Better Plants
U.S. DEPARTMENT OF ENERGY

Industrial Process Cooling (Chilled Water) Systems
Virtual INPLT Training & Assessment

Session 2
Thursday – June 9, 2022
10 am – 12:30 pm

Welcome

- Welcome to the 2nd Chilled Water Systems Virtual INPLT training series
- Eight, 2-1/2 hour webinars, focused on Industrial Process Cooling (Chilled Water) Systems Energy Assessment and Optimization
- These webinars will help you gain a significant understanding of your industrial process cooling system, undertake an energy assessment using a systems approach, evaluate and quantify energy and cost-saving opportunities using CWSAT and other US DOE tools and resources
- Thank you for your interest!

Acknowledgments

- US Department of Energy, Advanced Manufacturing Office
  - Oak Ridge National Laboratory
- United Nations Industrial Development Organization
  - National Cleaner Production Center – South Africa
- Hudson Technologies Company
- Dr. Beka Kosanovic – University of Massachusetts, Amherst, MA
- Several industrial clients – both in the US and internationally

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Process Cooling (Chilled Water Systems) Virtual INPLT Facilitator

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Agenda – Session 2

- Welcome and Introductions
- Safety and Housekeeping
- Today's Content:
  - Review of Session 1 & Homework
  - Chilled Water system Scoping Tool
  - Description of example chilled water system
  - Chilled water system efficiency metrics
  - Load profiles
- Kahoot Quiz Game
- Q&A

Better Buildings is an initiative of the U.S. Department of Energy

Safety and Housekeeping

- Safety Moment
  - Chillers (compressors) are extremely loud – use hearing protection whenever nea turbomachinery equipment
- You are welcome to ask questions at any time during the webinar

- When you are not asking a question, please <u>MUTE</u> your mic and this will provide the best sound quality for all participants
- We will be recording all these webinars and by staying on-line and attending the meeting you are giving your consent to be recorded
  - A link to the recorded webinars will be provided, afterwards

Process Cooling Virtual INPLT Agenda (2022)

- **Week 1 (June 2) – Industrial Chilled Water Systems Fundamentals**
- **Week 2 (June 9) – Review of Chilled Water System Scoping Tool; Efficiency Metrics & Calculations**
- **Week 3 (June 16) – Introduction to Chilled Water System Assessment Tool (CWSAT)**
- **Week 4 (June 23) – Using CWSAT to Quantify Energy Efficiency Opportunities – Part 1**
- **Week 5 (June 30) – Using CWSAT to Quantify Energy Efficiency Opportunities – Part 2**
- **Week 6 (July 7) – US DOE MEASUR, 3EPlus, etc.; Undertaking a VINPLT Assessment & Reporting**
- **Week 7 (July 14) – Case Studies; Refrigerants – Past, Present & Future; Reclamation and O&M**
- **Week 8 (July 21) – Industrial Process Cooling (Chilled water) System VINPLT Wrap-up Presentations**

Quick Review – Session 1

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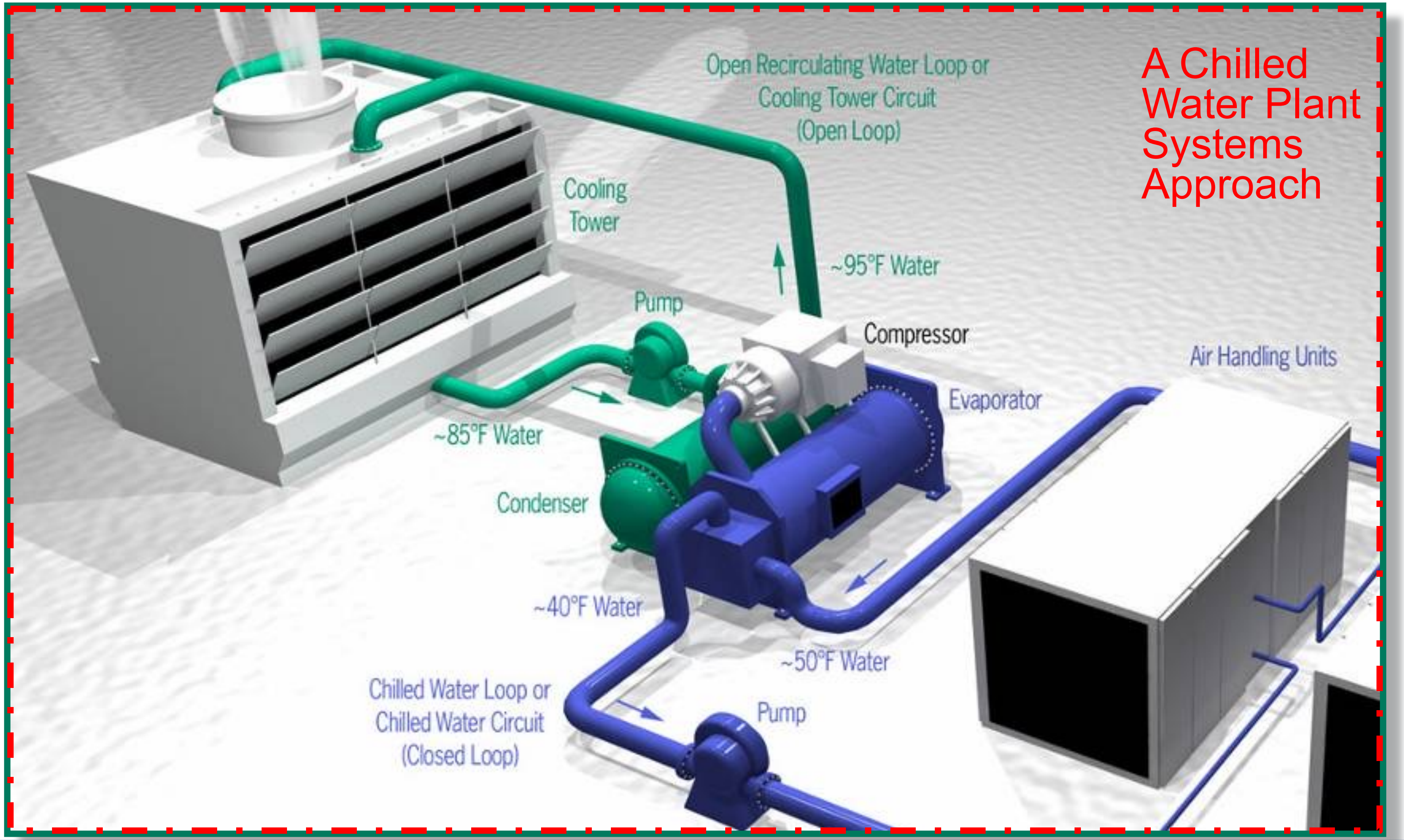
Industrial Energy Consumption

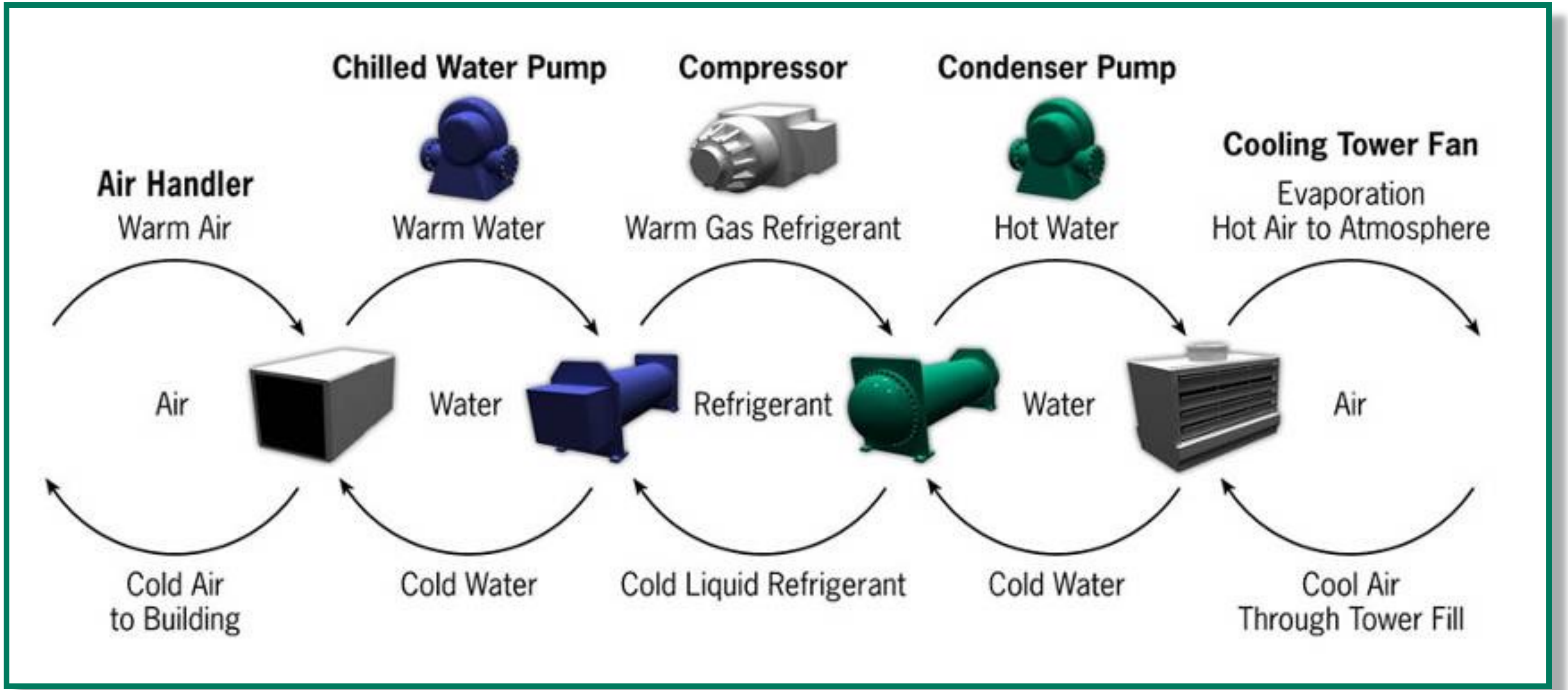
NAICS	Industry Sector	Electricity Consumption (TBtu)				Percent of Total (%)
		Sector Total	Process Cooling & Refrigeration	Facility HVAC	Auxiliaries	
311, 312	Food & Beverage	363	97	40	14	42
334, 335	Electronics	113	15	27	4	41
336	Transportation Equipment	172	12	31	4	28
313-316	Textiles	49	2	8	1	22
326	Plastics & Rubber	170	14	18	3	21
325	Chemicals	700	69	40	11	17
321, 322	Forest Products	373	10	21	3	9
	Total	**1,940**	**219**	**185**	**40**	**23**

- Manufacturing Energy and Carbon Footprints

A Chilled Water Plant Systems Approach



The Air, Water & Refrigerant Cycle



Refrigerants

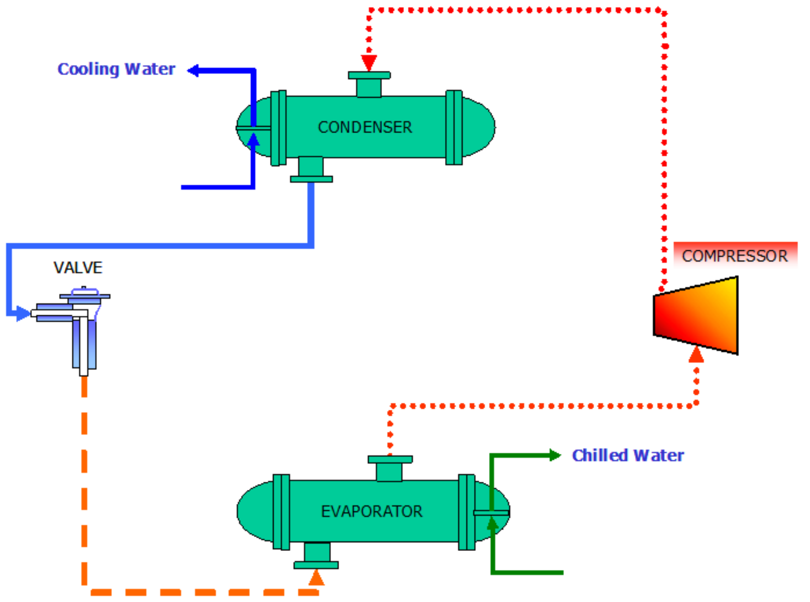
- Refrigerants
  - Freons – CFC's, HCFC's, HFC's and HFO's
  - Hydrocarbons
  - Azeotropic Mixtures
    - Behave like a pure substance
    - Temperature is constant during phase change
  - Near Azeotropic Mixtures
    - Temperature varies during phase change
  - Natural (Inorganic) – Ammonia, Water, Carbon dioxide
- Nomenclature
  - R-number
  - Typical Freons – 1-399, 1XXX
    - Easy convention for C, H, F
  - Near Azeotropes – 400 series
  - Azeotropes – 500 series
  - Natural (Inorganic) – 700 series
    - Easy convention – 7 + Molecular wt.

