MINISTRY OF INDUSTRY AND TRADE

EU - VIET NAM SUSTAINABLE ENERGY TRANSITION PROGRAMME (SETP)

Global Gateway

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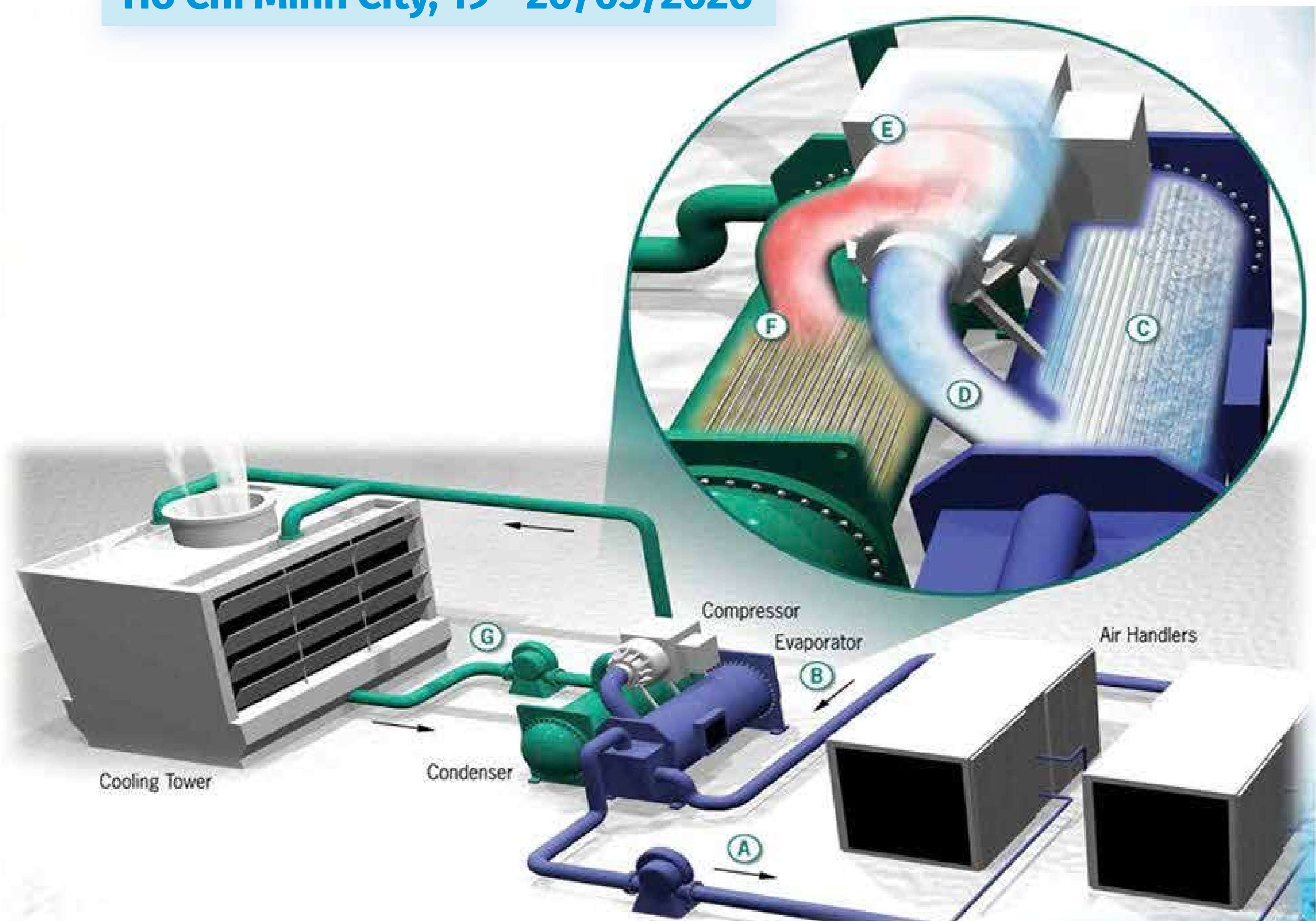
Project "Accelerating energy efficiency (EE) in large industries through energy management system, system optimisation and the promotion and adoption off EE in SMEs" (IEEP)

TRAINING PROGRAMME COOLING - REFRIGERATION SYSTEM OPTIMISATION (CRSO)

Ho Chi Minh City, 19 - 20/05/2026



AGENDA

TRAINING PROGRAMME
COOLING & REFRIGERATION SYSTEM OPTIMISATION (CRSO)

From 19 May to 20 May 2026

Victory Hotel, 14 Vo Van Tan Street, Xuan Hoa Ward, Ho Chi Minh city

Day 1: 19/05/2026

Time	Contents	Speakers
8.00-8.30	Registration and welcome	
8.30-8.35	Participants Introduction	IEEP Project
8.35-8.40	Opening speech	Representative of MOIT/IEEP Project
8.40-10.15	Section 1: Fundamentals	International Expert
10.15-10.30	**Tea break**	
10.30-11.40	Section 2: Large Scale Cooling & Industrial Refrigeration Scoping Tool (CRST)	International Expert
11.40-12.00	Quiz	International Expert
12.00-13.00	**Lunch at the Hotel**	
13.00-14.00	Section 3: Calculations of Unit & System Efficiency	National Expert
14.00-15.15	Section 4: Chilled Water System Assessment Tool (CWSAT-SI)	National Expert
15.15-15.30	**Tea break**	
15.30-16.40	Section 5: Energy Efficiency Opportunities in Chilled Water Systems	International Expert
16.40-17.00	Quiz	International Expert

Day 2: 20/05/2026

Time	Contents	Speakers
8.00-8.30	Registration and welcome	
8.30-8.45	Questions from Day 1 (One on one with Facilitator), Software issues & help	International Expert Facilitator
8.45-9.15	Section 6: Refrigerants – Past, Present & Future	National Expert
9.15-10.15	Section 7: Industrial Refrigeration Systems	International Expert
10.15-10.30	**Tea break**	
10.30-11.05	Section 8: Modeling an Industrial Refrigeration System	International Expert
11.05-11.40	Section 9: Energy Efficiency Opportunities in Industrial Refrigeration Systems	International Expert
11.40-12.00	Quiz	International Expert
12.00-13.00	**Lunch at the Hotel**	
13.00-14.00	Section 10: CR Systems Optimisation Case Studies	National Expert
14.00-14.45	Section 11: Other Energy Efficiency Software Tools for CR Systems	National Expert
14.45-15.00	**Tea break**	
15.00-16.00	Section 12: Next Generation CR Systems	International Expert
16.00-16.20	Section 13: Chilled Water & Refrigeration System Optimisation - Conclusions	International Expert
16.20-16.40	Quiz	International Expert
16.40-17.00	Course Evaluation, Feedback	International Expert

Large-Scale Cooling & Industrial Refrigeration System Optimisation

2-Day End User Training

Day 1

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Facilitator

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Acknowledgements

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Acknowledgements

- Riyaz Papar, Hudson Technologies / ORNL
- Dr. Dragoljub Kosanovic
  University of Massachusetts, Amherst - USA

- UNIDO Team – Vienna, Austria
- UNIDO Team – Vietnam
- Hudson Technologies Company – USA
- Oak Ridge National Laboratory – USA

Housekeeping

- Emergency exits
- Toilets
- Mobile phones
- Tea and lunch breaks
- Restrict emails to breaks

Training Objectives

- Use a Systems Approach to evaluate Cooling and Refrigeration (CR) systems
- Model simple CR systems and calculate operating costs
- Get an overview of CR BestPractices software tools (CRST, CWSAT-SI, CoolPack, 3EPlus, MEASUR)
- Understand developing a load profile and an energy baseline of the CR systems
- Identify the measurements required to manage CR systems and sub-system efficiency
- Measure individual unit and overall plant performance (COP, COSP)

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Training Objectives

- Identify and prioritize areas of potential efficiency improvement in CR systems
- Understand different end-uses and identify areas of end-use efficiency improvements
- Impacts of the Montreal Protocol, Kyoto Protocol, Kigali amendment for refrigerants
- Calculate the energy costs of overall CR system operation and individual sub-systems
- Increase familiarity to undertake field work to do CR system assessments

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Agenda – Day 1

Agenda			
DAY 1			
08:00	-	08:30	Registration and welcome
08:30	-	08:40	Opening speech
08:40	-	10:15	Section 1: Fundamentals
10:30	-	10:45	Tea/Coffee Break
10:45	-	11:40	Section 2: Large Scale Cooling & Industrial Refrigeration Scoping Tool (CRST)
11:40	-	12:00	Quiz
12:00	-	13:00	Lunch
13:00	-	14:00	Section 3: Calculations of Unit & System Efficiency
14:00	-	15:15	Section 4: Chilled Water System Assessment Tool (CWSAT-SI)
15:15	-	15:30	Tea/Coffee Break
15:30	-	16:40	Section 5: Energy Efficiency Opportunities in Chilled Water Systems
16:40	-	17:00	Quiz

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Agenda – Day 2

Agenda			
DAY 2			
08:00	-	08:30	Registration and welcome
08:30	-	08:45	Questions from Day 1 (One on one w/Facilitator), Software issues & help
08:45		09:15	Section 6: Refrigerants – Past, Present & Future
09:15	-	10:15	Section 7: Industrial Refrigeration Systems
10:15	-	10:30	Tea/Coffee Break
10:30	-	11:05	Section 8: Modeling an Industrial Refrigeration System
11:05	-	11:40	Section 9: Energy Efficiency Opportunities in Industrial Refrigeration Systems
11:40	-	12:00	Quiz
12:00	-	13:00	Lunch
13:00	-	14:00	Section 10: CR Systems Optimisation Case Studies
14:00	-	14:45	Section 11: Other Energy Efficiency Software Tools for CR Systems
14:45	-	15:00	Tea/Coffee Break
15:00	-	16:00	Section 12: Next Generation CR Systems
16:00	-	16:20	Section 13: Chilled Water & Refrigeration System Optimisation - Conclusions
16:20	-	16:40	Quiz
16:40	-	17:00	Course Evaluation, Feedback & Adjourn

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Trainee Background / Objectives / Questions

Let’s take 1-2 minutes and at a high-level everyone can chime in

- What brings you here today?
- What issues / concerns do you have about your chilled water and refrigeration systems?
- What energy efficiency projects / upgrades have you done recently in your plants?

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What we don’t have

Power Start – General Summary

- The 2-Day End-User training begins with Fundamentals and by defining the Systems Approach for optimizing an industrial Chilled water and Refrigeration (CR) system
- The training covers the operation of typical industrial CR systems that include
  - Chilled water and/or Refrigeration machines/systems/plants
  - Distribution
  - End-uses
- The training identifies performance improvement opportunities that lead to the optimization of the overall CR systems

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Power Start – General Summary

- The workshop discusses methods of CR system efficiency improvements, methodologies for quantifying energy and cost savings, aspects of implementation, maintenance and continuous improvement programs
- Demonstration of Best Practices Tools:
  - Chilled Water & Industrial Refrigeration Scoping Tool (CRST)
  - Chilled Water System Assessment Tool (CWSAT-SI)
  - CoolPack
  - 3E-Plus insulation appraisal software
  - US DOE's MEASUR
- Case studies and applications of optimizing CR systems
- Next generation CR systems & Refrigerants

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1 FUNDAMENTALS
2 LARGE SCALE COOLING & INDUSTRIAL REFRIGERATION SCOPING TOOL (CRST)
3 CALCULATIONS OF UNIT & SYSTEM EFFICIENCY
4 CHILLED WATER SYSTEM ASSESSMENT TOOL (CWSAT)
5 ENERGY EFFICIENCY (EE) OPPORTUNITIES IN CHILLED WATER SYSTEMS
6 REFRIGERANTS – PAST, PRESENT & FUTURE
7 INDUSTRIAL REFRIGERATION SYSTEMS
8 MODELING AN INDUSTRIAL REFRIGERATION SYSTEM
9 EE OPPORTUNITIES IN INDUSTRIAL REFRIGERATION SYSTEMS
10 CR SYSTEM OPTIMISATION CASE STUDIES
11 OTHER EE SOFTWARE TOOLS FOR CR SYSTEMS
12 NEXT GENERATION CR SYSTEMS
13 CONCLUSIONS

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1 FUNDAMENTALS

1.1 The Systems Approach

1.2 CR System Optimisation

1.3 Refrigerants

1.4 CR System Fundamentals

1.5 CR System Types

1.6 CR System Drives

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1.1 The Systems Approach

- Look at the Forests and DO NOT get lost in the individual tree issue
- Start at the 10,000 ft level, understand the big picture and purpose and then drill down to the street level
- DO NOT rob Paul to pay Peter
- There is NO free lunch
- If something is too good to be true, then it probably isn't
- DO NOT jump to a solution before understanding the full problem and situational issues
- Every system is unique and deserves the same level of due diligence

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The Systems Approach

- Key to cost-effective plant utility system operations and maintenance
- Pay attention to the system as a whole, not just to individual pieces of equipment (chiller, fans, pumps, etc.)
- Analyze both the supply and demand sides of systems and how they interact
- Most systems will need a Systems Approach for proper analysis
- Will lead to significantly higher energy and cost savings than a "component level analysis"

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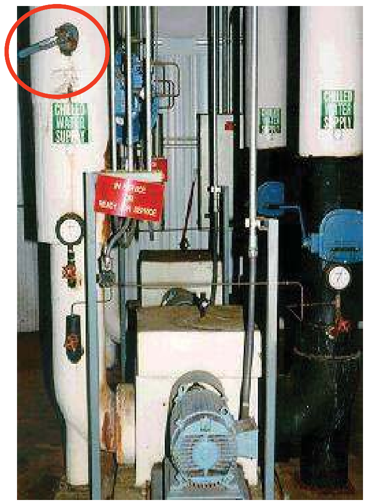
The Systems Approach (with a simplified example)

15 kW motor
efficiency = 91%

Combined motor & pump
efficiency = 59%



System efficiency = 13%

Source: US DOE Better Plants Program

Courtesy: Don Casada, PE – Diagnostic Solutions

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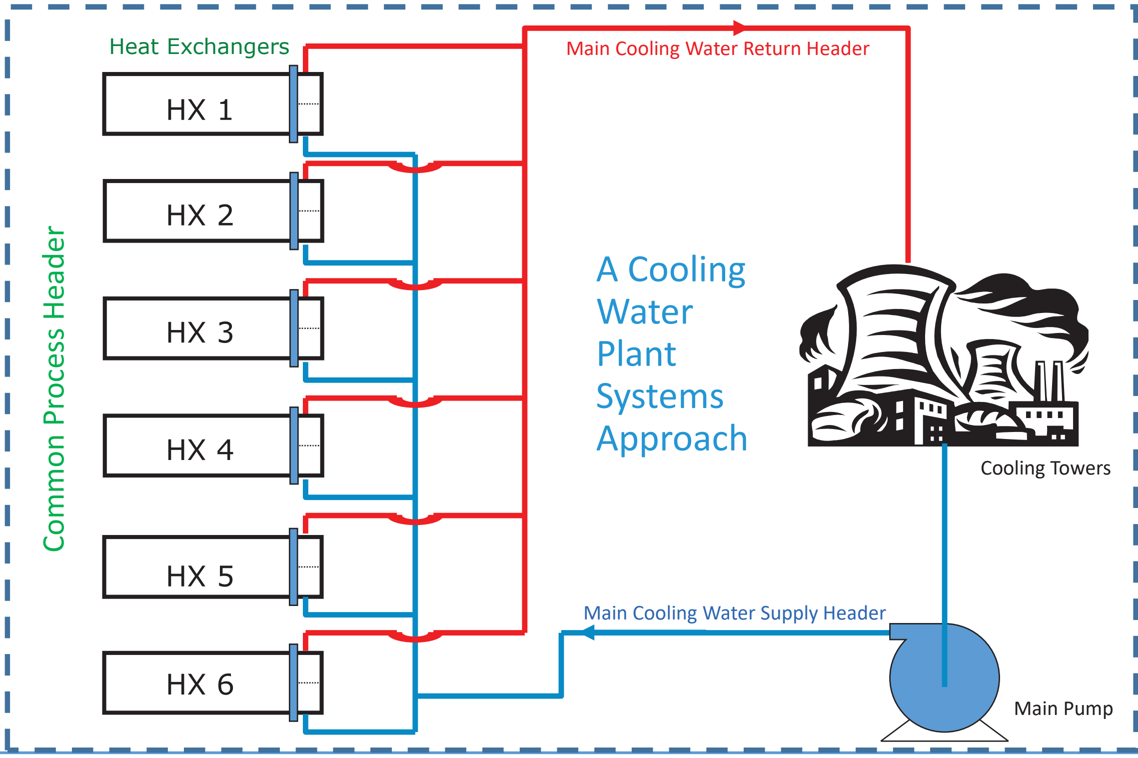
The Systems Approach

- **Establish** current system conditions, operating parameters, and system energy use
- **Investigate** how the total system presently operates
- **Identify** potential areas where system operation can be improved
- **Analyze** the impacts of potential improvements to the plant system
- **Implement** system improvements that meet plant operational and financial criteria
- Continue to **monitor** overall system performance



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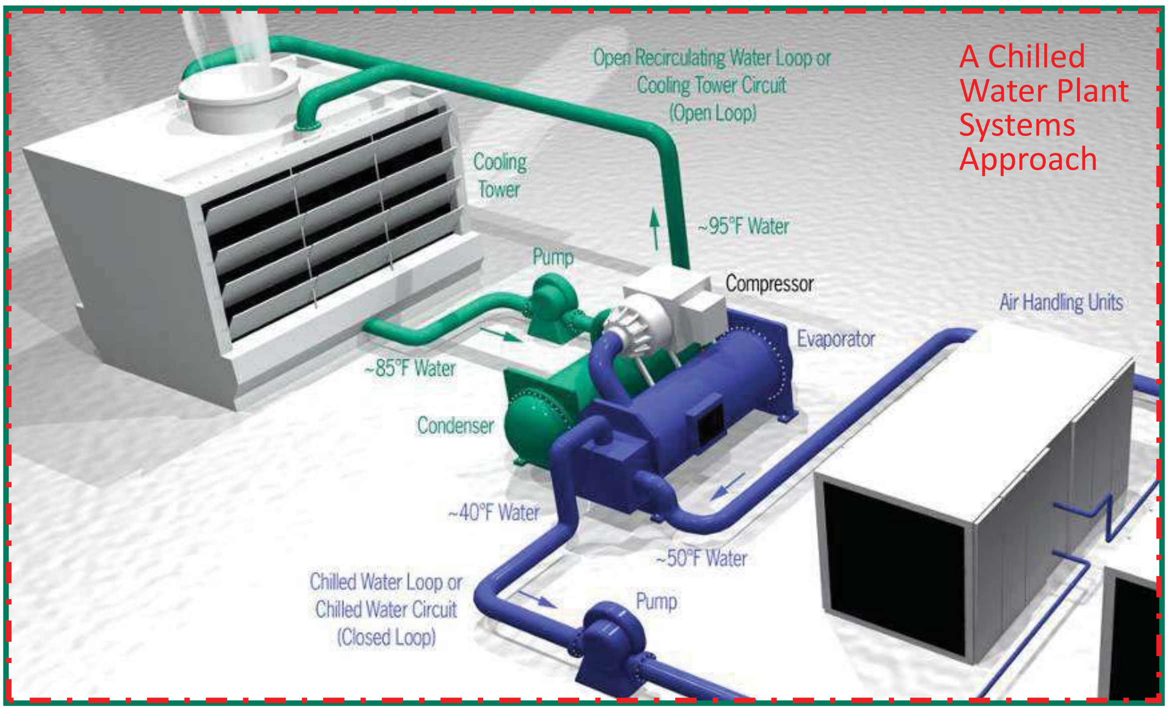

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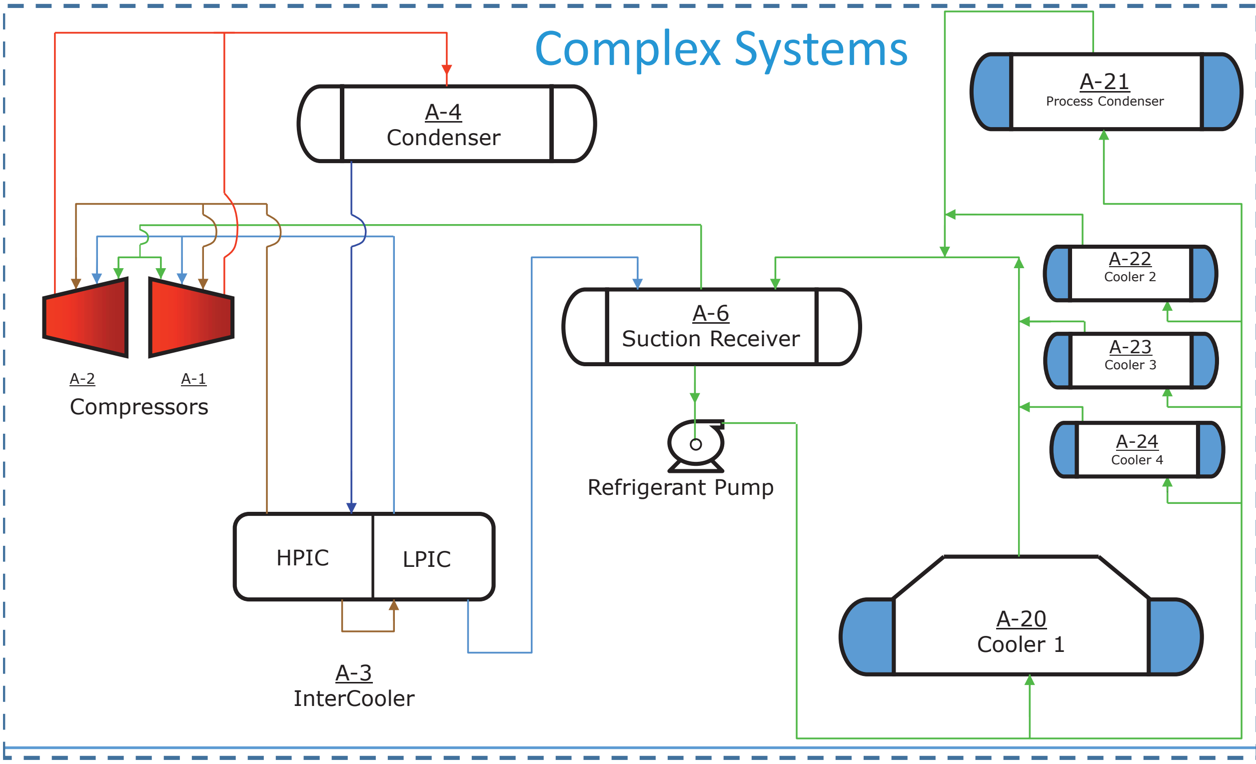
Complex Systems



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1 FUNDAMENTALS

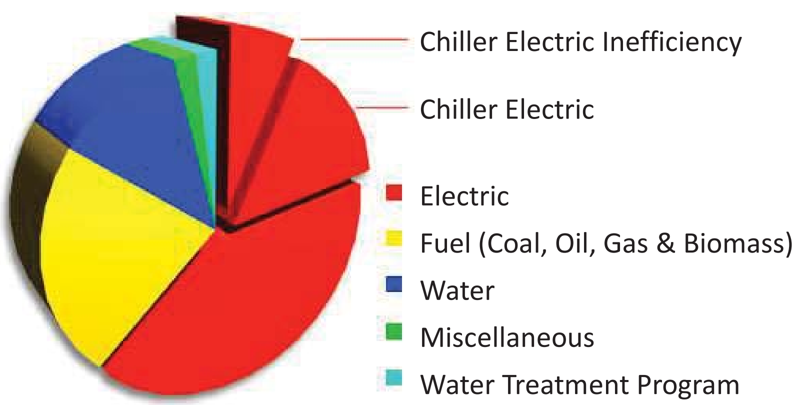
1.2 CR Systems Optimization

- CR – Chilled Water & Refrigeration Plant / System
- How do we take a Systems Approach to optimize these systems?

