Cooling Towers and Condenser Water Systems
Design and Operation

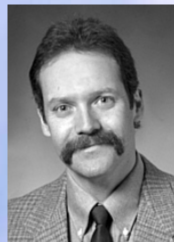
TRANE

an
Engineers Newsletter Live
telecast

Today's Topics

- **Fundamentals**
  - Chiller–tower interaction
  - Cooling-tower terminology, operation
- **Design conditions**
- **Cooling-tower control options**
- **System optimization**
- **Answers to your questions**

Today's Presenters



Dave Guckelberger
applications engineer

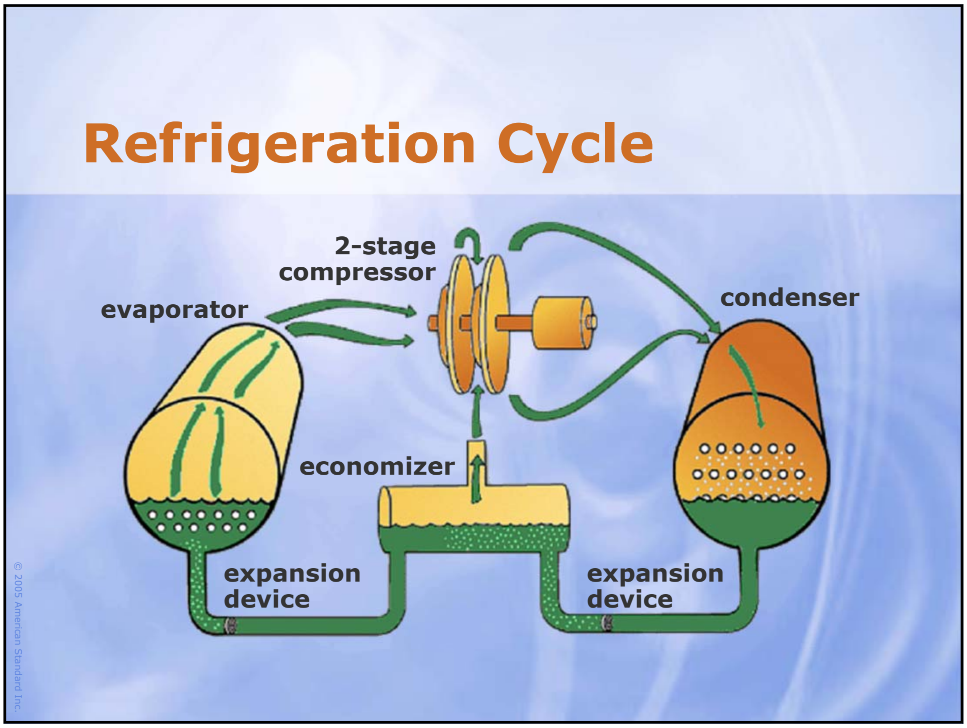
Mick Schwedler
applications engineer

Lee Cline
systems marketing engineer

Cooling Towers and Condenser Water Systems
Design and Operation

engineers newsletter LIVE

Cooling tower fundamentals


Refrigeration Cycle
2-stage compressor
evaporator
condenser
economizer
expansion device
expansion device
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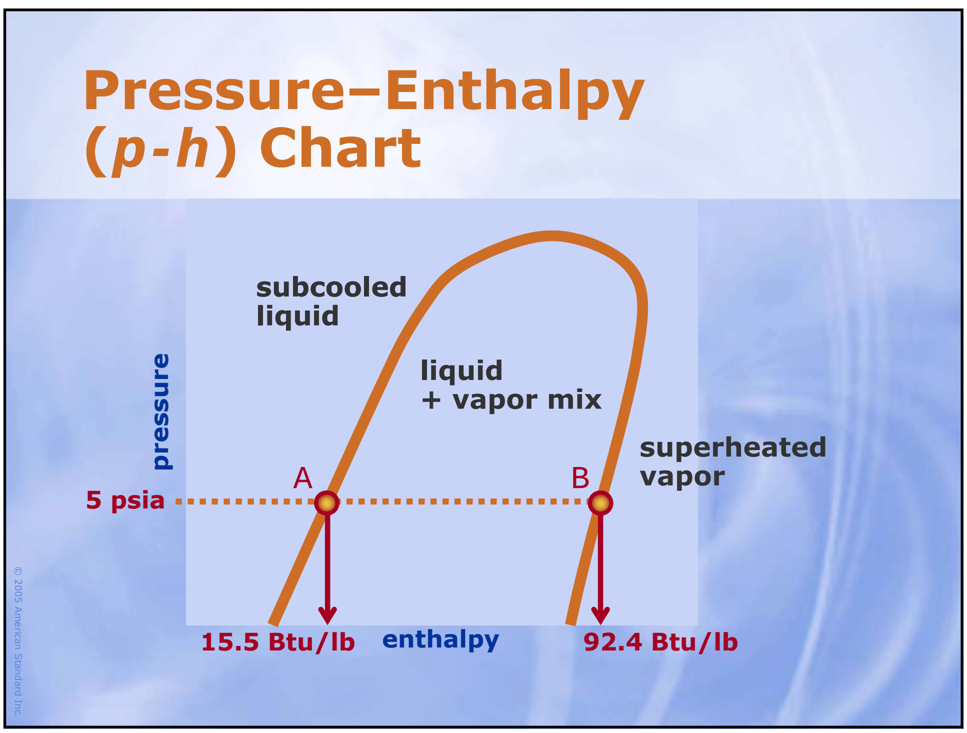
Pressure–Enthalpy (*p*-*h*) Chart
subcooled liquid
liquid + vapor mix
superheated vapor
pressure
5 psia
A
B
15.5 Btu/lb
enthalpy
92.4 Btu/lb
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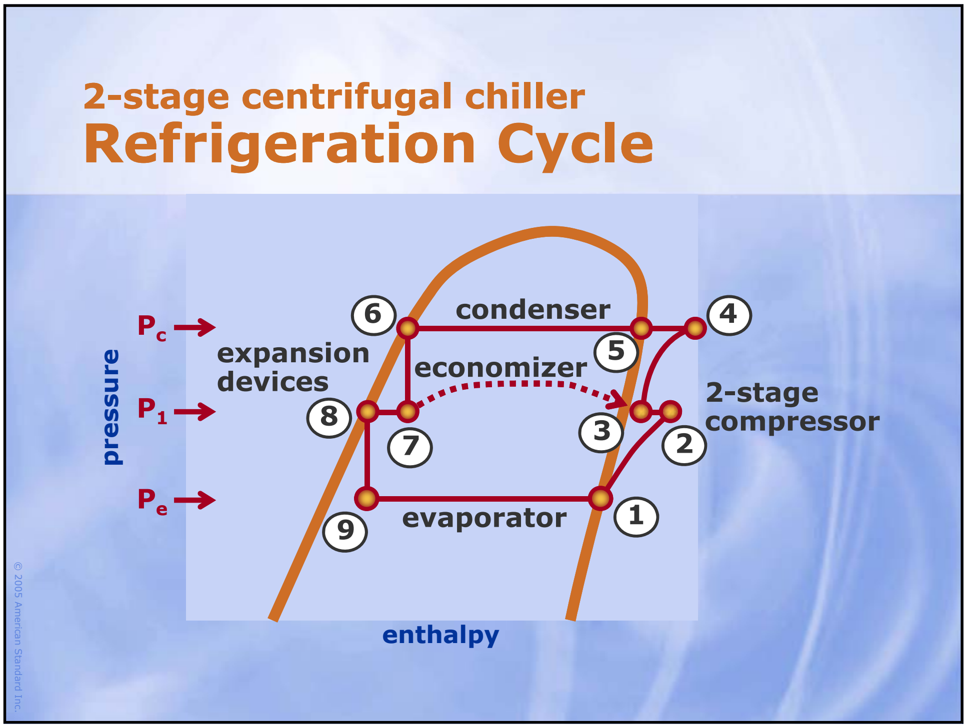
2-stage centrifugal chiller
Refrigeration Cycle
pressure
Pc
P1
Pe
expansion devices
condenser
economizer
evaporator
2-stage compressor
enthalpy
1
2
3
4
5
6
7
8
9
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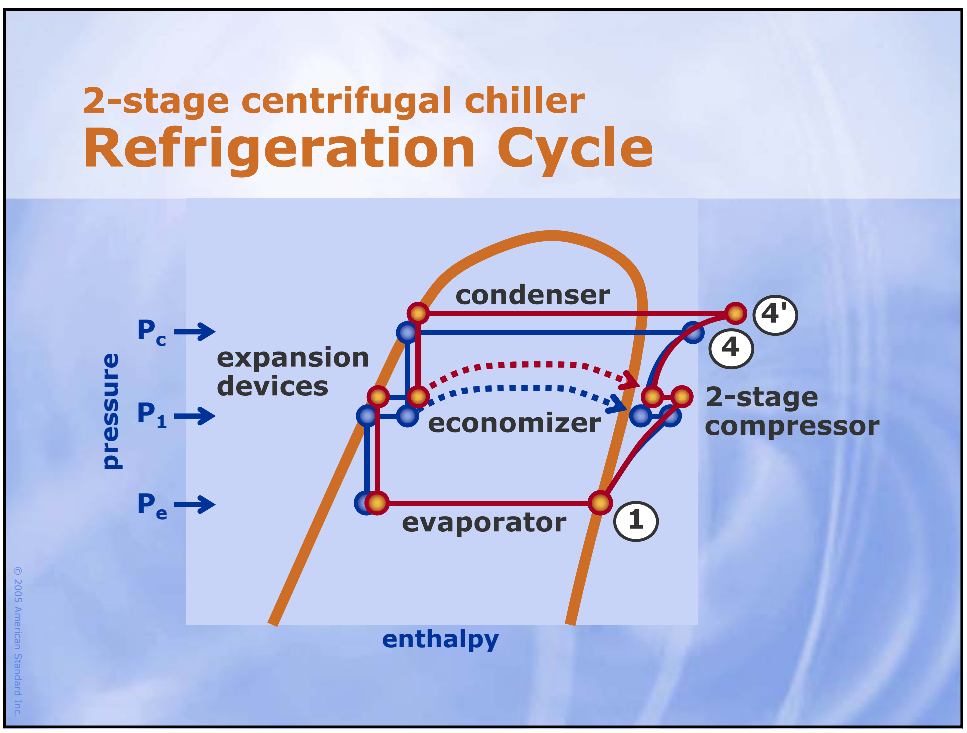
2-stage centrifugal chiller
Refrigeration Cycle
pressure
Pc
P1
Pe
expansion devices
condenser
economizer
evaporator
2-stage compressor
enthalpy
4'
4
1
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chiller–tower interaction
Heat Rejection

- **Tower determines return condenser water temperature**
- **Chiller determines required heat rejection rate of tower**
  - Evaporator load
    +
  - Compressor energy