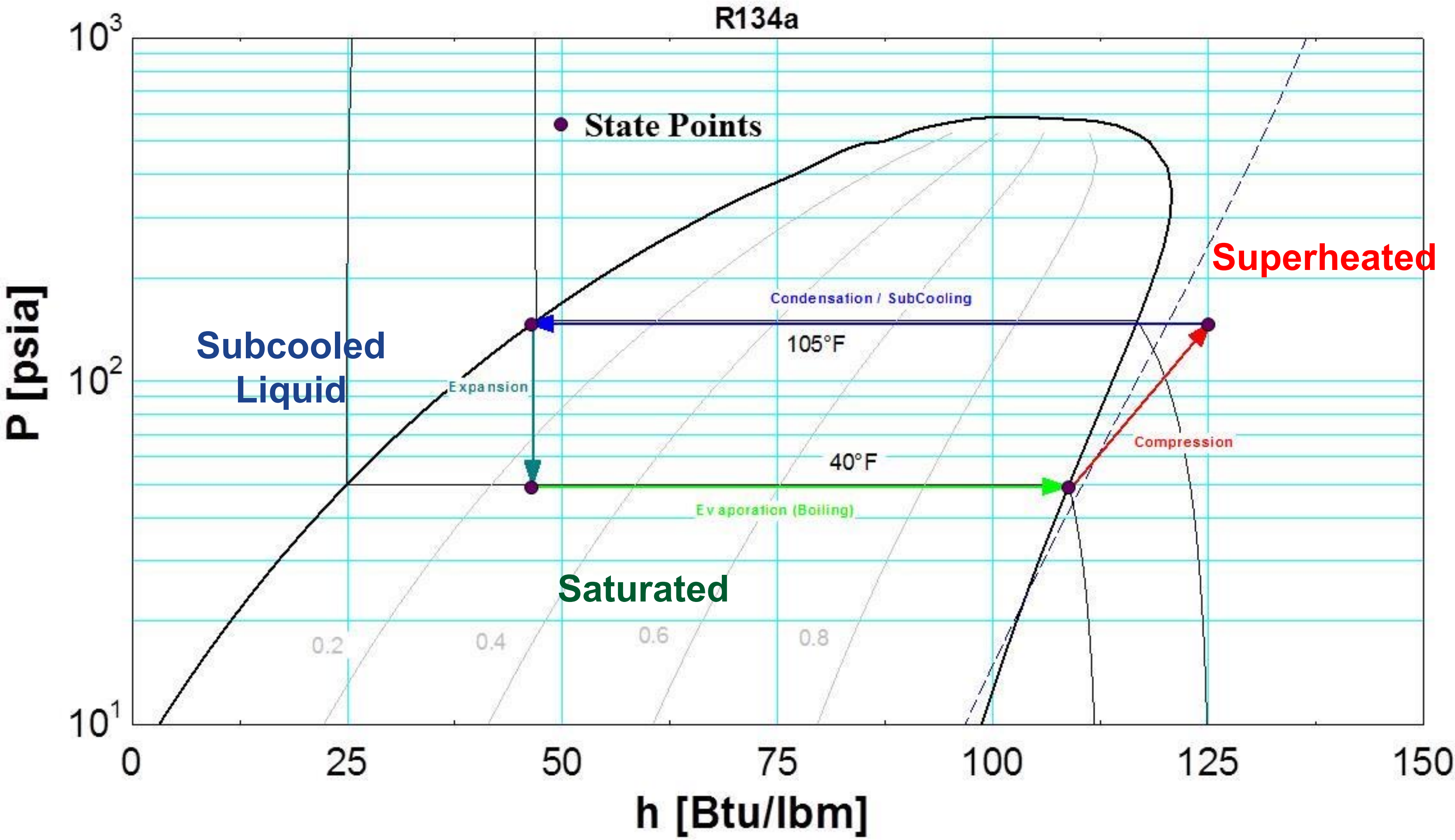
Refrigerants

R134a Saturation Properties

Temperature [°F]	Pressure [psig]	Liquid Density [lb/ft^3]	Vapor Volume [ft^3/lb]	Liquid Enthalpy [Btu/lb]	Vapor Enthalpy [Btu/lb]	Liquid Entropy [Btu/lb-R]	Vapor Entropy [Btu/lb-R]
(14.95)	-	85.96	3.0460	7.58	100.90	0.01752	0.22728
(5.23)	4.00	84.94	2.4270	10.57	102.30	0.02414	0.22603
2.96	8.00	84.07	2.0210	13.11	103.50	0.02966	0.22510
10.09	12.00	83.30	1.7320	15.34	104.60	0.03442	0.22436
16.43	16.00	82.60	1.5170	17.33	105.50	0.03862	0.22377
22.16	20.00	81.96	1.3490	19.14	106.30	0.04238	0.22327
27.40	24.00	81.37	1.2150	20.81	107.10	0.04581	0.22285
32.24	28.00	80.82	1.1060	22.36	107.70	0.04895	0.22248
36.74	32.00	80.30	1.0140	23.81	108.40	0.05187	0.22216
40.95	36.00	79.81	0.9364	25.17	108.90	0.05458	0.22188
44.92	40.00	79.34	0.8697	26.46	109.50	0.05713	0.22162
48.67	44.00	78.89	0.8118	27.69	110.00	0.05953	0.22139

The Refrigeration Cycle

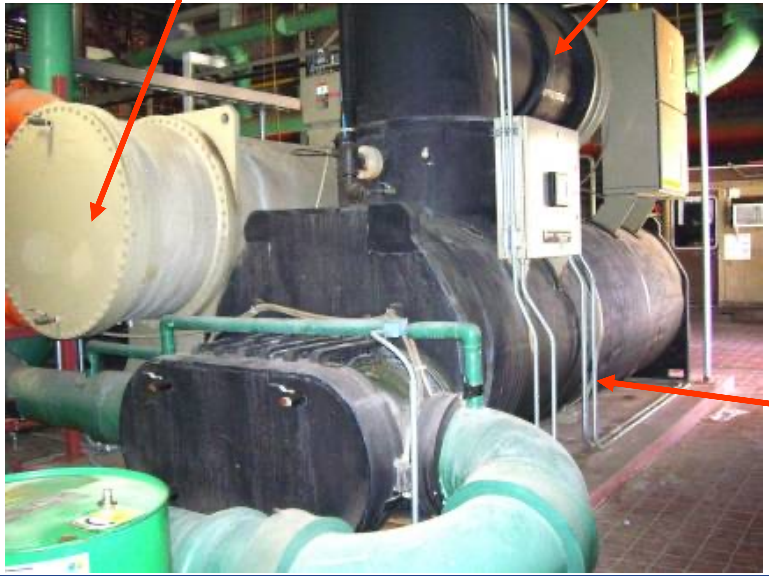




A Field Chiller

Condenser

Compressor



Evaporator (Chiller Barrel)

Compressor

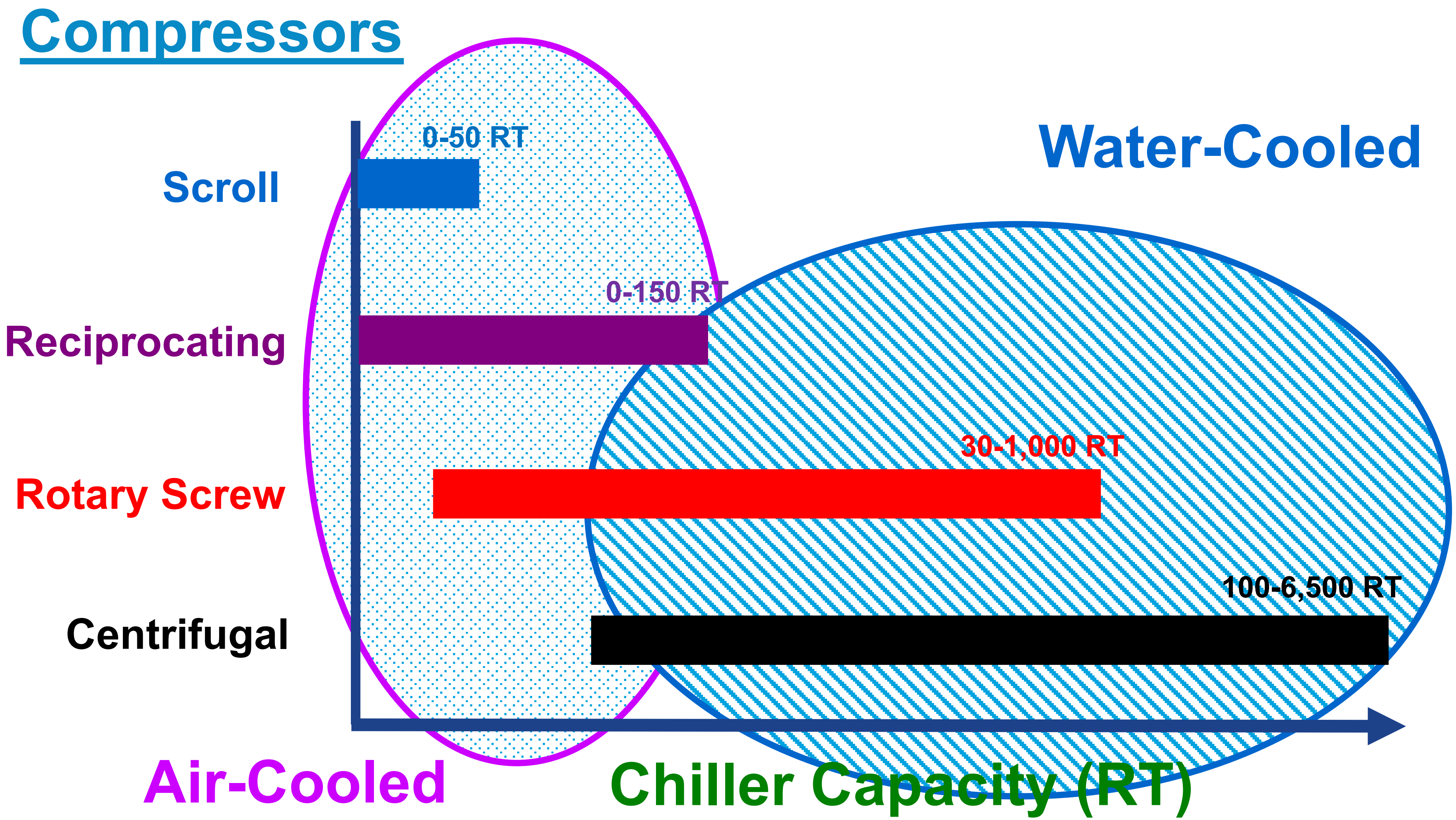
- Main Driver of the system
- Compressor Efficiency compares isentropic operation to actual operation
- Dynamic and Positive Displacement machines
  - The main difference is the way the gas compression is achieved
- Dynamic
  - Large systems
  - Centrifugal machines
- Positive Displacement
  - Smaller systems
  - Screw machines
  - Reciprocating machines
  - Scrolls

Heat Rejection Mechanism

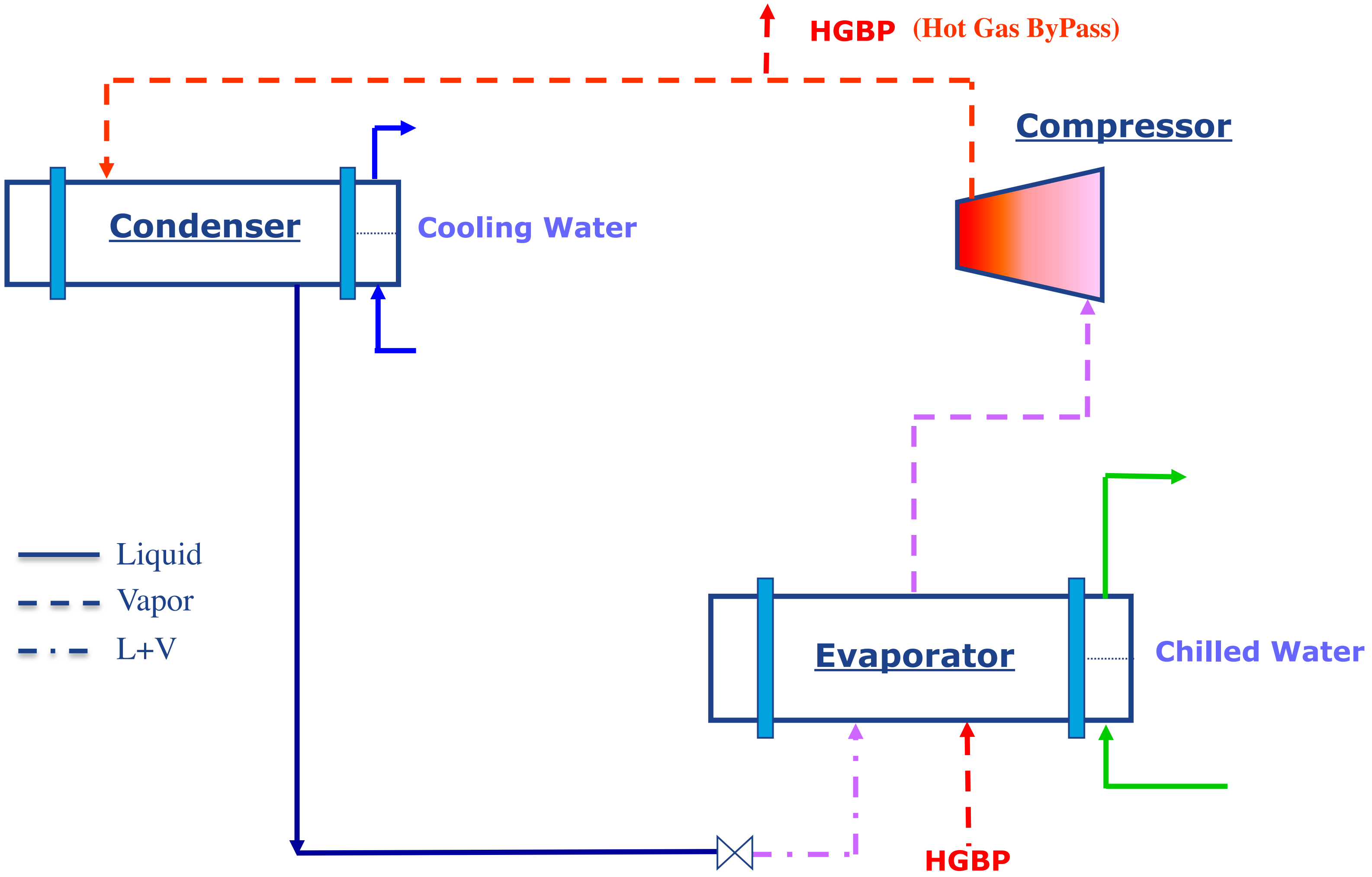
- Very efficient heat rejection mechanism
- Evaporation of water provides the cooling effect
- Water temperature approaches ambient wet-bulb temperature
- Possible use of water-side economizers (free cooling) during colder ambient temperatures
- Fouling and water chemistry needs to be managed & controlled
- Dry weather – significant advantage

Water-Cooled Condenser
Using Cooling Tower (Open Loop)