Why is CR System Optimization Important?

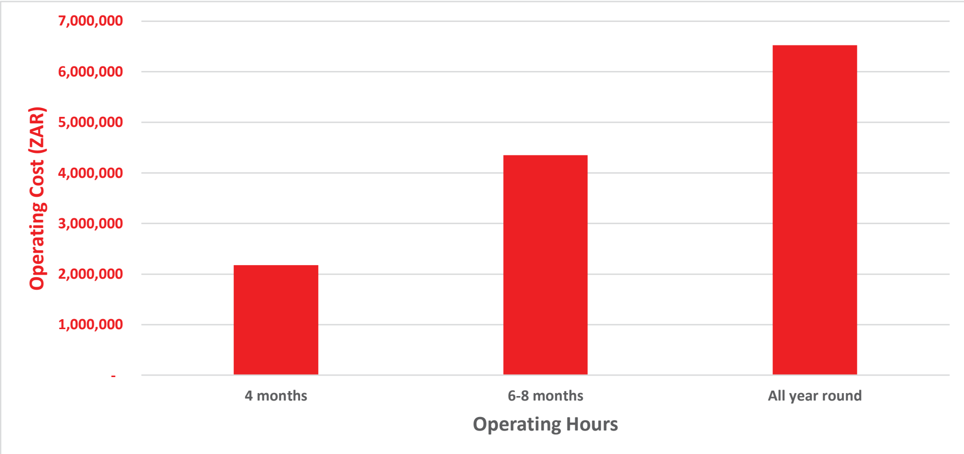
- CR systems can be the single largest energy consumer
- CR systems can use up to 40% of a facility's electrical usage
- CR systems can waste up to 30% due to inefficiencies
- 15% chiller energy savings = 6% reduction of the energy bill

Average Facility Utility Budget



CR System Annual Operating Energy Cost

- 3,500 kW CR plant cooling load
- Chiller System COP = 4.7
- Bundled power cost = R 1.0/kWh



Plant's Energy Usage - H - >40%; M - >10% and <40%; L - <10%

Industry	Comfort Cooling	Process Cooling	Refrigeration
Agro – Processing	L	H	M
Chemicals & Liquid Fuels	L	H	L
Mining	H	H	L
Automotives	L	H	L
Metals & Fabrication	L	H	L
Non-metallic Minerals	L	M	L
Food & Beverage	L	H	H
Pulp & Paper	L	M	L
Textiles & Leather	L	M	L
Commercial Buildings	H	L	L
Data Centers	L	H	L
Tourism & Hospitality	H	L	L
Medical Centers / Hospitals	H	M	L

Main Driving Force for Change

- **Energy**
- Reliability
- Maintenance
- Productivity
- Quality
- Cost avoidance
- Emissions reductions

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The Philosophy

You do not know what you do not measure

You cannot control what you do not know

You cannot manage what you do not control

Management ⇔ Measurement

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Key Points / Action Items

1. *Chiller plants and refrigeration systems are very commonly found in Industry*
2. *Use a Systems Approach to optimize chiller plants and refrigeration systems*
3. *Overall chiller plant operating costs can be significant and though energy consumed is the major component there could be significant costs related to system reliability, etc.*
4. *Use a systematic approach to measure critical operating parameters to identify potential energy saving opportunities, optimize and manage chiller plant systems*

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1 FUNDAMENTALS

1.1 The Systems Approach

1.2 CR System Optimisation

1.3 Refrigerants

1.4 CR System Fundamentals

1.5 CR System Types

1.6 CR System Drives

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1.3 Refrigerants

- It is important to understand the basic properties of refrigerants to understand the operations of any chilled water or refrigeration system

- Depending on the level of due-diligence refrigerants' physical, thermodynamic and transport properties will be required

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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
  - Inorganic – Ammonia, Water, Carbon dioxide

- Nomenclature
  - R-number
  - Typical Freons & some hydrocarbons – 1-399
    - Easy convention for C, H, F
  - Near Azeotropes – 400 series
  - Azeotropes – 500 series
  - Inorganic – 700 series
    - Easy convention – 7 + Molecular wt.

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Most commonly used types of Refrigerants

- CFC (Chlorofluorocarbon) Refrigerants
  - R-11 - Was used in residential, commercial and industrial applications
  - R-12 - Was used in residential, commercial and industrial applications
- HCFC (Hydro chlorofluorocarbon) Refrigerants
  - R-22 - Extensively used in residential, commercial and industrial applications
  - R-123
- HFC (Hydro fluorocarbon) Refrigerants
  - R-134a - Primarily used in automobile applications
  - R-32
- Refrigerant Blends (Azeotropic and Zeotropic)
  - R-410a - Replacement refrigerant for residential A/C
  - R-407C - Replacement for R-22

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Refrigerants

- Thermodynamic Properties
  - P - Pressure (kPa, bars, etc.)
  - T - Temperature (°C)
    - Absolute Temperature (K)
  - X - Quality
  - ρ - Density (kg/m^3)
- Thermodynamic Properties
  - V – Specific Volume (m^3/kg)
  - H - Enthalpy (kJ, kcal)
    - Specific Enthalpy (kJ/kg, kcal/kg)
  - S - Entropy (kJ/K, kcal/K)
    - Specific Entropy (kJ/kg-K, kcal/kg-K)

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Refrigerants

- Other Thermophysical Properties
  - C_p - Specific Heat at constant pressure (kJ/kg-K, kcal/kg-K)
  - C_v – Specific Heat at constant volume (kJ/kg-K, kcal/kg-K)
  - V_s - Velocity of sound (m/s)
  - μ - Viscosity (Pa.s)
  - K – Thermal Conductivity (W/m-K)
  - σ - Surface Tension (N/m)

Refrigerants

- Thermophysical Property Information
  - ASHRAE Fundamentals Handbook
    - Tabulated Data
    - P-h diagram
  - Software Programs
    - Equation of State for different refrigerants
    - Martin Hou Correlations
    - REFPROP
    - Engineering Equation Solver (EES)
    - Other
  - Manufacturer's Property Data
  - National Institute of Standards & Testing (NIST)
- Reference Point
  - Maybe different for different sources!!

Refrigerants

R134a Saturation Properties

Temperature (°C)	Pressure (MPa)	Liquid Density (kg/m³)	Vapor Density (kg/m³)	Liquid Enthalpy (kJ/kg)	Vapor Enthalpy (kJ/kg)	Liquid Entropy (kJ/kg-K)	Vapor Entropy (kJ/kg-K)
-10.0	0.201	1327.1	10.041	186.70	392.66	0.95065	1.7334
-5.00	0.243	1311.1	12.077	193.32	395.66	0.97544	1.7300
0.000	0.293	1294.8	14.428	200.00	398.60	1.0000	1.7271
5.00	0.350	1278.1	17.131	206.75	401.49	1.0243	1.7245
10.0	0.415	1261.0	20.226	213.58	404.32	1.0485	1.7221
15.0	0.488	1243.4	23.758	220.48	407.07	1.0724	1.7200
20.0	0.572	1225.3	27.780	227.47	409.75	1.0962	1.7180
25.0	0.665	1206.7	32.350	234.55	412.33	1.1199	1.7162
30.0	0.770	1187.5	37.535	241.72	414.82	1.1435	1.7145
35.0	0.887	1167.5	43.416	249.01	417.19	1.1670	1.7128
40.0	1.02	1146.7	50.085	256.41	419.43	1.1905	1.7111
45.0	1.16	1125.1	57.657	263.94	421.52	1.2139	1.7092
50.0	1.32	1102.3	66.272	271.62	423.44	1.2375	1.7072

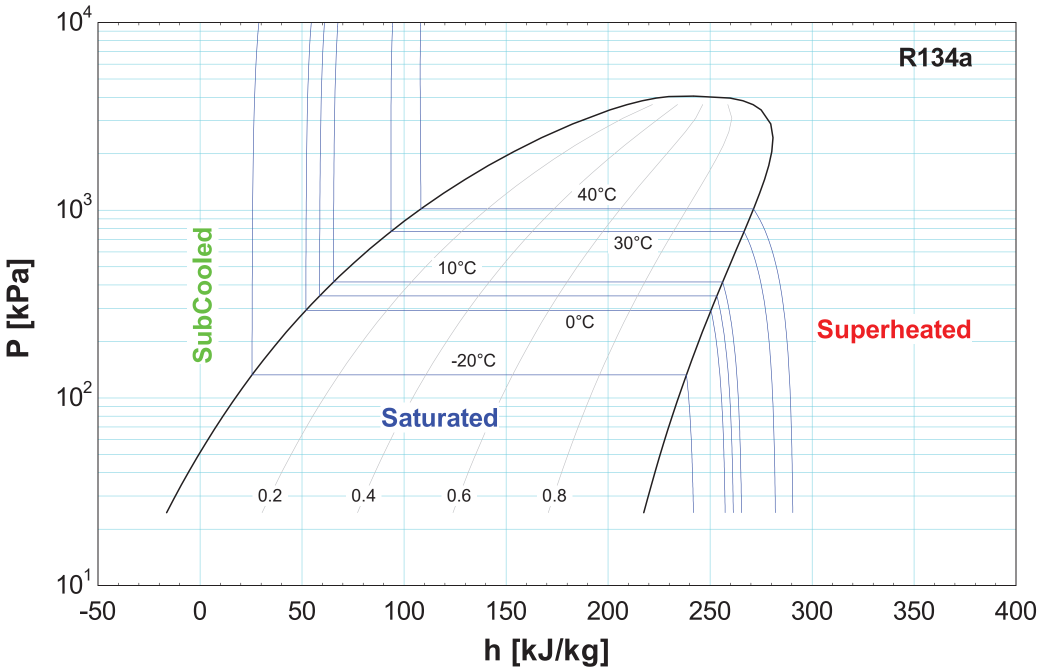
Refrigerant State Points

- In any chiller system, the refrigerant fluid passes through a number of state points
- There are a minimum number of state points that define a refrigeration cycle
- These state points can be thermodynamically represented on a P-h (Pressure - Enthalpy) or a T-s (Temperature - Entropy) diagram
- Each state point typically represents the start or end point of a process in the cycle
- State points are very important. They are the basic building blocks of any system!

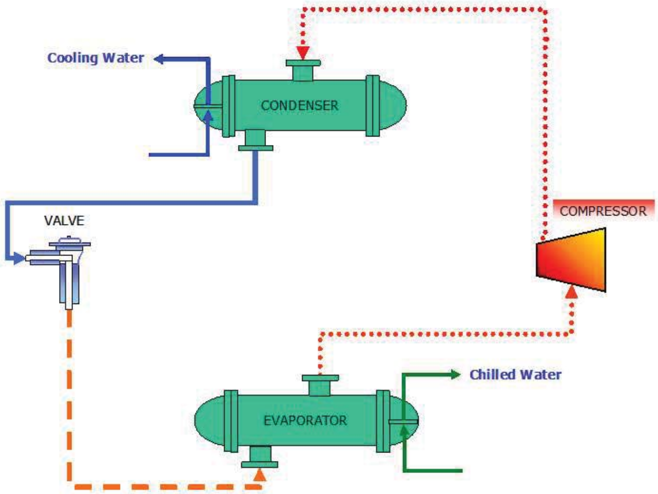
Refrigerants

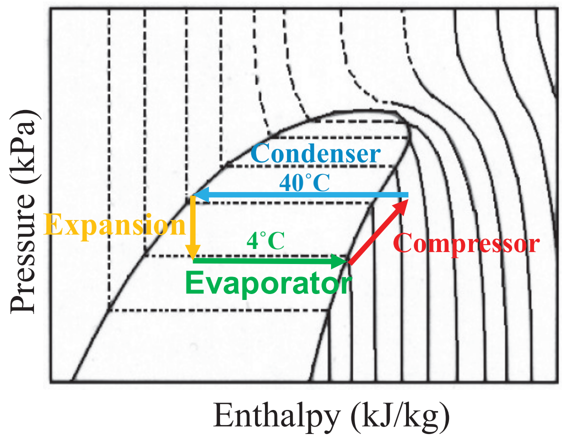
- Thermodynamic States
  - Subcooled
    - Liquid
    - Temperature and Pressure are independent
    - Energy content ∝ Temperature
  - Saturated
    - Liquid / 2-Phase / Vapor
    - Temperature and Pressure are **dependent**
    - $0 \leq$ Quality ≤ 1
  - Superheated
    - Vapor
    - Temperature and Pressure are independent
    - Energy content ∝ Temperature & Pressure

Refrigerants



The Refrigeration Cycle





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Refrigerants (Worked Example)

- Classroom Problems
  - For refrigerant R134a, identify the state of the substance and possibly, where this temperature and pressure were measured in a R134a chiller:
    - T=30°C, P=0.887 MPa
    - T=50°C, P=0.887 MPa
    - T=5.0°C, P=0.35 MPa
  - For refrigerant R134a, determine saturation pressure for the following operating temperatures:
    - T=0.0°C
    - T=2.5°C
  - For refrigerant R134a, determine liquid and vapor densities and latent heat of vaporization at the following state point:
    - P=0.35 MPa

Key Points / Action Items

1. *Understanding refrigerants and their thermodynamic properties is fundamental when analyzing chillers*

2. *Properties of refrigerants can be obtained from publicly available literature*

3. *A refrigeration / chiller system will have the following basic processes: Evaporation, Condensation, Compression and Expansion (throttling)*

4. *A systems approach in a cooling cycle will include end-use (cooling load to be provided), chiller(s), cooling towers (heat rejection to ambient), pumps, fans, etc.*

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1 FUNDAMENTALS

1.1 The Systems Approach

1.2 CR System Optimisation

1.3 Refrigerants

1.4 CR System Fundamentals

1.5 CR System Types

1.6 CR System Drives

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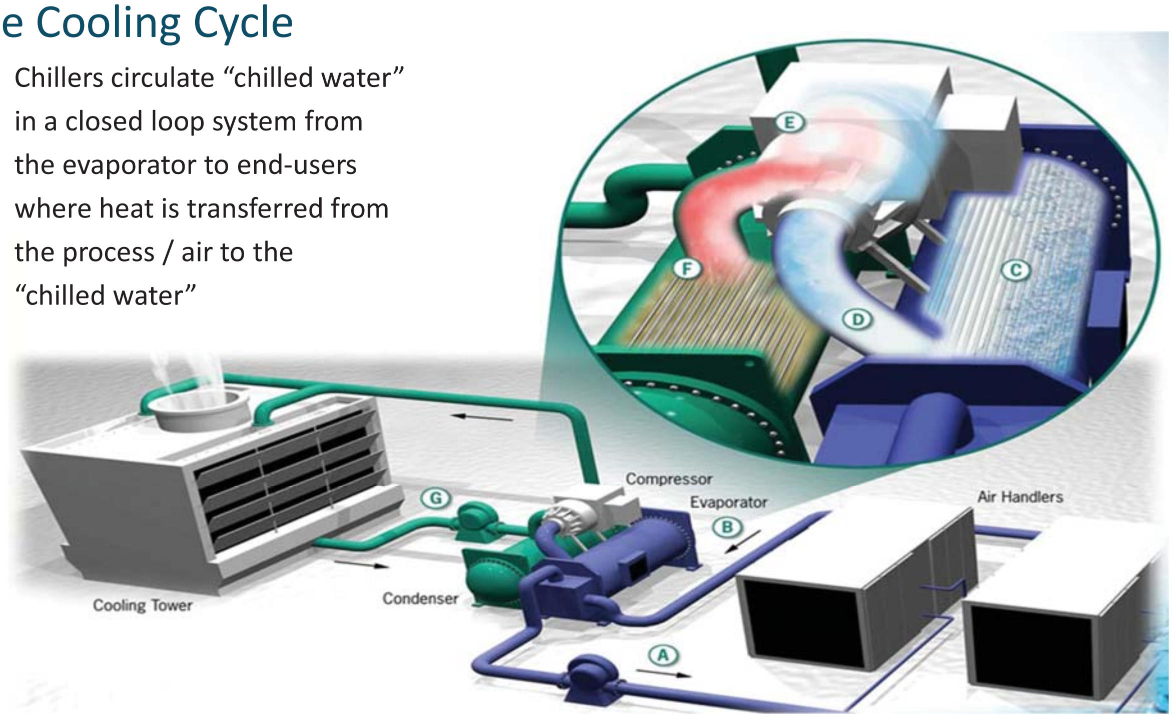
1.4 CR System Fundamentals

- Understanding terminology and specifics
- Understanding CR Systems – similarities & differences
- Foundations of this class – define scope of training

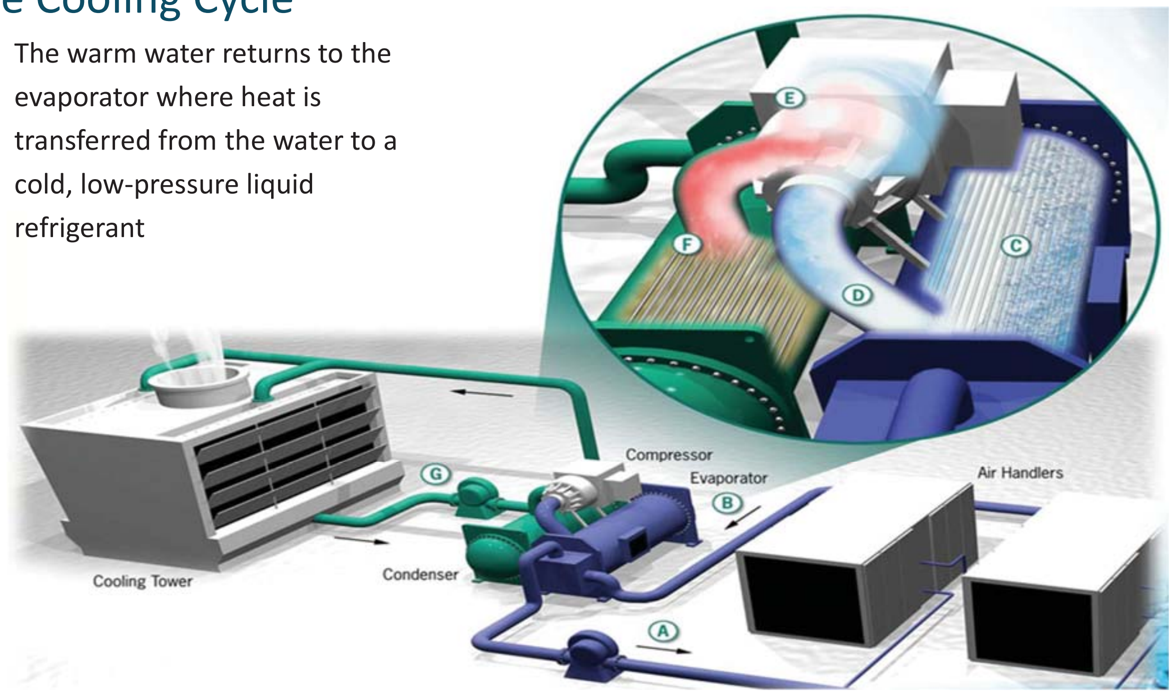
The Cooling Cycle

A. Chillers circulate "chilled water" in a closed loop system from the evaporator to end-users where heat is transferred from the process / air to the "chilled water"



The Cooling Cycle

B. The warm water returns to the evaporator where heat is transferred from the water to a cold, low-pressure liquid refrigerant



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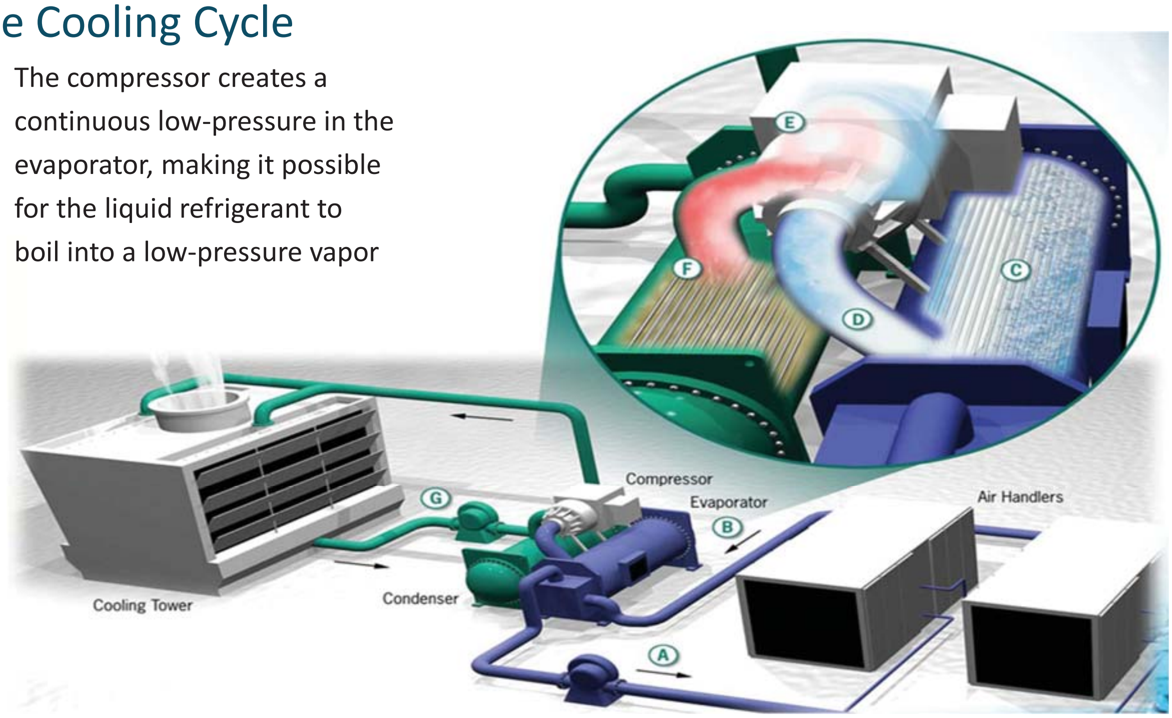
The Cooling Cycle