Hermetic motor: 100% of electrical input

Open motor: electrical input × motor efficiency

chiller–tower interaction
Heat Rejection, *Q*

Q = evaporator load + input energy

or

Q = evaporator load × (1 + 1/COP)

electric chiller
Heat Rejection Example

For 1 ton of evaporator load:

$$Q = 12{,}000 \text{ Btu/h} \times (1 + 1/6.10)$$
$$= 12{,}000 \text{ Btu/h} \times (1 + 0.16)$$
$$= 13{,}967 \text{ Btu/h}$$

electric chiller
Heat Rejection Example

$$\Delta T = Q\ (\text{Btu/h}) / (500 \times \text{gpm})$$

For 1 ton of evaporator load, condenser water temperature rises …

… 9.3°F at 3 gpm/ton

$$\Delta T = 13{,}967 / (500 \times 3) = 9.3°\text{F}$$

… 14.0°F at 2 gpm/ton

$$\Delta T = 14{,}000 / (500 \times 2) = 14.0°\text{F}$$

chiller–tower interaction
Heat Rejection

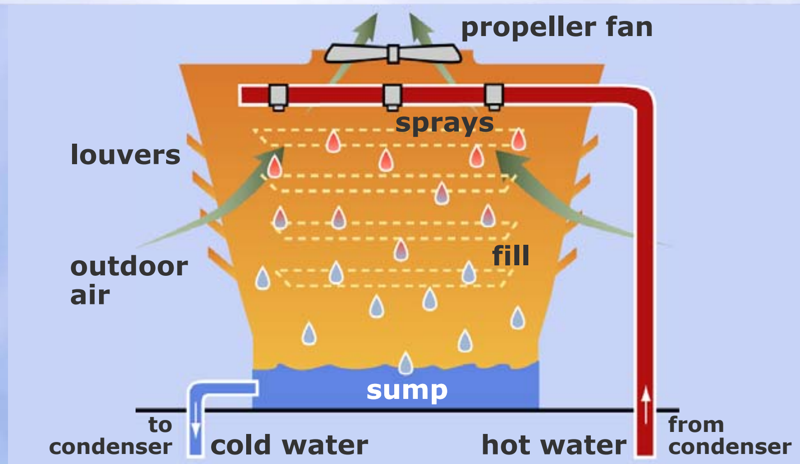
- Condenser water warms in proportion to heat rejection and condenser water flow rate
- Condenser pressure rises with condenser temperature
- Compressor work increases as condenser pressure rises

Cooling Tower

"Heat transfer device, often tower-like, in which atmospheric air cools warm water, generally by direct contact (evaporation)."

ASHRAE Terminology of HVAC&R

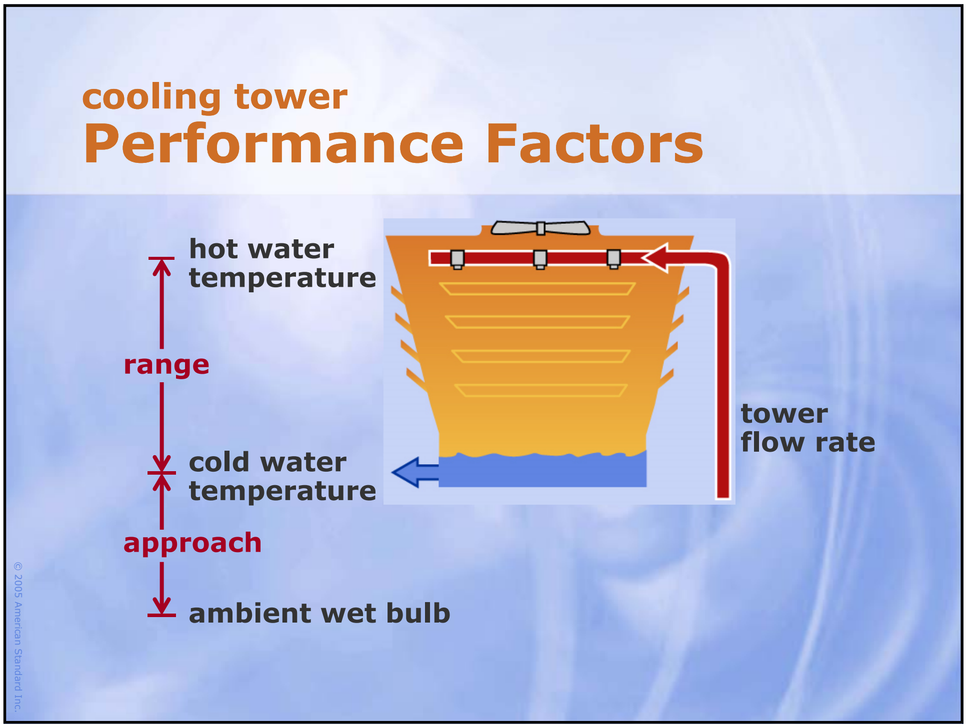
cooling tower
Components



cooling tower
Performance Factors

Ambient wet-bulb temperature drives tower design and selection

- ASHRAE Fundamentals Handbook, "Evaporation"
- 0.4% value is most conservative … exceeded ~35 hours/year


cooling tower
Performance Factors
hot water temperature
range
cold water temperature
approach
ambient wet bulb
tower flow rate
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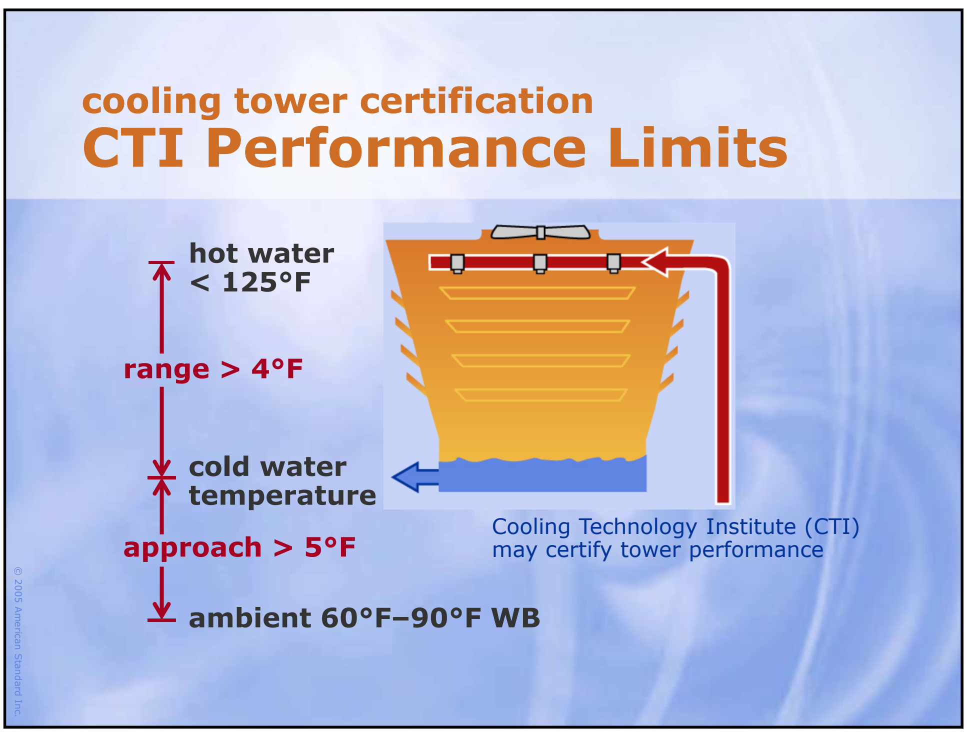
cooling tower certification
CTI Performance Limits
hot water < 125°F
range > 4°F
cold water temperature
approach > 5°F
ambient 60°F–90°F WB
Cooling Technology Institute (CTI) may certify tower performance
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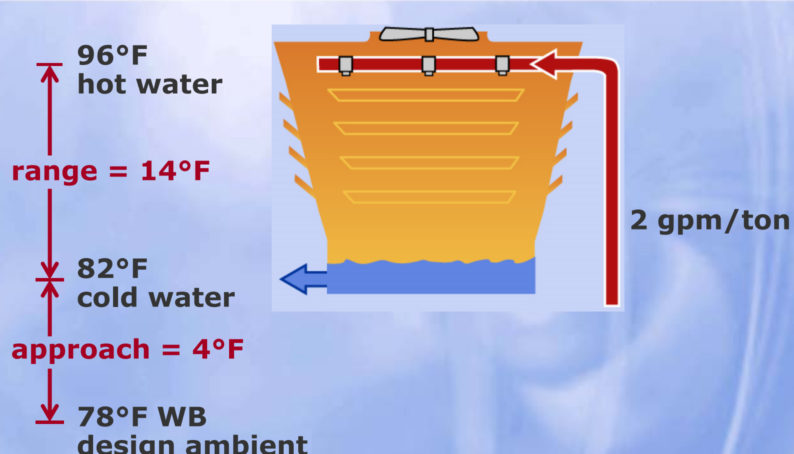
example at standard rating conditions
Tower Performance

	Base condition
Flow rate, gpm	1500
Design WB, °F	78
Approach, °F	7
Hot water, °F	94.3
Cold water, °F	85
Fan power, hp	40

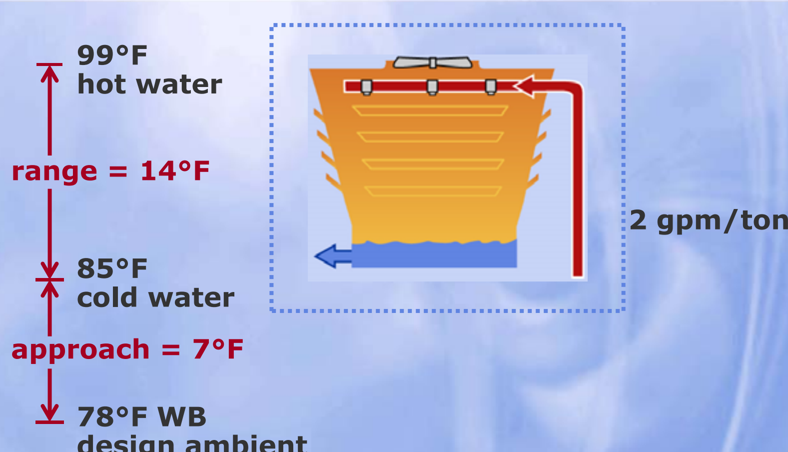
example at standard rating conditions
Same Tower, Lower Flow



example at standard rating conditions
Tower Performance

	Base condition	Same tower, lower flow
Flow rate, gpm	1500	1000
Design WB, °F	78	78
Approach, °F	7	4
Hot water, °F	94.3	96
Cold water, °F	85	82
Fan power, hp	40	40

