Compare multiple chillers
- Payback based on your building and utility rates



Job Name: ____________________

myPLV™ Test and Submittal Points

% Full Load	tons	ton-hrs	weighting	ECWT
25%	125	397,942	15.1%	55.0° F
50%	250	887,691	33.7%	68.7° F
75%	375	1,012,357	38.4%	77.1° F
94%	470	337,910	12.8%	79.7° F
design	500			85.0° F
	Total ton-hrs	2,635,900		

Peak Loads for Demand Charge Calculations

Month	Peak tons	Demand tons
Jan	283	500
Feb	286	500
Mar	476	500
Apr	517	517
May	781	781
Jun	1,000	1,000
Jul	996	996
Aug	999	999
Sep	815	815
Oct	676	676
Nov	685	685
Dec	283	500

Electric Utility Rates

$ per kWh	$ 0.10
$ per kW demand	$ 8.32
Ratchet Rate	50%

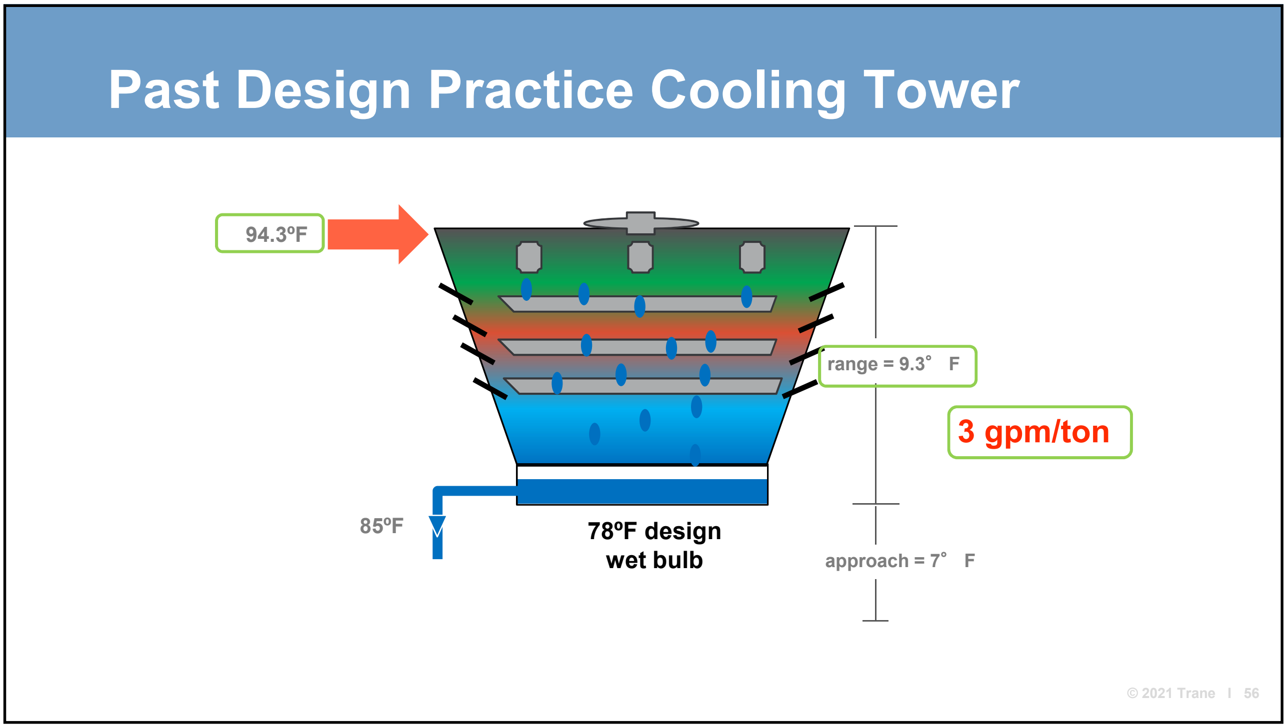
Submitted Chiller Performance Alternatives at myPLV Operating Points

myPLV Operating Poin	Base	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
kW/ton @ 25% load, ECWT = 55.0°F	0.342	0.325						
kW/ton @ 50% load, ECWT = 68.7°F	0.291	0.274						
kW/ton @ 75% load, ECWT = 77.1°F	0.449	0.415						
kW/ton @ 94% load, ECWT = 79.7°F	0.487	0.455						
kW/ton @ 100% load, ECWT = 85.0°F	0.541	0.515						
Total Cost for All Chillers	$450,000.00	$480,000.00						
myPLV™ Rating (kW/ton)	0.368	0.345						
Annual Energy Consumption (kWh)	1,013,525	946,436						
Annual Consumption Charge ($)	$ 101,352	$ 94,644						
Annual Demand Charge Estimate ($)	$ 38,117	$ 36,285						
Total Annual Energy Charge ($)	$ 139,469	$ 130,929						
Simple Payback (years)		3.5Years						

State of the Art Chilled Water Systems

Design Parameters: ΔTs

Source	Chilled Water	Condenser Water
ASHRAE 90.1 (since 2016)	15ºF ΔT Minimum return 57ºF	
ASHRAE Fundamentals of Design and Control of Central Chilled-Water Plants	Begin at 25ºF ΔT Provides process to refine	15ºF ΔT
ASHRAE GreenGuide	12-20ºF ΔT	12-18ºF ΔT
AEDGs (those with chilled water)	At least 15ºF ΔT (hospitals) 12-20ºF ΔT (K-12 schools)	At least 14ºF ΔT

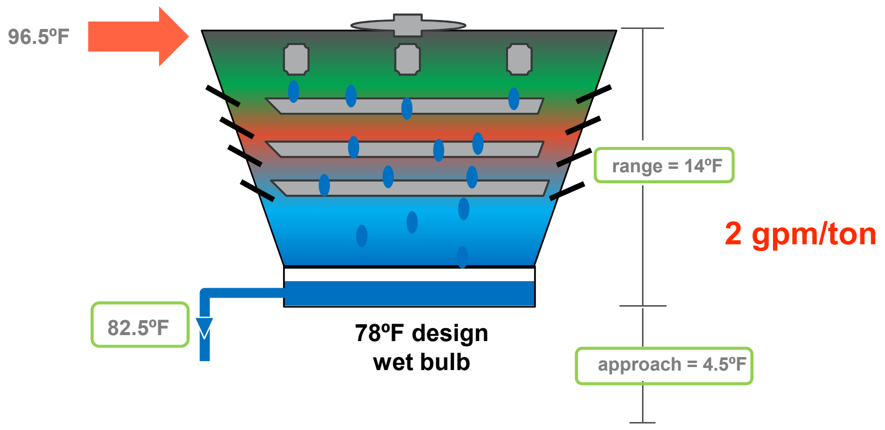


Past Design Practice Cooling Tower

Example Tower at Standard Rating Conditions

	Past Conditions
Flow rate (gpm)	1500
Capacity (tons)	500
Design wet bulb (ºF)	78
Approach (ºF)	7
Entering water temperature (ºF)	94.3
Entering water temperature (ºF)	85
Fan power (hp)	40