C. The compressor creates a continuous low-pressure in the evaporator, making it possible for the liquid refrigerant to boil into a low-pressure vapor



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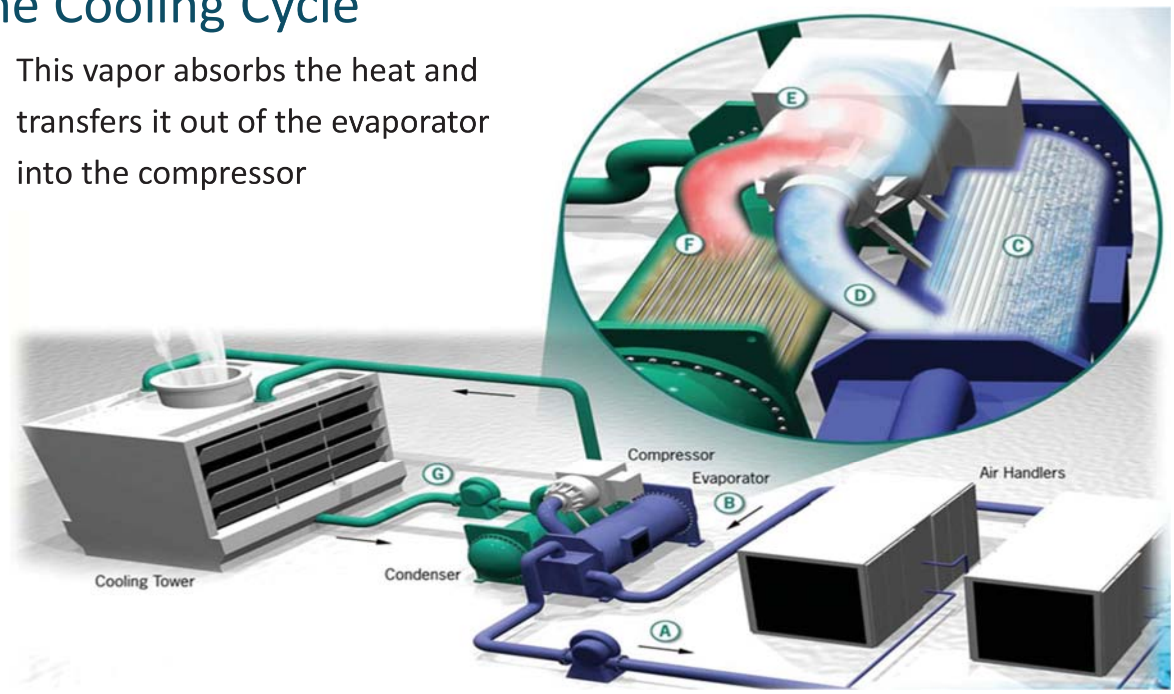
The Cooling Cycle

D. This vapor absorbs the heat and transfers it out of the evaporator into the compressor



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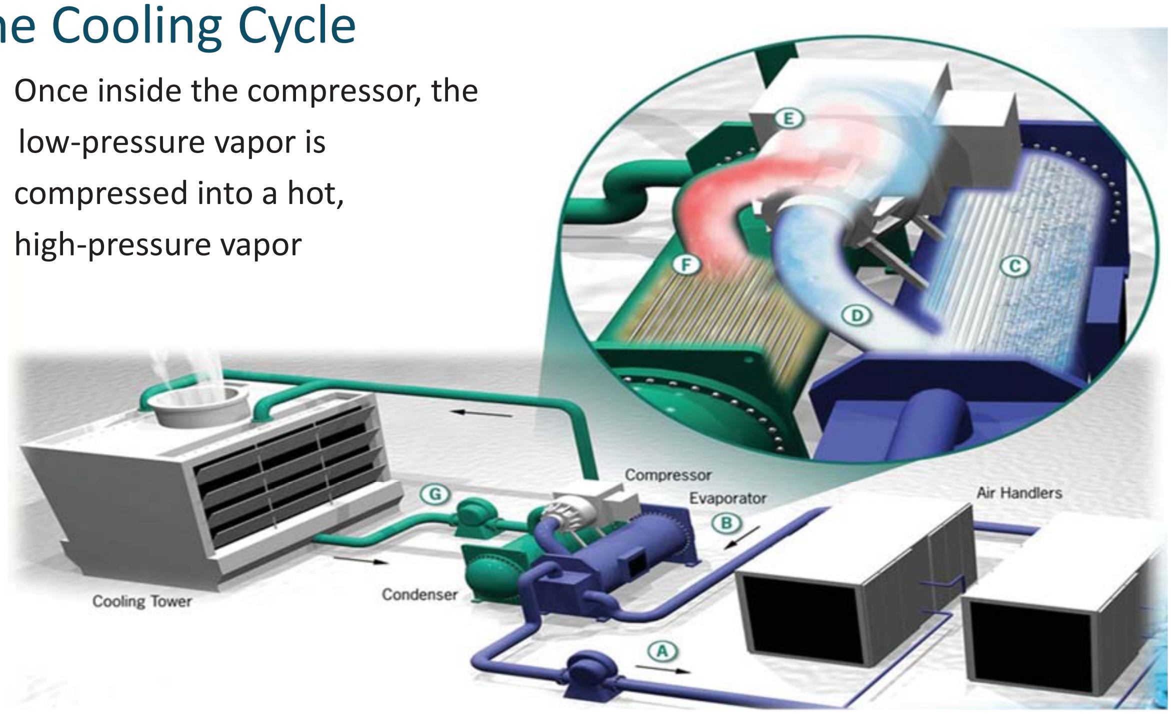
The Cooling Cycle

E. Once inside the compressor, the low-pressure vapor is compressed into a hot, high-pressure vapor



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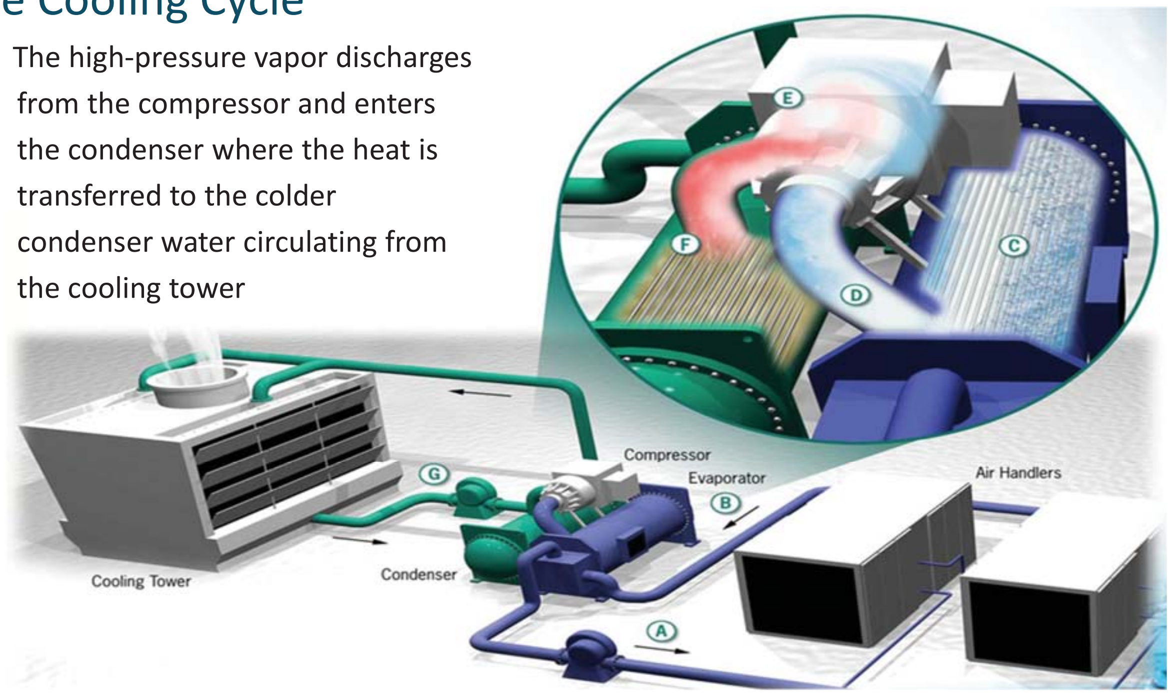
The Cooling Cycle

F. The high-pressure vapor discharges from the compressor and enters the condenser where the heat is transferred to the colder condenser water circulating from the cooling tower



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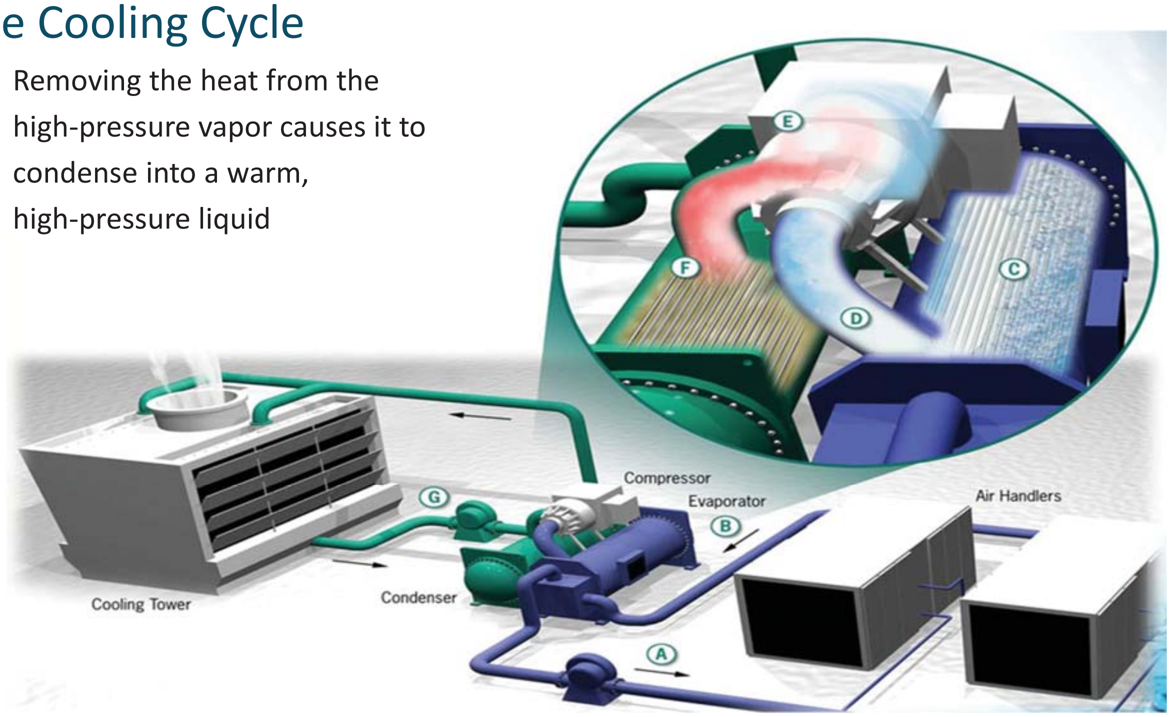
The Cooling Cycle

F. Removing the heat from the high-pressure vapor causes it to condense into a warm, high-pressure liquid



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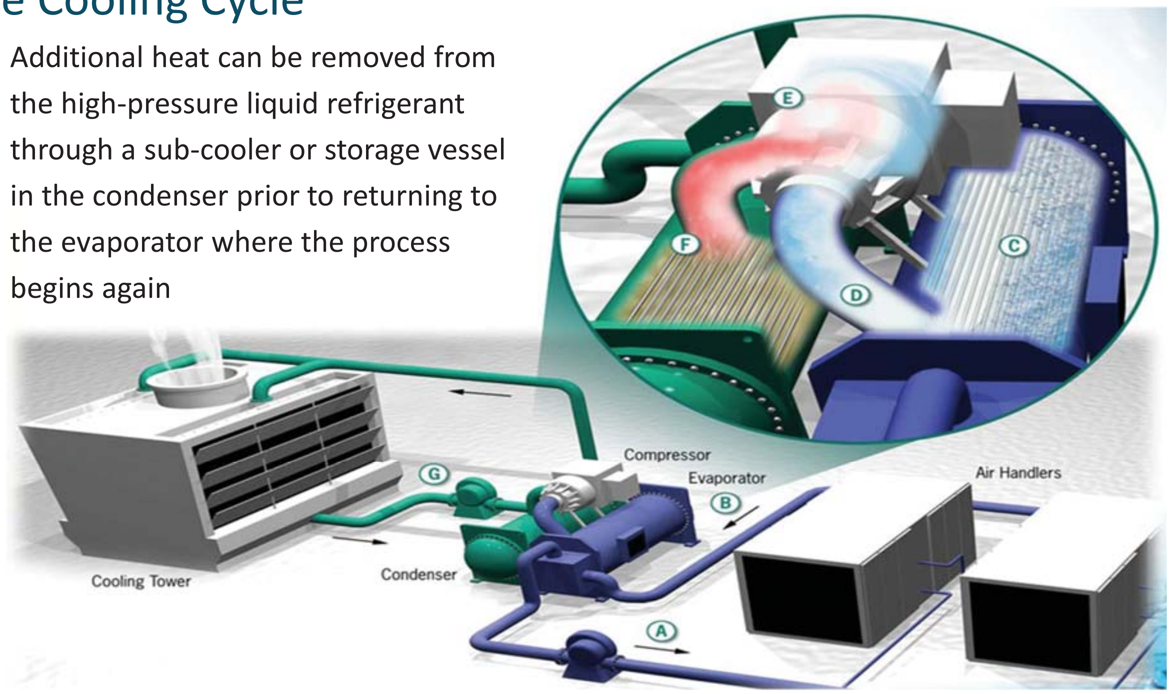
The Cooling Cycle

F. Additional heat can be removed from the high-pressure liquid refrigerant through a sub-cooler or storage vessel in the condenser prior to returning to the evaporator where the process begins again



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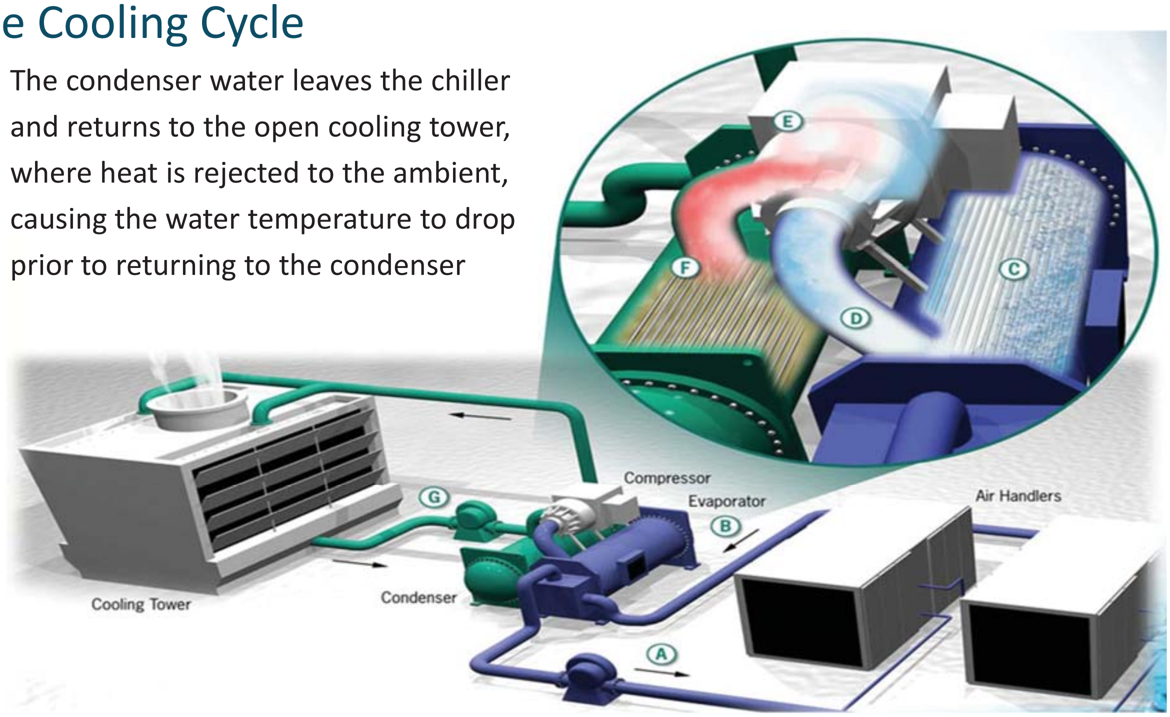
The Cooling Cycle

G. The condenser water leaves the chiller and returns to the open cooling tower, where heat is rejected to the ambient, causing the water temperature to drop prior to returning to the condenser



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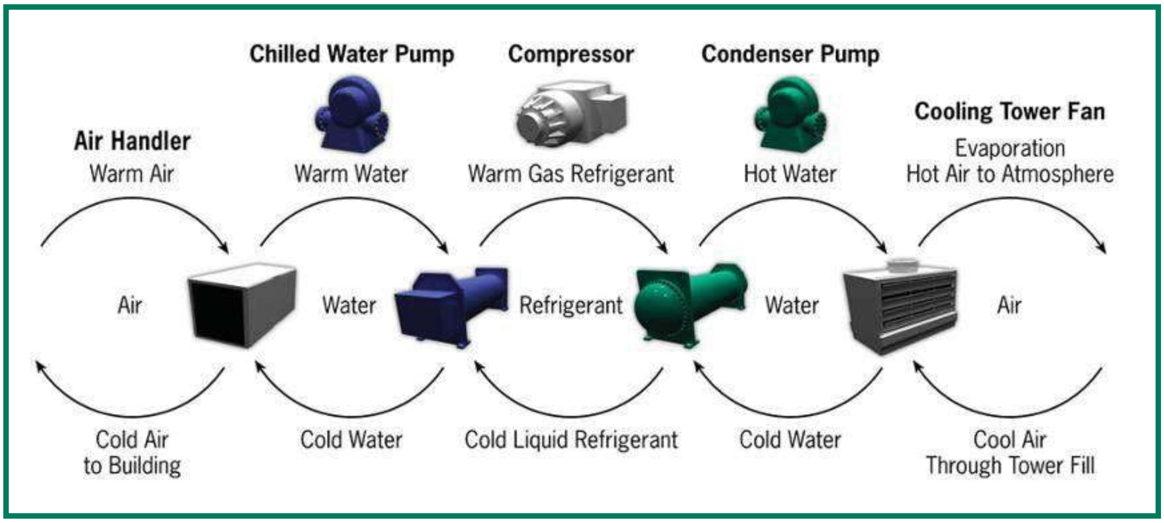
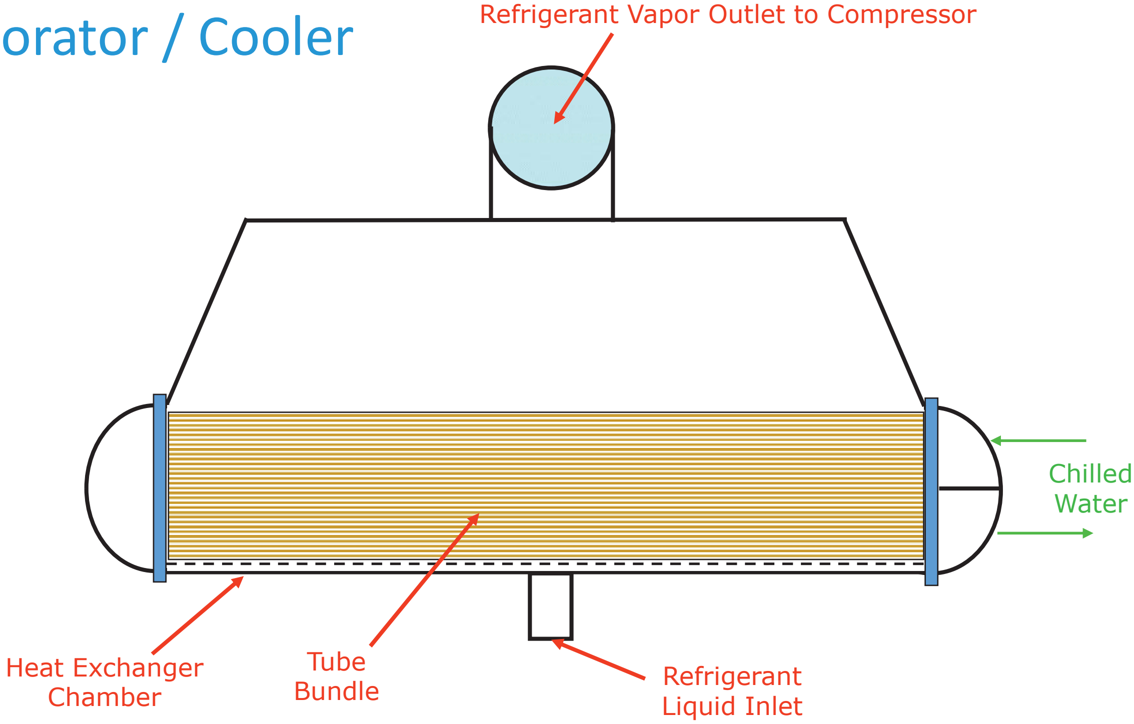
The Air, Water and Refrigerant Cycle



A Chiller System

- Evaporator (Chiller)
  - Shell and tube heat exchangers
  - Refrigerant on shell side (pool boiling)
  - Refrigerant on tube-side (direct expansion)
  - Coolant or air on the other side
  - Some plate & frame type
- Condenser
  - Shell and tube heat exchangers
  - Water cooled - refrigerant on shell side
  - Air cooled – refrigerant on tube side
  - Evaporative Condensers (a combination of the above)
  - Plate and frame more common in some applications