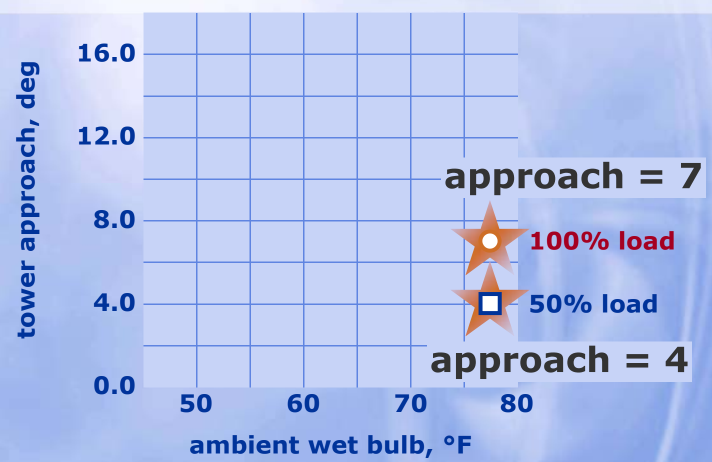
example at standard rating conditions
Same Approach, Lower Flow



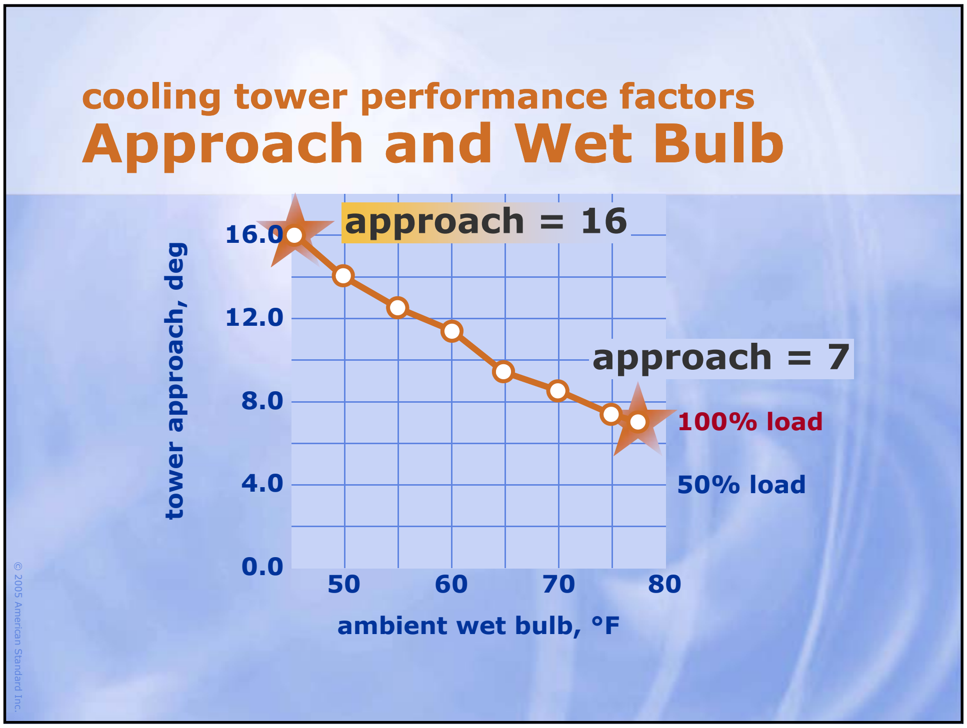
example at standard rating conditions
Tower Performance

	Base condition	Same tower, lower flow	Smaller tower, lower flow
Flow rate, gpm	1500	1000	1000
Design WB, °F	78	78	78
Approach, °F	7	4	7
Hot water, °F	94.3	96	99
Cold water, °F	85	82	85
Fan power, hp	40	40	25

cooling tower performance factors
Approach and Range



Trane, in proposing these system design and application concepts, assumes no responsibility for the performance or desirability of any resulting system design. Design of the HVAC system is the prerogative and responsibility of the engineering professional.


cooling tower performance factors
Approach and Wet Bulb
approach = 16
approach = 7
100% load
50% load
tower approach, deg
16.0
12.0
8.0
4.0
0.0
50
60
70
80
ambient wet bulb, °F
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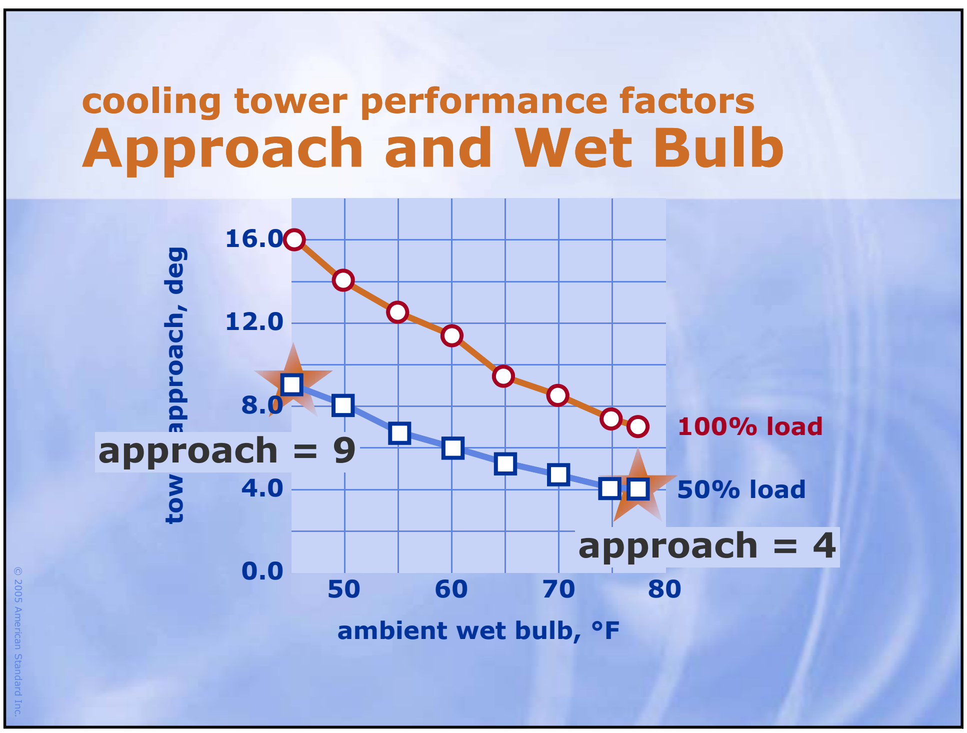
cooling tower performance factors
Approach and Wet Bulb
approach = 9
approach = 4
100% load
50% load
16.0
12.0
8.0
4.0
0.0
50
60
70
80
ambient wet bulb, °F
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Cooling Towers and
Condenser Water Systems
Design and Operation
engineers newsletter LIVE
Design conditions
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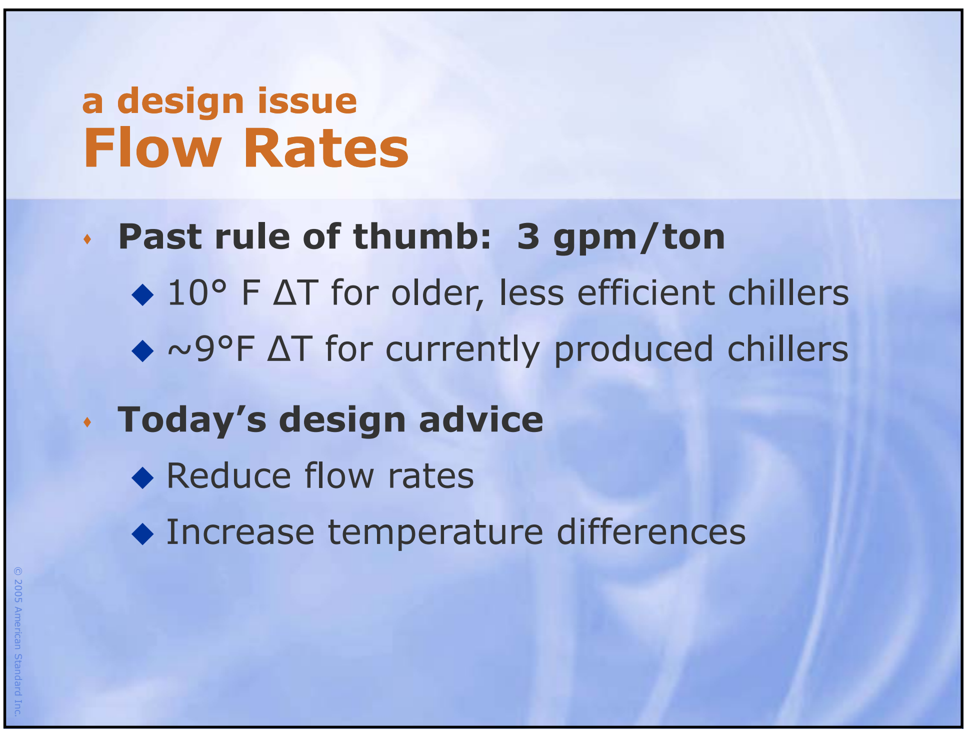
a design issue
Flow Rates
Past rule of thumb: 3 gpm/ton
10° F ΔT for older, less efficient chillers
~9°F ΔT for currently produced chillers
Today's design advice
Reduce flow rates
Increase temperature differences
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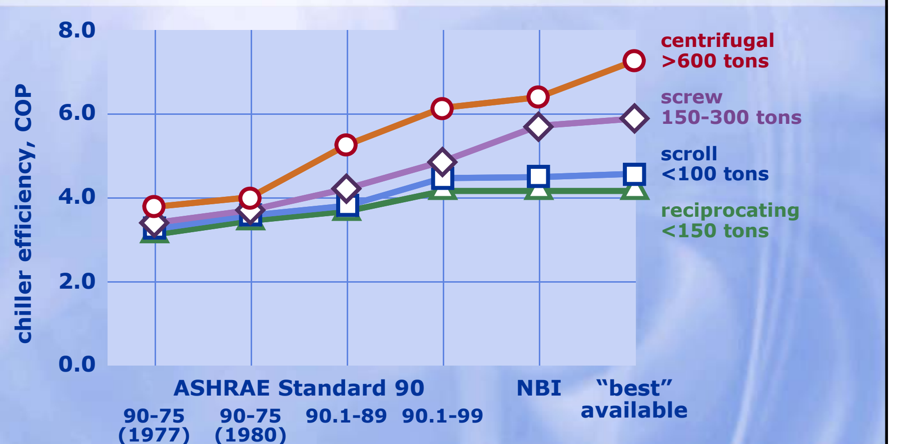
increase ΔT, reduce flow rate
Condenser Water

Industry advisor	Recommendation
Pacific Gas and Electric CoolTools™	10°–15°F ΔT single stage 12°–18°F ΔT multistage or positive displacement
Kelly and Chan	14.2°F ΔT for 3.6–8.3% energy savings in various climates
ASHRAE Green Guide	12°–18°F ΔT

a history of
Chiller Performance



chilled water plant design
Condensing Components

- Chiller
- Condenser water pump
- Cooling tower

chilled water plant design
Chiller Selection

Certified selections help assure expected chiller performance

- Full-load and part-load conditions
- Air-Conditioning & Refrigeration Institute (ARI)

chilled water plant design
Cooling Tower Selection

Cooling Technology Institute (CTI) rates tower performance

chilled water plant design
Pump Selection

$$\text{hp} = \frac{\text{gpm} \times \Delta P}{3960 \times \text{pump efficiency}}$$

$$\text{kW} = \frac{0.746 \times \text{hp}}{\text{motor efficiency}}$$

chilled water plant design
Pressure Drops

… in the condenser water loop:

- Condenser bundle
- Pipes, valves, fittings
- Tower static head

chilled water plant design
Base Design: 500 Tons

Assumptions for our example …

◆ 0.1% design ambient	78°F WB
◆ Entering condenser water temperature (ECWT)	85°F
◆ Condenser flow rate	3 gpm/ton, 1500 gpm
◆ Loop pressure drop	30 ft
◆ Pump efficiency	75%
◆ Pump motor efficiency	93%

chilled water plant design: example
Chiller Selection

	Condenser flow rate, gpm/ton: 3.0
Power used, kW	**286.0** **0.572/ton**
Condenser ΔP, ft	**25.7**
	Base design

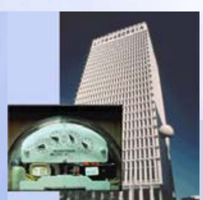
chilled water plant design: example
Cooling Tower Selection

	Condenser flow rate, gpm/ton: 3.0
Flow rate, gpm	**1500**
Power rating, bhp **kW**	**40** **31.2**
Static head, ft	**13**
	Base design

chilled water plant design: example
Pump Selection

	Condenser flow rate, gpm/ton: 3.0
System head, ft	30
Bundle head, ft	25.7
Tower static, ft	13
Flow rate, gpm	1500
Pump power, hp kW	34.7 27.8
	Base design

chilled water plant design: example
System Energy Use



	Condenser flow rate, gpm/ton: 3.0
Chiller	286.0
Condenser pump	27.8
Cooling tower	32.1
Total kW	345.9 Base design

chilled water plant design: example
Reduce Flow Rate

- **Assumptions that won't change …**
  - Pipes
    (Head varies with square of flow)
  - Chiller cost
- **What we'll alter …**
  - Condenser flow
  - Cooling tower size, as appropriate

chilled water plant design: example
Chiller Selection

	Condenser flow rate, gpm/ton: 3.0	2.0
Power used, kW	**286.0 0.572/ton**	**307.0 0.614/ton**
Condenser ∆P, ft	**25.7**	**17.7**
	Base design	**Reduced flow**

chilled water plant design: example
Cooling Tower Selection

Costs 10% less than base

Condenser flow rate, gpm/ton:	3.0	2.0
Flow rate, gpm	1500	1000
Power rating, bhp	40	25
kW	31.2	20
Static head, ft	13	13
	Base design	Reduced flow

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chilled water plant design: example
Pump Selection

Condenser flow rate, gpm/ton:	3.0	2.0	
System head, ft	30	13.3	(30 × [2.0/3.0]²)
Bundle head, ft	25.7	17.7	
Tower static, ft	13	13	
Flow rate, gpm	1500	1000	(500 × 2.0)
Pump power, hp	34.7		
kW	27.8	10.7	
	Base design	Reduced flow	

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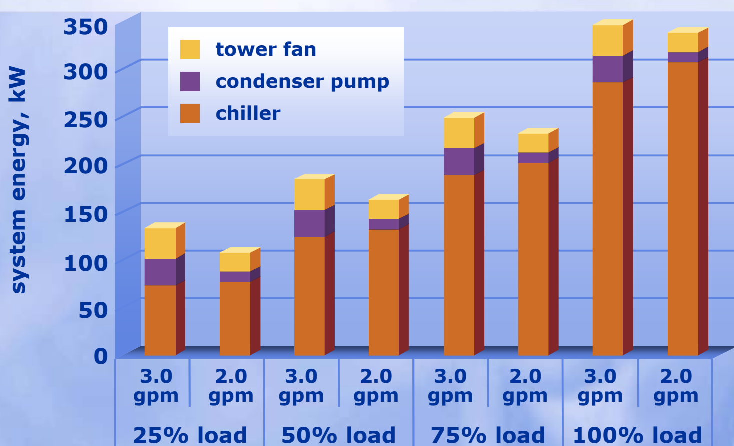
chilled water plant design: example
System Energy Use

	Condenser flow rate, gpm/ton: 3.0	2.0
Chiller	286.0	307.0
Condenser pump	27.8	10.7
Cooling tower	32.1	20.1
Total kW	345.9	337.7
	Base design	Reduced flow

chilled water plant design: example
System Energy Use



chilled water plant design
Options

- **Downsize pumps and tower to take <u>full</u> energy cost savings**

OR

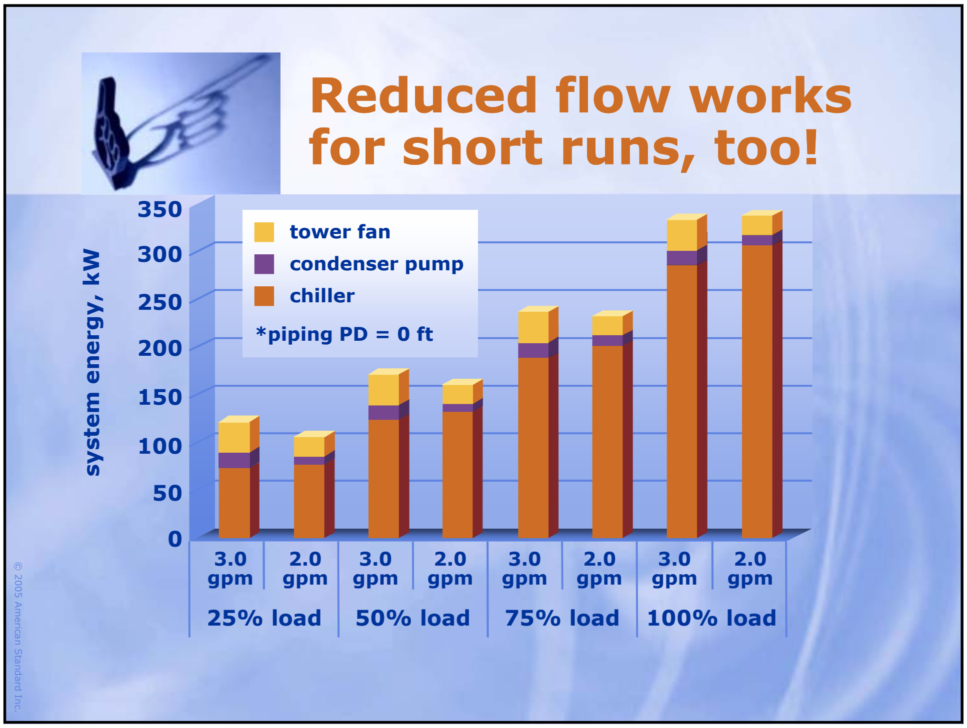
- **Reduce pipe size to cut installed cost**
  - Reduces structural costs (tower, pipes, water in pipes)
  - Can reinvest part of savings in more efficient chiller
  - Reduces pump savings

Is reduced flow only for long piping runs?

Condenser water pump must overcome pressure drops

- Condenser bundle
- Tower static lift
- <u>Pipes, valves, fittings</u>

What if it was 0 ft of head?


Reduced flow works for short runs, too!
system energy, kW
350
300
250
200
150
100
50
0
tower fan
condenser pump
chiller
*piping PD = 0 ft
3.0 gpm
2.0 gpm
3.0 gpm
2.0 gpm
3.0 gpm
2.0 gpm
3.0 gpm
2.0 gpm
25% load
50% load
75% load
100% load
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Does reduced flow work for all chillers?
Logan Airport, Boston
Cost savings: $426,000 construction
7.3% operation
DuPont, Greenville
Cost savings: $45,000 excavation, concrete
6.5% operation
Hewlett Packard, San Francisco
Cost savings: Piping
2% operation (existing tower)
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Proven savings for <u>all</u> manufacturers

- **Logan Airport, Boston**

  Cost savings: $426,000 construction
  7.3% operation

- **DuPont, Greenville**

  Cost savings: $45,000 excavation, concrete
  6.5% operation

- **Hewlett Packard, San Francisco**

  Cost savings: Piping
  2% operation (existing tower)

Does reduced flow work for retrofits?

Opportunity:

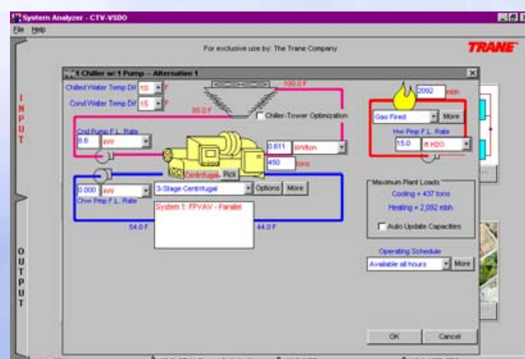
- Chiller must be replaced
- Cooling needs increased by 50%
- Cooling tower was replaced two years ago
- Condenser pump and pipes in good shape

Reduced flow can aid retrofit budgets

	Condenser-side opportunity: Existing	Retrofit
Capacity, tons	500	750
Flow rate, gpm	1500	1500
Condenser water:		
entering, °F	85	88
leaving, °F	95	102.4
Design wet bulb, °F	78	78

chilled water plant design
Analysis Tools

- System Analyzer™
- Chiller Plant Analyzer
- TRACE™ 700
- DOE 2.1
- HAP



OADB does <u>not</u> correlate directly to load!

chilled water plant design

Guidance

- **Reduced flow saves installed and operating costs**
- **No "magic" flow rate … Start at 2 gpm/ton and adjust**
- **Reinvest part of first-cost savings in more efficient chillers**

always, always, ALWAYS

Remember …

The meter is on the BUILDING

a win-win-win situation

Saving Energy–And More

"In addition to the electric energy savings, this chiller plant will have prevented the emissions of 1.1 million lb of CO_2 per year, 8,800 lb of SO_2 per year, and 3,100 lb of NO_x per year. This is an overall win-win-win situation where the first cost is reduced, operating cost is minimized, plus significant environmental benefits are realized as an additional benefit."

from "A Chiller Challenge" by T. Chan

Cooling Towers and Condenser Water Systems

Design and Operation

engineers newsletter LIVE

Cooling-tower control options

chiller–tower optimization
Control

- **Capacity**
  - Design requirements
  - Tower control options
  - Sequence to conserve energy
- **System protection**
  - Chiller requirements
  - Tower requirements

cooling tower design requirements
ASHRAE 90.1-2001

Maximum allowable fan power …

- Centrifugal fan < 20.0 gpm/hp
- Propeller or axial fan < 38.2 gpm/hp

… at 95°F EWT/85°F LWT/75°F WB

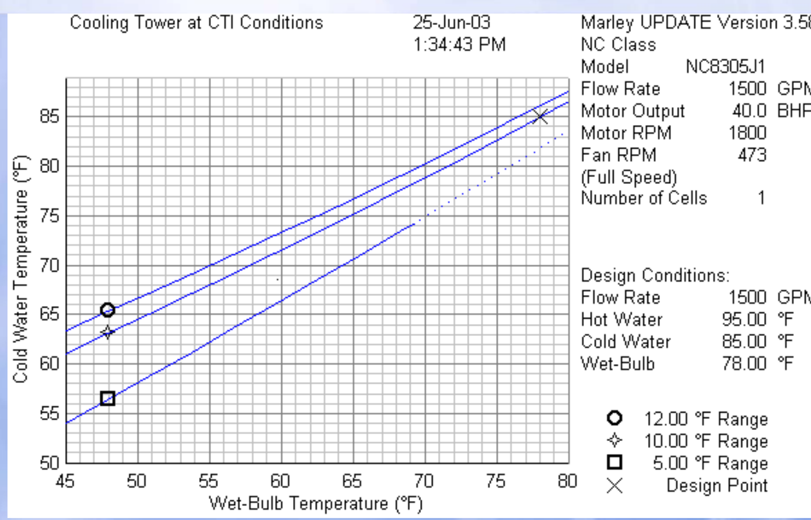
cooling tower design requirements
ASHRAE 90.1- 2001