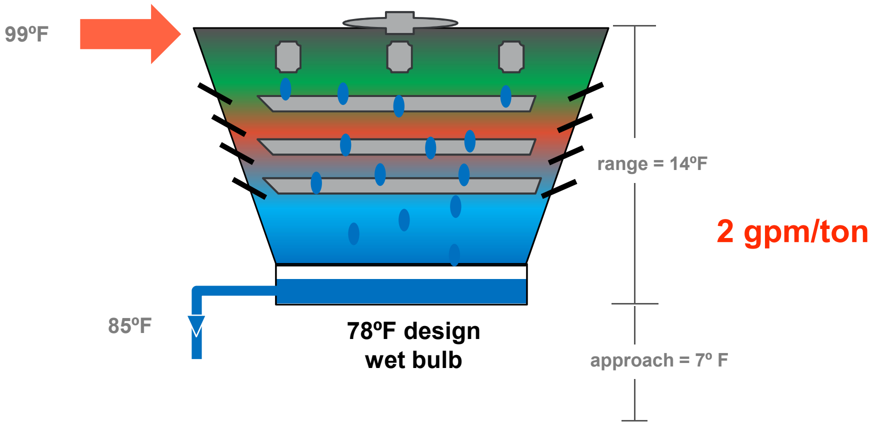
Same Tower at GreenGuide Flow Rate



Same Tower, GreenGuide Flow Rate

	Past Conditions	SAME TOWER GREENGUIDE FLOW RATE
Flow rate (gpm)	1500	1000
Design wet bulb (ºF)	78	78
Approach (ºF)	7	4.5
Entering water temperature (ºF)	94.3	96.5
Entering water temperature (ºF)	85	82.5
Fan power (hp)	40	40

Smaller Tower, GreenGuide Flow Rate



Smaller Tower, GreenGuide Flow Rate

	Past Conditions	SAME TOWER GREENGUIDE FLOW RATE	SMALLER TOWER GREENGUIDE FLOW RATE
Flow rate (gpm)	1500	1000	1000
Design wet bulb (°F)	78	78	78
Approach (°F)	7	4.5	7
Entering water temperature (°F)	94.3	96.5	99
Entering water temperature (°F)	85	82.5	85
Fan power (hp)	40	40	25

State-of-the-Art Chilled Water Systems

Pumps and Pipes

6 Heating, Ventilating, and Air Conditioning

Table 6.5.4.6 *Piping System* Design Maximum Flow Rate in GPM

Operating Hours/Year	≤2000 Hours/Year		>2000 and ≤4400 Hours/Year		>4400 Hours/Year	
Nominal Pipe Size, in.	Other	Variable Flow/ Variable Speed	Other	Variable Flow/ Variable Speed	Other	Variable Flow/ Variable Speed
2 1/2	120	180	85	130	68	110
3	180	270	140	210	110	170
4	350	530	260	400	210	320
5	410	620	310	470	250	370
6	740	1100	570	860	440	680
8	1200	1800	900	1400	700	1100
10	1800	2700	1300	2000	1000	1600
12	2500	3800	1900	2900	1500	2300
Maximum velocity for pipes over 14 to 24 in. in size	8.5 ft/s	13.0 ft/s	6.5 ft/s	9.5 ft/s	5.0 ft/s	7.5 ft/s

Condenser System Assumptions

- Total Head Pressure 3 gpm/ton = 70’
  - Tower static head = 23’ (constant)
  - Chiller head determined by base selection = 25’
  - Pipe Head (= Total – tower – chiller) so pipe head at base = 90’-23’-25’ = **22’**

- Pipe Head at low flow with same size pipe
  - System ∆P drops with about flow squared
  - 22/PD = (3/2)^2 so new pipe PD = **9.8’**

Condenser Water Pump

$$Pump\ kW = \frac{gpm\ \times\ \Delta P\ \times 0.746}{3960\ \times Pump\ eff\ \times Motor\ eff\ \times Drive\ Eff}$$

Pump kW at Design

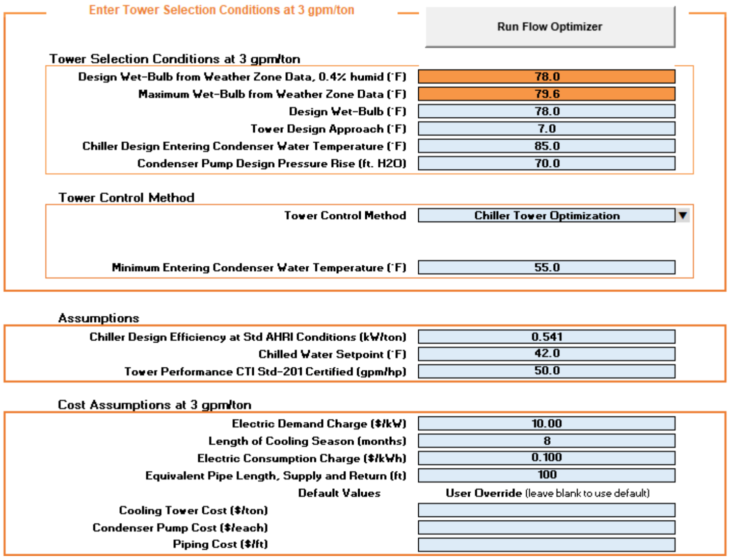
Description	Chiller PD (ft)	Tower PD (ft)	Pipe PD (ft)	Total PD (ft)	Total Flow (gpm)	Cond pump kW/ton
3 gpm/ton	25.0	23	22	70	1500	0.0530
2 gpm/ton same tower	12.4	23	9.8	45.2	1000	0.0228

State-of-the-Art Chilled Water Systems

Condenser Flow Optimization - Inputs

Design Parameter Inputs

- Wet bulb
- Delta P
- Cooling tower Control
- Equipment Costs



Enter Tower Selection Conditions at 3 gpm/ton

Tower Selection Conditions at 3 gpm/ton

Design Wet-Bulb from Weather Zone Data, 0.4% humid (°F)	78.0
Maximum Wet-Bulb from Weather Zone Data (°F)	79.6
Design Wet-Bulb (°F)	78.0
Tower Design Approach (°F)	7.0
Chiller Design Entering Condenser Water Temperature (°F)	85.0
Condenser Pump Design Pressure Rise (ft. H2O)	70.0