Evaporator / Cooler



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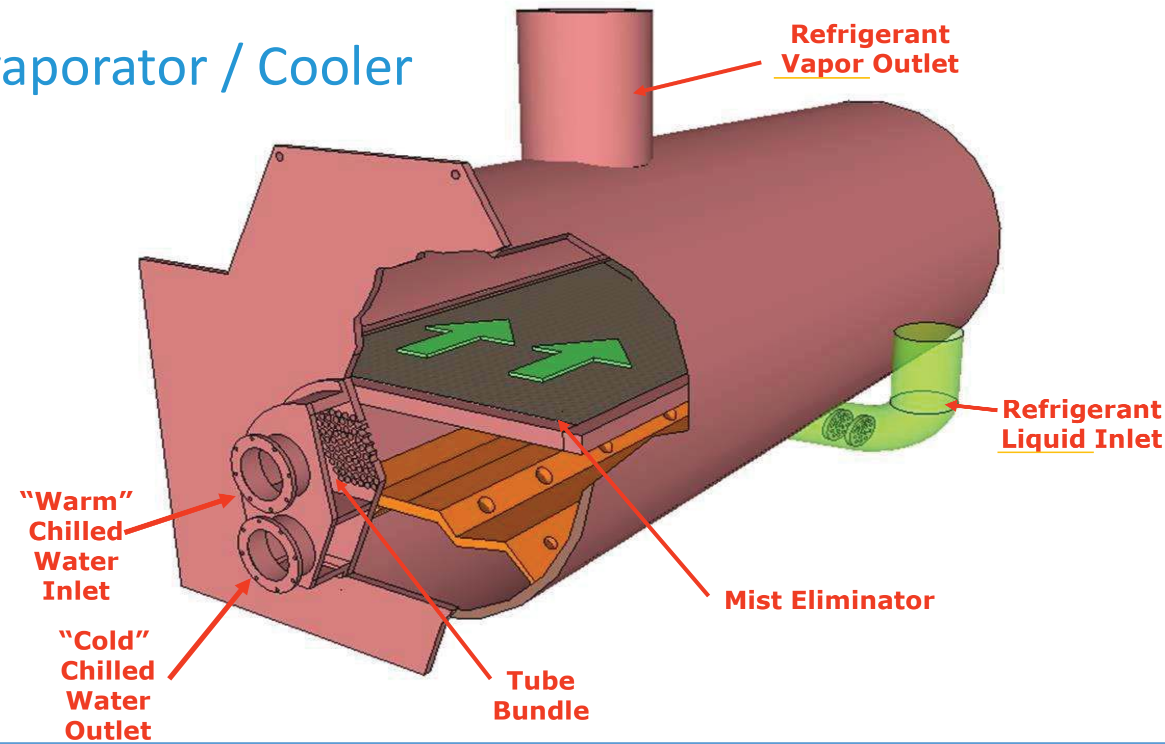
Evaporator / Cooler



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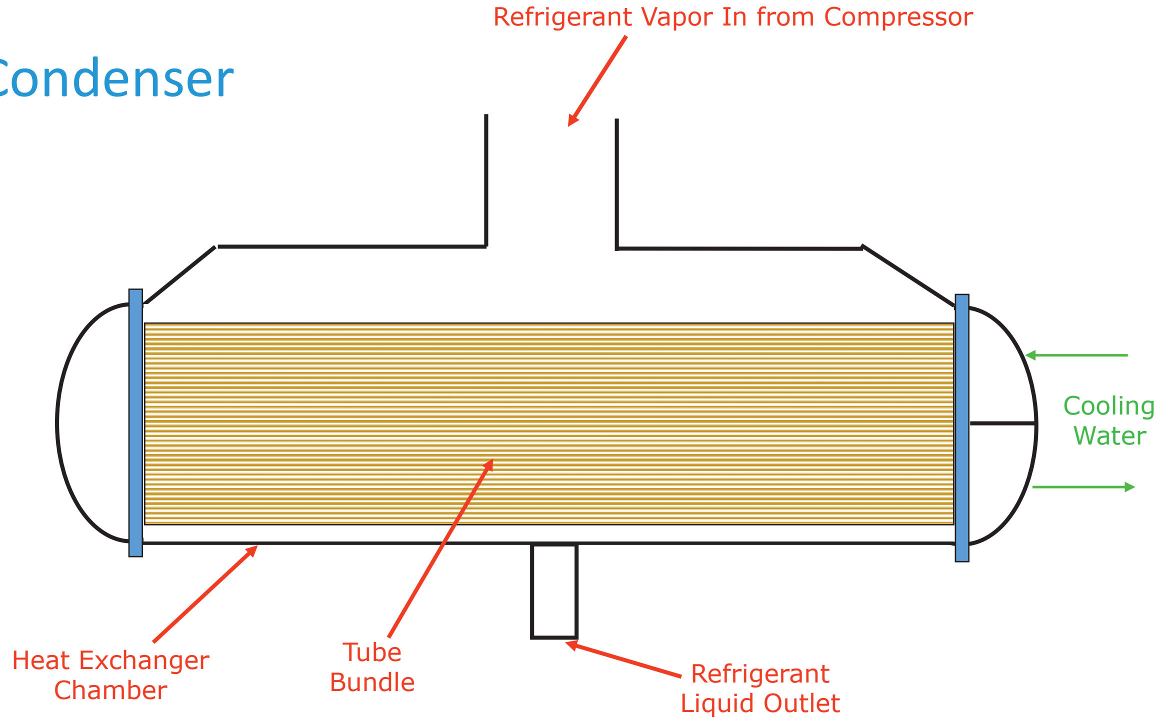
Condenser



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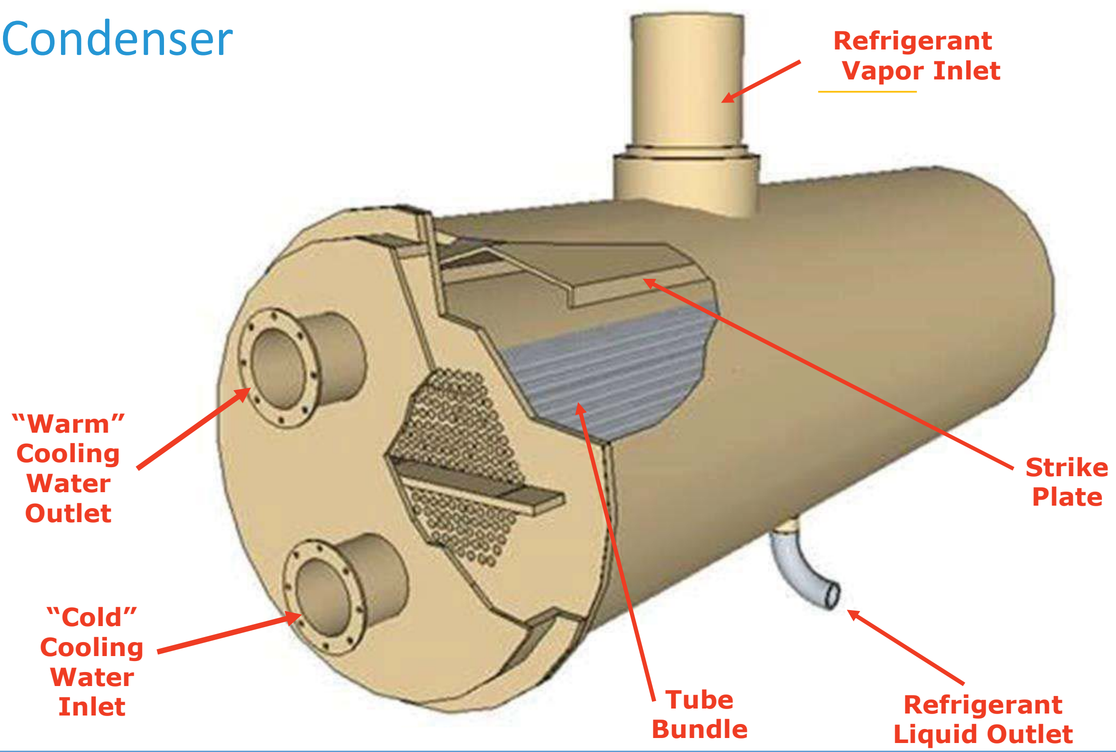
Condenser



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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, etc.

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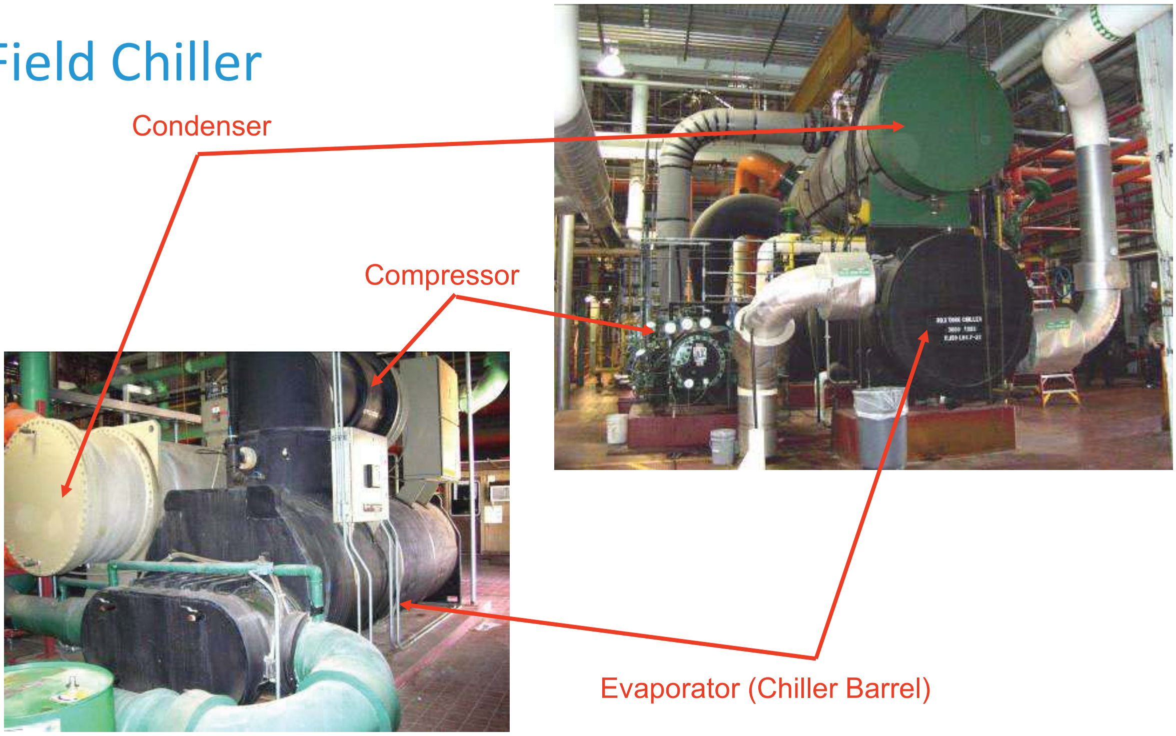
Expansion Device

- Fixed orifice
- Level control float valve
- Thermostatic / Electronic expansion valve
- Other kinds of throttling devices (capillary tube, control valves, etc.)

Flow Control Valve

Electronic Expansion Valve

A Field Chiller



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Auxiliary Components

- SubCooler
  - Internal / External
- Desuperheater
- Heat Recovery Equipment
- Receiver (or Refrigerant Storage Tank)
- Refrigerant Pump
- Oil Separator
- Suction Accumulator
- InterCooler
- Purge Unit
- Pump Out unit

Process End-Users

Shell-and–tube Heat Exchangers

Plate and Frame Exchangers

65

End Use - Air Handling Unit

- Components
  - Supply duct
  - Fan compartment
  - Flexible connection
  - Heating and/or cooling coil
  - Filter compartment
  - Return and fresh air duct

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Cooling Tower

- Components
  - Frame & casing
  - Fill
  - Cooling water basin
  - Drift eliminators
  - Air inlet
  - Louvers
  - Nozzles
  - Fans

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Cooling Tower Internals

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Air-Cooled Condenser

- Reject energy from the hot refrigerant gas following compression
- Unlike cooling towers, there is no mass transfer occurring (just heat transfer).
- Refrigerant can be cooled to within 10°C of the ambient dry-bulb temperature
- Not as efficient as water-cooled, BUT simplify the installation process, are easier to maintain, have a higher reliability, and can be more easily operated in freezing temperatures than cooling towers

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Pumps

- Circulate chilled water and condenser water
- Energy consumption is highly dependent of proper pump selection
- Commonly have constant flow on both chilled water and condenser water loops…can also have variable flow on both
- Chilled water lines should be insulated
- Valves often used to obtain desired flow through evaporator and condenser (when pumps are incorrectly sized)

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Key Points / Action Items

1. *A typical packaged water chiller includes the following components: Evaporator (chiller barrel), Condenser, Compressor, Expansion device (orifice plate) and Economizer (if applicable)*

2. *Understanding the Air-Water-Refrigerant cycles and interactions are key drivers and fundamental in understanding CR system operations*

3. *Heat rejection mechanism can be achieved in several different ways – air-cooling; water-cooling; both*

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1

FUNDAMENTALS

1.1 The Systems Approach

1.2 CR System Optimisation

1.3 Refrigerants

1.4 CR System Fundamentals

1.5 CR System Types

1.6 CR System Drives

72

1.5 CR System Types

- There are different kinds of CR systems
- Classification is based on type of components, compression stages, how cooling is supplied to the end-users, etc.

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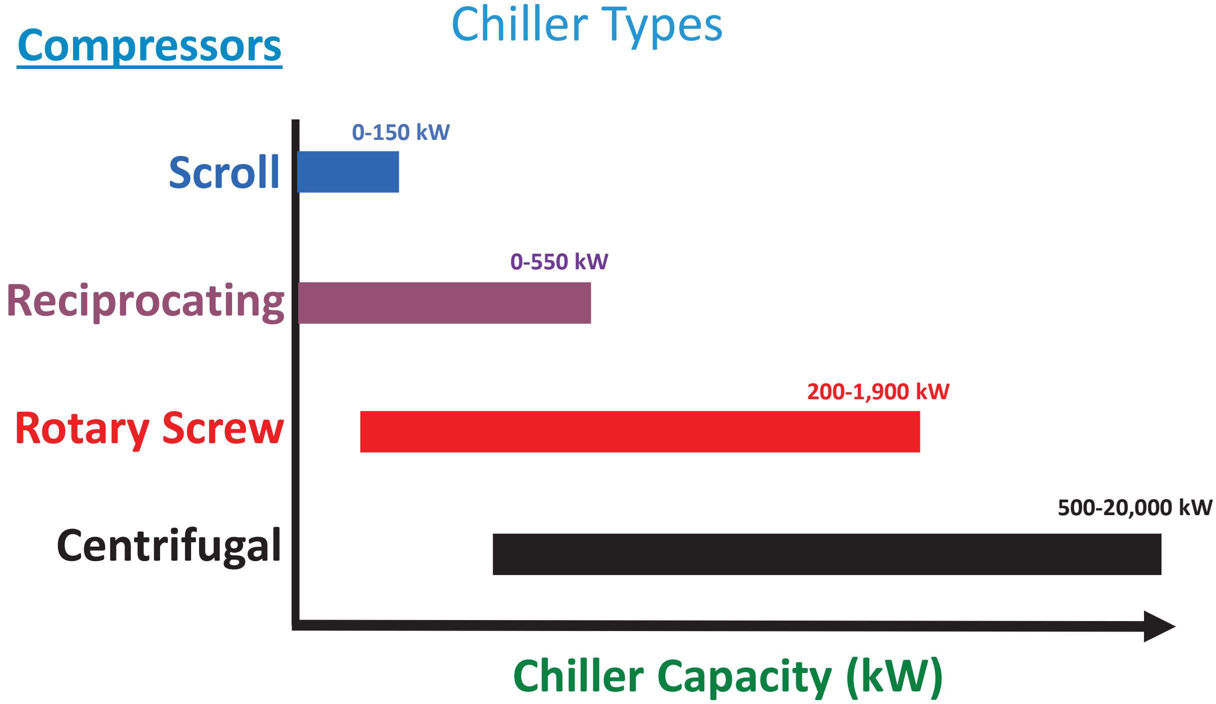
Chiller Types



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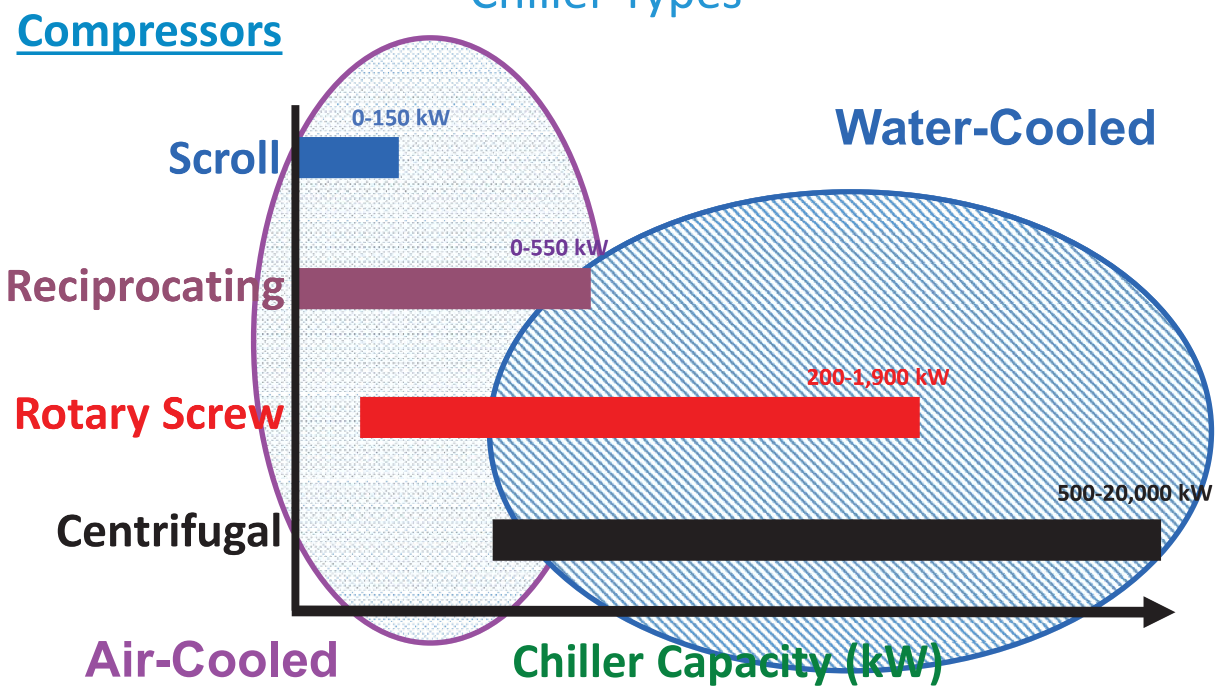
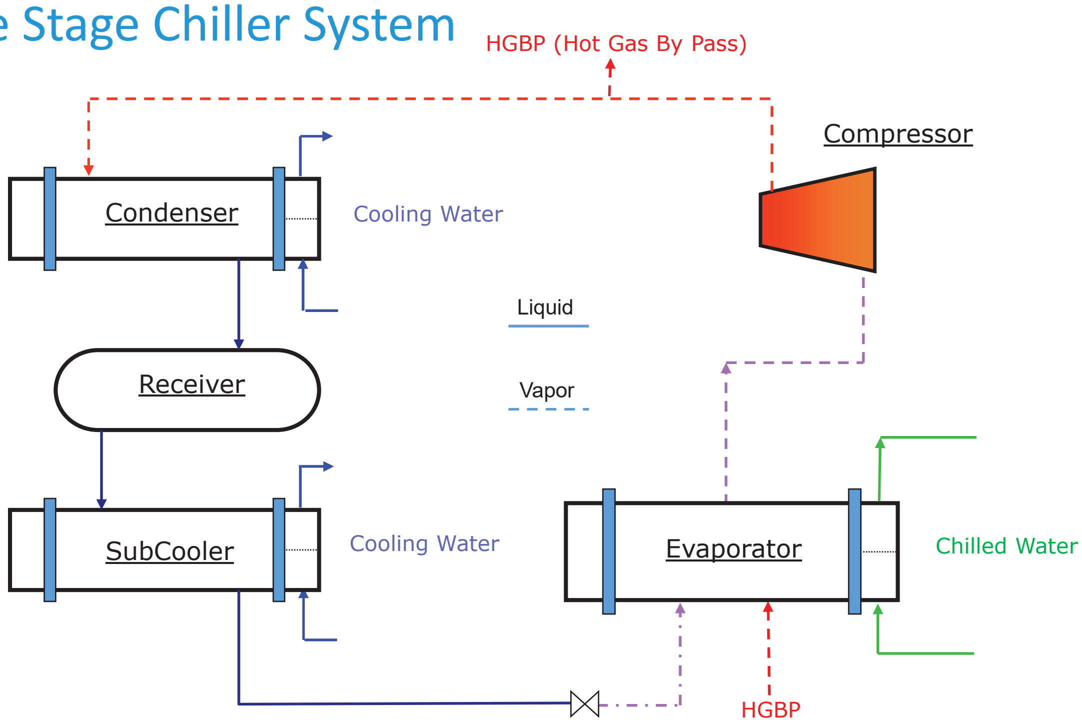
Chiller Types



Single Stage Chiller System



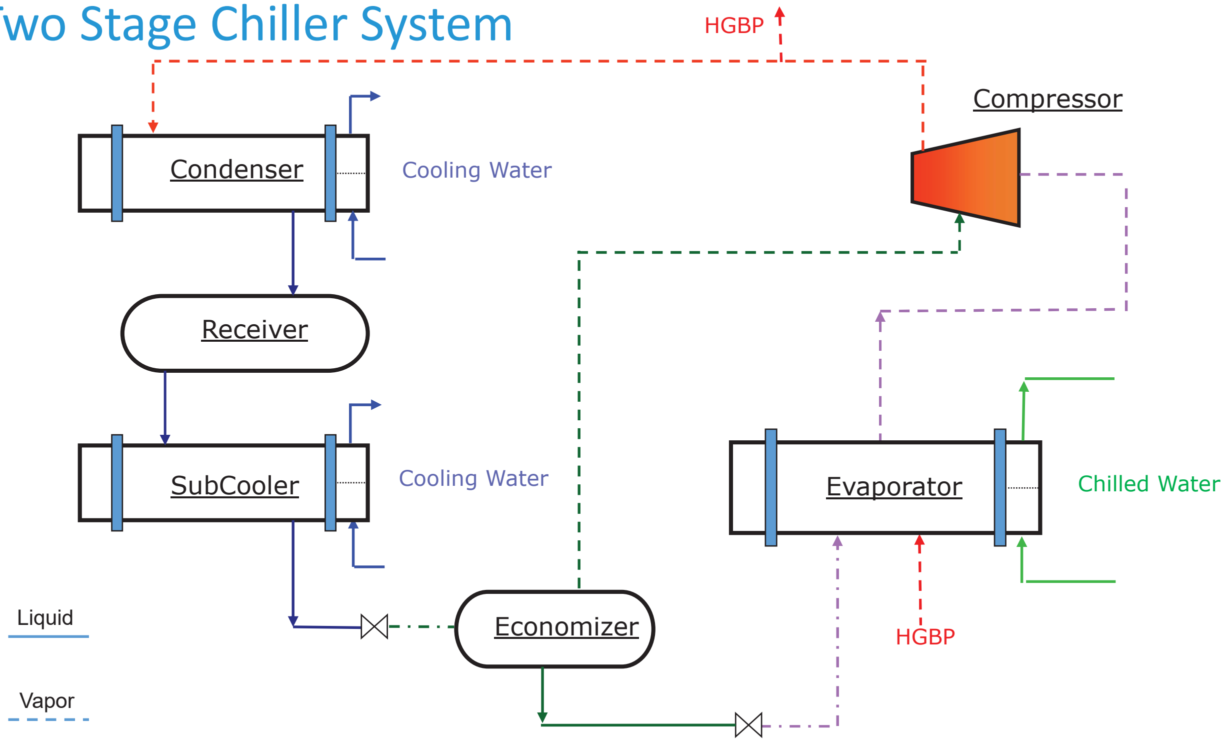
Multi-Stage Chiller System

- The need for multistage systems
  - Compressor size limitations
  - As the ratio of condenser pressure to evaporator pressure increases, compressor capacity drops
  - To achieve lower chiller temperatures and maintain desired capacity
  - Very significant impact on system efficiency
    - Reduced flashing losses
    - Reduced compressor work due to intercooling
    - Lower refrigerant flow rates, thereby reducing sensible heat losses
- The downside
  - Requires additional components
  - May have higher first costs