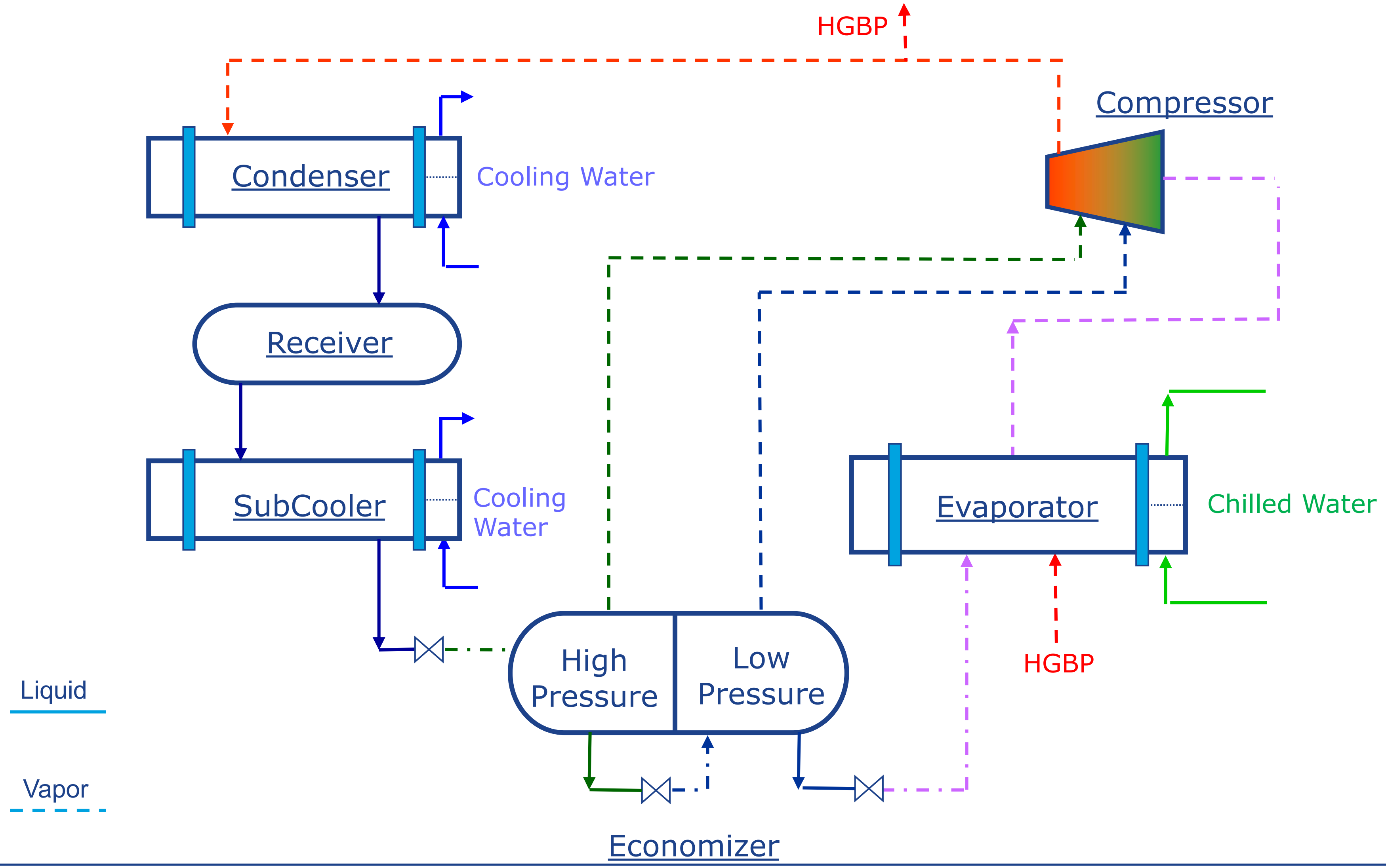
Different Compressor Types, Sizes & Heat Rejection Mechanism



Single Stage Chiller System



Three Stage Chiller System



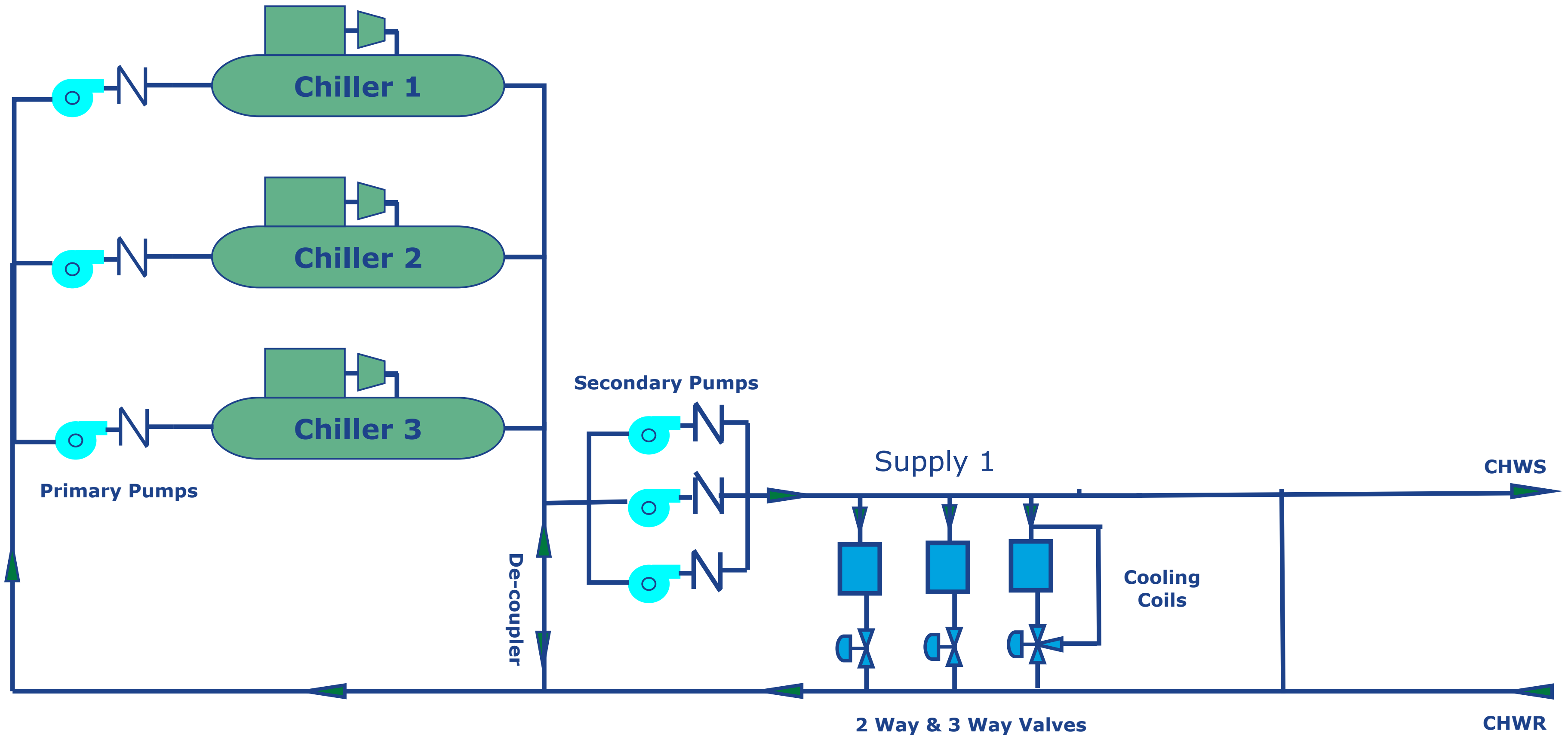
Absorption Chiller Systems

- Absorption systems have a pair of working fluids
- They are operated using heat
  - Direct fuel
  - Steam or hot water
  - Exhaust or waste heat
- Lithium Bromide / Water Chillers
  - Refrigerant – Water
  - Absorbent – LiBr salt
- Ammonia / Water Chillers
  - Refrigerant – Ammonia
  - Absorbent - Water

Electric Motor Drives (Variable Frequency)

- May not be a standard option but becoming very prevalent with new chillers and also a retrofit option in some cases
- Provides for very high power factors (>0.97)
- Provides soft start capability
- VFD efficiency is very high >98% and so doesn’t introduce any losses
- Compressor flow is controlled by varying the speed of the compressor
- Tremendous ability to match Loads with Lift and provide significant savings at part-load conditions

Primary & Secondary Loops Chiller Plant



* CHWR is always reverse return but shown here as direct return for simplicity

Chilled Water System Scoping Tool (CWST)

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Introduction & Scope of CWST

- The Chilled Water System Scoping Tool (CWST) is an excel-based software questionnaire
- It is designed to enhance awareness of areas of chilled water plant system management
- Divided into typical chilled water system focus areas
- Provides the user a score that is indicative of management intensity and serves as a guide to useful information
- Tool to identify potential improvement opportunity areas
- Will NOT quantify the energy savings opportunities

Chilled Water System Scoping Tool (CWST)

Chilled Water System Scoping Tool (CWST) Summary

Points Details	
Maximum Score =	420
Your Score =	420
Best Practices Rating =	100%

Based on plant information, there is low potential and energy savings in the range of 0-10% can be anticipated.

Section	Your Score	Maximum Score	%
General	90	90	100
System Components			
Compressors	80	80	100
Condensers	75	75	100
Evaporators	70	70	100
Cooling Towers	62	62	100
Plate Heat Exchangers/Waterside Economizers	23	23	100
Pumps	20	20	100
Total	**420**	**420**	100

Acknowledgments: National Cleaner Production Center, South Africa (UNIDO IEE Project)

Intended CWST Users

- Industrial manufacturers
  - Plant managers
  - Utility managers
  - Plant process engineers

- Energy consultants
  - Energy efficiency experts (high-level)
  - System-focused experts

- Can also be used by institutional, commercial chilled water HVAC users

CWST Organization

- Instructions
- Background information
  - Contact and site information
  - Operating hours, etc.
- General questions on the chilled water plant system
- Chilled water system component questions
  - Compressors
  - Condensers (Water / Air – cooled)
  - Evaporators
  - Cooling towers
  - Waterside economizers / heat exchangers
  - Pumping systems

Obtaining Data for CWST Input

- Sources of data:
  - Information on operational equipment/data from:
    - Plant engineer/utilities/maintenance manager(s)
    - Piping & Instrumentation Diagrams
    - Chilled water system walk-through
    - Chilled water system operators
  - Actual current measurements
  - Computerized or print copy of historical records

- Expected time: 1.0 hours (60 minutes)

Steps for Use of CWST

- Open CWST file in Excel
- Review CWST sections to identify needed input data
- Work with very knowledgeable chilled water system personnel at the plant
- Obtain input data
- Insert answer choices or use pull-down menus provided for each question in the different CWST sections
- Be honest and be conservative w/answers
- SAVE file manually

Demonstration and Functionality of CWST

Chilled Water System Scorecard

Sr.	Question	Answer	Score
	Chilled Water Plant		
	General		90
1	How old is the chilled water plant system (equipment)?	<10 Years	10
2	When was the last time the chilled water system was audited?	1 year or less	10
3	Is the chilled water system operating energy cost monitored? How often?	Yes, monthly or more frequently	10
4	How is the chilled water plant controlled?	DCS / BMS & state of the art optimization package	10
5	Has a detailed chilled water system load analysis ever done to minimize the cooling done?	Yes	10
6	What percent of the chilled water plant capacity is generally utilized versus design?	Close to design or higher (>=80%)	10
7	Is there a regular maintenance program?	Yes	10
8	How is the overall quality of insulation of the chilled water system?	Very Good	10
9	Is the refrigerant charge level in each chiller inspected regularly? How often?	Yes, monthly or more frequently	10

CWST – Instructions

Chilled Water System Scoping Tool (CWST)

Color Legend

Orange	User Input / Choose Value
Green	User Input / Numeric / Text
Grey	Intermediate/ Calculation

Objective/Intended Use Notes:

The tool uses two evaluation question sets to infer the general energy efficiency potential of a facility. The first set of questions requires users to input company and plant level information that includes the background information, industry sector, and application type. This information is used to determine the fraction of energy consumed for process cooling compared to overall energy consumed by the plant. Then the user is asked about general plant-level operations and bestpractices. The second level of questionnaire is more detailed and looks at individual equipment and their operations in the system. The tool uses information from these questionnaires to evaluate operating practices and general upkeep of the individual equipment. Based on the answers provided the tool assigns highest scores to most efficient equipment and practices and lower scores to less efficient equipment or practice. This allows the tool to estimate the level of energy efficiency opportunity present in the system.

Instructions for filling out details:

1. Please use the color legend indicated above to input answers to the questions indicated.
2. Include information for all chilled water plant system equipment such as compressors, evaporators, condensers, cooling towers, heat exchangers, associated fans and pumps etc.

Disclaimer:

This scoping tool is created as a supplemental guidance tool to accompany 'Process Cooling Virtual INPLT Training' delivered by the US DOE. US DOE, ORNL, C2A Sustainable Solutions makes no warranty, express or implied, or assumes any legal liability or responsibility for the accuracy or completeness of any information provided or recommended. This tool should be used as a general guidance only.

Acknowledgments:

The developers of CWST would like to acknowledge the efforts of Subodh Chaudhari (Oak Ridge National Laboratory) and Hudson Technologies Company in helping to develop this tool. Additionally, the funding for this tool in its final form was provided by the Industrial Energy Efficiency UNIDO Project (National Cleaner Production Center - South Africa).