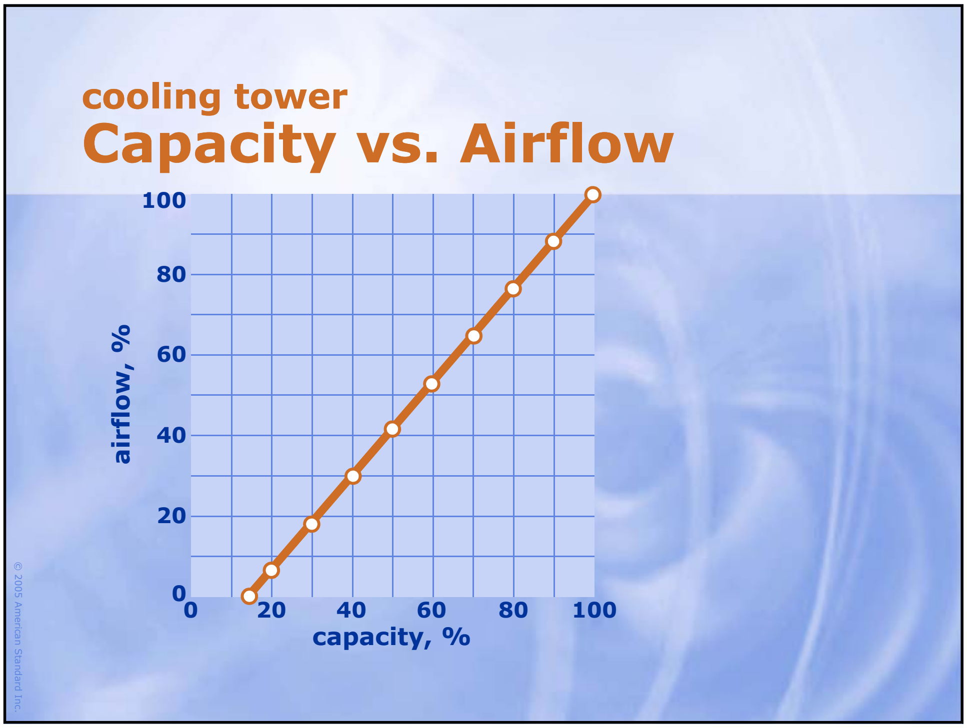
Fan speed control required for motors 7.5 hp or larger … reduce fan speed to 2/3 or less (VFD, two-speed or pony motor)

EXCEPTIONS

- **Multiple-fan systems: 1/3 of fans may be on/off**
- **Fans that serve multiple refrigeration circuits**
- **Climates with >7,200 cooling-degree days (e.g., Phoenix, Miami, Taipei, Riyadh)**

cooling tower
Capacity Control




cooling tower
Capacity vs. Airflow
airflow, %
100
80
60
40
20
0
0
20
40
60
80
100
capacity, %
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cooling tower
Control Options
Fan control
Cycling single-speed fan
Two-speed fan
Variable-speed drive
Modulating dampers
Centrifugal two-speed fan
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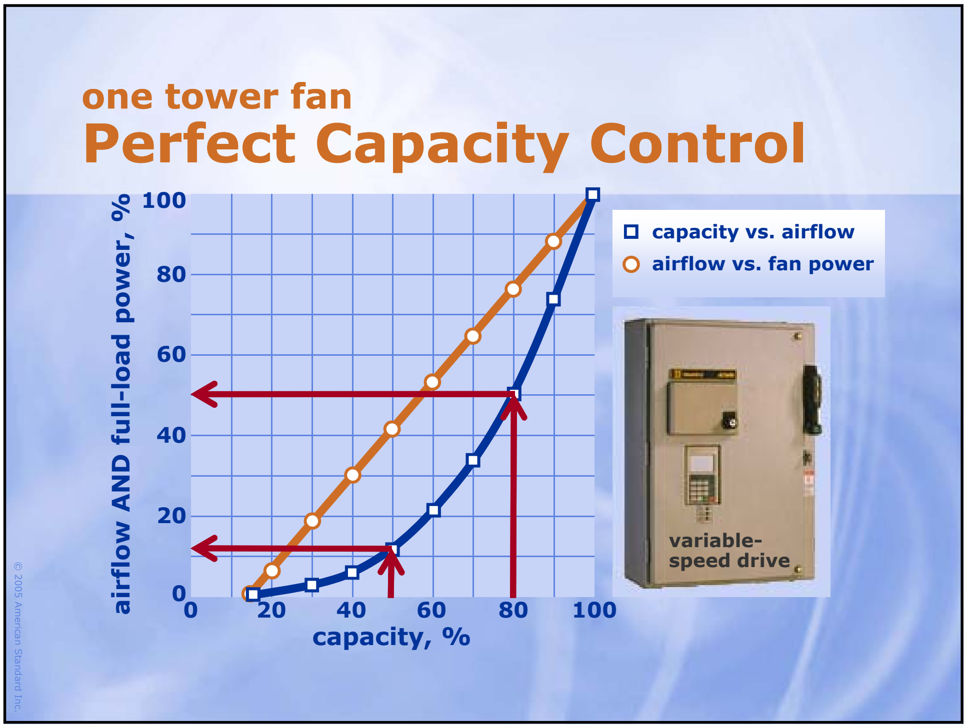
one tower fan
Perfect Capacity Control
capacity vs. airflow
airflow vs. fan power
airflow AND full-load power, %
capacity, %
0
20
40
60
80
100
variable-
speed drive
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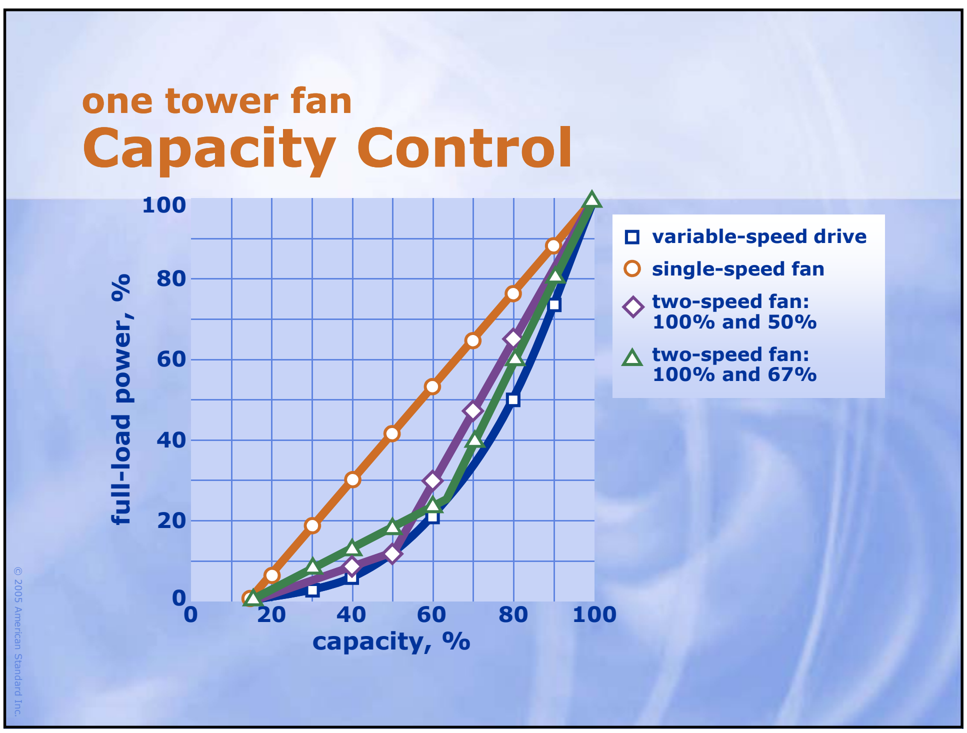
one tower fan
Capacity Control
variable-speed drive
single-speed fan
two-speed fan:
100% and 50%
two-speed fan:
100% and 67%
full-load power, %
capacity, %
0
20
40
60
80
100
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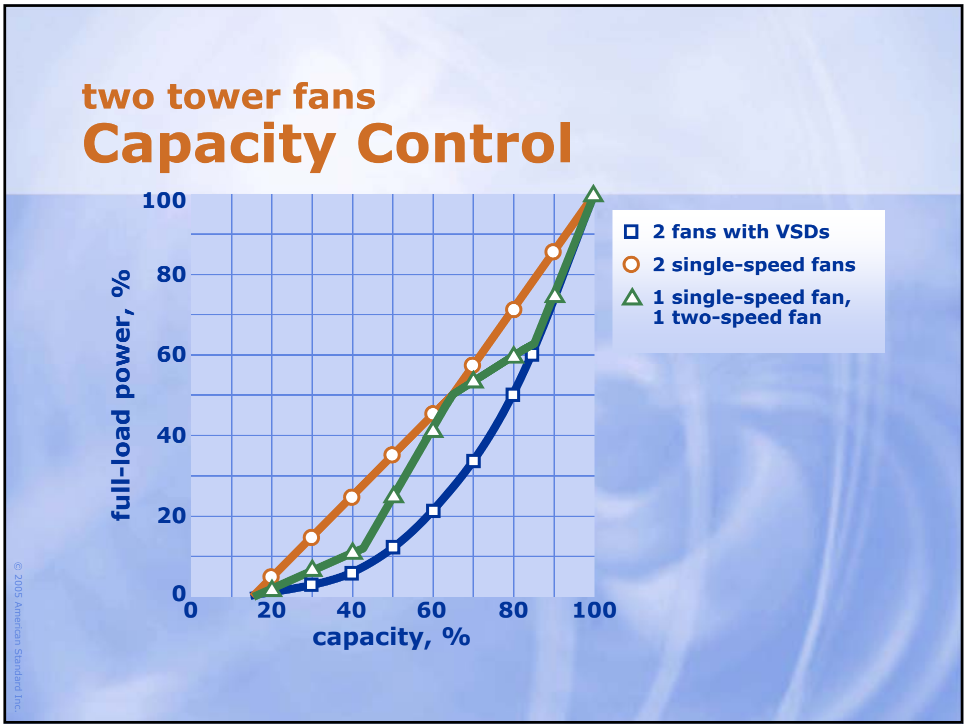
two tower fans
Capacity Control
full-load power, %
100
80
60
40
20
0
0
20
40
60
80
100
capacity, %
2 fans with VSDs
2 single-speed fans
1 single-speed fan,
1 two-speed fan
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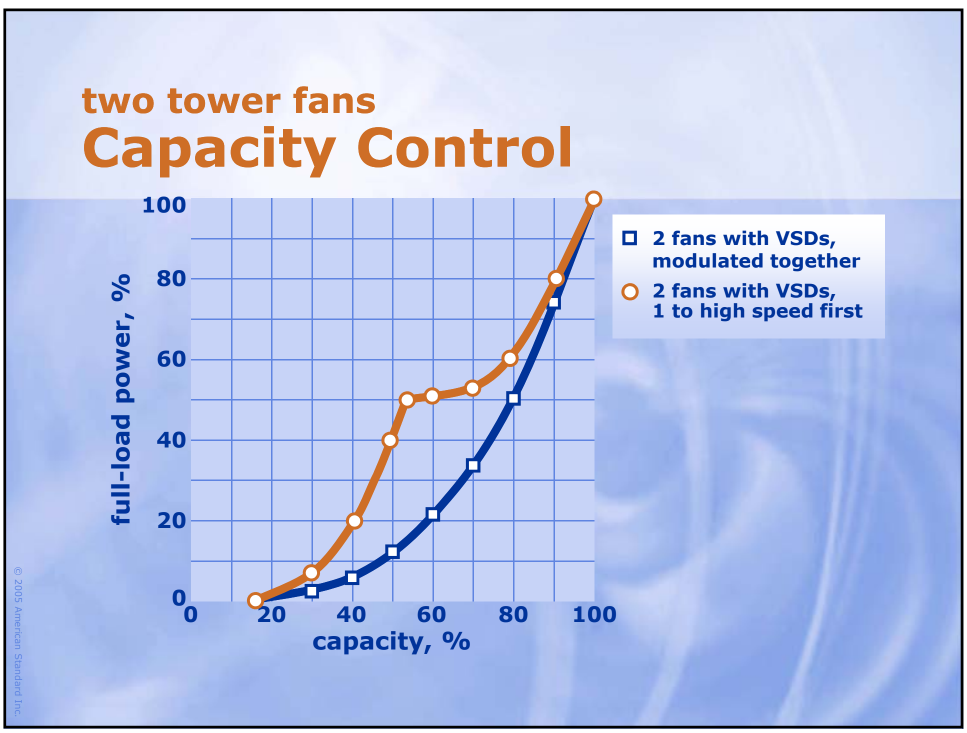
two tower fans
Capacity Control
full-load power, %
100
80
60
40
20
0
0
20
40
60
80
100
capacity, %
2 fans with VSDs,
modulated together
2 fans with VSDs,
1 to high speed first
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cooling tower
Rules for Capacity Control