Multi-Stage Chiller System

- InterCooler / Economizer / Flash Chamber
  - Thermodynamically
    - Warm saturated liquid flashes at intercooler pressure
    - Saturated cooler liquid (@ intercooler pressure) continues to the evaporator / lower stage intercooler
    - Saturated cooler vapor (@ intercooler pressure) continues to the compressor to cool the lower stage discharge gas
  - Typically, a float mechanism controls level in the intercooler
  - Will require engineering evaluation when considering operation with different refrigerants

Two Stage Chiller System



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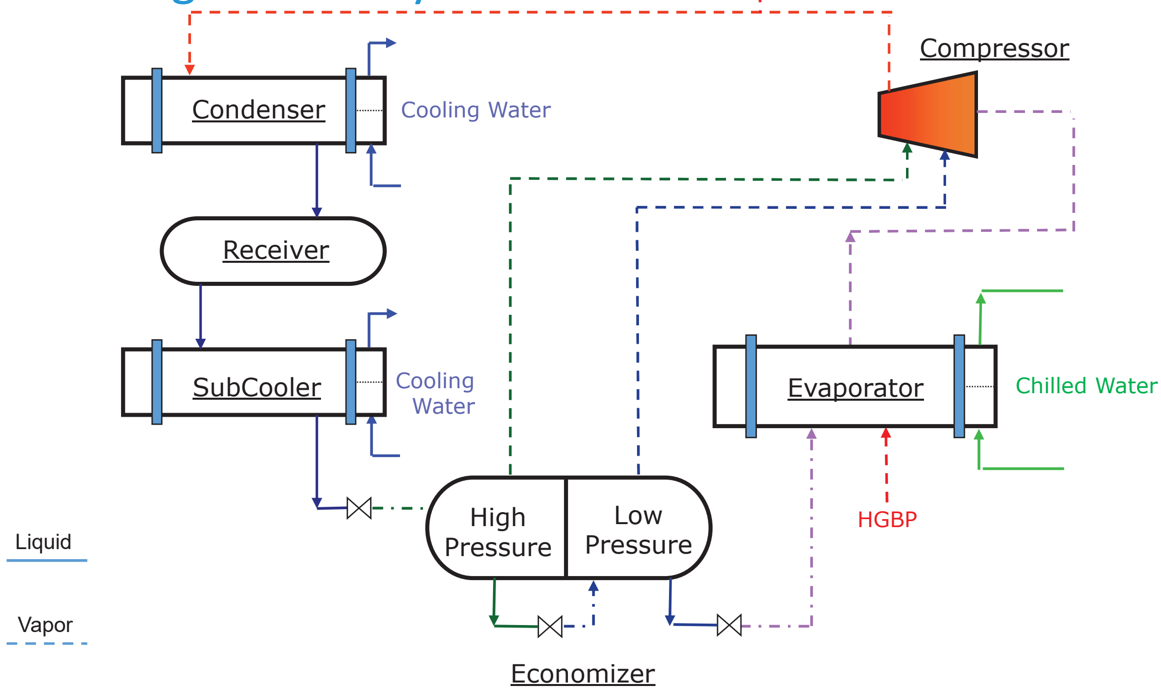
Three Stage Chiller System



Complex Built-up Refrigeration Systems

- They will be found in industrial settings
  - Food and Beverages industry
  - Chemicals and Petro-chemicals
  - Large manufacturing facilities
  - "Non-HVAC" loads
- Serve one or an array of multiple process loads
- Low temperature (<0°C) operation
- Will have one or more single / multi-stage compressors
- Controls may be tied to process operation and have a very complex logic
- Operation all year round and downtime cannot be tolerated
- Tremendous energy-savings potential by monitoring performance and optimizing the systems
- They cost a lot of money to operate and maintain

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Absorption Chiller / Refrigeration Systems

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

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Absorption Chiller Systems

- Absorption systems have much less parasitic load than electric chillers
- Applications
  - Waste heat recovery
  - Low temperature exhaust steam
- Less moving parts
- Smooth operation and low maintenance cost

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Absorption Chiller / Refrigeration Systems

- Evaporation and Condensation
- Generation (Desorption)
  - Refrigerant vapor rich solution is heated to remove the refrigerant vapor
  - Temperature and solution concentration changes but pressure remains the same
  - Significant increase in the enthalpy
  - Heat input can take several different forms
  - Refrigerant vapor travels to the Condenser
  - Solution depleted of the refrigerant returns to the Absorber

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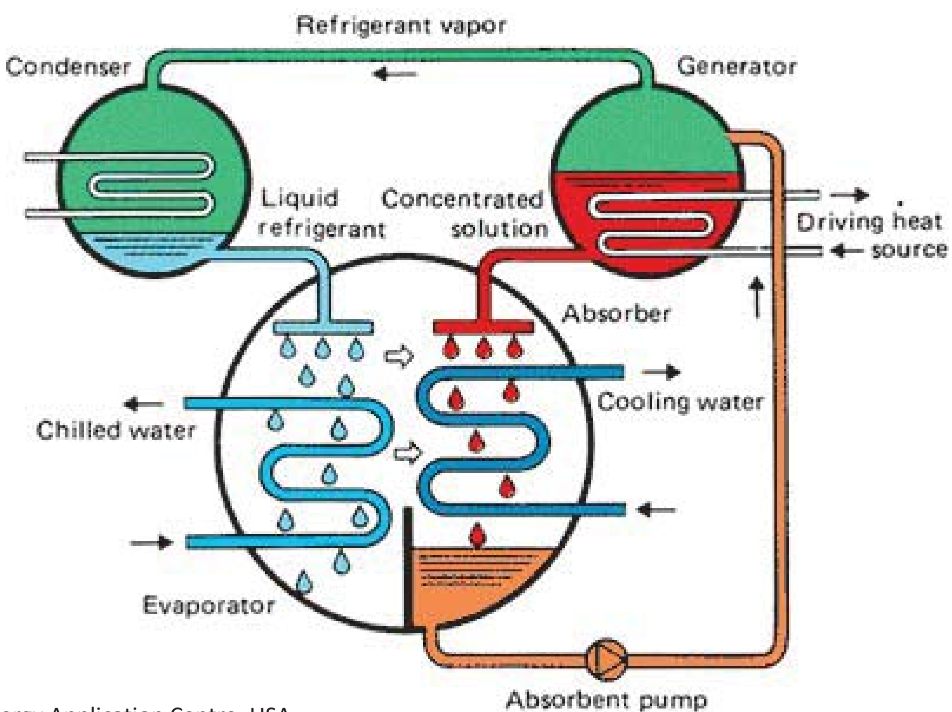
Absorption Chiller / Refrigeration Systems

- Absorption
  - Refrigerant depleted solution from the Generator absorbs the refrigerant vapor from the Evaporator
  - Temperature and solution concentration change but pressure remains the same
  - Heat is rejected to the cooling tower water
  - Solution rich in refrigerant is pumped back to the Generator
- Sensible Heat Exchange
  - Hot refrigerant depleted solution from the Generator exchanges sensible heat with refrigerant rich solution from the Absorber
  - Temperature changes but concentration and pressure remains the same

85

LiBr-Water Absorption Chillers



Courtesy: Midwest Clean Energy Application Centre, USA

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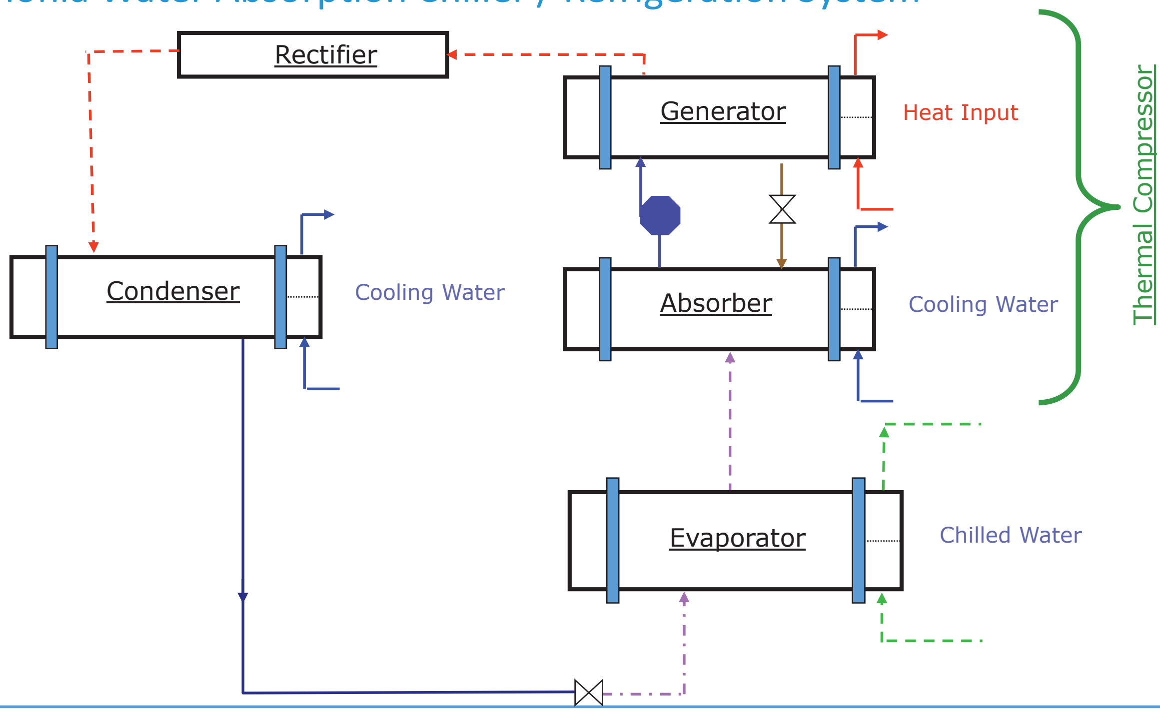
Ammonia Water Absorption Chiller / Refrigeration System



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Key Points / Action Items

1. *Single-stage mechanical vapor compression chiller systems are most common*

2. *Refrigeration systems will typically be multistage to allow for higher temperature lifts, multi-temperature levels, etc.*

3. *Two-stage and Three-stage systems will require one and two economizers (intercoolers), respectively*

4. *There can also be complex built-up refrigeration systems*

5. *Absorption chiller systems use heat to move the refrigerant vapor from evaporator to condenser instead of mechanical shaft power driven compressor*

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1 FUNDAMENTALS

1.6 CR System Drives

- Energy is provided to CR systems either in the form of electricity or thermal (heat) which drives the CR system
- Additionally, pumps are used to circulate the heat transfer fluid (water, glycol, brine, refrigerant) to the end-users

Chiller Compressor Drives

- The refrigerant compressor needs rotational shaft "horsepower" to compress the refrigerant vapor and move it from the evaporator (low pressure) to the condenser (high pressure)
- Several options exist
  - Electric motor drives
    - Constant speed (most common)
    - Variable frequency
  - Steam turbine drives
  - Engine drives (least common)

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Electric Motor Drives (Fixed Speed)

- Most common and standard option with all packaged chillers and refrigeration systems
- Motor efficiency >93% and stays relatively flat and high unless loads drop below 35-40%
- Compressor flow is controlled by one of the following mechanisms
  - Inlet guide vanes
  - Exit dampers
  - Slide valves
  - Unloading
  - Hot gas bypass
- Generally, these systems will show strong part-load impacts – depending on other parameters also

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Electric Motor Drives (Variable Frequency)

- May not be a standard option but becoming very prevalent with new CR systems and a retrofit option
- 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

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Steam Turbine Drives

- Classic cogeneration (CHP) application where both steam and chilled water are required simultaneously
  - Backpressure steam turbines
- Condensing steam turbines for large tonnage chillers
- Compressor flow is controlled by
  - Speed control
  - Inlet guide vanes
  - Hot gas bypass
- Used also for
  - Emergency purposes
  - In locations where electric grid reliability maybe an issue
  - Existing electric infrastructure cannot support additional capacity
  - Significant amounts of low (or no) cost fuel available

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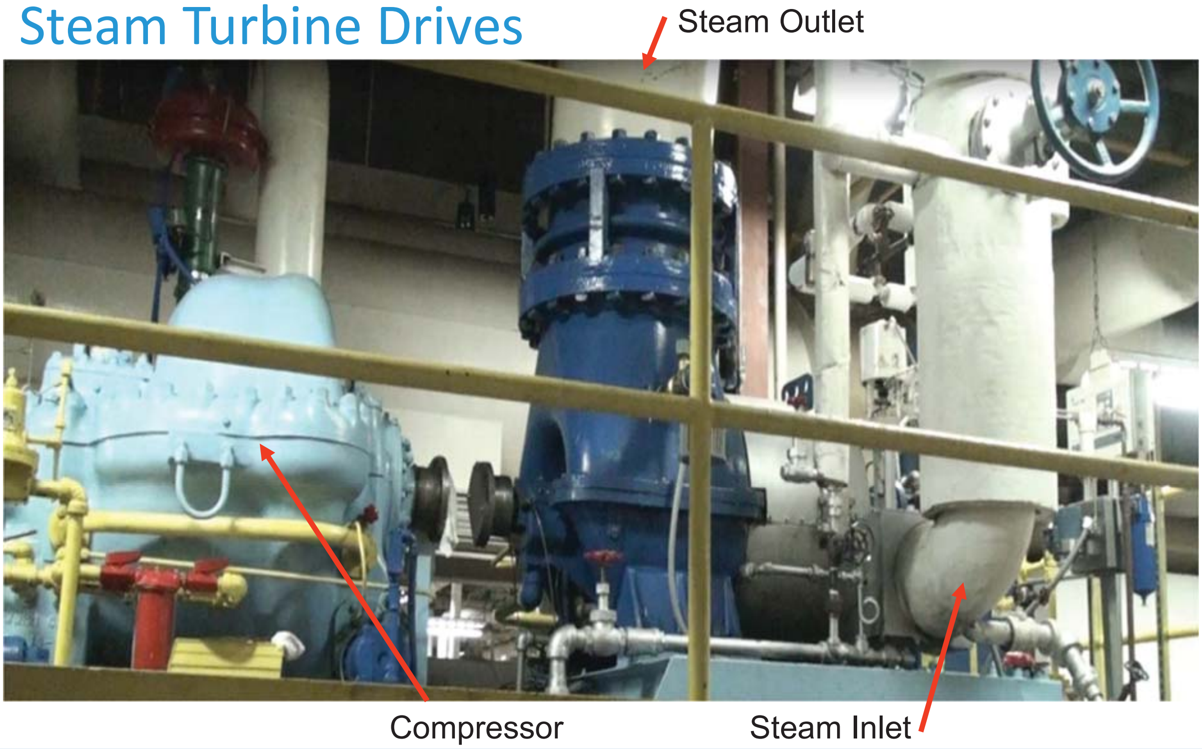
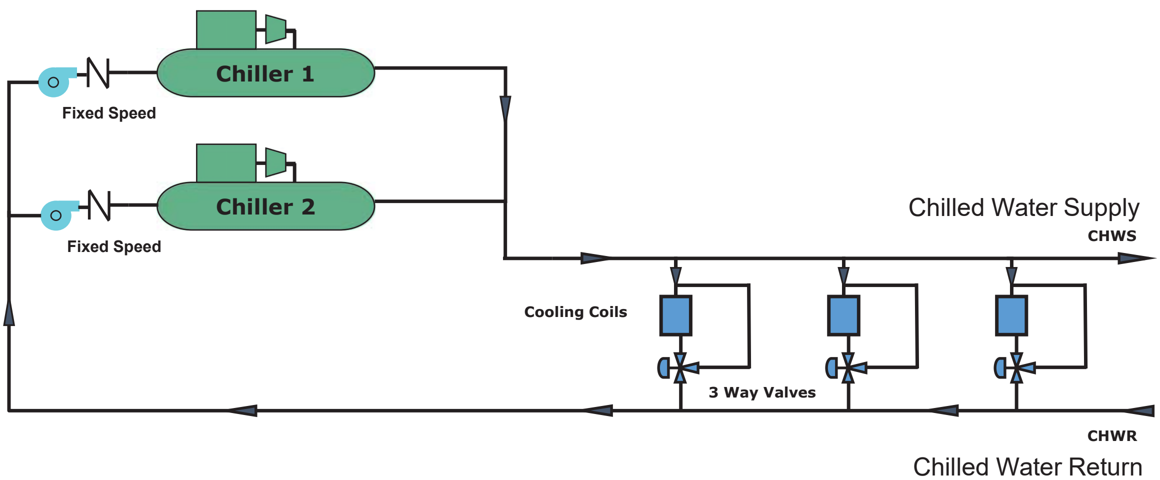
Steam Turbine Drives

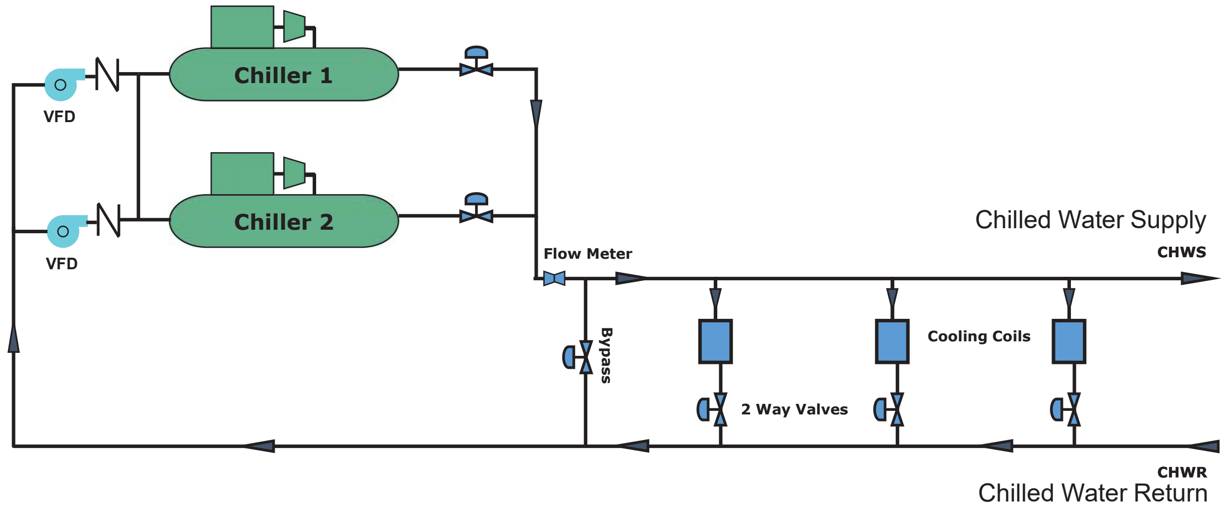


Fixed Speed Primary ONLY Chiller Plant



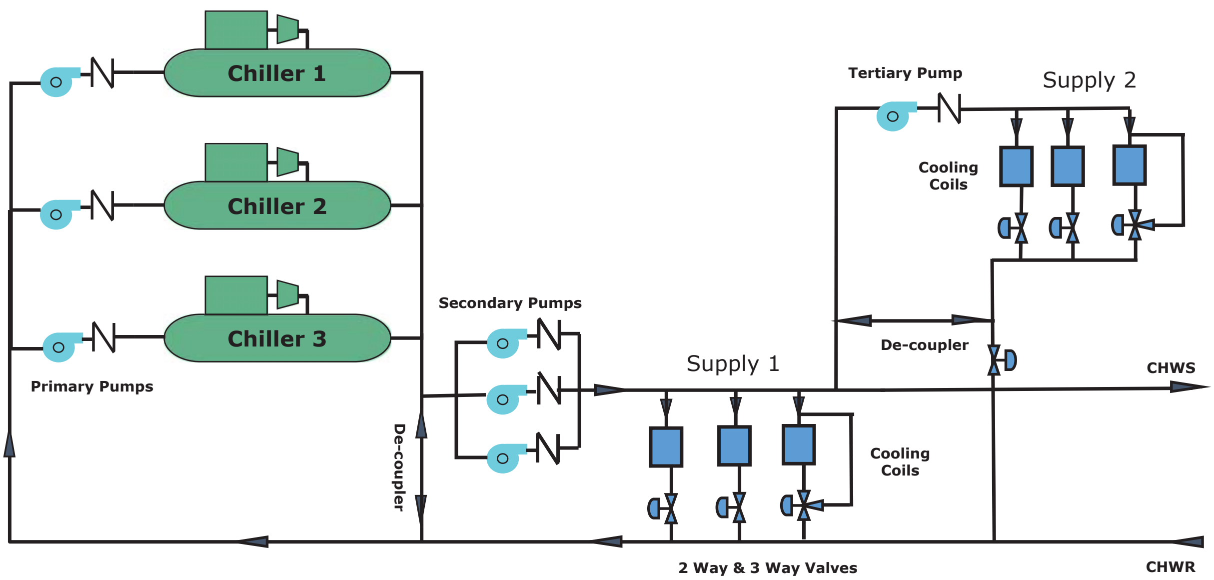
* CHWR is always reverse return but shown here as direct return for simplicity

Variable Speed Primary ONLY Chiller Plant



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

Primary, Secondary & Tertiary Loop Chiller Plant



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

Key Points / Action Items

1. *The most common compressor drive is the fixed-speed electric motor but other drivers are available*
2. *There are several control mechanisms to control the compressor operation*
3. *Part-load operation can be very inefficient and several state-of-the-art technologies are available including VFDs to improve efficiency*
4. *Simple chiller plants can have fixed / variable primary loops*
5. *Complex chiller plant systems have fixed and variable primary, secondary and tertiary chilled water distribution systems*

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1

2 LARGE-SCALE COOLING & INDUSTRIAL REFRIGERATION SCOPING TOOL (CRST)

2.1 Introduction and Scope of CRST

2.2 Demonstration & Functionality of CRST

2.3 Trainee Exercise - CR System

2

2.1 Introduction & Scope of CRST

- The Large Scale Cooling & Industrial Refrigeration System Scoping Tool (CRST) is an excel-based software questionnaire
- It is designed to enhance awareness of areas of CR system management
- Divided into typical CR 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

Large-Scale Cooling & Industrial Refrigeration System Scoping Tool (CRST)

Large-Scale Cooling and Industrial Refrigeration System Scorecard

Points Details	
Maximum Score =	540
Your Score =	402
Best Practices Rating =	74%

From the questionnaire information provided, the plant has medium potential and energy savings in the range of 5-15% can be anticipated.