Tower Control Method

Tower Control Method	Chiller Tower Optimization ▼
Minimum Entering Condenser Water Temperature (°F)	55.0

Assumptions

Chiller Design Efficiency at Std AHRI Conditions (kW/ton)	0.541
Chilled Water Setpoint (°F)	42.0
Tower Performance CTI Std-201 Certified (gpm/hp)	50.0

Cost Assumptions at 3 gpm/ton

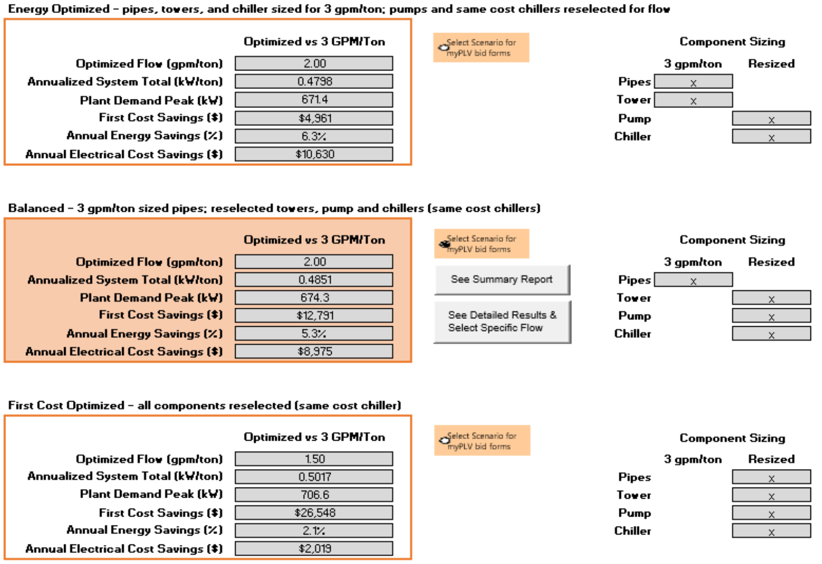
Electric Demand Charge ($/kW)		10.00
Length of Cooling Season (months)		8
Electric Consumption Charge ($/kWh)		0.100
Equivalent Pipe Length, Supply and Return (ft)		100
	Default Values	**User Override** (leave blank to use default)
Cooling Tower Cost ($/ton)		
Condenser Pump Cost ($/each)		
Piping Cost ($/ft)		

State-of-the-Art Chilled Water Systems

Condenser Flow Optimization – Summary Results

Design Choices

- Energy optimized
- Lowest first cost
- Balanced approach



Energy Optimized – pipes, towers, and chiller sized for 3 gpm/ton; pumps and same cost chillers reselected for flow

	Optimized vs 3 GPM/Ton
Optimized Flow (gpm/ton)	2.00
Annualized System Total (kW/ton)	0.4798
Plant Demand Peak (kW)	671.4
First Cost Savings ($)	$4,961
Annual Energy Savings (%)	6.3%
Annual Electrical Cost Savings ($)	$10,630

Component Sizing

	3 gpm/ton	Resized
Pipes	x	
Tower	x	
Pump		x
Chiller		x

Balanced – 3 gpm/ton sized pipes; reselected towers, pump and chillers (same cost chillers)

	Optimized vs 3 GPM/Ton
Optimized Flow (gpm/ton)	2.00
Annualized System Total (kW/ton)	0.4851
Plant Demand Peak (kW)	674.3
First Cost Savings ($)	$12,791
Annual Energy Savings (%)	5.3%
Annual Electrical Cost Savings ($)	$8,975

Component Sizing

	3 gpm/ton	Resized
Pipes	x	
Tower		x
Pump		x
Chiller		x

First Cost Optimized – all components reselected (same cost chiller)

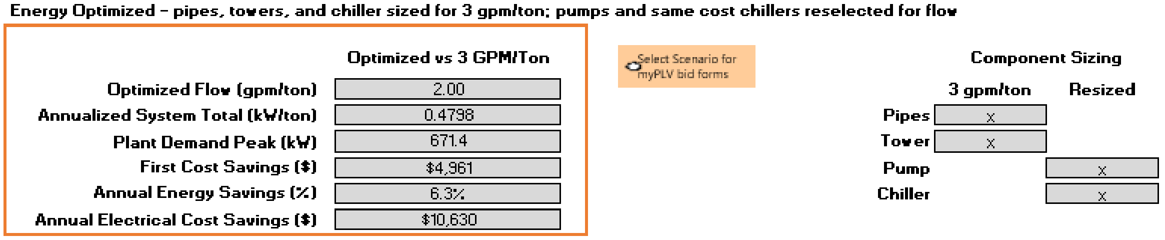
	Optimized vs 3 GPM/Ton
Optimized Flow (gpm/ton)	1.50
Annualized System Total (kW/ton)	0.5017
Plant Demand Peak (kW)	706.6
First Cost Savings ($)	$26,548
Annual Energy Savings (%)	2.1%
Annual Electrical Cost Savings ($)	$2,019

Component Sizing

	3 gpm/ton	Resized
Pipes		x
Tower		x
Pump		x
Chiller		x

State-of-the-Art Chilled Water Systems

Condenser Flow Optimization – Energy Optimized



Energy Optimized – pipes, towers, and chiller sized for 3 gpm/ton; pumps and same cost chillers reselected for flow

	Optimized vs 3 GPM/Ton
Optimized Flow (gpm/ton)	2.00
Annualized System Total (kW/ton)	0.4798
Plant Demand Peak (kW)	671.4
First Cost Savings ($)	$4,961
Annual Energy Savings (%)	6.3%
Annual Electrical Cost Savings ($)	$10,630

Component Sizing

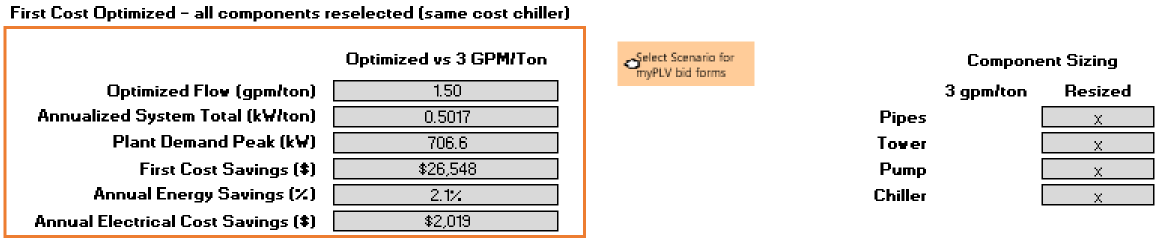
	3 gpm/ton	Resized
Pipes	x	
Tower	x	
Pump		x
Chiller		x