- **ASHARE 90.1 requirements make sense**
- **Invest in VFDs on all tower fans**
- **Operating multiple fans at part speed saves energy**
  - Consumes less power than one fan at full speed and the other off

cooling tower capacity control
Sequence of Operation

1. When a chiller is operating and the cooling tower basin temperature rises to two (2) degrees F above the current tower leaving water setpoint, the lead cooling tower fan shall be turned on at minimum speed and the DDC control loop enabled.

a. When the operating fan(s) are operating at 50 percent speed, an additional fan shall be enabled and controlled at the same speed as the operating fans until all active cooling tower cell fans are enabled.

b. When operating fans are running at minimum speed and the tower supply water temperature is five (5) degrees below the current tower leaving water setpoint, the most lag tower fan shall be turned off.

c. Cooling tower fans shall have five (5) minute minimum on and off time delays.

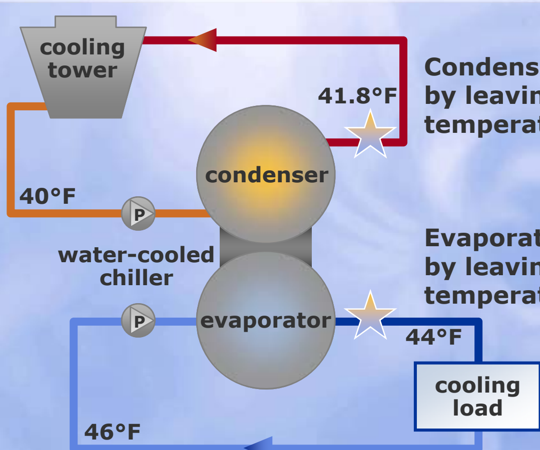
chiller–tower optimization

Control

- **Capacity**
  - Design requirements
  - Tower control options
  - Sequence to conserve energy
- **System protection**
  - Chiller requirements
  - Tower requirements

system protection

Chiller Head Pressure



Condenser pressure set by leaving-condenser water temperature

Evaporator pressure set by leaving-evaporator water temperature

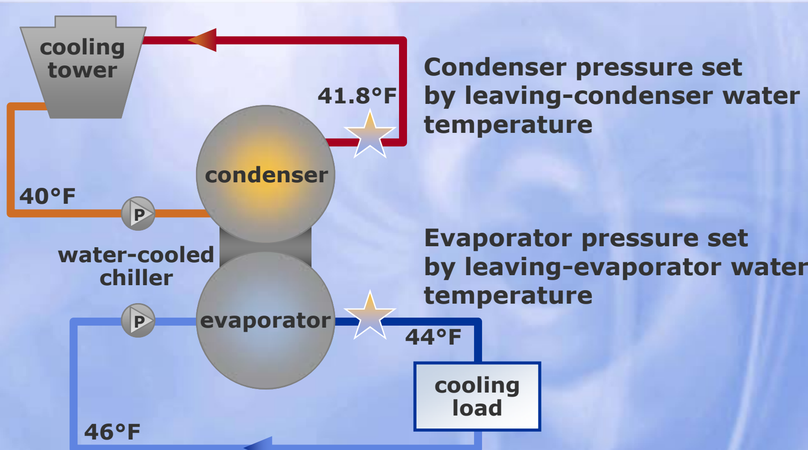
system protection
Chiller Requirements

Achieve and maintain sufficient "head" pressure

Pressure and time required varies by chiller type …

- Oil return
- Refrigerant flow (through expansion devices)
- Motor cooling
- Oil supply

system protection
Chiller Head Pressure

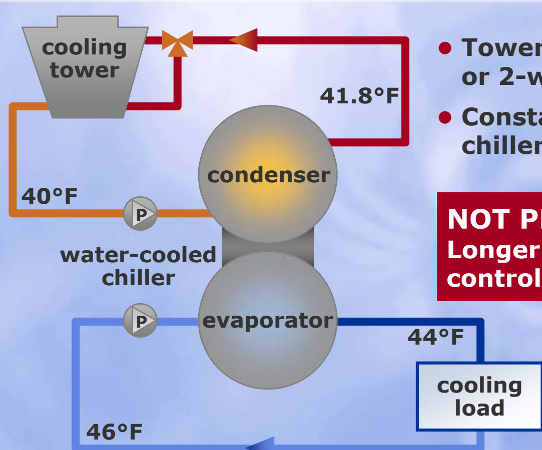


system protection
Chiller Head Pressure

Measure evaporator–condenser ΔP
<u>or</u> condenser pressure <u>or</u> water temperatures … then:

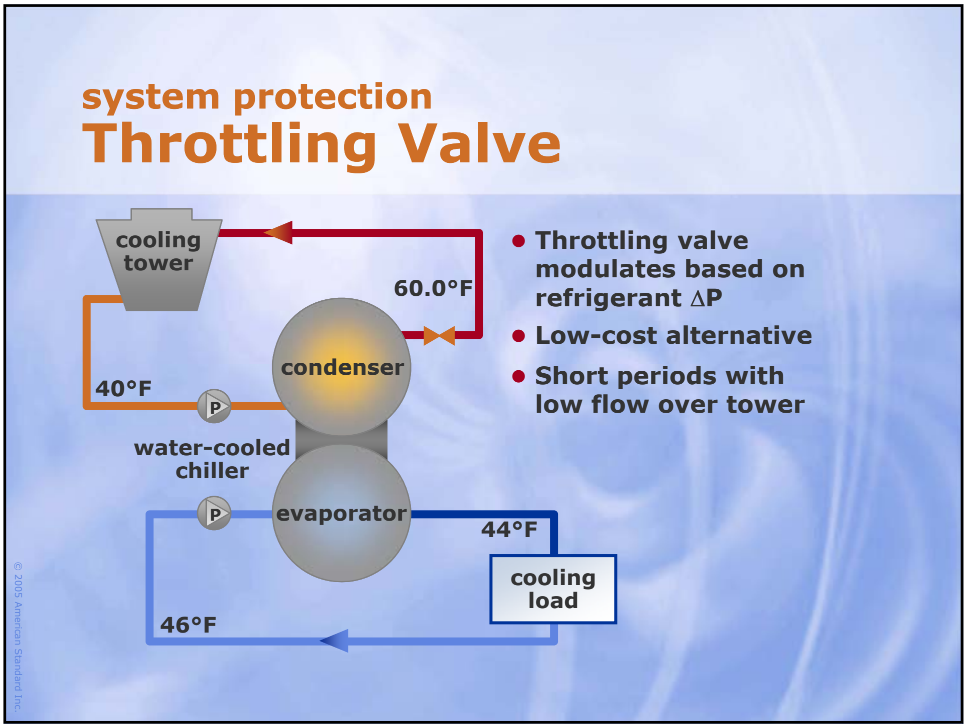
- Control entering water temperature
  - Fan control
  - Reduce water flow over tower—
    e.g., 3-way bypass into sump *(not preferred)*
- Reduce flow through condenser
  - 2-way valve
  - VFD on condenser pump
  - condenser bypass with 3-way valve

system protection
Diverting Valve at Tower



- **Tower bypass with 3-way or 2-way valves**
- **Constant flow through chiller**