Sr.	Question	Answer	Score
	Large Scale Cooling / Industrial Refrigeration Plant		
	General		60
1	How old is your cooling/refrigeration system (equipment)?	<10 Years	10
2	When was the last time your cooling/refrigeration system was audited?	1 year or less	10
3	Do you monitor your refrigeration system cost? How often?	Yes, monthly or more frequently	10
4	How is your plant controlled?	DCS / BMS	5
5	Have you ever performed Pinch Analysis to check if refrigeration load can be minimized?	No	0
6	What percent of your plant capacity is generally utilized versus design?	Close to design or higher (>=80%)	10
7	Do you have a regular maintenance program?	Yes	10
8	Do you inspect the refrigerant charge level regularly? How often?	Yes, monthly or more frequently	10

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Intended CRST 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

5

CRST Organization

- Instructions
- Background information
  - Contact and site information
  - Operating hours, etc.
- General questions on the CR plant
- CR system component questions
  - Compressors
  - Water / Air – cooled / Evaporative condensers
  - Evaporators
  - Cooling towers
  - Waterside economizers / heat exchangers
  - Pumping systems

6

Obtaining Data for CRST Input

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

- Expected time: 1.5 hours (90 minutes)

7

Steps for Use of CRST

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

8

2 LARGE-SCALE COOLING & INDUSTRIAL REFRIGERATION SCOPING TOOL (CRST)

2.1 Introduction and Scope of CRST

2.2 Demonstration & Functionality of CRST

2.3 Trainee Exercise - CR System

2.2 Demonstration and Functionality of CRST

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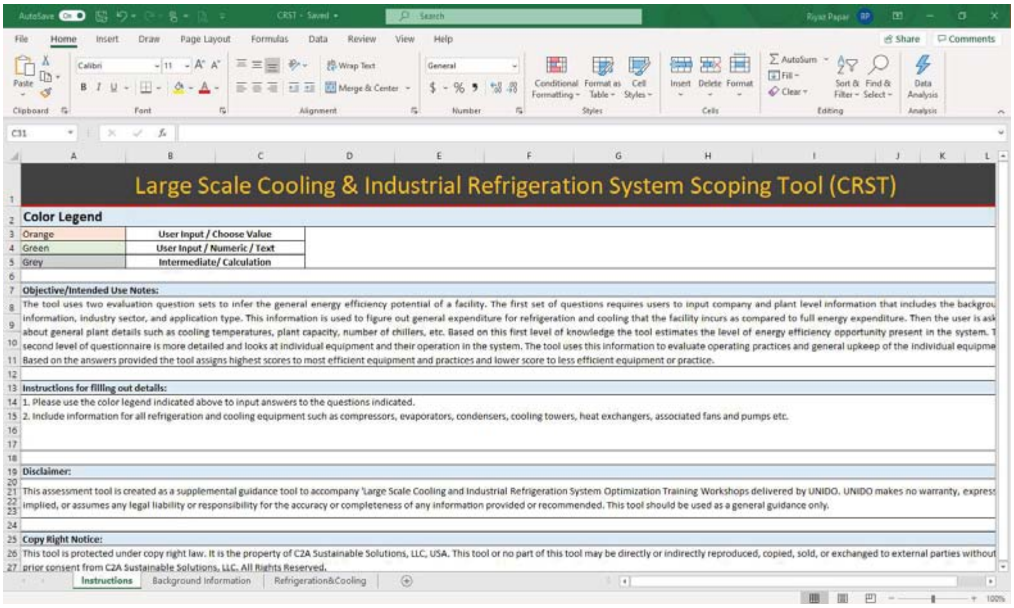
CRST – Instructions



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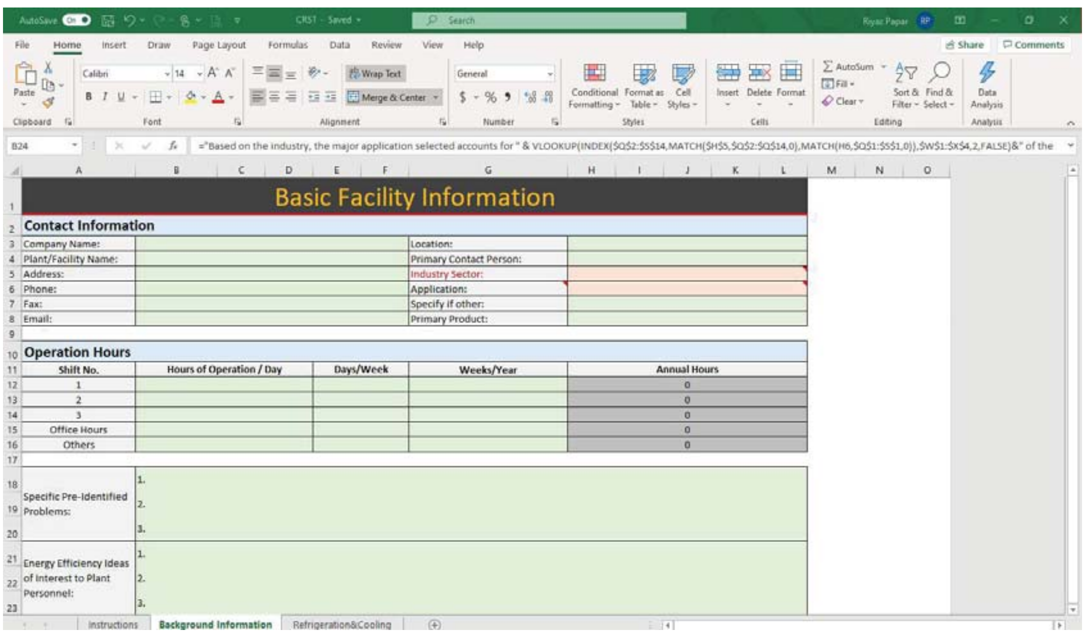
CRST – Basic Facility Information



CRST – CR System Scorecard - General

Large-Scale Cooling and Industrial Refrigeration System Scorecard

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CRST – CR System Scorecard – System Components

Sr.	Question	Answer	Score
	System Components		
1	Choose main components for your system		
	Compressors	Yes	1
	Condensers	Yes	1
	Evaporators	Yes	1
	Cooling Towers	Yes	1
	Evaporative Condensers	Yes	1
	Water Side Economizers/Plate Heat Exchangers	Yes	1
	Pumps	Yes	1
	Compressors		75
1	Do you inspect and conduct regular maintenance on the compressors?	Yes, as per manufacturers recommendations	10
2	What is your average running compressor load factor versus design?	Close to design or higher (>=80%)	10
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?	Yes, monthly or more frequently	10
5	Select the most common control mechanism for your compressors	Variable speed drives	10
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	50%	
	Variable Speed Electric Motor	0%	

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CRST – CR System Scorecard – Large Scale Cooling

	(iii) Approach temperature higher than design	No	10
Large Scale Cooling Plant			
Cooling Towers			87
1	What is general condition of the cooling towers?	Good	5
2	How are your cooling tower fans controlled?	Automated on / off control	10
3	How is your cooling tower water blowdown controlled?	Automatic	10
4	Do you monitor the following operating parameters continuously?		
	(i) Cooling tower water flow	Yes	10
	(ii) Water outlet temperature	Yes	5
	(iii) Water Inlet Temperature	Yes	2
	(iv) Ambient air wet bulb temperature	Yes	5
	(v) Ambient air temperature	Yes	2
	(vi) Cooling tower water chemistry	Yes	3
5	Are your overall cooling water flow rates lower than design?	No	10
6	Do you see an evenly spread and uniform water distribution in your cooling towers?	Yes	10
7	What is the type of your cooling tower fill?	Splash fill	5
8	How close is the approach of supply cooling water temperature to the wet bulb temperature?	Within 2 to 5 °C	10
9	Do you have sludge or sediment problems in cooling tower basins?	Yes	0
10	Do you have any fouling on distribution piping?	No	1
Industrial Refrigeration			

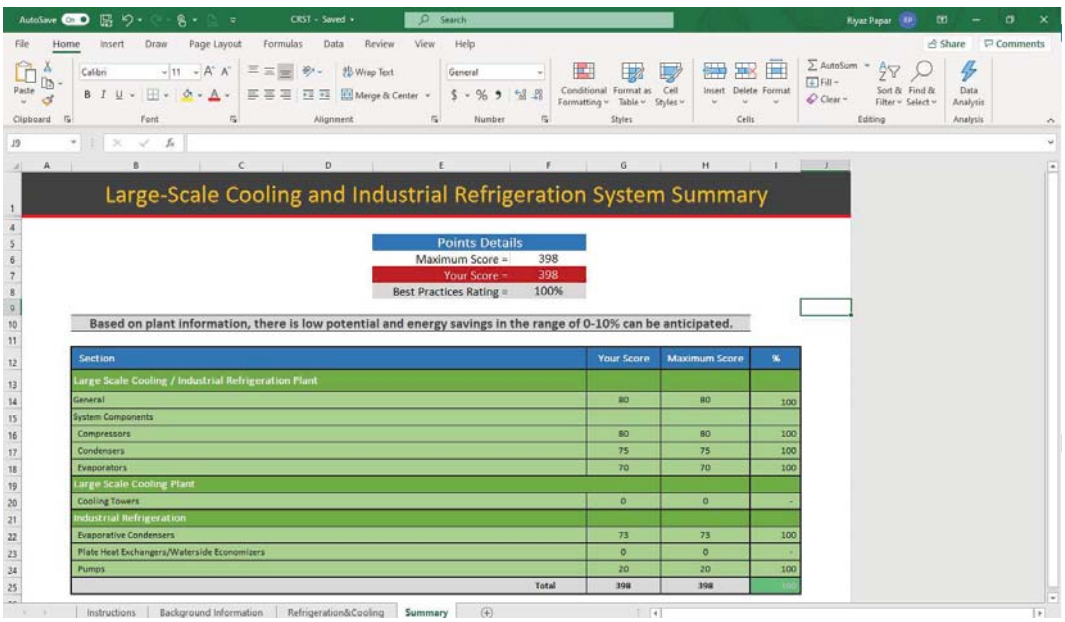
CRST – CR System Scorecard – Industrial Refrigeration

Industrial Refrigeration			
Evaporative Condensers			53
1	What is general condition of the evaporative condensers?	Good	5
2	How are your evaporative condenser fans controlled?	Automated on / off control	10
3	How is your evaporative condenser water blowdown controlled?	Automatic	10
4	Do you monitor the following operating parameters continuously?		
	(i) Refrigerant outlet temperature	No	0
	(ii) Ambient air wet bulb temperature	Yes	5
	(iii) Evaporative condenser water chemistry	Yes	3
5	Do you see an evenly spread and uniform water distribution in your evaporative condenser?	Yes	10
6	How close is the approach of refrigerant outlet temperature to the wet bulb temperature?	Within 5 to 10°C	10
7	Do you have sludge or sediment problems in evaporative condenser basins?	Yes	0
Plate Heat Exchangers/Waterside Economizers			31
1	Do you observe fouling on cooling tower water heat exchangers?	Yes	0
2	Do you routinely experience higher than design cooling loads?	Yes	0
3	Do you monitor cooling water exchanger pressure drop (ΔP)?	Yes	1
4	Do you have capacity problem due to cooling water flow issues?	No	10
5	Are there any end users that are starved of cooling water flow?	Yes	0
6	Are the following conditions representative during operations:		
	(i) Cooling tower water flow and/or coolant flow lower than design	Don't Know	0
	(ii) Cooling tower water dP and/or coolant dP higher than design dP	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 CR system
  - An average plant would score between 60-75%
- A "line in the sand" effort on potential energy savings possible in the CR system is provided based on
  - Past experiences in CR systems
  - Data collected over the years from different energy assessments in CR 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 CRST

CRST – CR System Summary Results



2 LARGE-SCALE COOLING & INDUSTRIAL REFRIGERATION SCOPING TOOL (CRST)

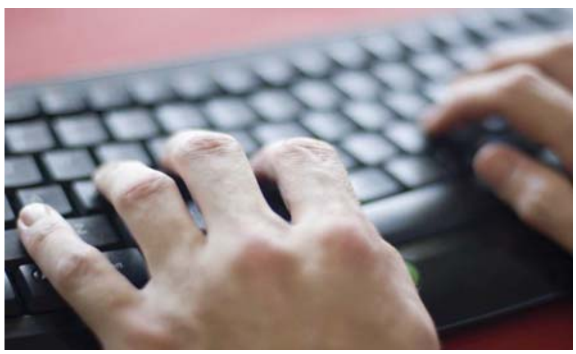
2.1 Introduction and Scope of CRST

2.2 Demonstration & Functionality of CRST

2.3 Trainee Exercise - CR System

2.3 Trainee Exercise – CRST on CR System

- You have been tasked with a CR 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 CRST and input available plant data
- Identify missing data and determine appropriate plant source for this data
- List possible CR system improvement opportunities that you would like to investigate during the energy assessment



Using CRST on a Large-Scale Chilled Water Plant at a Food & Beverages Plant

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Facility Description

- The plant / facility is a large Food & Beverages plant located in the Johannesburg, SA
- 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 CRST software tool

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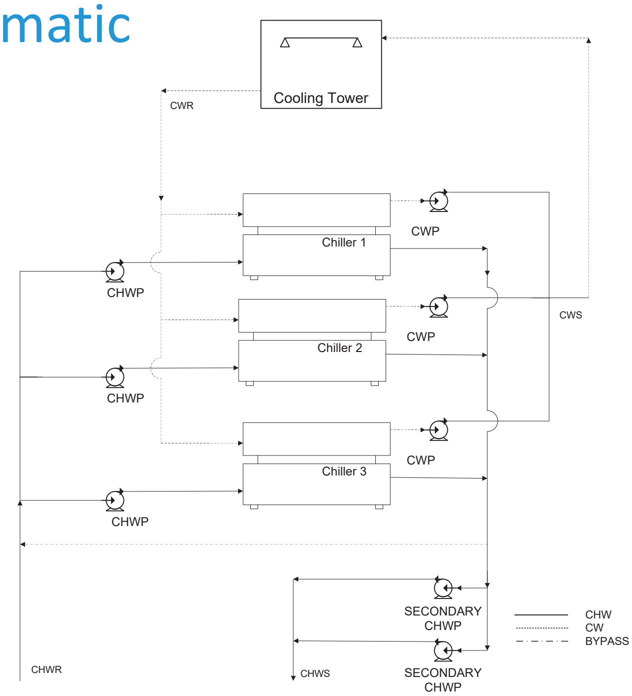
System Schematic



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System Information

- The facility is 10-15 years old
- It has been a while since an energy assessment was done on the system but plant personnel do keep a tab on annual spend / budget for the operations to identify any major issues
- 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 we are not close to any capacity limitations
- A maintenance contractor provides regular support (quarterly site visit) to keep the plant in operation without any issues

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Sub-System Information

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

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Sub-System Information (Compressors)

- Since the system is relatively old, maintenance is done on an as-needed basis
- Since we have two centrifugal compressor chillers, we run them to collect equal operating hours annually but there are times when they are both operating at higher loads
- We have manual operator logs which record load levels – guide vane positions
- The compressors have capacity control with guide vanes and but we really don't have much instrumentation on the compressors per se
- We believe that we are operating the compressors in their expected operating ranges

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Sub-System Information (Condensers)

- Since the system is relatively old, maintenance is done on an as-needed basis
- We do see issues sometimes with condensers and during the high-load season scaling does occur in the tubes
- We have temperature monitors on the supply and return water and manual operator logs provide the information, if required
- We do keep a tab on the approach temperature periodically and the maintenance contractor keeps a record of that during the visit

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Sub-System Information (Evaporators)

- Since the system is relatively old and it is mostly a closed loop on the chilled water side, maintenance is done on an as-needed basis
- We have not seen any issues with evaporator operations and it meets our process setpoints always
- Instrumentation is fairly limited on the evaporator but we do measure inlet and outlet temperature and pressure of the refrigerant
- We have manual operator logs to provide the information, if required
- We do keep a tab on the approach temperature

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Sub-System Information (Cooling Tower)

- The system is relatively old and we haven't done any upgrades other than basic maintenance and fixing flow nozzle heads, basin cleaning, etc.
- We have not seen any issues with cooling tower operations
- Fans are controlled automatically to meet setpoint
- Water chemistry is maintained by fixed blowdown
- We closely monitor water outlet temperature, ambient temperature and periodically check both with wet-bulb
- Manual operator logs record this information and we see a 5-10°C approach on the cooling tower

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
- We really don't understand how many pumps need to run based on load but we just run all the pumps so that all the chillers are satisfied with water flow all the time when they are operating

CRST Hands-on Exercise Instructions

- For the plant information presented, provide data input to the CRST and arrive at scores for each CRST 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 CRST analysis results, develop a list of priority actions to achieve energy conservation in the example plant

CRST Hands-on Exercise Results

Basic Facility Information

Contact Information

Company Name:	Class Example Facility	Location:	Johannesburg, SA
Plant/Facility Name:	Joburg Plant	Primary Contact Person:	Mr. John Doe
Address:	1234 Main Street	Industry Sector:	Food & Beverage
Phone:		Application:	Large Scale Cooling
Fax:		Specify if other:	
Email:		Primary Product:	Fruit Juice & Fruit Cup 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

CRST Hands-on Exercise Results

Large-Scale Cooling and Industrial Refrigeration System Scorecard

Sr.	Question	Answer	Score
	Large Scale Cooling / Industrial Refrigeration Plant		
	General		41
1	How old is your cooling/refrigeration system (equipment)?	10- 20 years	5
2	When was the last time your cooling/refrigeration system was audited?	>5 years ago or Never	0
3	Do you monitor your refrigeration system cost? How often?	Yes, annually	5
4	How is your plant controlled?	DCS / BMS	5
5	Have you ever performed Pinch Analysis to check if refrigeration load can be minimized?	Don't know	5
6	What percent of your plant capacity is generally utilized versus design?	Higher than 50%	5
7	Do you have a regular maintenance program?	Yes	10
8	Do you inspect the refrigerant charge level regularly? How often?	Yes, Quarterly	6
	System Components		
1	Choose main components for your system		
	Compressors	Yes	1
	Condensers (Water-Cooled or Air-Cooled)	Yes	1
	Evaporators	Yes	1
	Cooling Towers	Yes	1
	Evaporative Condensers	No	0
	Water Side Economizers/Plate Heat Exchangers	No	0
	Pumps	Yes	1

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CRST 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%	

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CRST 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

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CRST Hands-on Exercise Results

	Large Scale Cooling Plant		
	Cooling Towers		34
1	What is general condition of the cooling towers?	Good	5
2	How are your cooling tower fans controlled?	Automated on / off control	5
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?	5°C to 10°C	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%	
	Motor drives	75%	
	Condensing turbine drives	0%	
	Total	100%	
2	Are you only running the minimum number of pumps?	No	0

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CRST Hands-on Exercise Results

Large-Scale Cooling and Industrial Refrigeration System Summary

Points Details	
Maximum Score =	387
Your Score =	205
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	%
Large Scale Cooling / Industrial Refrigeration Plant			
General	41	80	51
System Components			
Compressors	53	80	66
Condensers	35	75	47
Evaporators	35	70	50
Large Scale Cooling Plant			
Cooling Towers	34	62	55
Industrial Refrigeration			
Evaporative Condensers & Compressors	0	0	-
Plate Heat Exchangers/Waterside Economizers	0	0	-
Pumps	7	20	35
Total	205	387	53

SUSTAINABLE SOLUTIONS

CRST Hands-on Exercise Next Steps

- Overall Chilled Water System (50%)
  - Calculate chilled water costs & trend
  - Correlate chilled water costs with production and benchmark
  - 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

CRST 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

CRST Hands-on Exercise Next Steps

- Cooling Towers (55%)
  - 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 CR systems
2. The Large-Scale Cooling & Industrial Refrigeration System Scoping Tool (CRST) can be used to identify these improvement opportunities
3. The CRST is an intake questionnaire to collect preliminary plant level information
4. It shouldn't take more than 90 minutes to complete but we need to be speaking to the RIGHT (knowledgeable) person in the plant

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3 CALCULATIONS OF UNIT & SYSTEM EFFICIENCY

3.1 System Efficiency Metrics

- Every CR system is built up of multiple CR units
  - Individual packaged units serving a specific load
  - Packaged units combined with a central loop system
  - Distributed CR 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 CR system will provide a cooling effect (load, demand) – summation of multiple units

- Every CR system will need energy (most times electric) but in certain systems can be thermal (gas, oil, steam, hot water, etc.)

3

Chiller or Refrigeration Unit Capacity

- CR unit capacity (kW or tonnage) is the amount of full load cooling capacity provided by the CR unit at design conditions

- Units of cooling capacity or refrigerating effect are kW or MW

- In 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 / ~887 kg) of water at 0°C to make it into ice at 0°C in one day (24 hr) is 1 RT

- **1 RT = 12,000 Btu/hr = 3.517 kW**

4

Unit Performance Metrics

- 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

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

  - Depending on the system
    - Cooling COP
    - Heating COP

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Unit Performance Metrics

- 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

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

  - 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

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Unit Performance Metrics

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

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

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

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

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Example - Determining CR Unit Energy and Costs

- CR unit information provided
  - Cooling capacity = 3,500 kW
  - $COP_{cooling}$ = 5.40
  - Annual operation = 6,250 hours
  - Electric power cost = 1.0 R/kWh

$$Power = Cooling\ Load\ /\ COP_{cooling}$$

$$Annual\ Energy\ =\ Power * Hours$$

$$Operating\ Cost\ =\ Annual\ Energy * Energy\ Cost$$

Example - Determining CR System Energy and Costs

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

Example - Determining CR System COP

- CR System information provided
  - Cooling capacity = 3,500 kW
  - CR Unit COP = 5.40

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

Example - Determining Other CR System Metrics

- Specific Cooling Cost

$$Specific\ CR\ Unit\ Cooling\ Cost = \frac{CR\ Unit\ Annual\ Energy\ Cost}{Annual\ Cooling\ kWh}$$

$$Specific\ CR\ System\ Cooling\ Cost = \frac{CR\ System\ Annual\ Energy\ Cost}{Annual\ Cooling\ kWh}$$

Chiller Unit Performance Metric Ranges

- Best place to obtain COP (or EER) information is manufacturer's catalogs and websites
- Every manufacturer will define design conditions for heat rejection
  - Water-cooled – (30/35°C)
  - Air-cooled – (35°C)
- Every manufacturer will define design conditions for chilled water
  - 7/12°C
- COP ranges from OEMs – 3.5 to 10.0

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3 CALCULATIONS OF UNIT & SYSTEM EFFICIENCY

3.1 System Efficiency Metrics

3.2 Load Profile

3.3 Seasonal Energy Efficiency

3.4 Additional Performance Metrics

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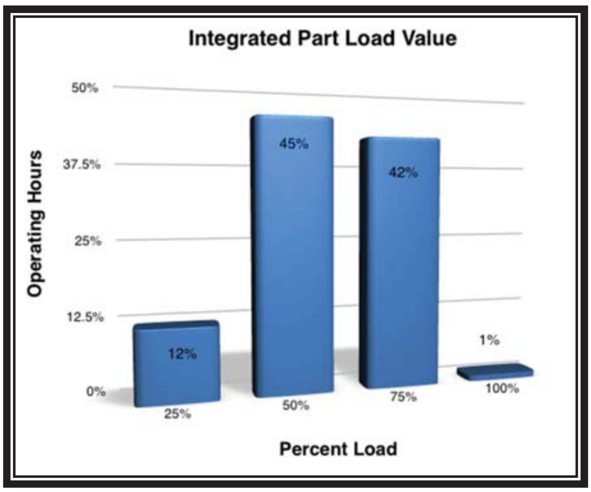
3.2 Load Profile

- CR 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 CR 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.