Equipment sizing at the various condenser flowrates

- Chiller is the same cost
- Tower is the same size as 3 gpm/ton
- Pipes are the same size as 3 gpm/ton
- Pumps are downsized

State-of-the-Art Chilled Water Systems

Condenser Flow Optimization – Lowest First Cost



First Cost Optimized – all components reselected (same cost chiller)

	Optimized vs 3 GPM/Ton
Optimized Flow (gpm/ton)	1.50
Annualized System Total (kW/ton)	0.5017
Plant Demand Peak (kW)	706.6
First Cost Savings ($)	$26,548
Annual Energy Savings (%)	2.1%
Annual Electrical Cost Savings ($)	$2,019

Component Sizing

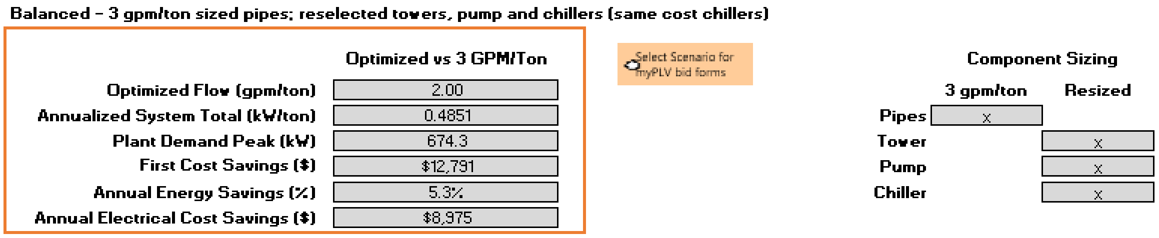
	3 gpm/ton	Resized
Pipes		x
Tower		x
Pump		x
Chiller		x

Equipment sizing at the various condenser flowrates

- Chiller is the same cost
- Tower is downsized
- Pipes are downsized
- Pumps are downsized

State-of-the-Art Chilled Water Systems

Condenser Flow Optimization - Balanced



Balanced – 3 gpm/ton sized pipes; reselected towers, pump and chillers (same cost chillers)

	Optimized vs 3 GPM/Ton
Optimized Flow (gpm/ton)	2.00
Annualized System Total (kW/ton)	0.4851
Plant Demand Peak (kW)	674.3
First Cost Savings ($)	$12,791
Annual Energy Savings (%)	5.3%
Annual Electrical Cost Savings ($)	$8,975

Component Sizing

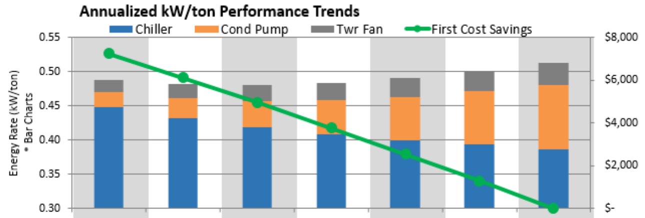
	3 gpm/ton	Resized
Pipes	x	
Tower		x
Pump		x
Chiller		x

Equipment sizing at the various condenser flowrates

- Chiller is the same cost
- Tower is downsized
- Pipes are the same size as 3 gpm/ton
- Pumps are downsized

State-of-the-Art Chilled Water Systems

Condenser Flow Optimization – Summary Report



Condenser Flow (gpm/ton)	1.5	1.75	2	2.25	2.5	2.75	3
Selected Flow			X				
Annualized Results							
Energy Savings (%)	4.7%	6.1%	6.3%	5.7%	4.4%	2.3%	0.0%
Energy Cost Savings ($)	$ 6,650	$ 9,640	$ 10,630	$ 10,083	$ 8,205	$ 4,381	$ -

First Cost Delta vs 3 gpm/ton	Condenser Pump Cost (Δ$)	$ 7,238	$ 6,117	$ 4,961	$ 3,771	$ 2,547	$ 1,290	$ -
	Cooling Tower Cost (Δ$)	-	-	-	-	-	-	-
	Condenser Piping Cost (Δ$)	-	-	-	-	-	-	-
	Total Installed Cost (Δ$)	$ 7,238	$ 6,117	$ 4,961	$ 3,771	$ 2,547	$ 1,290	$ -

Simple and easy evaluation in as little at 5 minutes

State of the Art System Control

Cooling towers, ppr/cwr

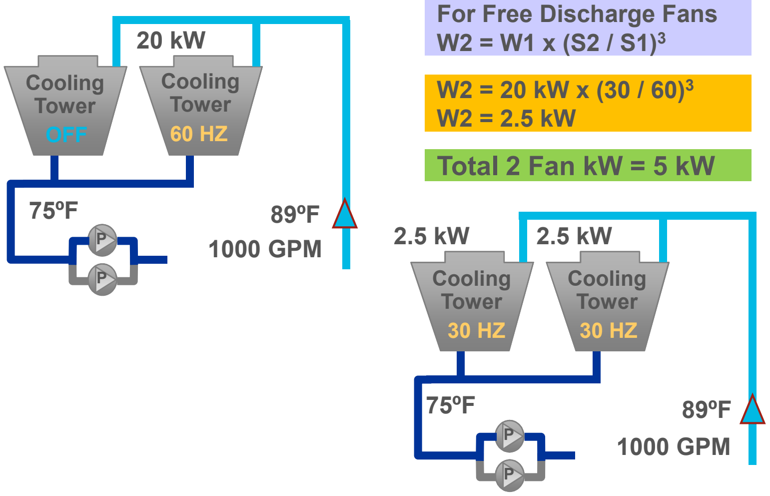
Trim and respond, Variable speed

TRANE

Cooling Tower Control
ASHRAE 90.1- 2019 Requirements

- Fan Speed Control: Total 5 hp or larger
  - Reduce fan power to 30% wattage at 50% airflow (VSD is usually applied)
    - Exceptions: Condenser fans:
      Serving multiple refrigerant circuits
      Serving flooded condensers
  - Multicell heat rejection equipment with variable-speed drives
    - Operate maximum number of fans allowed by manufacturer
    - Control all fans to the same speed
  - Tower flow turndown to larger of
    - Flow produced by smallest pump at minimum speed
    - 50% of the design flow for the tower