Copy Right Notice:

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CWST – Basic Facility Information

Basic Facility Information

Contact Information

Company Name:		Location:	
Plant/Facility Name:		Primary Contact Person	
Address:		Industry Sector:	Pulp & Paper
Phone:		Application:	Process Cooling
Fax:		Specify if other:	
Email:		Primary Product:	

Operation Hours

Shift No.	Hours of Operation / Day	Days/Week	Weeks/Year	Annual Hours
1				0
2				0
3				0
Office Hours				0
Others				0

Specific Pre-Identified Problems:	1. 2. 3.
Energy Efficiency Ideas of Interest to Plant Personnel:	1. 2. 3.
Energy Use:	Based on the industry, the major application selected accounts for < 10% of the annual plant energy spend

CWST – Chilled Water System Scorecard - General

Chilled Water System Scorecard

Sr.	Question	Answer	Score
	Chilled Water Plant		
	General		90
1	How old is the chilled water plant system (equipment)?	<10 Years	10
2	When was the last time the chilled water system was audited?	1 year or less	10
3	Is the chilled water system operating energy cost monitored? How often?	Yes, monthly or more frequently	10
4	How is the chilled water plant controlled?	DCS / BMS & state of the art optimization package	10
5	Has a detailed chilled water system load analysis ever done to minimize the cooling done?	Yes	10
6	What percent of the chilled water plant capacity is generally utilized versus design?	Close to design or higher (>=80%)	10
7	Is there a regular maintenance program?	Yes	10
8	How is the overall quality of insulation of the chilled water system?	Very Good	10
9	Is the refrigerant charge level in each chiller inspected regularly? How often?	Yes, monthly or more frequently	10

CWST – Chilled Water System Scorecard – System Components

	System Components		
1	Choose main components for the chilled water system		
	Compressors	Yes	1
	Condensers (Water-Cooled or Air-Cooled)	Yes	1
	Evaporators	Yes	1
	Cooling Towers	Yes	1
	Water Side Economizers/Plate Heat Exchangers	Yes	1
	Pumps	Yes	1

CWST – Chilled Water System Scorecard

	Condensers		75
1	What is the most common heat rejection methodology in the chilled water system?	Cooling Towers	10
2	Is inspection and regular maintenance conducted on the condensers?	Yes, as per manufacturers recommendations	10
3	Are there any condenser issues such as fouling, non-condensables, etc.?	No	10
4	Are the following operating parameters monitored continuously:		
	(i) Water flow	Yes	5
	(ii) Water supply & return temperature	Yes	5
	(iii) Refrigerant pressure	Yes	5
5	Are the following conditions representative during normal operations:		
	(i) Water flow lower than design	No	10
	(ii) Waterside pressure drop (dP) higher than design	No	10
	(iii) Approach temperature higher than design	No	10

Interpreting Summary Results

- Maximum possible score: Varies based on your system selections
- The scorecard reflects a general overview of existing bestpractices in the Chilled Water system
  - An average plant would score between 60-75%
- A “line in the sand” effort on potential energy savings possible in the chilled water system is provided based on
  - Past experiences in chilled water systems
  - Data collected over the years from different energy assessments in chilled water systems
  - Consultation with other experts in industry
- This score is “**Qualitative**” in nature and no effort of performance guarantees, promises of savings, etc. should be made based on the results of CWST

CWST – Chilled Water System Summary Results

Chilled Water System Scoping Tool (CWST) Summary

Points Details	
Maximum Score =	420
Your Score =	420
Best Practices Rating =	100%

Based on plant information, there is low potential and energy savings in the range of 0-10% can be anticipated.

Section	Your Score	Maximum Score	%
General	90	90	100
System Components			
Compressors	80	80	100
Condensers	75	75	100
Evaporators	70	70	100
Cooling Towers	62	62	100
Plate Heat Exchangers/Waterside Economizers	23	23	100
Pumps	20	20	100
Total	**420**	**420**	100

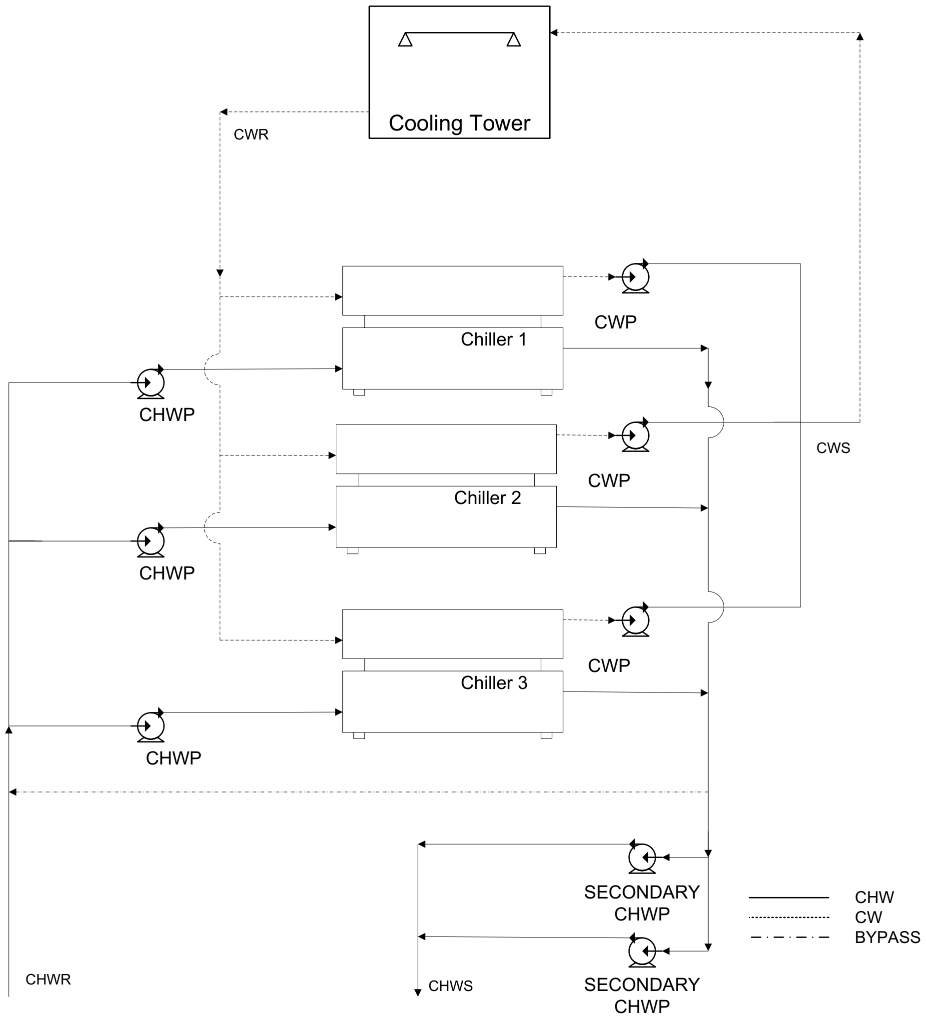
Example Chilled Water System

- You have been tasked with a Chilled water system assessment at a food and beverages plant
- The plant Utilities Manager & Utilities Engineer are available to provide information to you about the plant
- Open CWST and input available plant data
- Identify missing data and determine appropriate plant source for this data
- List possible Chilled water system improvement opportunities that you would like to investigate during the energy assessment

Facility Description

- The plant / facility is a large Food & Beverages plant located in the St. Louis, MO area
- The system selected for the energy assessment provides chilled water for process, packaging, air-conditioning plant areas and warehouse storage
- The plant operates a 3-shift per day operation, 8-hour per shift and runs all year round
- Possible shut-downs are planned for periodic maintenance activities
- The Plant Engineering Manager and the Plant Engineer/Maintenance person are available to answer questions and complete the CWST software tool

System Schematic



Chilled Water System Information

- The facility is 15-20 years old
- It has been a while since an energy assessment was done on the system
- Plant personnel do keep a tab on annual spend / budget for the operations
- The chilled water system has been upgraded with some dashboards and controls for operator / user interface
- Overall, there is a consistent demand on the chilled water system but system is not close to any capacity limitations
- Insulation is generally good but no audit has ever been performed on it
- A maintenance contractor provides regular support (quarterly site visit) to keep the plant in operation without any issues

Sub-System Information

- Compressors
- Water-cooled condensers
- Chiller barrels (evaporators)
- Cooling tower
- Pumps
  - Primary chilled water
  - Secondary chilled water
  - Condenser Water

Sub-System Information (Compressors)

- The system is relatively old and maintenance is done on an as-needed basis
- There are two centrifugal compressor chillers – they are run to collect equal operating hours annually but there are times when they are both operating at high loads (>60%)
- Manual operator logs indicate load levels – guide vane positions
- The compressors have capacity control with guide vanes but don’t have much instrumentation on the compressors per se
- Compressors are believed to be running in their expected operating ranges

Sub-System Information (Condensers)

- Maintenance is done on an as-needed basis
- Sometimes with condensers and during the high-load season - scaling does occur in the tubes
- Temperature monitors exist on the supply and return water and manual operator logs provide the information, if required
- A tab is kept on the wet-bulb approach temperature periodically and the maintenance contractor keeps a record of that during the visit

Sub-System Information (Evaporators)

- Since the system is mostly a closed loop on the chilled water side, maintenance is done only on an as-needed basis
- No issues with evaporator operations and it meets process setpoints always
- Instrumentation is fairly limited on the evaporator but inlet and outlet temperatures and pressure of the refrigerant is measured
- Manual operator logs to provide the information, if required
- A tab is kept on the approach temperature

Sub-System Information (Cooling Tower)

- The system is relatively old and no upgrades other than basic maintenance and fixing flow nozzle heads, basin cleaning, etc.
- No issues with cooling tower operations
- Fans are controlled automatically to meet setpoint
- Water chemistry is maintained by fixed blowdown
- Water outlet temperature, ambient temperature are monitored and periodically checked with wet-bulb temperature
- Manual operator logs record this information and 10-12°F approach to wet-bulb temperature on the cooling tower is very normal

Sub-System Information (Pumps)

- The primary chilled water and cooling tower water pumps are constant speed electric motor drives
- The secondary chilled water pumps are variable speed drives
- It is not exactly clear as to how many pumps are needed to run based on the cooling load but enough pumps are run so that all the chillers are satisfied with water flow all the time when they are operating and so also the end-users

CWST Hands-on Exercise Instructions

- For the plant information presented, provide data input to the CWST and arrive at scores for each CWST sub-section and the summary listing
- For all questions for which input data is unavailable or insufficient, specify how you would obtain the needed information during your plant visit
- Based on your CWST analysis results, develop a list of energy efficiency opportunities in the example chilled water plant

CWST Hands-on Exercise Results

Basic Facility Information

Contact Information

Company Name:	ABC Food Industries	Location:	St. Louis, MO
Plant/Facility Name:	St. Louis, MO Plant	Primary Contact Person	John Doe
Address:	1234 Main Street, St. Louis, MO	Industry Sector:	Food & Beverage
Phone:		Application:	Process Cooling
Fax:		Specify if other:	
Email:		Primary Product:	Fruit products

Operation Hours

Shift No.	Hours of Operation / Day	Days/Week	Weeks/Year	Annual Hours
1	8	7	52	2,912
2	8	7	52	2,912
3	8	7	52	2,912
Office Hours				0
Others				0

Specific Pre-Identified Problems:	1. 2. 3.
Energy Efficiency Ideas of Interest to Plant Personnel:	1. 2. 3.
Energy Use:	Based on the industry, the major application selected accounts for > 40% of the annual plant energy spend

CWST Hands-on Exercise Results

Sr.	Question	Answer	Score
	Chilled Water Plant		
	General		46
1	How old is the chilled water plant system (equipment)?	10- 20 years	5
2	When was the last time the chilled water system was audited?	>5 years ago or Never	0
3	Is the chilled water system operating energy cost monitored? How often?	Yes, annually	5
4	How is the chilled water plant controlled?	DCS / BMS	5
5	Has a detailed chilled water system load analysis ever done to minimize the cooling done?	Don't know	5
6	What percent of the chilled water plant capacity is generally utilized versus design?	Higher than 50%	5
7	Is there a regular maintenance program?	Yes	10
8	How is the overall quality of insulation of the chilled water system?	Good but can be improved	5
9	Is the refrigerant charge level in each chiller inspected regularly? How often?	Yes, Quarterly	6

	System Components		
1	Choose main components for the chilled water system		
	Compressors	Yes	1
	Condensers (Water-Cooled or Air-Cooled)	Yes	1
	Evaporators	Yes	1
	Cooling Towers	Yes	1
	Water Side Economizers/Plate Heat Exchangers	No	0
	Pumps	Yes	1

CWST Hands-on Exercise Results

	Compressors		53
1	Do you inspect and conduct regular maintenance on the compressors?	Yes, as needed only	5
2	What is your average running compressor load factor versus design?	Higher than 50%	5
3	What percent of operating time do you spend at less than 50% load?	30% or less	10
4	Do you monitor compressor efficiencies? How often?	No	0
5	Select the most common control mechanism for your compressors	Variable inlet guide vanes (centrifugal)	8
6	Is the operating suction pressure lower than the design suction pressure by more than 15%?	No	10
7	Is the operating discharge pressure higher than the design discharge pressure by more than 10%?	No	10
8	What percent of your compressor power is delivered via the following drive types? (Total must be less than or equal to 100%)		5
	Backpressure (extraction) steam turbines	0%	
	Variable Speed Electric Motor	0%	
	Electric motor w/o variable speed drives	100%	
	Condensing steam turbines	0%	
	Total	100%	

CWST Hands-on Exercise Results

	Condensers		35
1	What is your most common heat rejection methodology?	Cooling Towers	10
2	Do you inspect and conduct regular maintenance on the condensers?	Yes, as needed only	5
3	Do you have condenser issues such as fouling, non-condensables, etc.?	Yes, sometimes	5
4	Do you monitor following operating parameters continuously:		
	(i) Water flow	No	0
	(ii) Water supply & return temperature	Yes	5
	(iii) Refrigerant pressure	No	0
5	Are the following conditions representative during operations:		
	(i) Water flow lower than design	Don't Know	0
	(ii) Waterside pressure drop (dP) higher than design	Don't Know	0
	(iii) Approach temperature higher than design	No	10

	Evaporators		35
1	Do you inspect and conduct regular maintenance on the evaporator for fouling?	Yes, as needed only	5
2	Do you monitor chilled water exchanger pressure drop (ΔP)?	No	0
3	Do you have evaporator issues such as fouling, high superheat, frosting issues, etc.?	No	10
4	Do you monitor following operating parameters continuously:		
	(i) Coolant flow	No	0
	(ii) Coolant supply and return temperatures	Yes	5
	(iii) Refrigerant pressure	Yes	5
5	Are the following conditions representative during operations:		
	(i) Coolant flow lower than design	Don't Know	0
	(ii) Coolant pressure drop (dP) higher than design	Don't Know	0
	(iii) Approach temperature higher than design	No	10

CWST Hands-on Exercise Results

	Cooling Towers		33
1	What is general condition of the cooling towers?	Good	5
2	How are your cooling tower fans controlled?	Automated ON/OFF	4
3	How is your cooling tower water blowdown controlled?	Manual	2
4	Do you monitor the following operating parameters continuously?		
	(i) Cooling tower water flow	No	0
	(ii) Water outlet temperature	Yes	5
	(iii) Water Inlet Temperature	No	0
	(iv) Ambient air wet bulb temperature	No	0
	(v) Ambient air temperature	Yes	2
	(vi) Cooling tower water chemistry	No	0
5	Are your overall cooling water flow rates lower than design?	No	5
6	Do you see an evenly spread and uniform water distribution in your cooling towers?	Yes	5
7	How close is the approach of supply cooling water temperature to the wet bulb temperature?	10°F to 20°F	5

	Pumps		7
1	What percent of cooling water pump power delivered by the following drive types (Total must be less than or equal to 100%)		7
	Backpressure turbine drives	0%	
	Variable speed drives	25%	
	Constant speed motors	75%	
	Condensing turbine drives	0%	
	Total	100%	
2	Are you only running the minimum number of pumps?	No	0

CWST Hands-on Exercise Results

Chilled Water System Scoping Tool (CWST) Summary

Points Details	
Maximum Score =	397
Your Score =	209
Best Practices Rating =	53%

Based on plant information, there is medium potential and energy savings in the range of 5-15% can be anticipated.