CR System Load Profile

- 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 COP but instead they should be used as a guide to reach optimal solutions



CR System Load Profile

- Every CR 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 CR system
- Every CR energy efficiency assessment should require the inclusion of a representative load profile

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CR 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

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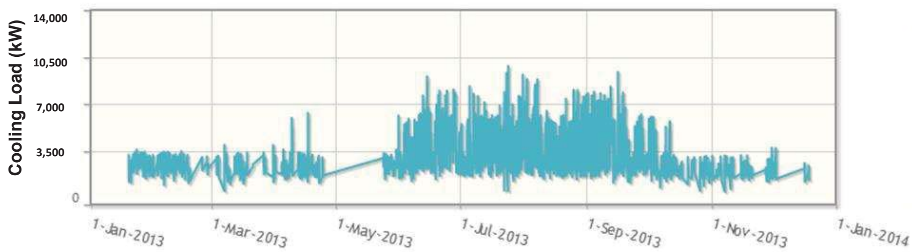
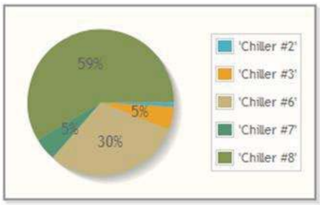
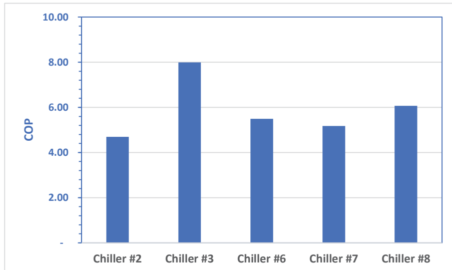
Large Commercial Central Plant

Plant Cooling Capacity - 21,000 kW





Cooling Load Hours (kWh) Contribution of Operating Chillers



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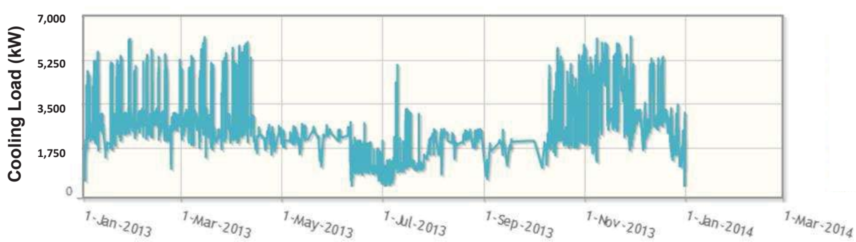
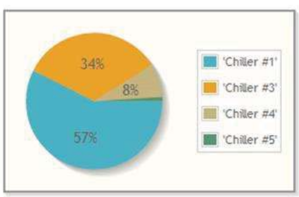
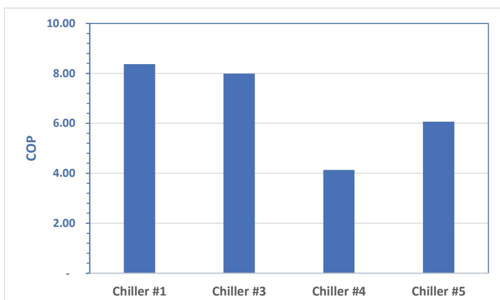
Food Manufacturing Plant Seasonal Operation

Plant Cooling Capacity - 12,500 kW





Cooling Load Hours (kWh) Contribution of Operating Chillers



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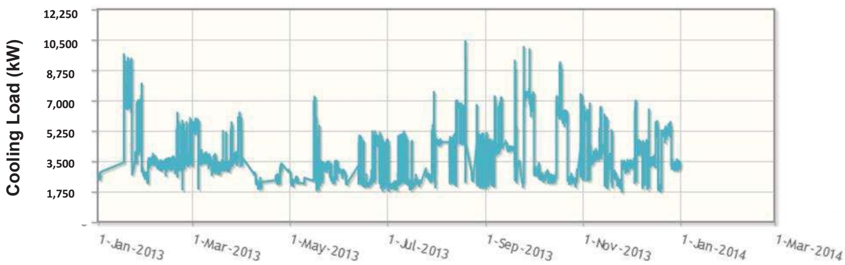
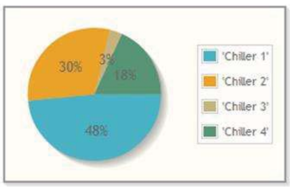
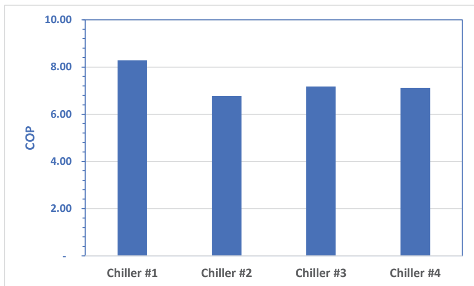
Data Center Central Plant

Plant Cooling Capacity - 16,000 kW



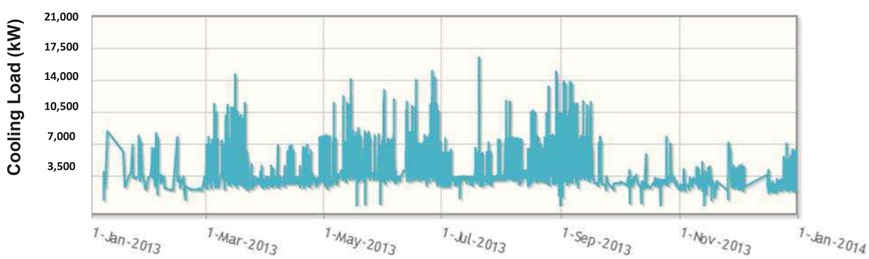


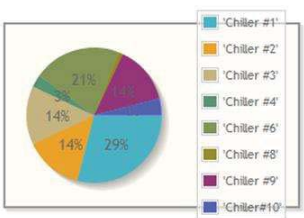
Cooling Load Hours (kWh) Contribution of Operating Chillers



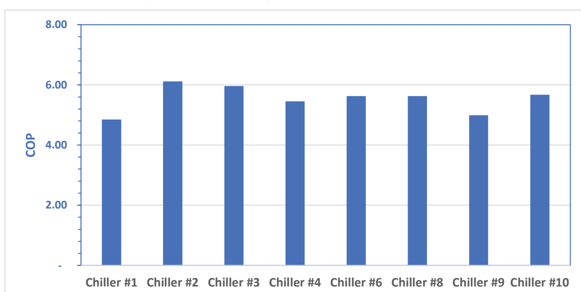
Casino Operation

Plant Cooling Capacity - 46,500 kW





Cooling Load Hours (kWh) Contribution of Operating Chillers



3 CALCULATIONS OF UNIT & SYSTEM EFFICIENCY

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3.3 Seasonal Energy Efficiency

- The COP (or EER) of CR 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

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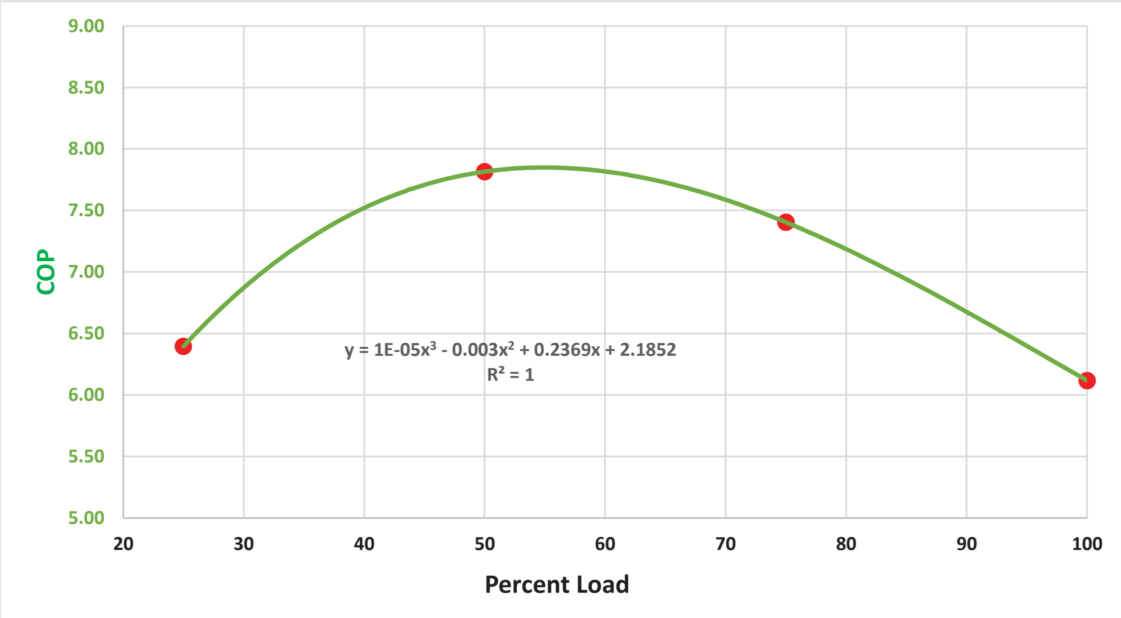
Overall CR System Performance



Chiller Design Specifications

- In the US, each chiller can be tested at the manufacturer's testing facility per AHRI Standard 550
  - There is an extra charge for this test
  - There maybe limitations based on size of chiller and testing facility capability
- COP for typical commercial chiller units
  - Water cooled – 4.4 – 8.8
  - Air cooled – 2.4 – 5.0
- Full load design rating conditions versus seasonal operating rating conditions
- ASHRAE Standard 90.1 provides minimum COP (or EER) requirements for chillers

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 @ 29.4°C ECWT
  - 75% load @ 23.9°C ECWT
  - 50% load @ 18.3°C ECWT
  - 25% load @ 18.3°C ECWT

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Seasonal COP (SCOP)

- SCOP is analogous to IPLV from the perspective of understanding overall performance over the whole year
- It takes into account seasonality and allows for an apples-to-apples comparison amongst different units/systems
- SCOP is specified by the manufacturer and available in catalogs
- SCOP is a great way to do energy consumption forecasts, budgets on chiller plant systems

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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	7,000 kW
COP	5.63	Seasonal COP	6.5
Full Load Amps	198	Volts	4160
Evaporator Entering Water Temperature	12.4°C	Condenser Entering Water Temperature	29.4°C
Evaporator Leaving Water Temperature	6.7°C	Condenser Leaving Water Temperature	34.7°C
Evaporator Flow	292 L/s	Condenser Flow	379 L/s
Evaporator Pressure Drop	69 kPa	Condenser Pressure Drop	56 kPa

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Key Points / Action Items

1. *Coefficient of Performance (or EER) is the system metric used*
2. *System COP 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, COP and electric utility cost*
5. *Chiller manufacturers design, specify and test chillers*
6. *SCOP is most commonly used to determine average rating*

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3 CALCULATIONS OF UNIT & SYSTEM EFFICIENCY

3.1 System Efficiency Metrics

3.2 Load Profile

3.3 Seasonal Energy Efficiency

3.4 Additional Performance Metrics

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3.4 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 CR system controllers that optimize the operations of the CR system real-time

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

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Calibration & Accuracy of Sensors

- To calculate CR system performance metrics, the operating data must be accurate
- All sensors drift over time
- Regular calibration is required
- Sensor Accuracy:
  - Temperature sensors must be accurate to 0.05°C
  - Differential pressures (dP) must be accurate to 0.1 kPa
  - Water flows must be accurate to within 0.5%
  - Refrigerant pressures must be accurate to within 0.5%

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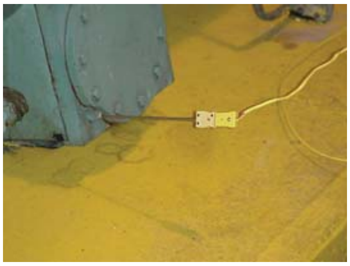
Temperature Measurements



- 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

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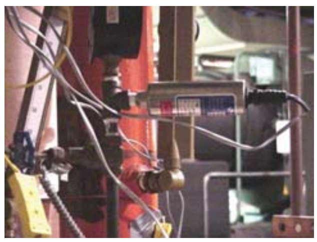
Pressure Measurements



- 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

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Flow Measurements

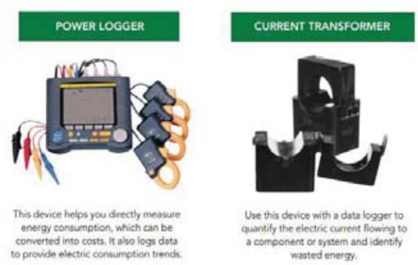
- There are different kinds of flowmeters
  - Orifice plate / Annubar / Pitot tube
  - Turbine type
  - Vortex shedder
  - Magnetic
  - Ultrasonic (non-intrusive)
  - Coriolis, etc.

- 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

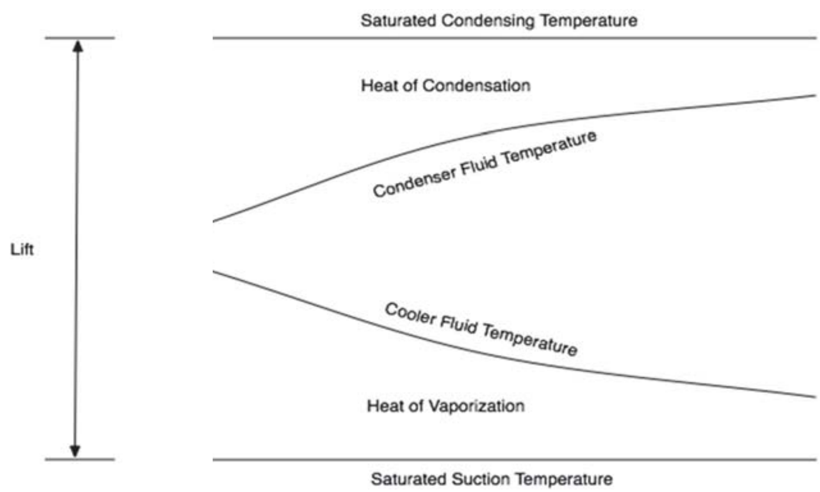


General CR System Performance Metrics

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

CR System / Unit Lift

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



Carnot Efficiency

- Ideal Coefficient of Performance (COP)
  - Carnot Efficiency
  - Dependent of cooling supply temperature and heat rejection temperature ONLY

$$Carnot\ COP = \frac{T_{cold}}{T_{reject} - Tcold}$$

  - All temperatures should be in the absolute temperature scale (K)
    - Absolute Temperature (K) = Temperature (°C) + 273.15

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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!

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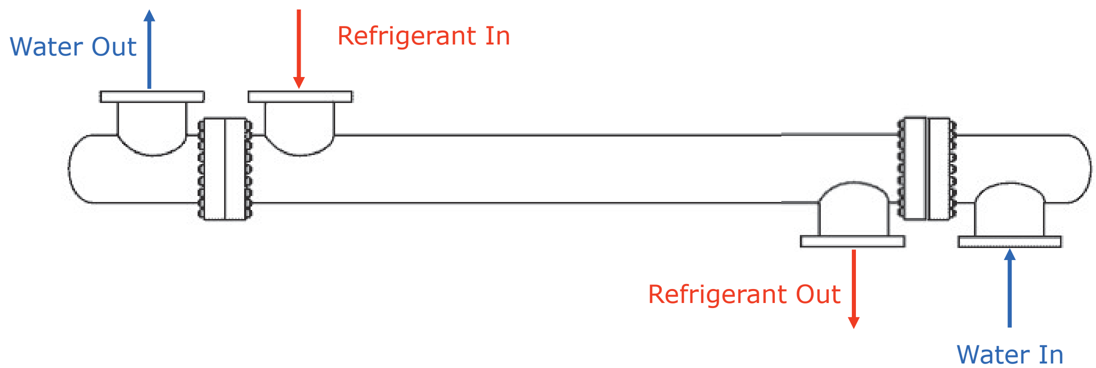
Heat Exchangers

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



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Heat Exchangers

- 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)

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Key Points / Action Items

1. *Actual operating performance calculations for CR 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 COP and increase in operating costs*
5. *Refrigerant Approach Temperature (RAT) serves as a good proxy for LMTD (driving force)*

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4 CHILLED WATER SYSTEM ASSESSMENT TOOL (CWSAT)

4.1 Installation of CWSAT (SI – Metric version)

4.2 Review of CWSAT

4.3 Trainee Exercise – Building a Baseline Model of a CR System

Acknowledgments: Dr. Dragoljub (Beka) Kosanovic
University of Massachusetts, Amherst, USA

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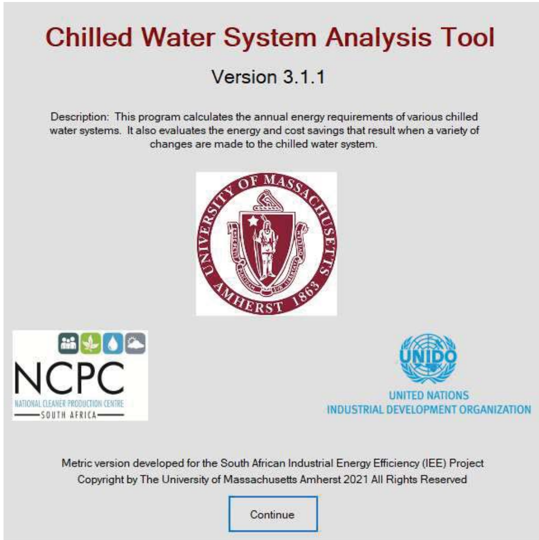
4.1 Installation of CWSAT (SI-Metric version)



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Installation of CWSAT

- Available in class on a USB drive
- Minimum system requirements
  - Windows-based PC
- Extract all the files from the zipped folder and store in CWSAT_SI folder
- Administrative privileges maybe required for computer
- CWSAT (SI – Metric version) has been developed by funding from NCPC-SA and UNIDO IEE Project

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4

CHILLED WATER SYSTEM ASSESSMENT TOOL (CWSAT)

4.1 Installation of CWSAT (SI – Metric version)

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4.3 Trainee Exercise – Building a Baseline Model of a CR System

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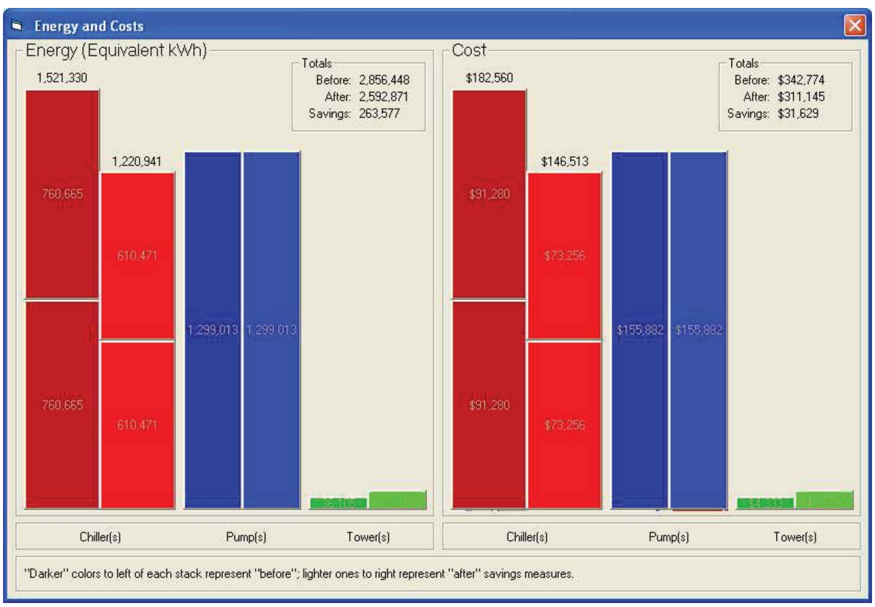
4.2 Review of CWSAT



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CWSAT INTRODUCTION

- A central chilled water system may account for a quarter to a third of facility energy consumption.
- The main goals of any cooling system
  - Provide adequate cooling to process or comfort load
  - Reduce energy consumption of the chilled water SYSTEM
- CWSAT IS NOT intended to determine system energy use down to the last kWh
- CWSAT IS intended to direct analysis effort toward the most promising cost reduction opportunities

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Chilled Water System Analysis Tool (CWSAT – SI Metric version)

The University of Massachusetts College of Engineering Department of Mechanical & Industrial Engineering

The University of Massachusetts Industrial Assessment Center funded by the U.S. Department of Energy

The Center for Energy Efficiency & Renewable Energy, Massachusetts

NCPC NATIONAL CLEANER PRODUCTION CENTRE SOUTH AFRICA

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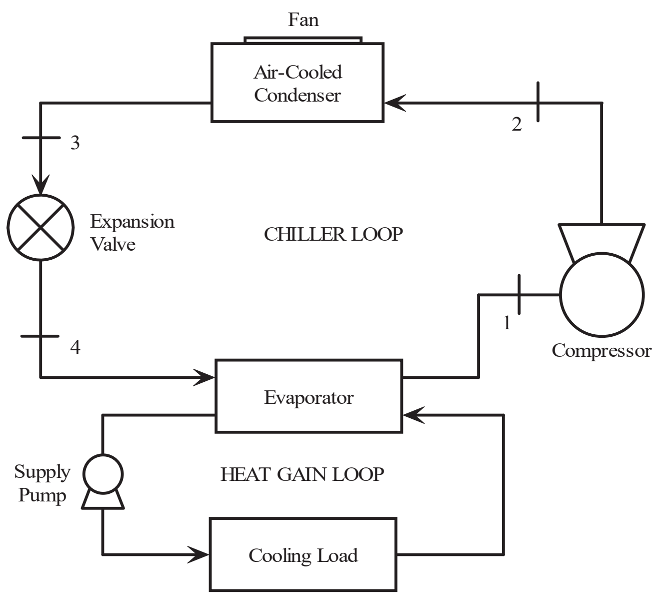
ACRONYMS