Cooling Tower Sequencing
Two Fans Operating



For Free Discharge Fans
$W2 = W1 \times (S2 / S1)^3$

$W2 = 20\ kW \times (30 / 60)^3$
$W2 = 2.5\ kW$

Total 2 Fan kW = 5 kW

Operating multiple fans at part speed saves more energy than one fan at full speed and one fan off

Cooling Tower Cell Sequencing

- Operate as many tower cells as possible
  - MUST keep tower fill wetted
    - Stay above minimum cell flow rate
    - Tower providers may provide different nozzles or “nozzle cups”
  - Limit fan speed when additional tower cells are operating

$$N \text{ x } hp/fan = (N + A) \text{ x } hp/fan \text{ x } (MaxSpd)^3$$

$$\text{Rearranged: } MaxSpd = [N / (N + A)]^{1/3}$$

where,

N = the number of tower cells normally operating

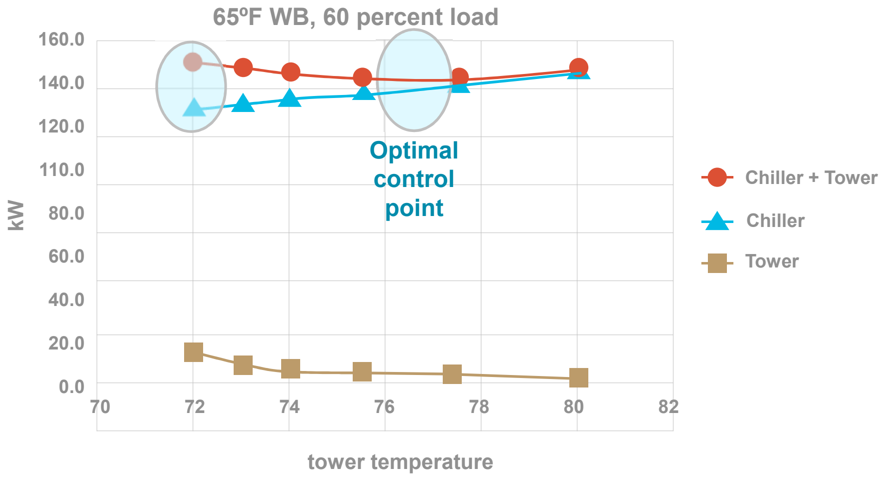
A = the number of additional tower cells operating

MaxSpd = the maximum speed at which the tower cells should operate so the fan power does not exceed “normal” operation

Table 3. Maximum tower fan speed when operating additional tower cells

Number of tower cells normally operating (N)	Number of additional tower cells operating (A)	Maximum fan speed
1	1	79%
1	2	69%
1	3	63%
2	1	87%

Chiller-Tower Optimization
Temperature Control



High Performance Chiller-Tower Control

- **Crowther & Furlong, ASHRAE Journal 2004**
- **("Optimized" vs. driving water to 65° F)**
  - **Chicago:** **5.4%**
  - **Las Vegas:** **2.6%**
  - **Miami:** **8.5%**

The following article was published in ASHRAE Journal, July 2004. © Copyright 2004 American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. It is presented for educational purposes only. This article may not be copied and/or distributed electronically or in paper form without permission of ASHRAE.

Water-cooled centrifugal chiller plant.

Optimizing Chillers & Towers

By **Hugh Crowther, P.Eng.**, Member ASHRAE and **James Furlong, P.E.**, Member ASHRAE

How a system operates at design conditions is not always a good indicator of its overall annual performance. This article emphasizes controls logic and design conditions and how they can be used to optimize chiller, cooling tower and condenser pump system performance throughout the year. A software model of hour-by-hour energy use for a typical office building in three cities demonstrates the effect of different cooling seasons and wet-bulb profiles. (Results are presented in energy use [kWh]. Actual dollar savings can be estimated by assuming a blended energy rate.)

Discuss This Article ASHRAE Forums www.ashrae.org/discuss

the annual cooling load profile for the three locations—Chicago, Las Vegas and Miami.

Design conditions are based around the Air Conditioning and Refrigeration Institute Standard 550/590 – *Water Chilling Packages Using the Vapor Compression Cycle* (54°F /44°F [12.2°C/6.7°C] chilled water, 85°F/95°F [29.4°C/35°C] condenser water) and the Cooling Tower Institute's (78°F [25.6°C] wet-bulb) test conditions, where possible, with excep-

- Braun, Diderrich
- Hydeman, Gillespie, Kammerud
- Schwedler, ASHRAE Journal 1998
- Cascia
- Li, Li, Seem & Li

Follow 50% Hospital AEDG recommendation:
Minimize the sum of chiller+tower energy

Pumping Control
Pump PR or CWTR

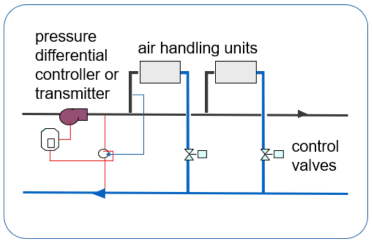
Pump pressure reset

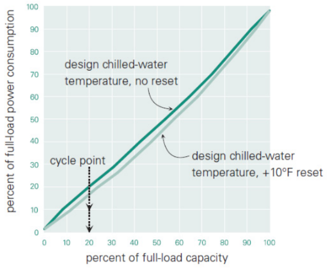
Lower pumping power

- OR -

Chilled water reset

Lower chiller power





Pumping Control
Pump PR or CWTR

% Load	Constant Speed Chiller plus pump power at LEWT		Variable Speed Chiller plus pump power at LEWT	
	44	**Reset to 48**	**44**	**Reset to 48**
75%	Flow too high at 48		Flow too high at 48	
50% at 65F ECWT	82.7 kW	89.9 kW **9% worse**	50.8 kW	48.6 kW **4% better**
25% at 65F ECWT	51.8 kW	51.6 kW **0.3% better**	30.2 kW	27.2 kW **10% better**
50% at 75F ECWT	89.3 kW	95.9 kW **7% worse**	66.6 kW	63.4 kW **5% better**
25% at 75F ECWT	56.5 kW	56.1 kW **0.7% better**	41.8 kW	38.1 kW **9% better**