NOT PREFERRED
Longer lag time makes control difficult


system protection
Throttling Valve
cooling tower
60.0°F
condenser
40°F
P
water-cooled chiller
P
evaporator
44°F
cooling load
46°F
• Throttling valve modulates based on refrigerant ΔP
• Low-cost alternative
• Short periods with low flow over tower
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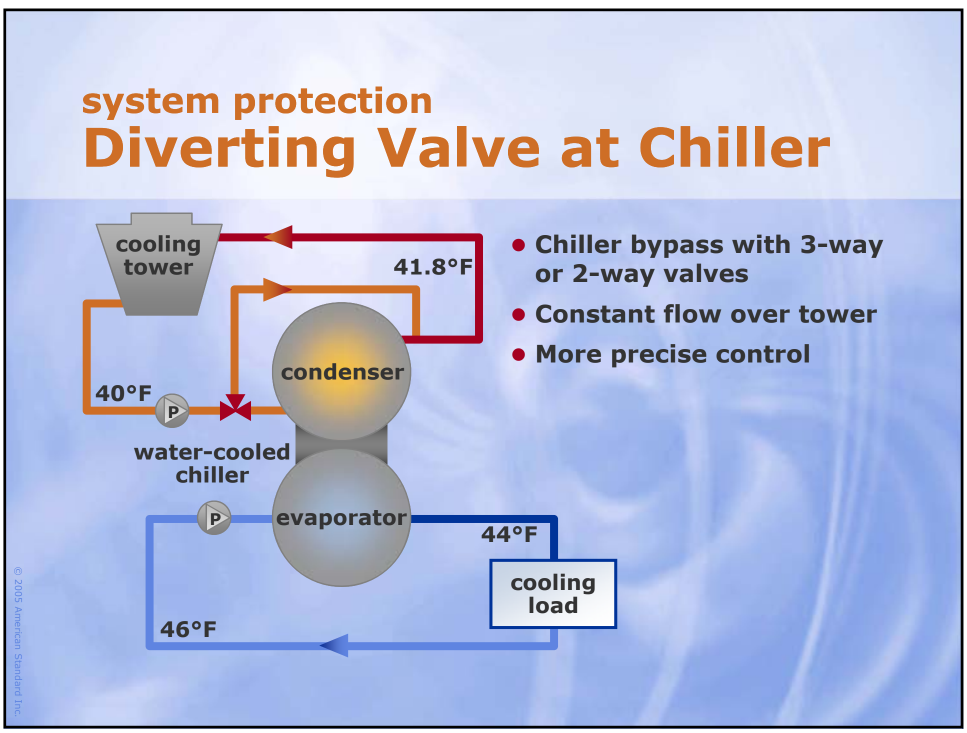
system protection
Diverting Valve at Chiller
cooling tower
41.8°F
condenser
40°F
P
water-cooled chiller
P
evaporator
44°F
cooling load
46°F
• Chiller bypass with 3-way or 2-way valves
• Constant flow over tower
• More precise control
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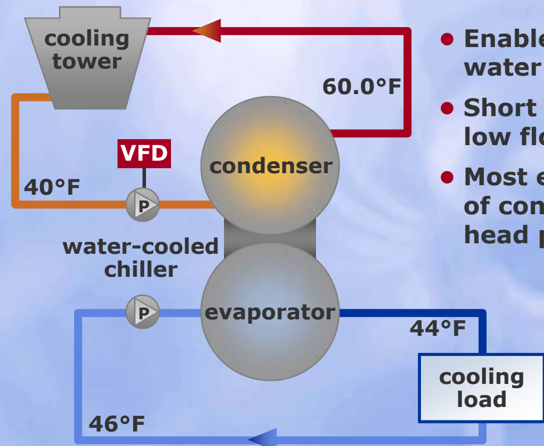
system protection
VFD on Pump



- Enables more efficient water balancing
- Short periods with low flow over tower
- Most efficient method of controlling chiller head pressure

system protection
Sequence of Operation

… for chiller head pressure:

1. The BAS shall monitor the refrigerant pressure in each chiller’s evaporator and condenser. The BAS shall use PID-based DDC control of the *[chiller-condenser-pump VFD][cooling-tower bypass valve][chiller-condenser bypass valve]* to maintain no less than the minimum pressure differential specified by the chiller manufacturer.

Trane literature
Condenser Water Control

CTV-PRB006-EN
Condenser Water Temperature Control for CenTraVac Centrifugal Chiller Systems

RLC-PRB017-EN
Water-Cooled Series R Chiller Models RTHB & RTHD Condenser Water Control

system protection
Flow Limits: An Example

Flow	500-ton chiller	500-ton cooling tower
Design	1000 gpm	1000 gpm
Maximum	2469 gpm	1290 gpm
Minimum	449 gpm	780 gpm

Tower flow range can be much narrower than that of chiller

system protection
Tower Flow Limits

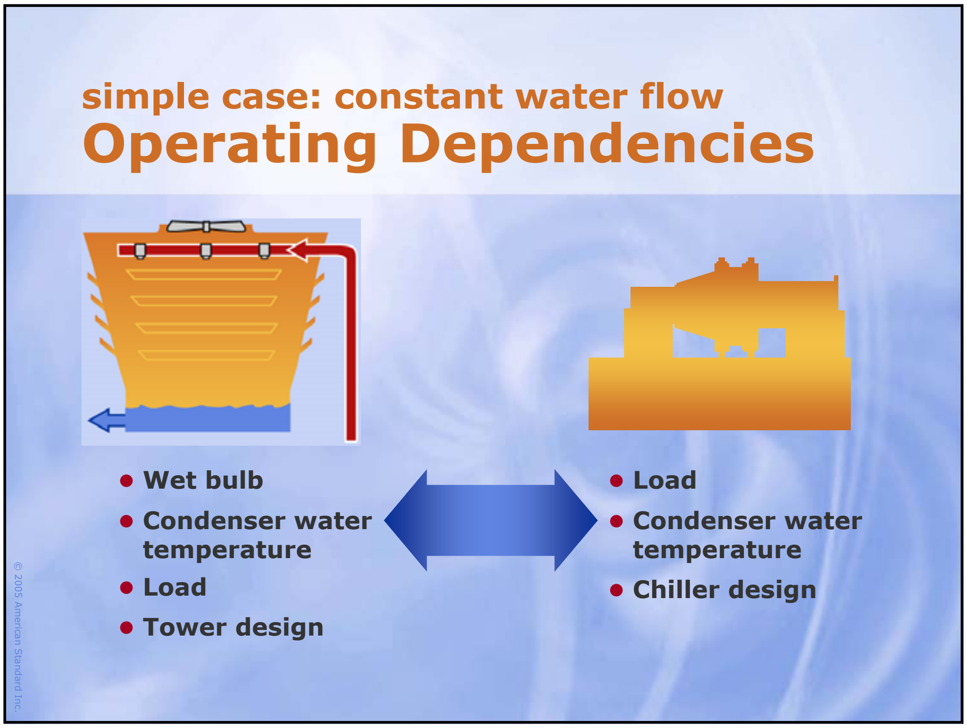
Flow violation	Result
Too low	• "Holes" in fill coverage • Lost efficiency • Mineral deposits
Too high	• "Over-flow" distribution • Lost efficiency • Lost water • Lost treatment chemicals

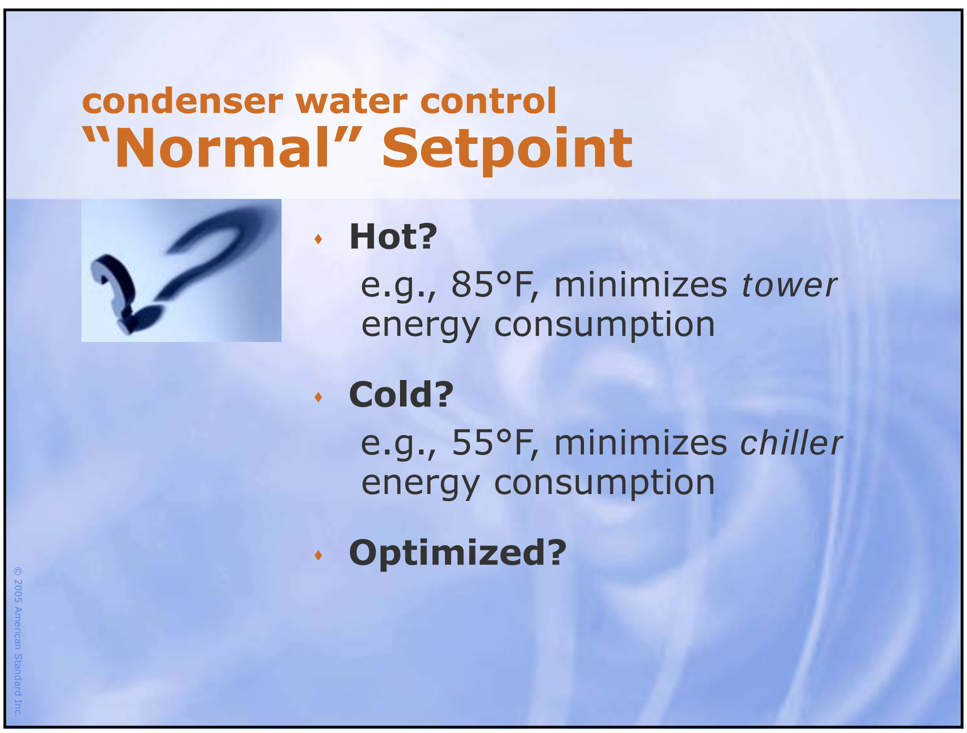
Consult tower manufacturer … Specify limits

Cooling Towers and Condenser Water Systems
Design and Operation

engineers newsletter LIVE

System optimization


simple case: constant water flow
Operating Dependencies
Wet bulb
Condenser water temperature
Load
Tower design
Load
Condenser water temperature
Chiller design
© 2005 American Standard Inc.


condenser water control
"Normal" Setpoint
Hot?
e.g., 85°F, minimizes *tower* energy consumption
Cold?
e.g., 55°F, minimizes *chiller* energy consumption
Optimized?
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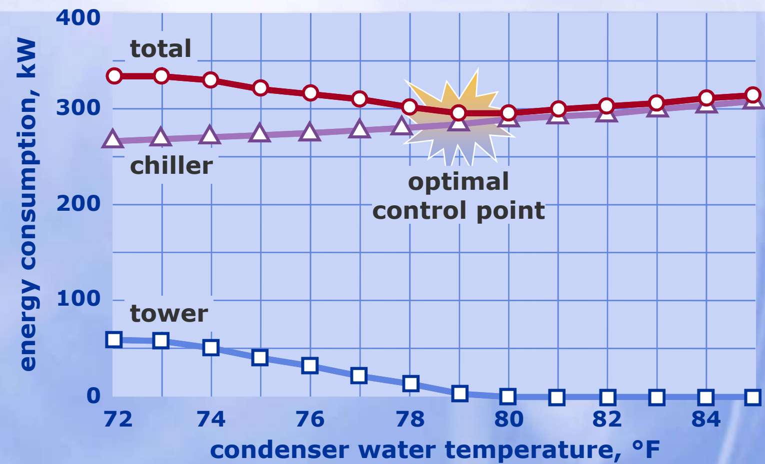
optimal condenser water control
Chiller–Tower Interaction