Section	Your Score	Maximum Score	%
General	46	90	51
System Components			
Compressors	53	80	66
Condensers	35	75	47
Evaporators	35	70	50
Cooling Towers	33	62	53
Plate Heat Exchangers/Waterside Economizers	0	0	-
Pumps	7	20	35
Total	**209**	**397**	53

CWST Hands-on Exercise Next Steps

- Overall Chilled Water System (51%)
  - Calculate chilled water costs & trend
  - Correlate chilled water costs with production and benchmark
  - Undertake insulation appraisal
  - Consider doing a chilled water system audit, possible process integration and improve to state-of-the-art controls
- Compressors (66%)
  - Incorporate appropriate instrumentation to allow for compressor efficiency calculations
  - Investigate compressor capacity control using variable speed drives
  - Optimize load and compressor operations given there are multiple chiller units

CWST Hands-on Exercise Next Steps

- Condensers (47%)
  - Improve maintenance practices
  - Add instrumentation and apply fault detection and diagnostics to provide for optimized operations
- Evaporators (50%)
  - Improve maintenance practices
  - Add instrumentation and apply fault detection and diagnostics to provide for optimized operations
  - Evaluate changes in set-point temperature, if possible

CWST Hands-on Exercise Next Steps

- Cooling Towers (53%)
  - Improve cooling tower controls and maybe evaluate floating cooling tower water temperature
  - Add instrumentation and apply fault detection and diagnostics to provide for optimized operations
  - Automate blowdown based on water chemistry
- Pumps (35%)
  - Evaluate potential of operating the optimal number of pumps
  - Consider a separate energy system audit on the pump systems
  - Look for bypass flows and low temperature differences to identify excess pump flows

Key Points / Action Items

1. Use a systematic approach (gap analysis, comparison to BestPractices) to identify potential energy saving opportunities that may exist in Chilled Water systems

2. The Chilled Water System Scoping Tool (CWST) can be used to identify these improvement opportunities

3. The CWST is an intake questionnaire to collect preliminary plant level information

4. It shouldn't take more than 60 minutes to complete but we need to be speaking to the RIGHT (knowledgeable) person in the plant

Chilled Water System Energy Efficiency Metrics

System Efficiency Metrics

- Every chilled water system is built up of multiple chiller units
  - Individual packaged units serving a specific load
  - Packaged units combined with a central loop system
  - Distributed chilled water systems with certain components integrated with process while others in a central loop (typical of multiple temperature levels)
  - One or more combinations of the above
- Every chilled water system will provide a cooling effect (load, demand) – summation of multiple chiller units
- Every chilled water system will need energy (most times electric) but in certain systems can be thermal (steam, hot water, etc.)

Chiller Unit Capacity

- Chiller unit capacity (Tonnage) is the amount of full load cooling capacity provided by the chiller unit at design conditions

- Units of cooling capacity or refrigerating effect are RT (or sometimes TR)

- In the USA and some other places - Refrigeration Ton (RT) is used
  - The amount of thermal energy to be removed from 1 short tonne (2,000 lbs) of water at 32°F to make it into ice at 32°F in one day (24 hr) is 1 RT

- **1 RT = 12,000 Btu/hr**

Unit Performance Metrics

$$COP = \frac{\boldsymbol{Cooling\ or\ Heating\ Load}}{\boldsymbol{Energy\ Required}}$$

- Coefficient of Performance (COP)
  - ASHRAE definition - Ratio of the benefit provided to the energy used
  - COP is dimensionless – units of Cooling / Heating Load and Energy used should be the same
  - Depending on the system
    - Cooling COP
    - Heating COP

Unit Performance Metrics

$$\text{EER} = \frac{\textit{Cooling Load}}{\textit{Compressor Power}}$$

- Energy Efficiency Ratio (EER)
  - Used for packaged cooling systems that are electric motor driven with compressors
  - EER is dimensionless – units of Cooling Load and Compressor Power used should be the same
  - EER is calculated at a single point of operation (design)
  - EER will not be able to provide energy consumption but will be needed for every energy-related calculation

Unit Performance Metrics

$$kW/RT = \frac{Compressor\ Power\ (kW)}{Cooling\ Load\ (RT)}$$

- Most standard rating in USA for Chilled Water systems - kW/RT
- Amount of compressor power (kW or hp) required to produce 1 RT of cooling or refrigeration

$$COP_{cooling} = EER = \frac{3.517}{(\frac{kW}{RT})}$$

- Conversion between Cooling COP, EER and kW/RT is simple

Example - Determining Chiller Unit Energy and Costs

- Chiller unit information provided
  - Cooling capacity = 1,000 RT
  - Chiller performance (efficiency) = 0.65 kW/RT
  - Annual operation = 6,250 hours
  - Electric power cost = 0.10 $/kWh

$$\boldsymbol{Power = Cooling\ Load * Efficiency}$$

$$\boldsymbol{Annual\ Energy = Power * Hours}$$

$$\boldsymbol{Operating\ Cost = Annual\ Energy * Energy\ Cost}$$

Example - Determining Chiller Unit Energy and Costs

- Chiller unit information provided
  - Cooling capacity = 1,000 RT
  - Chiller performance (efficiency) = 0.65 kW/RT
  - Annual operation = 6,250 hours
  - Electric power cost = 0.10 $/kWh

$$\textbf{Power} = 1,000 * 0.65 = 650\ \textbf{kW}$$

$$\textbf{Annual Energy} = 650 * 6{,}250 = 4{,}062{,}500\ \textbf{kWh}$$

$$\textbf{Operating Cost} = 4,062,500 * 0.10 = \$406{,}250$$

Example - Determining Chiller System Energy and Costs

- Additional Chiller System information provided
  - Pump motors = 75 kW
  - Cooling tower fan motor = 15 kW

Example - Determining Chiller System Efficiency

- Chiller System information provided
  - Cooling capacity = 1,000 RT
  - Chiller Unit Efficiency = 0.65

$$System\ Efficiency = \frac{\sum_n Power\ kW}{\sum_m Chiller\ Cooling\ RT}$$

Example - Determining Chiller System Energy and Costs

$$\textbf{System Power} = (1,000 * 0.65 + 75 + 15) = 740\ \text{kW}$$

$$\textbf{System Annual Energy} = 740 * 6{,}250 = 4{,}625{,}000\ \text{kWh}$$

$$\textbf{System Operating Cost} = 4,625,000 * 0.10 = \$462{,}500$$

$$\text{System Efficiency} = \text{Total Power / Cooling Tons}$$

$$= 740 / 1{,}000 = 0.740$$

Example - Determining Other Chiller System Metrics

- Specific Cooling Cost

$$\textit{Specific Chiller Unit Cooling Cost} = \frac{\textit{Chiller Unit Annual Energy Cost}}{\textit{Annual Cooling Tonhours}}$$

$$\textit{Specific Chiller System Cooling Cost} = \frac{\textit{Chiller System Annual Energy Cost}}{\textit{Annual Cooling Tonhours}}$$

Example - Determining Other Chiller System Metrics

- Specific Cooling Cost

$$Specific\ Chiller\ Unit\ Cooling\ Cost = \frac{406,250}{1,000\ x\ 6,250} = 0.065\ \$/RT$$

$$Specific\ Chiller\ System\ Cooling\ Cost = \frac{462,500}{1,000\ x\ 6,250} = 0.074\ \$/RT$$

Chiller Unit Performance Metric Ranges

- Best place to obtain Chiller Efficiency (Performance) information is manufacturer's catalogs and websites
- Every manufacturer will define design conditions for heat rejection
  - Water-cooled – (85 / 95°F)
  - Air-cooled – (95°F)
- Every manufacturer will define design conditions for chilled water
  - 44 / 55°F
- Efficiency ranges from OEMs – 0.3 to 1.0 kW/RT
  - This is dependent on several factors and control mechanisms

Polling Question 1

Polling Question

1) What is the typical average operational range for kW / RT for your chiller plant efficiency?
   A. < 0.5
   B. 0.5 – 0.75
   C. 0.75 – 1.00
   D. > 1.0
   E. Do not know

Polling Question 2

Polling Question

2) What do you believe is the typical annual operating energy cost for your chiller plant?

   A. < $250,000
   B. $250,000 - $1,000,000
   C. > $1,000,000
   D. Do not know

Seasonal Energy Efficiency Metrics

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Chiller Design Specifications

- In the US, each chiller can be tested at the manufacturer's testing facility per AHRI Standard 550
  - There maybe an extra charge for this test
  - There maybe limitations based on size of chiller and testing facility capability
- Performance for typical commercially available packaged chiller units
  - Water cooled – 0.4 – 0.8
  - Air cooled – 0.7 – 1.3
- Full load design rating conditions versus seasonal operating rating conditions
- ASHRAE Standard 90.1 provides minimum performance requirements for chillers

Seasonal Energy Efficiency of the Chiller System

- The efficiency of chilled water systems is dependent on several factors:
  - Cooling Load
  - Cooling supply temperature
  - Heat rejection temperature
  - Compressor efficiency
  - Control mechanisms
  - Variable Frequency Drives
  - Number of operating chiller units
  - Heat exchanger surface areas
  - Other site-specific factors

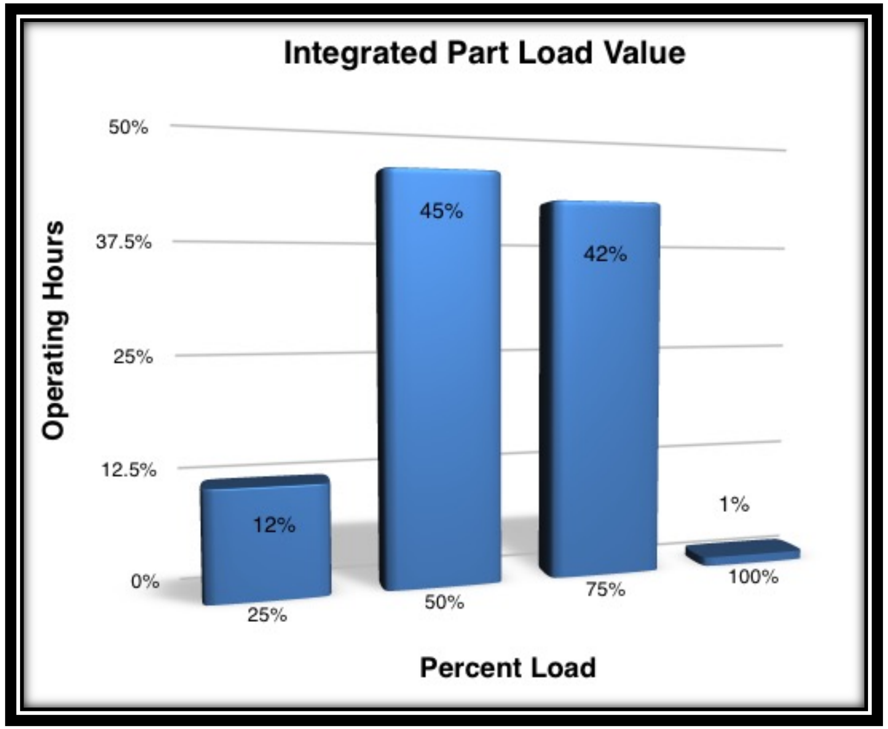
Integrated Part Load Value

- Integrated Part Load Value (IPLV) is defined by AHRI in the AHRI Standard 550/590
- It is accepted by the ASHRAE and compliant with ASHRAE 90.1
- IPLV is a weighted value of 4 standard loads and Entering Condenser Water Temperatures (ECWT):
  - 100% load @ 85°F ECWT
  - 75% load @ 75°F ECWT
  - 50% load @ 65°F ECWT
  - 25% load @ 65°F ECWT