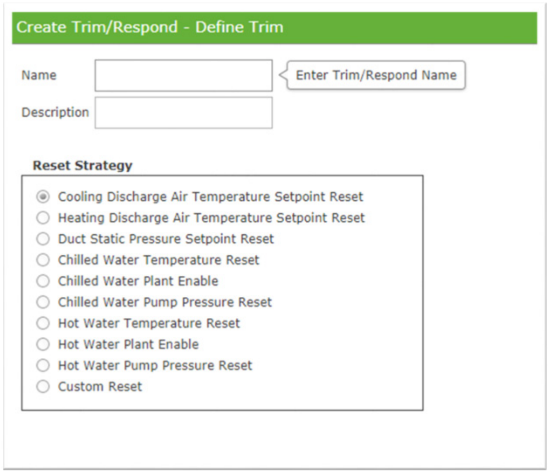
Consider Resetting Chilled-Water Temp

- Flow is constant
- Healthy delta T
  - 15-20° F design delta T systems
- Variable speed chillers, at low load conditions (< 50% system load)
- Waterside free cooling is taking place
- Minimum flow has already been reached using pump pressure reset – variable primary

SOTA control

Trim/Respond Application

- State of the art reset application
  - Balances energy consumption and comfort
- Pre-Engineered to align with ASHRAE Guideline 36 sequences
- Fully editable for tuning and customization



Create Trim/Respond - Define Trim

Name ☐ Enter Trim/Respond Name

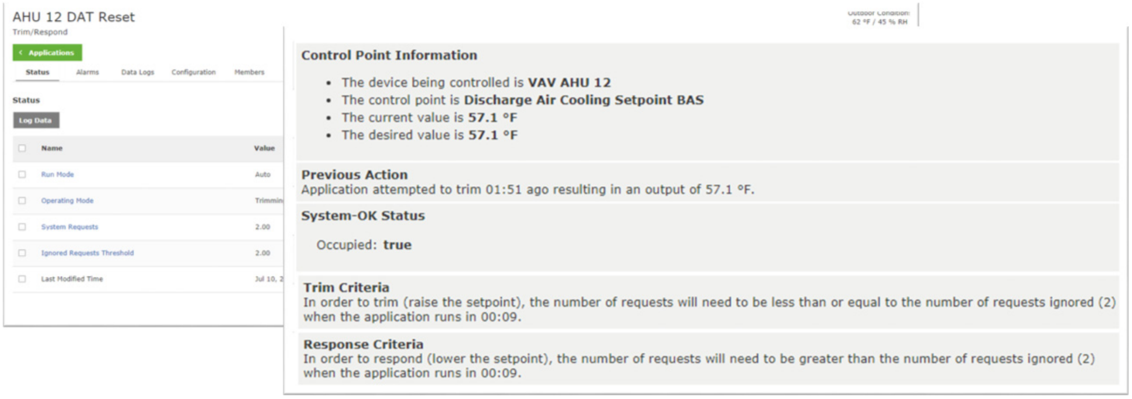
Description ☐

Reset Strategy

- ● Cooling Discharge Air Temperature Setpoint Reset
- ○ Heating Discharge Air Temperature Setpoint Reset
- ○ Duct Static Pressure Setpoint Reset
- ○ Chilled Water Temperature Reset
- ○ Chilled Water Plant Enable
- ○ Chilled Water Pump Pressure Reset
- ○ Hot Water Temperature Reset
- ○ Hot Water Plant Enable
- ○ Hot Water Pump Pressure Reset
- ○ Custom Reset

Trim/Respond Application

- Standard graphics suite for status, editing, troubleshooting, adjusting values, pausing and overriding the application



AHU 12 DAT Reset

Trim/Respond

Status

☐	Name	Value
☐	Run Mode	Auto
☐	Operating Mode	Trimmin
☐	System Requests	2.00
☐	Ignored Requests Threshold	2.00
☐	Last Modified Time	Jul 10, 2

Control Point Information

- The device being controlled is **VAV AHU 12**
- The control point is **Discharge Air Cooling Setpoint BAS**
- The current value is **57.1 °F**
- The desired value is **57.1 °F**

Previous Action

Application attempted to trim 01:51 ago resulting in an output of 57.1 °F.

System-OK Status

Occupied: **true**

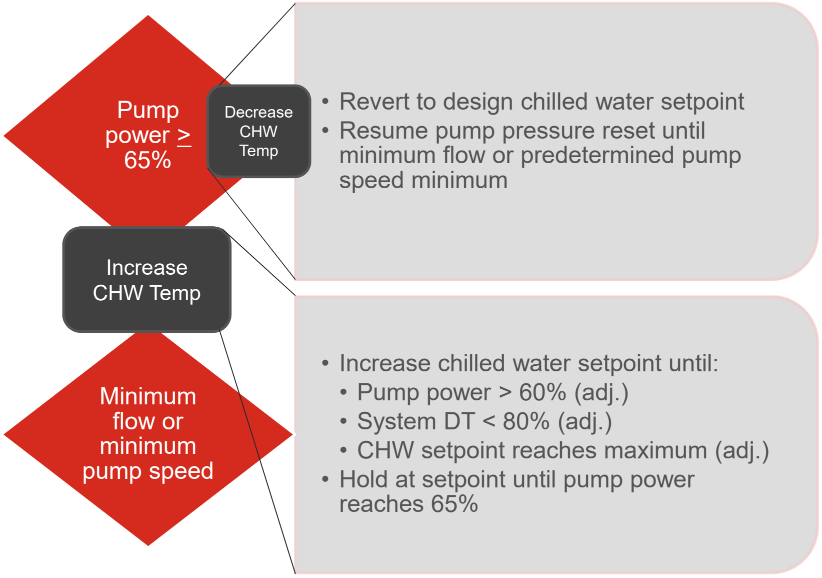
Trim Criteria

In order to trim (raise the setpoint), the number of requests will need to be less than or equal to the number of requests ignored (2) when the application runs in 00:09.