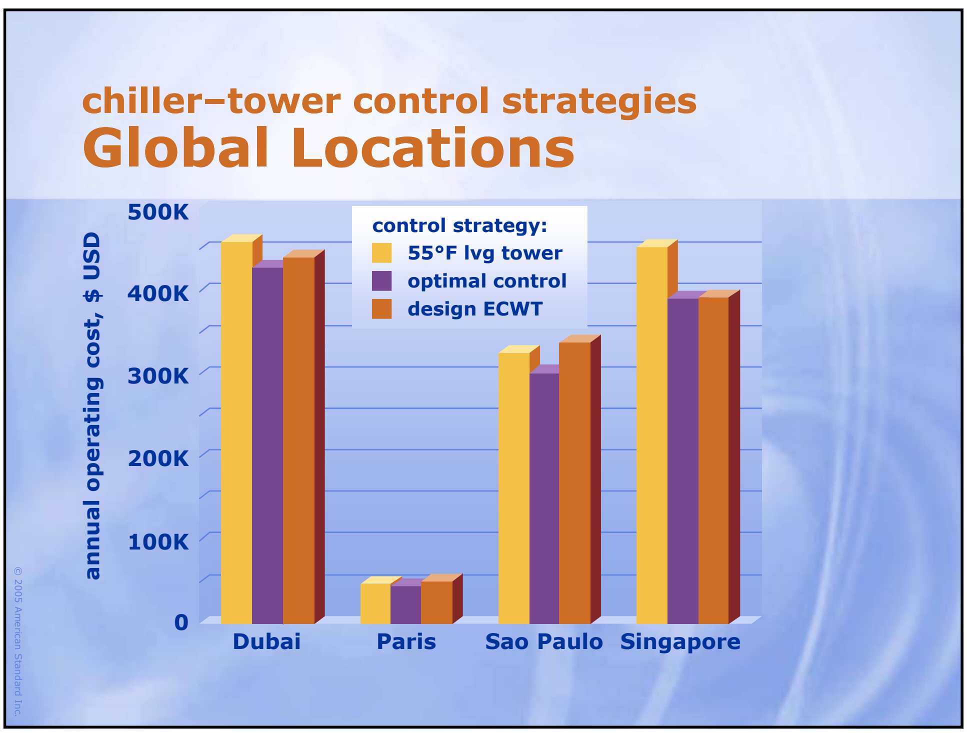


chiller–tower optimization
An Example …

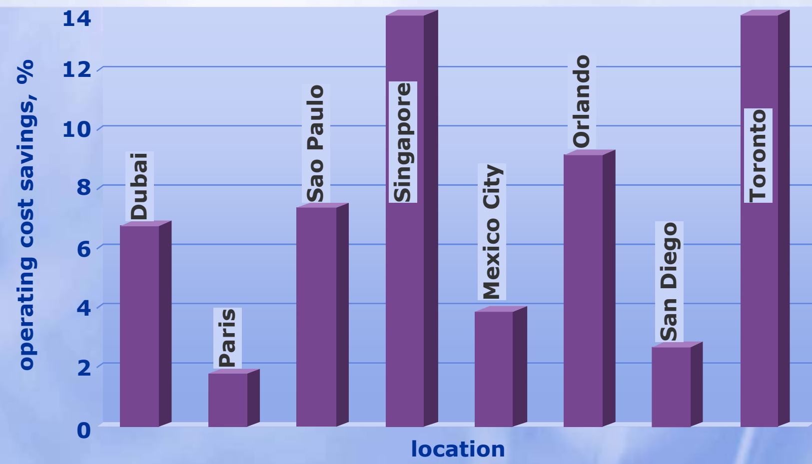
- **720,000 ft² hotel**
- **2 chillers, 2 tower cells**
- **Control strategies**
  - Make leaving-tower water cold as possible (55°F)
  - Optimize system operation
  - Entering-condenser setpoint equals design …

    85°F for humid climates,
    80°F for dry climates


chiller–tower control strategies
North America
annual operating cost, $ USD
350K
300K
250K
200K
150K
100K
50K
0
control strategy:
55°F lvg tower
optimal control
design ECWT
Mexico City
Orlando
San Diego
Toronto


chiller–tower control strategies
Global Locations
annual operating cost, $ USD
500K
400K
300K
200K
100K
0
control strategy:
55°F lvg tower
optimal control
design ECWT
Dubai
Paris
Sao Paulo
Singapore

chiller–tower optimization
Operating Cost Savings



chiller–tower optimization
Perspective on Savings

For centrifugal chillers ≥ 300 tons, ASHRAE 90.1 requires …

- 0.576 kW/ton at full load
- 0.549 kW/ton at IPLV

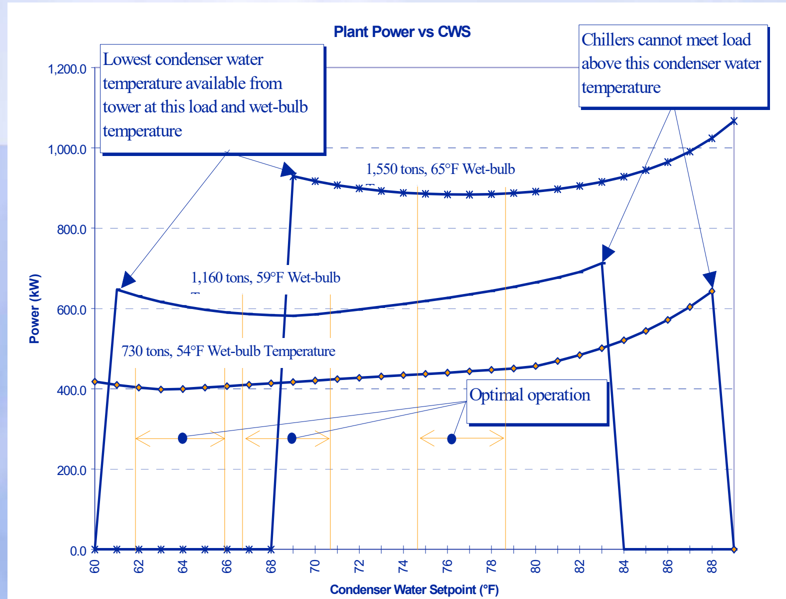
… under ARI standard rating conditions

chiller–tower optimization
Perspective on Savings

Savings, %	Equivalent chiller efficiency
0.0	0.576
2.8	0.560
4.5	0.550
6.2	0.540
14.0	0.495

chiller–tower optimization
Documented Savings

- **Braun, Diderrich: *ASHRAE Transactions* (1990)**
- **Hydeman, Gillespie, Kammerud: PG&E *CoolTools*™ program (2000)**
- **Schwedler: *ASHRAE Journal* (July 1998)**
- **Cascia: *ASHRAE Transactions* (2000)**
- **Crowther, Furlong: *ASHRAE Journal* (July 2004)**

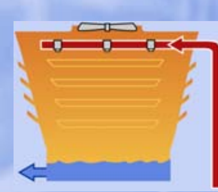


SOURCE: Hydeman, et al. Pacific Gas and Electric. Used with permission.

chiller–tower optimization
What's the "Catch"?

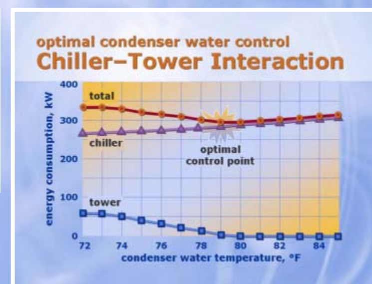
The chiller works harder

- Takes advantage of chiller COP
- Tower fans consume less energy



Where's the Meter?

On the
BUILDING



2004 award for
Best Sustainable Practice

presented to Trane for

"Near optimal chiller–tower operation"

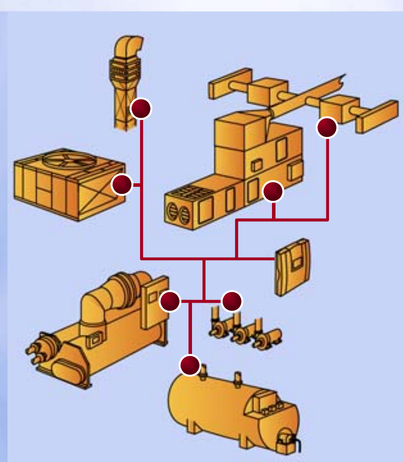
by the Sustainable Buildings Industry Council (SBIC)

Trane, in proposing these system design and application concepts, assumes no responsibility for the performance or desirability of any resulting system design. Design of the HVAC system is the prerogative and responsibility of the engineering professional.

chiller–tower optimization
Finding "Near Optimal"

- **Tower design**
  (flow rate, range, approach)
- **Chiller design**
  - Refrigeration cycle
    (vapor compression vs. absorption)
  - Compressor type
  - Capacity control (variable-speed drive)
- **Changing conditions**
  (chiller load, ambient wet bulb)

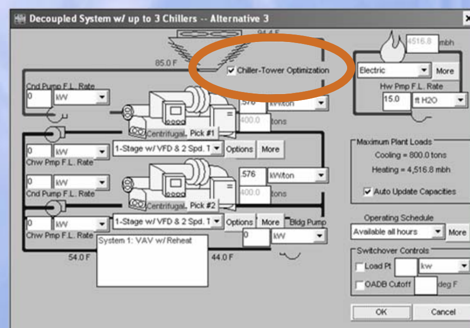
chiller–tower optimization
Necessities



- **System-level controls**
- **Variable-frequency drive on tower fans**
- **High-quality relative humidity sensor**

chiller–tower optimization
Calculating the Savings

Available tools include
TRACE™ 700, Chiller Plant Analyzer, System Analyzer™



chiller–tower optimization
Specification Chart

% Full load	Wet bulb (deg F)	Tower setpoint	Chiller + tower kW
100	78		
75	71		
50	60		
50	71		
25	60		

chiller–tower optimization: dry climate
Specification Chart

% Full load	Wet bulb (deg F)	Tower setpoint	Chiller + tower kW
100	71		
75	65		
50	57		
50	65		
25	57		

chiller–tower optimization
Summary

- **Coldest condenser water is not better**
- **Optimal control saves money**
  - Real, quantifiable savings
  - Proven control strategy that's more than 10 years old

condenser water flow
Variable-Speed Pump?

Limiting factors:

- Tower static lift
- Proper water distribution throughout tower fill (nozzles)
- Required flow through condenser

condenser water flow
Variable-Speed Pump?

Reduced speed/flow:

- Increases chiller power (warmer water leaving condenser)
- Alters heat-transfer effectiveness of tower

condenser water flow
Variable-Speed Pump?

No definitive answer … yet

Control strategy varies with each installation based on chiller and tower selections

Cooling Towers and Condenser Water Systems
Design and Operation

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Answers to your questions

Summary

- **Tower fundamentals**
  - Larger range (lower flow rate) reduces tower size or approach
  - Approach increases as ambient wet bulb decreases
- **Reduce flow rates**
  - Lowers capital and operating costs
  - Benefits the environment

Summary

- **Cooling-tower control options**
  - Invest in VFDs on *all* tower fans
  - Head pressure control is critical to reliability
- **Chiller–tower optimization**
  - Minimize *system* energy consumption
  - Offers significant operating-cost savings

references for this broadcast

Where to Learn More

- 2000 ASHRAE Handbook–Systems & Equipment (Chapter 36)
- Marley Cooling Technologies web site
  http://www.marleyct.com/publications.asp
- Cooling Technology Institute's CTI Standard STD-201-96
- Bibliography

Upcoming Broadcasts

- May 25 — Energy analysis–LEED™ modeling
- Sep 21 — ASHRAE Std 62.1-2004 ventilation requirements
- Nov 16 — Demand-controlled ventilation based on CO_2

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