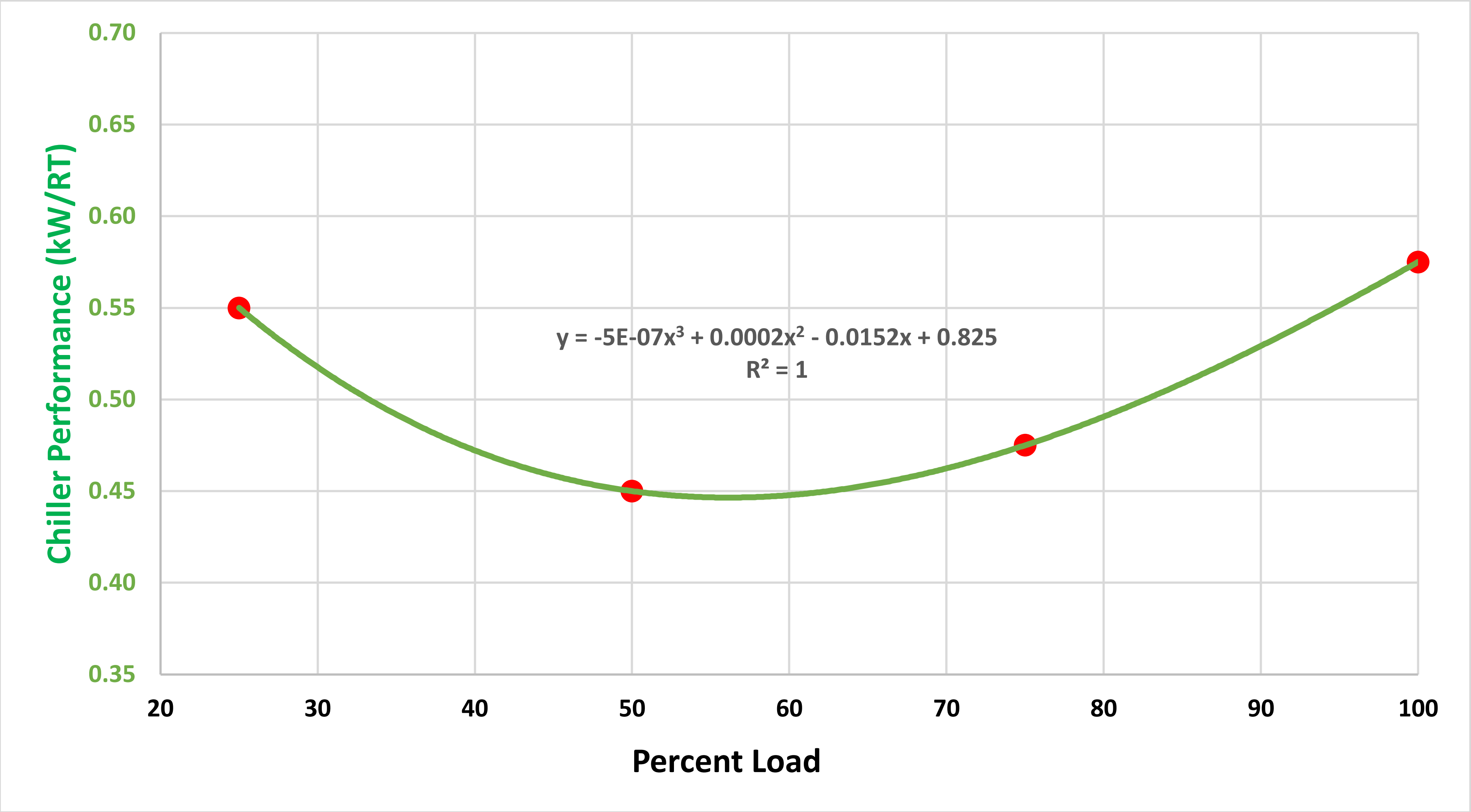
Integrated Part Load Value

- Generally, a chiller operates at full load design conditions for 1% of the total operating hours **ONLY**

- Hence, no decisions should be based on the design efficiency but instead they should be used as a guide to reach optimal solutions



Overall Chiller Performance



Chiller Full Load Design Specifications

Chiller ID	Chiller #6	Chiller Manufacturer	JCI
Year Commissioned	2005	Chiller Type	Constant Speed Centrifugal
Model Number	YKY4Y4J75DJF	Serial Number	YX24584BC
Refrigerant	R134a	Capacity	2,000 RT
Design Efficiency	0.625	IPLV	0.541
Full Load Amps	198	Volts	4160
Evaporator Entering Water Temperature	55°F	Condenser Entering Water Temperature	85°F
Evaporator Leaving Water Temperature	44°F	Condenser Leaving Water Temperature	95°F
Evaporator Flow	4,800 gpm	Condenser Flow	6,000 gpm
Evaporator Pressure Drop	10 psid	Condenser Pressure Drop	10 psid

Key Points / Action Items

1. kW / RT is the energy efficiency chiller and system metric used
2. System Efficiency includes power consumed by the chiller compressor motor, chilled water pumps, cooling tower pumps, fans and other parasitic users
3. Load profile is very important to understand the year-round system cooling / refrigeration demand
4. Chiller plant operating cost calculation will require load profile, operating hours, system efficiency and electric utility cost
5. Chiller manufacturers design, specify and test chillers
6. IPLV is most commonly used to determine average rating

Additional Metrics in Chilled Water Systems

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Additional Performance Metrics

- Generally needed for more detailed analysis
- Periodic assessment (if not continuous) is recommended
- Provides a good baseline and identifies a problem before failures
- SMART algorithms can implement these metrics for trending performance
  - Closed-loop feedback controls are programmed into chilled water system controllers that optimize the operations of the chilled water system real-time

Chilled Water Plant Operating Data

- There are several different data points that are required for a chiller plant assessment
  - Evaporator and Condenser Entering and Leaving Water Temperatures
  - Evaporator and Condenser Water Flow Rates / Delta Pressure
  - Evaporator and Condenser Refrigerant Pressures
  - Compressor suction and discharge temperatures
  - Amps, Volts and Power Factor (Input kW) or equivalent data for steam turbine horsepower
  - Pumping power (primary, secondary)
  - Cooling tower fan power

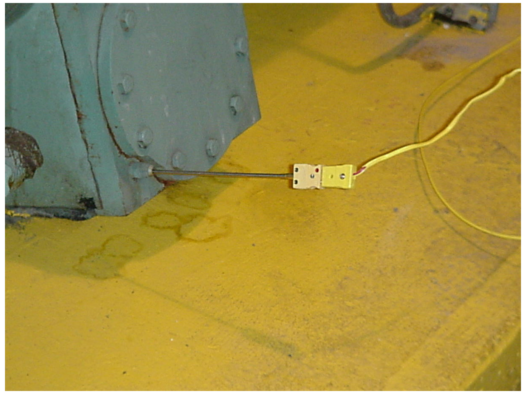
- This data can be collected at regular intervals
  - Manually through log sheets
  - By the BAS/EMS

Calibration & Accuracy of Sensors

- To calculate chilled water system performance metrics, the operating data must be accurate
- All sensors drift over time
- Regular calibration is required
- Sensor Accuracy (General guidelines):
  - Temperature sensors must be accurate to within 0.2 °F
  - Differential pressures (dP) must be accurate to 0.25 psid
  - Water flows must be accurate to within 2.0%
  - Refrigerant pressures must be accurate to within 0.5%

Temperature Measurements

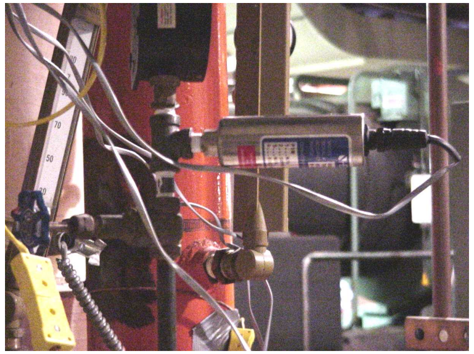
- Different types
  - Thermometers
  - Thermocouples
  - RTD’s
  - Infrared gun / camera



- Differential measurement can be done via a thermopile
- Load calculations require a “difference in two temperatures” – ΔT - accuracy very important

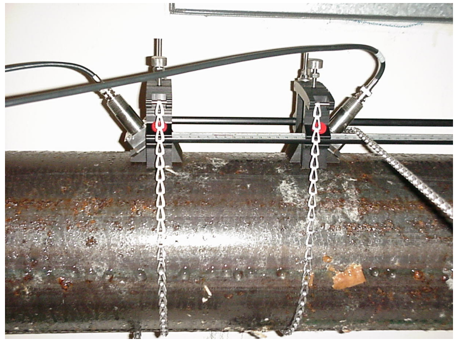
Pressure Measurements

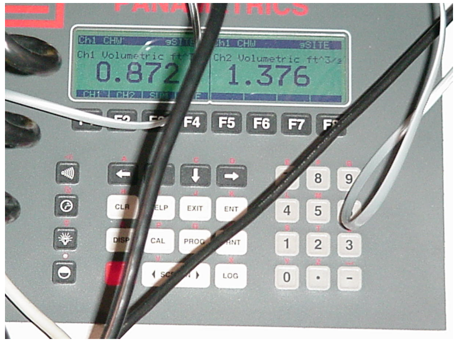
- Most common
  - Bourdon-tube gage
  - Capacitative
- Pressure transducers used very frequently for data monitoring
- Pressure monitoring devices will require specific ranges – understanding operating range of the chiller is required



Flow Measurements

- There are different kinds of flowmeters
  - Orifice plate / Annubar / Pitot tube
  - Turbine type
  - Vortex shedder
  - Magnetic
  - Ultrasonic (non-intrusive), etc.



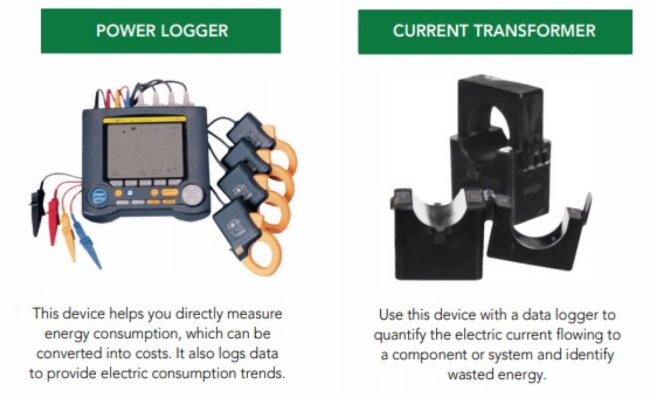


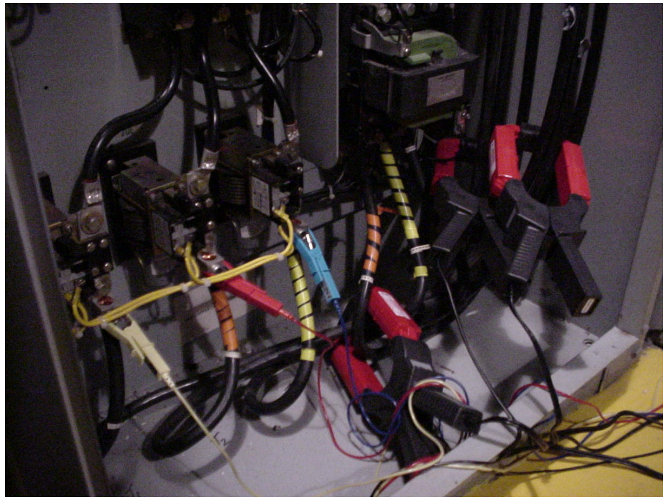
- Flow can also be measured using pressure drop (ΔP) in heat exchangers and comparing it to design flow and design pressure drop

$$Flow_{actual} = Flow_{design} \times \sqrt{\frac{\Delta Pactual}{\Delta Pdesign}}$$

Power Measurements

- Power meter is the common device for measuring power
- It will require simultaneous measurements of
  - Current on each phase
  - Voltage on each phase
  - Power factor
- First-order estimate can be made from current measurements
- Current Transducers (CTs) are very common



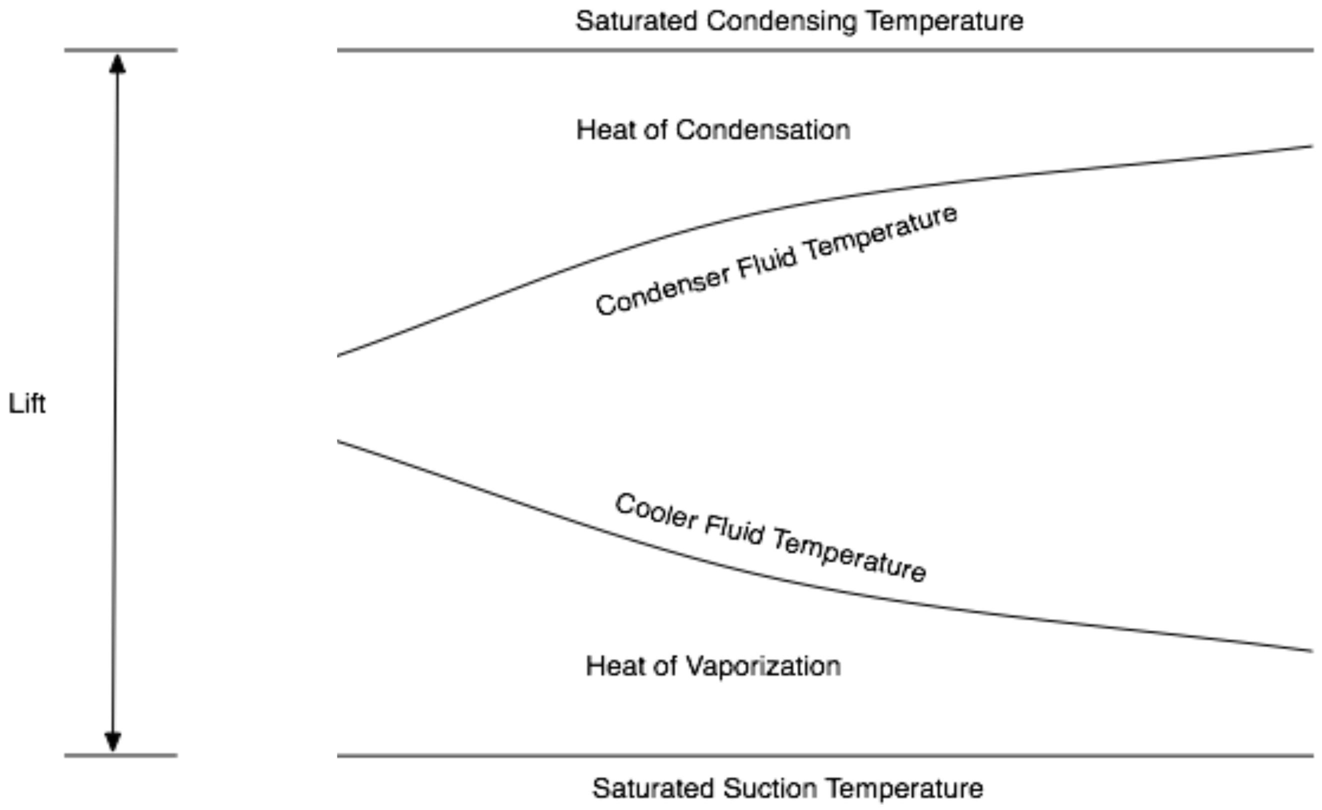


General Chiller System Performance Metrics

- Overall chiller system plant performance
  - Total cooling load
  - Total kW (including chillers and auxiliaries)
- Chiller Lift
- Chiller efficiency
  - Carnot efficiency
  - Chiller actual efficiency (kW / RT)
- Compressor isentropic efficiency
  - Suction and discharge temperatures
  - Suction and discharge pressures
- Heat exchanger effectiveness
  - Approach temperatures
  - ΔT on chilled water and cooling tower water