Response Criteria

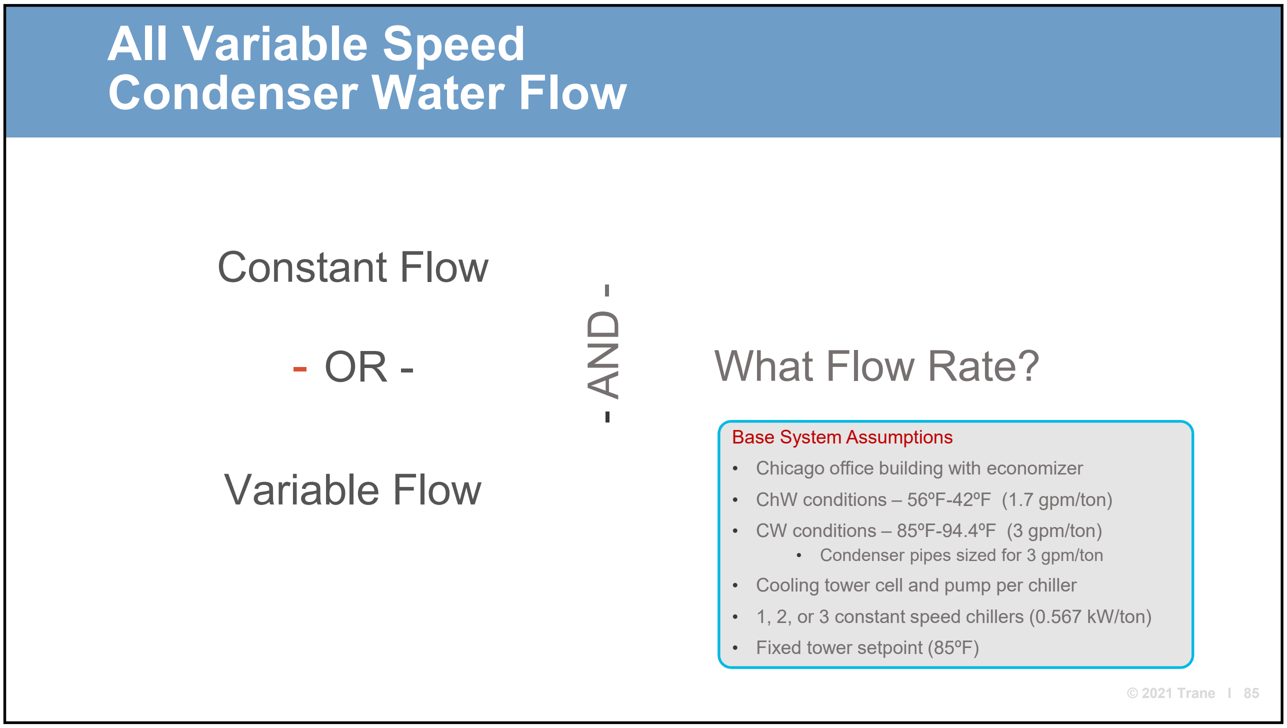
In order to respond (lower the setpoint), the number of requests will need to be greater than the number of requests ignored (2) when the application runs in 00:09.

Load Based Reset Sequence – Variable Flow Systems



- Revert to design chilled water setpoint
- Resume pump pressure reset until minimum flow or predetermined pump speed minimum

- Increase chilled water setpoint until:
  - Pump power > 60% (adj.)
  - System DT < 80% (adj.)
  - CHW setpoint reaches maximum (adj.)
- Hold at setpoint until pump power reaches 65%



All Variable Speed Condenser Water Flow

Constant Flow

- OR -

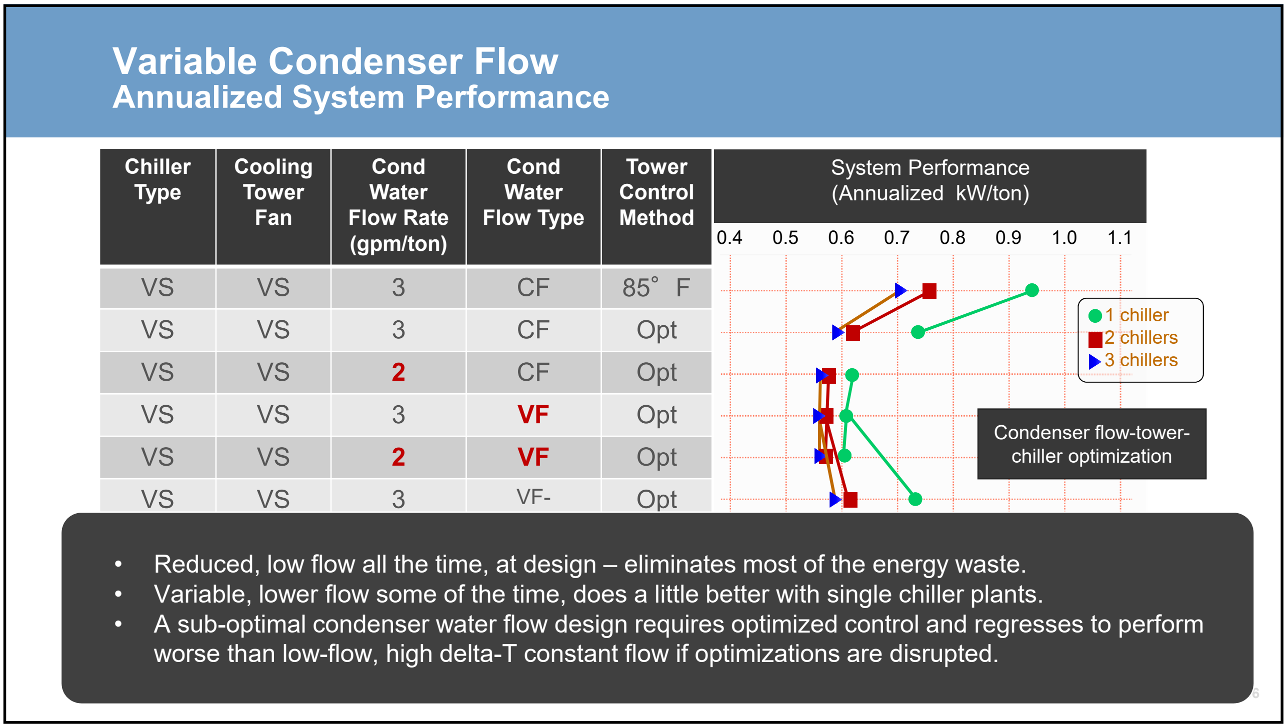
Variable Flow

- AND -

What Flow Rate?

Base System Assumptions

- Chicago office building with economizer
- ChW conditions – 56ºF-42ºF (1.7 gpm/ton)
- CW conditions – 85ºF-94.4ºF (3 gpm/ton)
  - Condenser pipes sized for 3 gpm/ton
- Cooling tower cell and pump per chiller
- 1, 2, or 3 constant speed chillers (0.567 kW/ton)
- Fixed tower setpoint (85ºF)



Variable Condenser Flow
Annualized System Performance

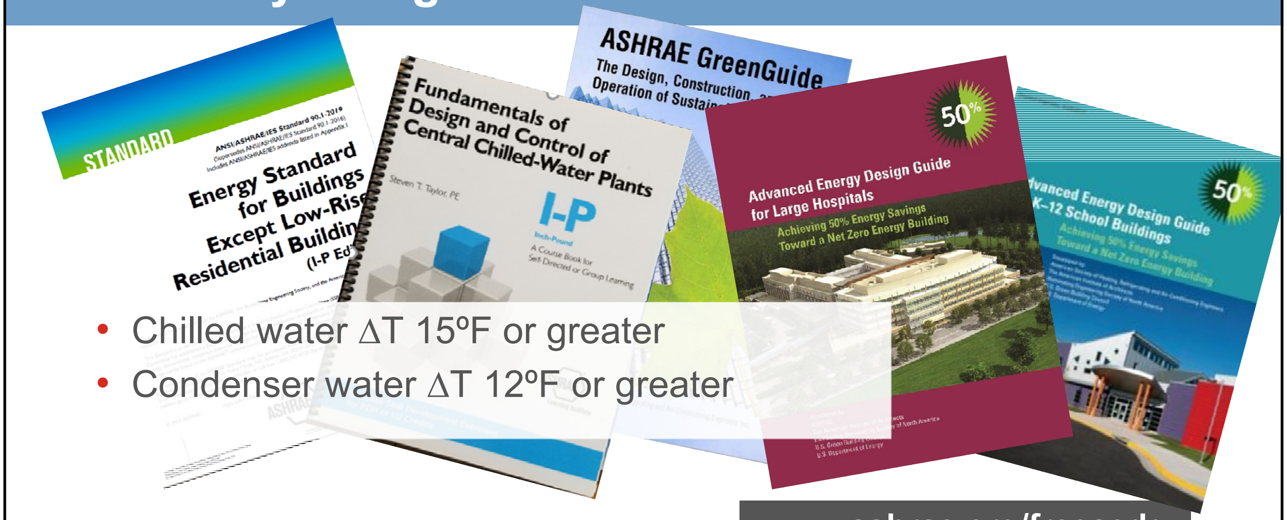
Chiller Type	Cooling Tower Fan	Cond Water Flow Rate (gpm/ton)	Cond Water Flow Type	Tower Control Method	System Performance (Annualized kW/ton)
VS	VS	3	CF	85˚ F	
VS	VS	3	CF	Opt	
VS	VS	**2**	CF	Opt	
VS	VS	3	**VF**	Opt	
VS	VS	**2**	**VF**	Opt	
VS	VS	3	VF-	Opt	

- Reduced, low flow all the time, at design – eliminates most of the energy waste.
- Variable, lower flow some of the time, does a little better with single chiller plants.
- A sub-optimal condenser water flow design requires optimized control and regresses to perform worse than low-flow, high delta-T constant flow if optimizations are disrupted.

Summary

State of the Art Chilled Water Systems

Industry Design Recommendation



- Chilled water ∆T 15ºF or greater
- Condenser water ∆T 12ºF or greater

www.ashrae.org/freeaedg

State of the Art Chilled Water Systems

Design Choices

- System
  - Variable Primary Flow (VPF) or
  - Variable Primary / Variable Secondary (VP/VS)
- Variable speed pumps
- Coils
  - ΔT 15ºF or greater
  - Select for part load operation
    - Turbulators offer great performance
- Valves
  - Select each valve properly or install pressure independent valves
- Chillers
  - Reliable
  - Efficient
  - Low emissions
- Select towers with ΔT 12ºF or greater
- Analyze the system to optimize
  - Energy reduction or
  - First cost or
  - A balanced approach

State of the Art Chilled Water Systems

Design Choices

- Chilled water pump pressure optimization or temperature reset
- Chiller tower optimization: Minimize sum of chiller plus cooling tower fan energy
- Cooling tower cell
  - Operate more, but keep above their minimum flow rate
  - Cap maximum fan speed to ensure savings

Where to Learn More

TRANE

providing insights for today's hvac system designer

Engineers Newsletter

volume 49–4

HVAC-related changes in ASHRAE® Standard 90.1-2019

TRANE

Water-Cooled Chilled Water

System Catalog

TRANE

System Catalog

Variable Refrigerant Flow Systems

An engineered system from Trane

Trane Engineers Newsletter LIVE: Demand Controlled Ventilation

www.trane.com

Continuing Education Courses

on-demand, no charge, earn LEED, PDH, AIA credits

EDUCATION PROVIDER

GBCI CMP

CONTINUING EDUCATION AIA

NEW Courses

- Impact of DOAS Dew Point on Space Humidity
- HVAC Considerations for Indoor Agriculture
- Electrification/Decarbonization of HVAC Systems
- Applying VRF for a Complete Building Solution

State of the Art Chilled-Water Systems

Trane Engineers Newsletter Live Series

Trane ***Engineers Newsletter LIVE: State-of-the-Art Chilled-Water Systems***

APP-CMC076-EN QUIZ

1. What is the minimum ΔT for coil selection required by ASHRAE 90.1 since 2016?
    a. 10°F
    b. 12°F
    c. 15°F
    d. 20°F
    e. There is no requirement

2. What condenser control methods are recommended by the Advanced Energy Design Guides?
    a. Operate the maximum number of cooling tower cells possible, while ensuring required flow rate
    b. Make the tower water temperature as cold as possible to optimize chiller performance
    c. Control tower temperature to optimize chiller plus tower energy use
    d. A and B
    e. A and C

3. True or False: Coil waterside ΔT should be expected to fall at part load.

4. True or False: Pressure independent control valves make chilled water systems work better.

5. What is the best metric to determine chiller efficiency?
    a. Full Load Kw/ton
    b. IPLV/NPLV
    c. Neither

6. True or False: Designing a chiller plant with low condenser flow can reduce the cost of this system and increase the efficiency of the chiller plant.

7. True or False: A chiller that can reduce flow 20% before reaching its minimum flow is a good candidate for VPF application.

8. Which system design choice(s) typically saves more plant energy?
    a. Low flow
    b. High flow
    c. System configuration
    d. High efficiency pumps

Resources

State-of-the-Art Chilled-Water Systems

ANSI/ASHRAE/IES Standard 90.1-2019—Energy Standard for Buildings Except Low-Rise Residential Buildings
(www.ashrae.org/technical-resources/bookstore/)

ASHRAE GreenGuide: Design, Construction, and Operation of Sustainable Buildings (www.ashrae.org/technical-resources/bookstore/)

Fundamentals of Design and Control of Central Chilled-Water Plants
(https://www.ashrae.org/professional-development/self-directed-learning-group-learning-texts/fundamentals-of-design-and-control-of-central-chilled-water-plants)

https://www.ashrae.org/freeaedg