Chiller Lift

- Difference between Saturated Condensing Temperature and the Saturated Suction (Evaporating) Temperature



Carnot Efficiency

$$Carnot\ Efficiency = \frac{T_{cold}}{T_{reject} - T_{cold}}$$

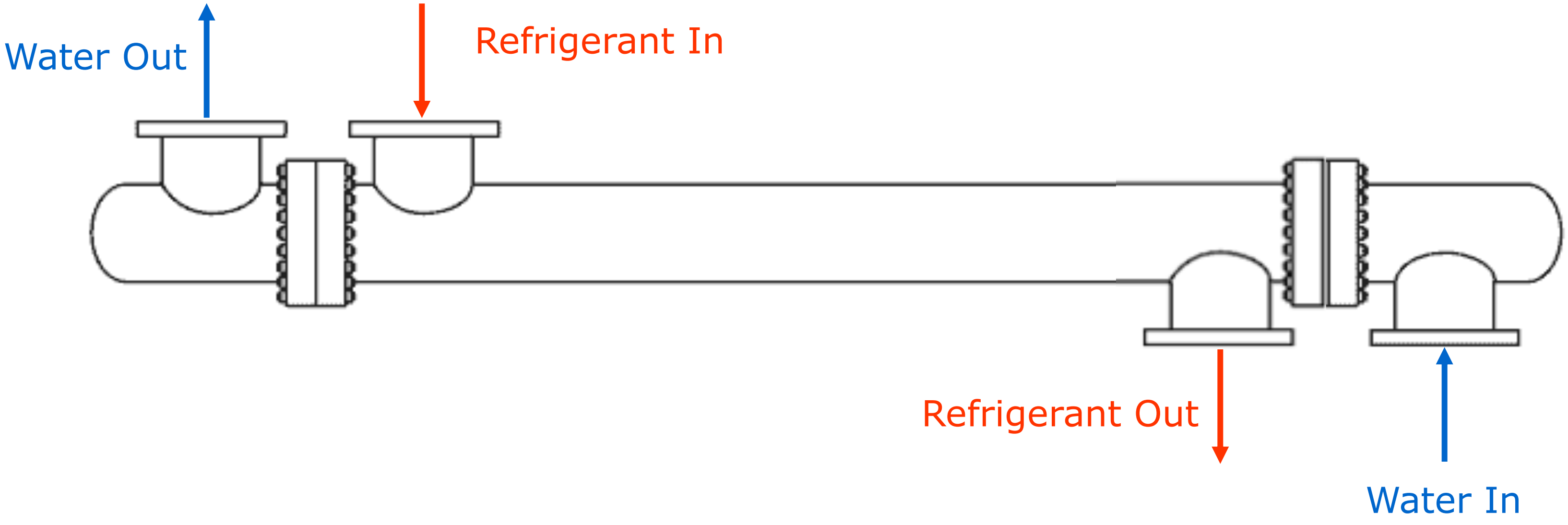
- Ideal Carnot Efficiency
  - Dependent of cooling supply temperature and heat rejection temperature ONLY
  - All temperatures should be in the absolute temperature scale (R)
    - Absolute Temperature (R) = Temperature (°F) + 460

Compressor Isentropic Efficiency

- Information required
  - Suction and discharge temperatures
  - Suction and discharge pressures
- Comparison of work done by ideal compressor (isentropic) versus the actual compressor
- Measure of energy lost in temperature increase compared to just pressure increase
- Lower efficiency implies higher compressor discharge temperatures and higher compressor power!

Heat Exchangers

- Principle of Conservation of Energy
  - First Law of Thermodynamics
  - Energy Flow In = Energy Flow Out



- Heat Exchanger Performance
  - Design Information
    - Operating Temperatures, Pressures, Flows
    - Fluid information
    - Heat exchanger area, Log Mean Temperature Difference, Fouling coefficient, Overall Heat Transfer coefficient (U)
    - Heat Duty
  - Log Mean Temperature Difference (LMTD)
    - Determines the driving force available for heat transfer
    - Higher LMTD's imply inefficiency and losses

Heat Exchangers

- Refrigerant Approach Temperatures (RAT)
  - RAT = Absolute (Leaving Water Temperature - Saturated Refrigerant Temperature)

- Saturated Refrigerant Temperature refers to the refrigerant being heated (evaporator) or cooled (condenser)

- Every CR unit has a manufacturer full load design Evaporator RAT and Condenser RAT

- When RAT increases for the same heat load, it indicates an increase in heat exchanger fouling (heat transfer resistance)

Key Points / Action Items

1. *Actual operating performance calculations for chiller systems will require temperatures, pressures, flows and power information*

2. *It is important to calculate both overall chiller plant and individual chiller operating efficiency*

3. *The other chiller plant efficiency metrics include: Lift, Isentropic compressor efficiency, Heat Exchanger effectiveness, etc.*

4. *Fouling impact in heat exchangers has to be determined and related to reduction in efficiency and increase in operating costs*

5. *Refrigerant Approach Temperature (RAT) serves as a good proxy for LMTD (driving force)*

Chilled Water System Load Profile

Load Profile

- Chilled water systems will NEVER have a constant cooling load
- Most high-level analysis (ASHRAE Level 1, plant walk-through) can be done using design information with a load factor approach
- Every chilled water system energy efficiency and optimization analysis will need to consider the cooling load profile of the system
- Level of detail and time intervals will vary based on several factors – availability of data, time-based sensitivity of the load, repeatable patterns and significant factors, etc.

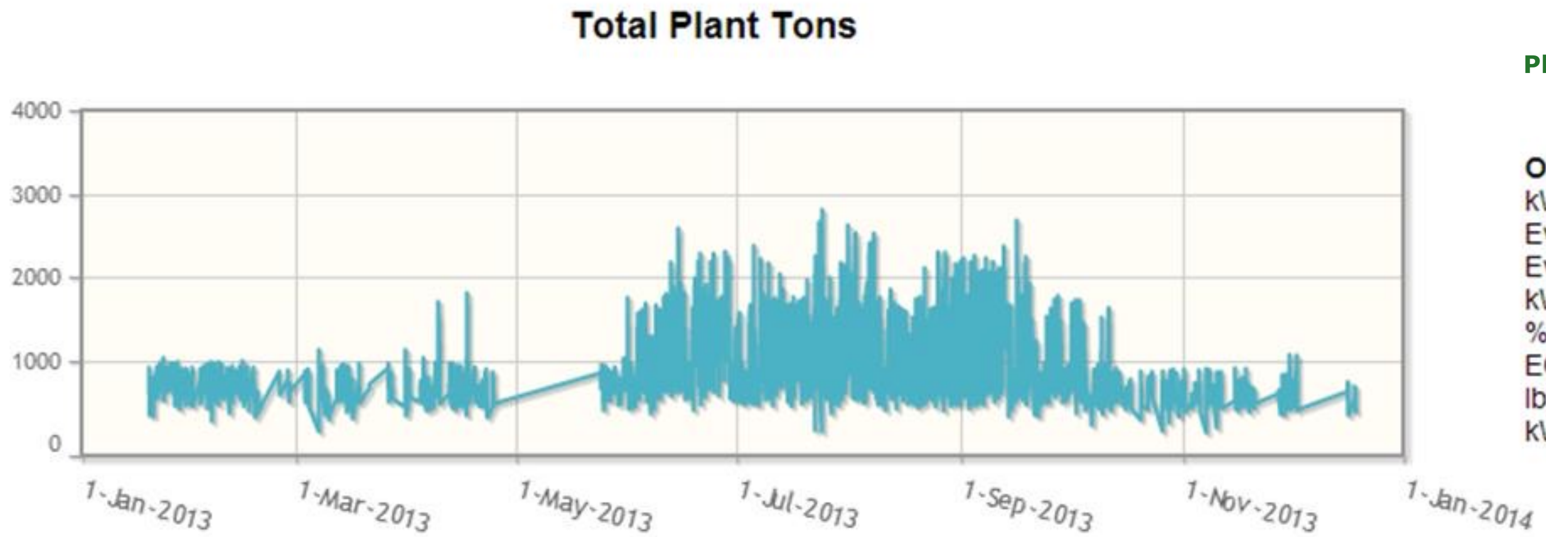
Chilled Water System Load Profile

- Every chilled water system and industrial plant is UNIQUE
- Nevertheless, the shape of the load profile may coincide across similar plants
- Determination of a true load profile is very difficult in a real-world scenario but there are several techniques and methods to define and develop a load profile for any chilled water system
- Every chilled water energy efficiency assessment should require the inclusion of a representative load profile

Chilled Water System Load Profile

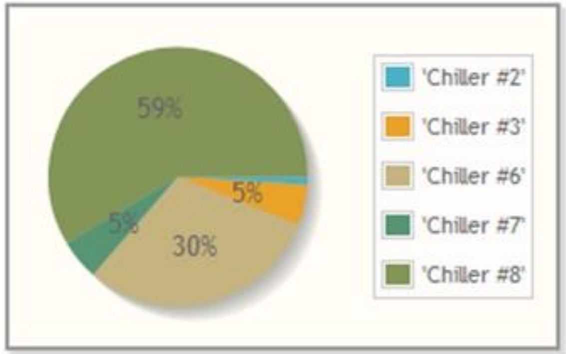
- Developing a load profile requires data collection
- Load profile should be developed for a certain time period
  - Annual – most common by using daily averages or hourly averages
  - Seasonal – production dependent; weather dependent
  - Monthly, Weekly, Daily – load is independent of weather and is strictly a function of product throughput
- Load profile can also be simulated using process modeling as well as using historian data and statistical analysis
- Actual real-time operating data – state-of-the-art

Large Commercial Central Plant

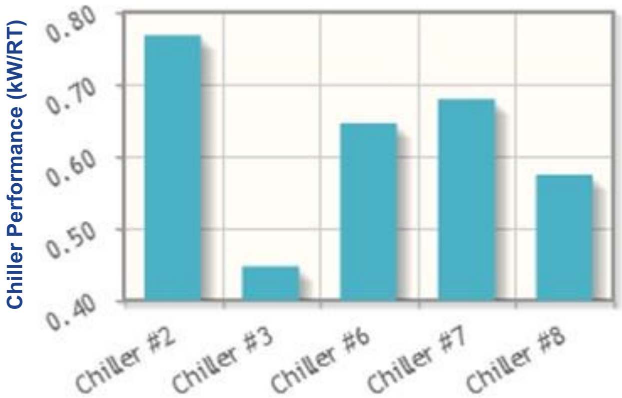


Plant Cooling Capacity - 6,000 RT

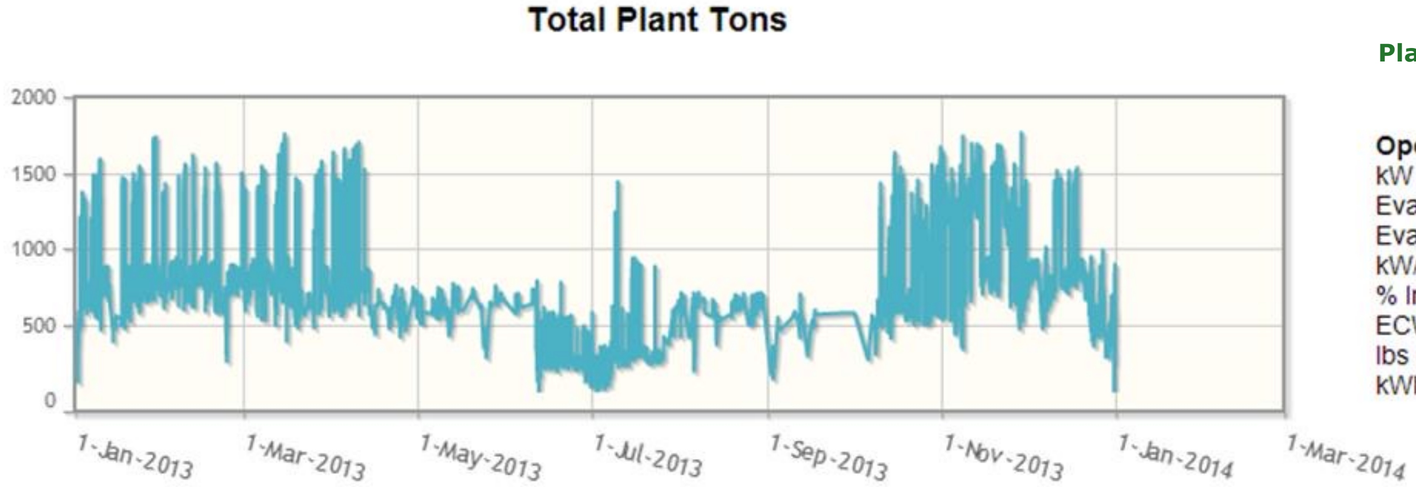
Operating Averages
kW = 410.53
Evaporator tons = 690
Evaporator Δ °F = 6.77
kW/ton = 0.596
% Input Power = 68.27
ECWT °F = 75.28
lbs CO_2 Eq. produced = 562.43
kWh Cost = 24.63 per Hour



Cooling Load Hours (Tonhours) Contribution of Operating Chillers

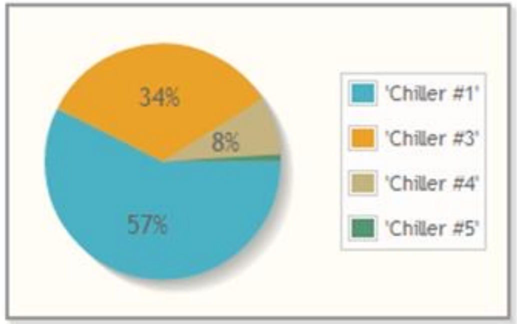


Food Manufacturing Plant Seasonal Operation

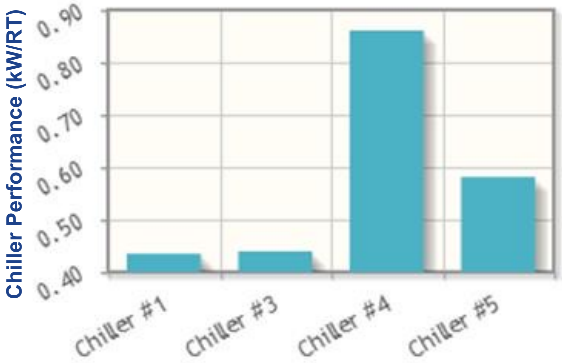


Plant Cooling Capacity - 3,500 RT

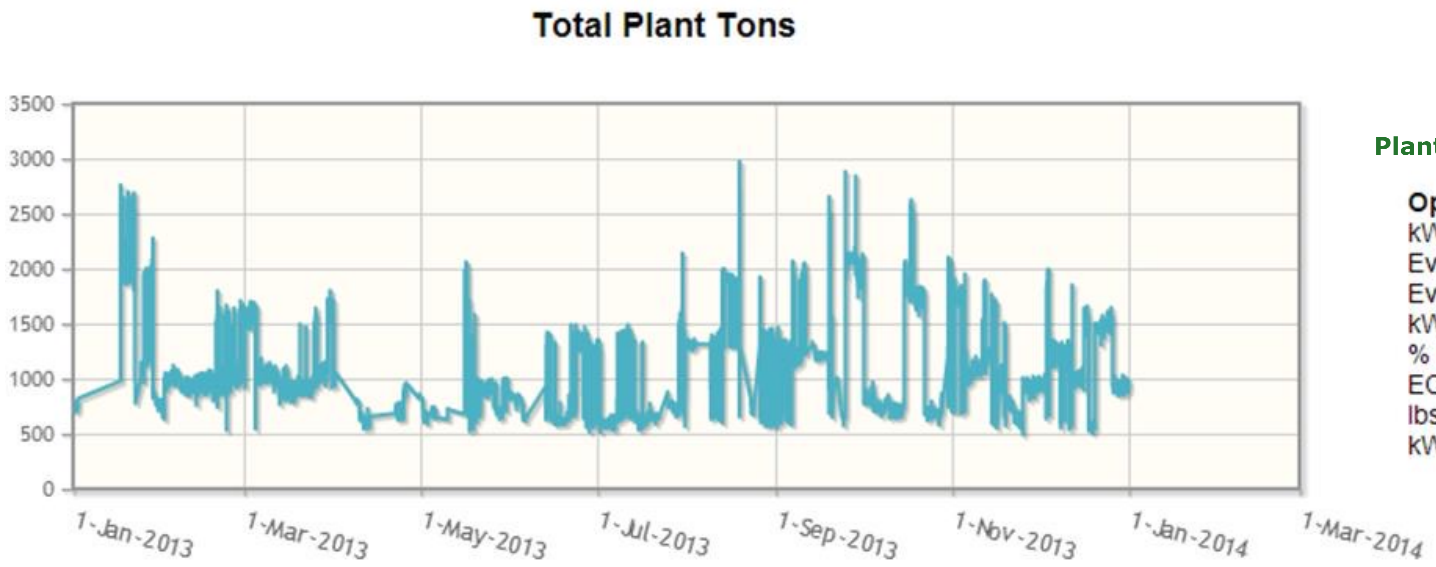
Operating Averages
kW = 273.83
Evaporator tons = 584
Evaporator Δ °F = 9.35
kW/ton = 0.515
% Input Power = 66.27
ECWT °F = 75.53
lbs CO2 Eq. produced = 375.14
kWh Cost = 13.69 per Hour



Cooling Load Hours (Tonhours) Contribution of Operating Chillers

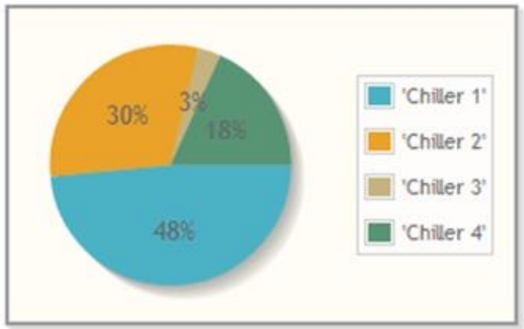


Data Center Central Plant

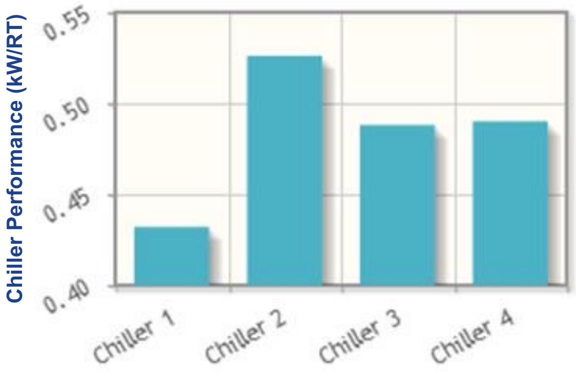


Plant Cooling Capacity - 4,500 RT

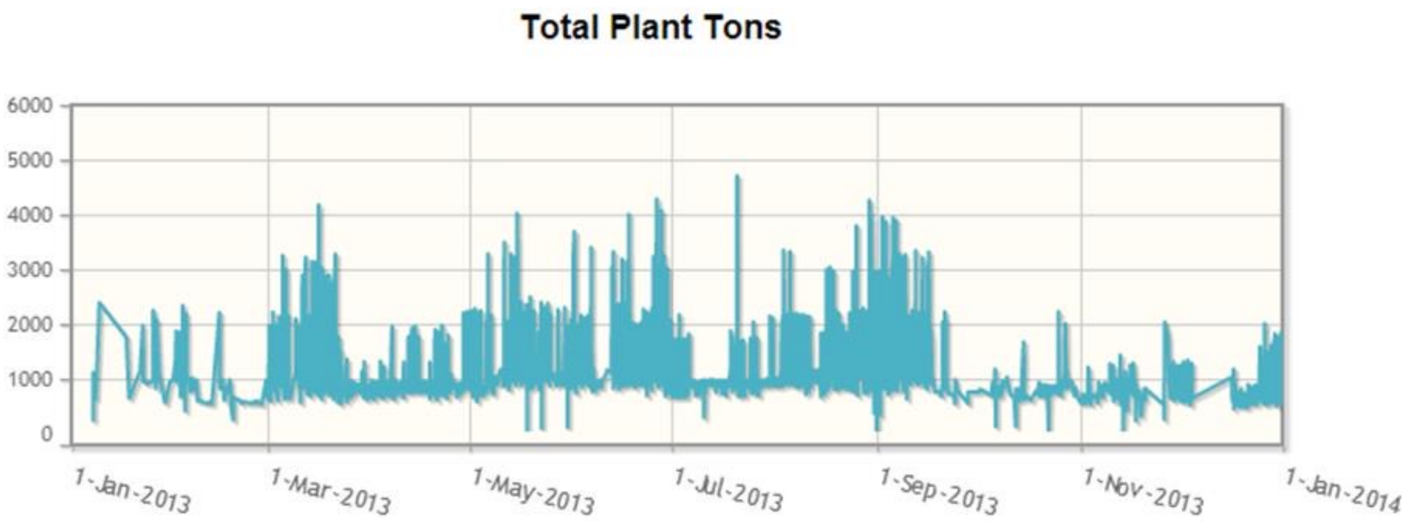
Operating Averages
kW = 391.85
Evaporator tons = 822
Evaporator Δ °F = 11.67
kW/ton = 0.481
% Input Power = 56.03
ECWT °F = 73.75
lbs CO2 Eq. produced = 1359.71
kWh Cost = 25.47 per Hour



Cooling Load Hours (Tonhours) Contribution of Operating Chillers

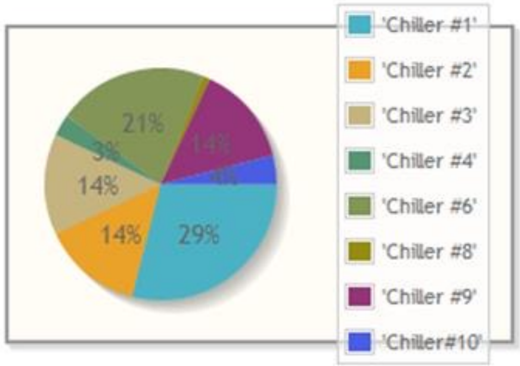


Casino Operation

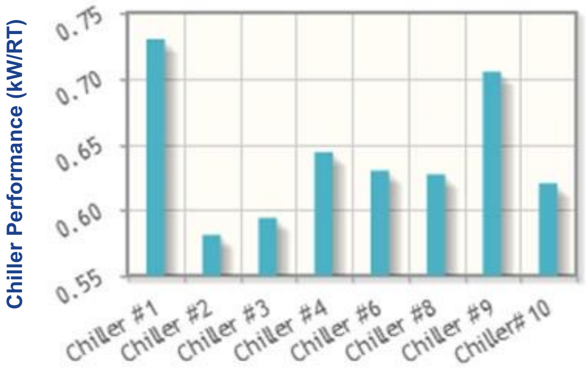


Plant Cooling Capacity - 43,000 RT

Operating Averages
kW = 585.97
Evaporator tons = 912
Evaporator Δ °F = 9.28
kW/ton = 0.663
% Input Power = 83.07
ECWT °F = 76.06
lbs CO2 Eq. produced = 802.77
kWh Cost = 64.46 per Hour



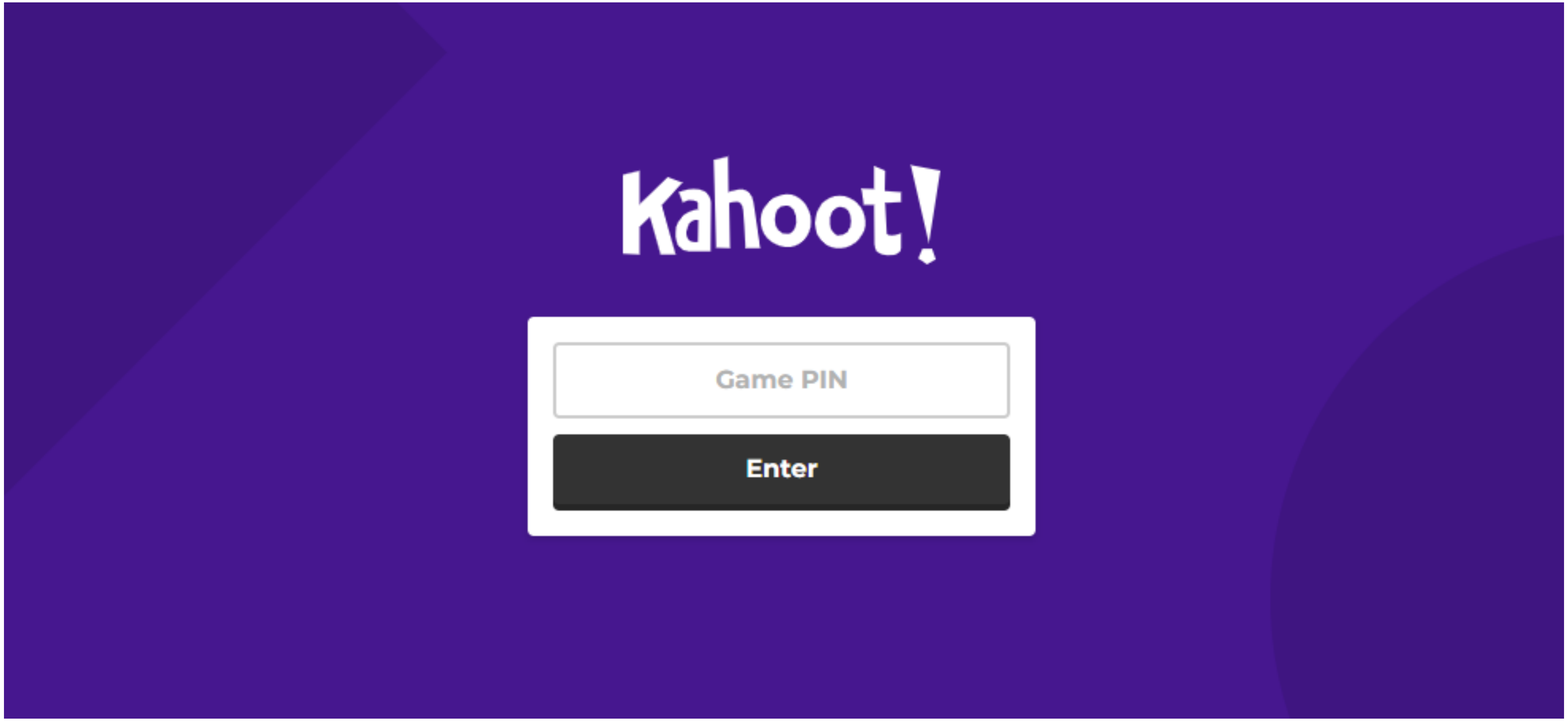
Cooling Load Hours (Tonhours) Contribution of Operating Chillers



Homework #2

- Complete the Chilled Water system Scoping Tool (CWST) on your specific plant and understand the current bestpractices and potential gaps in your plant
- How well is your chilled water system compared to a state-of-the-art system?
- Identify 3 bestpractices that have been implemented in your chilled water system operations and management
- Identify 3 energy efficiency improvement opportunities in your chilled water system after completing the CWST

Kahoot Quiz Time



Thank You all for attending today's webinar.

See you all on next Thursday – June 16, 2022 – 10 am ET

If you have specific questions, please stay online and we will try and answer them.

Alternately, you can email questions to me at rapapar@c2asustainable.com