- CHWS: Chilled Water Supply
- CHWR: Chilled Water Return
- CWS: Condenser Water Supply
- CWR: Condenser Water Return

- FLE: Full Load Efficiency

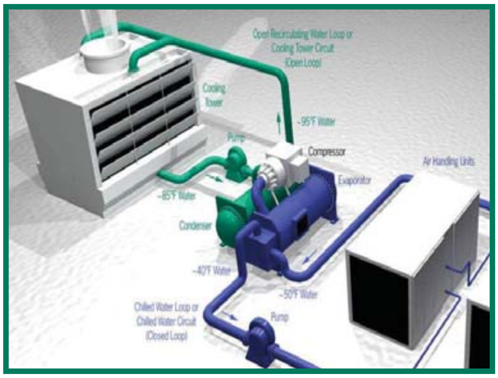
CWSAT System Configurations

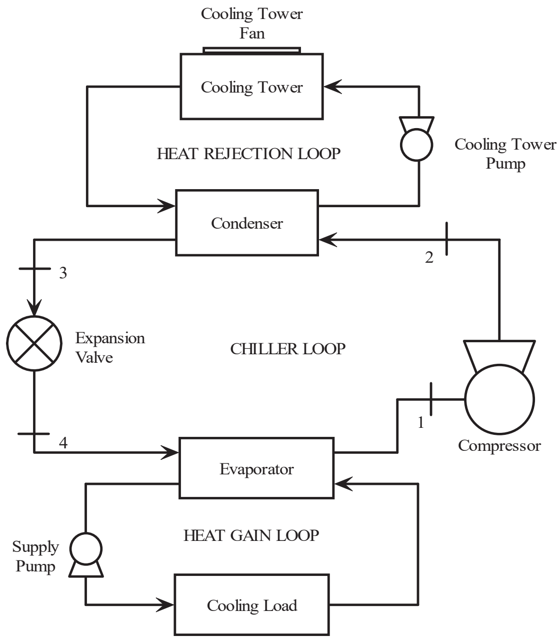
- Air-Cooled Chilled Water System: Single Chiller



CWSAT System Configurations

- Water-Cooled Chilled Water System: Single Chiller





CWSAT Supported Equipment Types

- Mechanical vapor compression chillers (Centrifugal, reciprocating, and twin-screw helical rotary compressors)
- Air or water-cooled condensers
- Direct contact towers
- Mechanical draft towers (crossflow or counterflow)
- Shell-and-tube evaporators (other designs are limited to low capacity applications)
- Simple pump control configurations on primary circuit

CWSAT Equipment Types NOT Supported

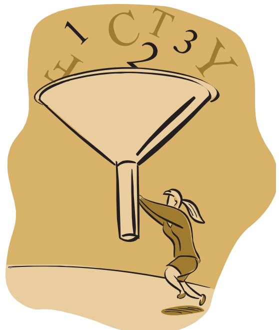
- Absorption chillers
- Single Screw, Scroll, or Troichoidal compressors
- Evaporative condensers
- Indirect contact towers such as wet/dry or dry towers
- Natural or spray-induced draft towers
- Secondary pumping circuit (on chilled water or condenser water loop)
- Chillers connected in series

CWSAT Energy Calculations

- Chillers
  - Uses catalog & manufacturer's data to follow typical performance curves
  - Uses correlations to adjust for actual condenser water (where applicable) and chilled water temperature
  - Uses schedules to determine hours at given load
- Cooling Towers
  - Uses iterative process and prototypical performance correlation to determine fan energy
  - Correlation inputs rely on weather data, chiller load, and condenser pump flow rate
- Pumps
  - Uses power provided as an input or utilizes pump energy equation to estimate pump horsepower & energy

Data Collection from Site

- Basic System Data (Observation)
  - Understand and observe the need for cooling/chilled water requirement
  - Number of Chillers & Chiller Type (Centrifugal, Reciprocating, Screw)
  - Number of Chilled Water Pumps
  - Number of Condenser Water Pumps
  - System Type – Air Cooled or Water Cooled
    - Location of Cooling Tower
      - Dedicated
      - Supplies to other processes
  - Number of towers / air-cooled condensers



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Data Collection from Site

- Nameplate data
  - Chiller manufacturer & model number
    - Cooling Capacity (kW)
    - Efficiency
    - Age
  - Cooling Tower manufacturer & model number
    - Tower size (kW)
    - Efficiency
    - Tower type (# fans / # cells / motor control)
  - Pump & Pump Motor manufacturer & model number
    - Pump Curve (flow rate, efficiency)
    - Motor kW & Efficiency

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Data Collection from Site

- General Operating Parameters
  (conversations with facility personnel, chiller control panels, temperature sensors, observations)
  - Chilled Water Supply Temperature (setpoint)
  - Condenser Water Supply Temperature (setpoint and/or strategy)
  - Chilled Water Supply Flow Control (constant or variable, primary/secondary system)
  - Condenser Water Supply Flow Control (constant or variable, Heat exchanger used)

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Chilled Water System Components

- Components Covered by CWSAT
  - Chiller Types:
    - Centrifugal
    - Helical Rotary / Screw
    - Reciprocating
  - Condenser Types:
    - Water Cooled with Cooling Towers
    - Air Cooled
  - Other Equipment:
    - Pumps
    - Fans
    - Piping & Valves
    - Heat Exchangers

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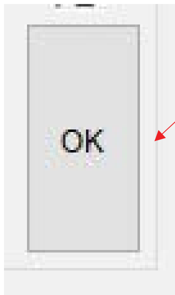
CWSAT INPUT Screenshots

- Geographic location
- System description
- Heat rejection setup
- Pump setups
  - Chilled water
  - Condenser water (if applicable)
- Chiller setup
  - Default
  - Custom
- Utility Cost
- Operation Schedule & Load Profile



Click the "OK" Button to proceed to the next Input Sub-block

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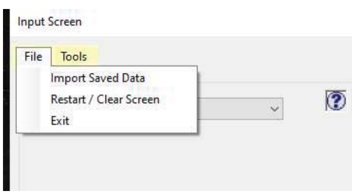
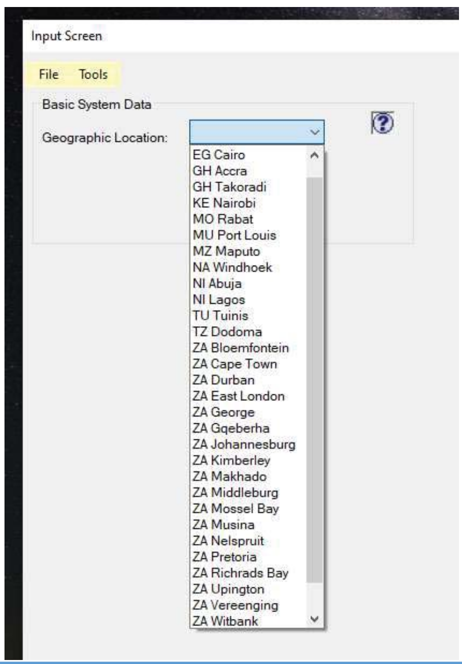
Screen Shots of CWSAT Inputs





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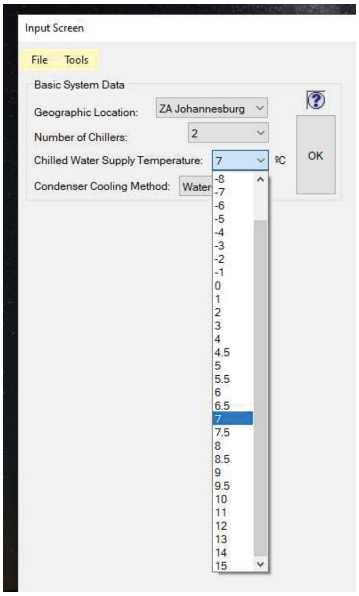
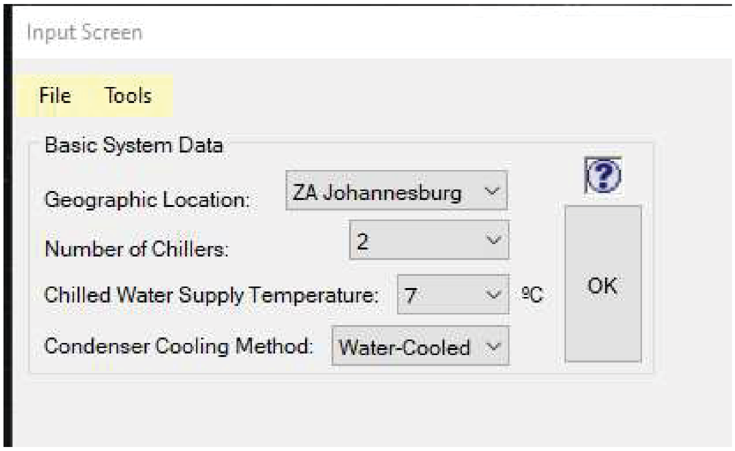
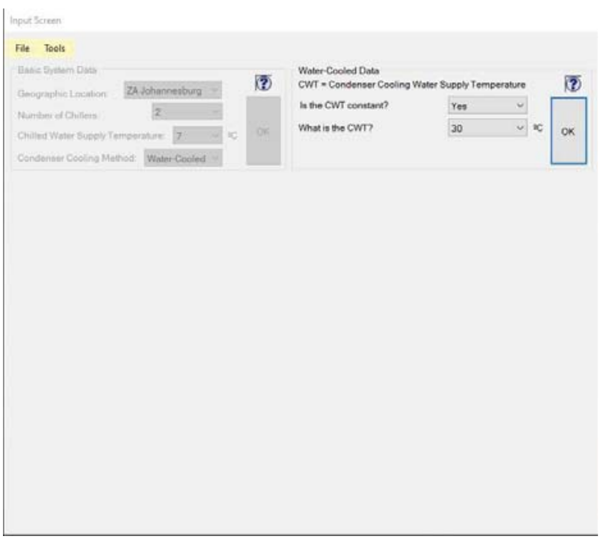
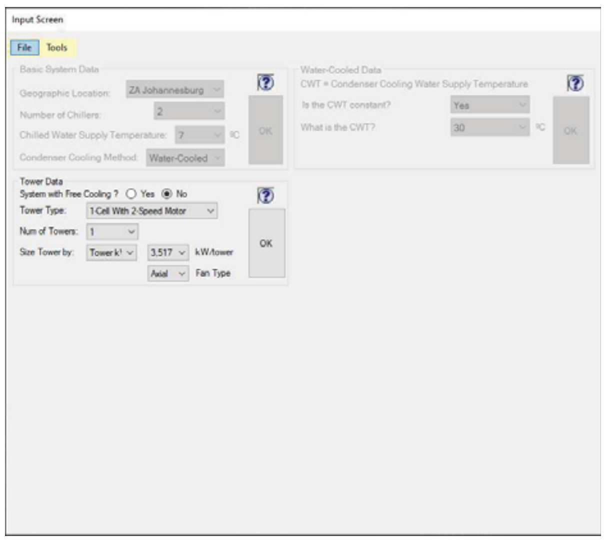
Screen Shots of CWSAT Inputs



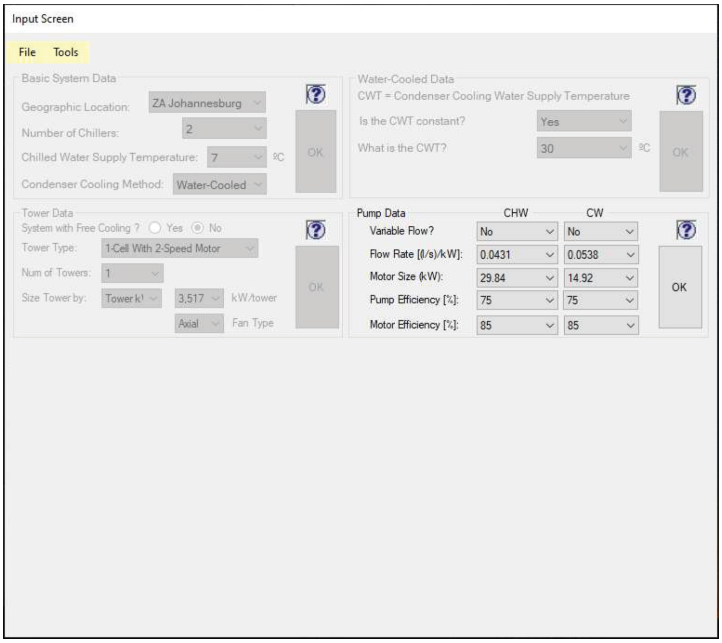


Screen Shots of CWSAT Inputs

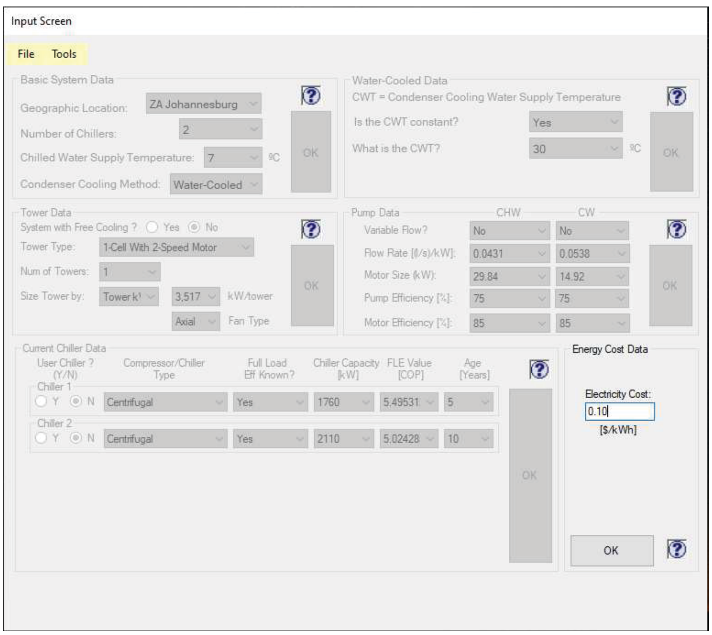




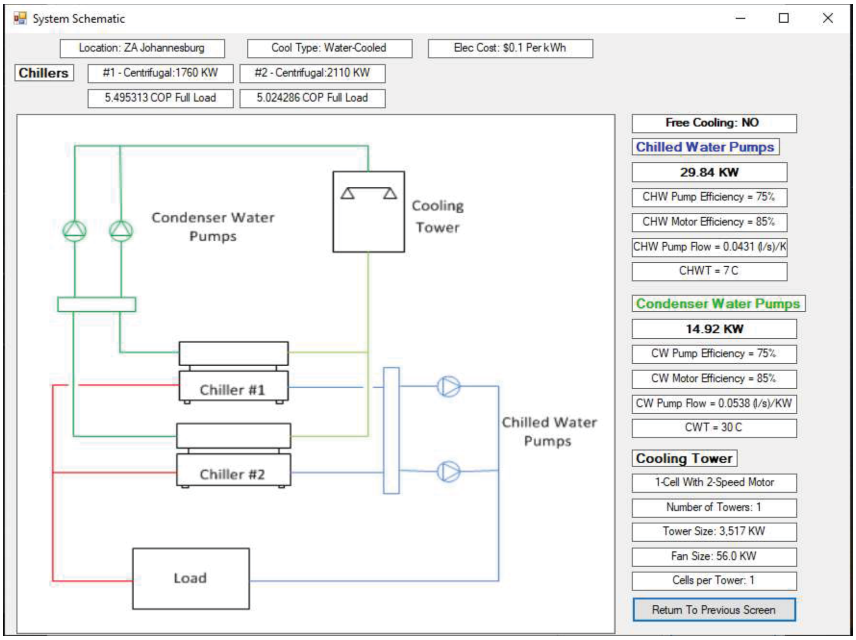
Screen Shots of CWSAT Inputs



Screen Shots of CWSAT Inputs



Screen Shots of CWSAT Analysis



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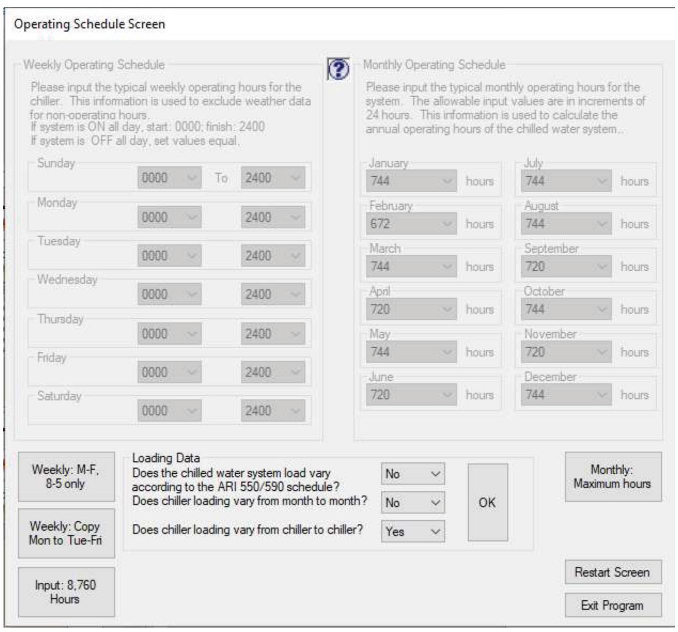
Screen Shots of CWSAT Detailed Inputs



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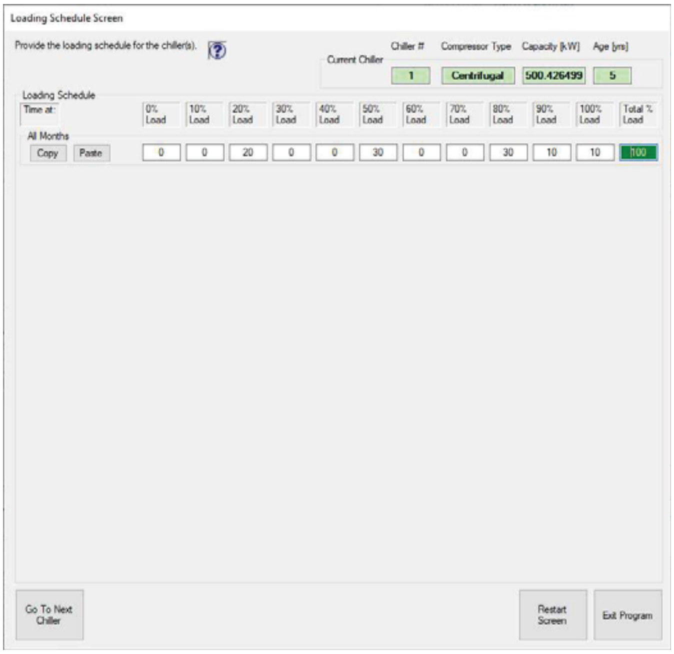
Screen Shots of CWSAT Detailed Inputs



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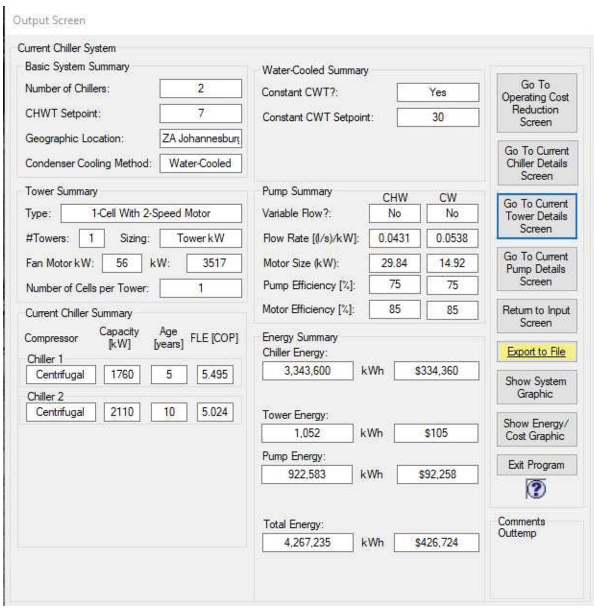
Screen Shots of CWSAT Outputs



Detailed Information

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Screen Shots of CWSAT Outputs

Current Chiller Details Screen

Chiller 1: Centrifugal (Rated Capacity: 500.426499857833 tons)

	0% Load	10% Load	20% Load	30% Load	40% Load	50% Load	60% Load	70% Load	80% Load	90% Load	100% Load	Total
[COP]:	∞	∞	4.474	∞	∞	6.346	∞	∞	5.880	5.556	5.242	
Hours:	0	0	1,754	0	0	2,626	0	0	2,634	873	873	8,760
Power [kW]:	0.0	0.0	78.7	0.0	0.0	138.7	0.0	0.0	239.4	285.1	335.7	
Energy [kWh]:	0	0	138,008	0	0	364,171	0	0	630,683	248,873	293,083	1,674,818

Chiller 2: Centrifugal (Rated Capacity: 599.943133352289 tons)

	0% Load	10% Load	20% Load	30% Load	40% Load	50% Load	60% Load	70% Load	80% Load	90% Load	100% Load	Total
[COP]:	∞	∞	∞	∞	∞	5.538	∞	∞	∞	∞	∞	
Hours:	0	0	0	0	0	8,760	0	0	0	0	0	8,760
Power [kW]:	0.0	0.0	0.0	0.0	0.0	190.5	0.0	0.0	0.0	0.0	0.0	
Energy [kWh]:	0	0	0	0	0	1,668,78	0	0	0	0	0	1,668,781

Return to Output Screen

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Screen Shots of CWSAT Outputs

Current Pump Details Screen

	Chilled Water Pump Summary	Condenser Water Pump Summary
Variable Flow?:	No	No
Flow Rate [(l/s)/kW]:	0.0431	0.0538
Motor Size (kW):	29.84	14.92
Pump Efficiency [%]:	75	75
Motor Efficiency [%]:	85	85

	Chilled Water Pumping Energy [kWh] Constant Flow	Condenser Water Pumping Energy [kWh] Constant Flow
Chiller 1:	307,528	153,764
Chiller 2:	307,528	153,764
Total:	615,055	307,528

Return to Output Screen

Screen Shots of CWSAT Outputs

4 CHILLED WATER SYSTEM ASSESSMENT TOOL (CWSAT)

4.1 Installation of CWSAT (SI – Metric version)

4.2 Review of CWSAT

4.3 Trainee Exercise – Building a Baseline Model of a CR System

4.3 Trainee Exercise - CWSAT

Building a Baseline Model of a Large-Scale Chilled Water Plant

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Aim of Trainee Exercise

- Provide an understanding of an actual industrial chilled water system
- Hands-on exercise to demonstrate operation and functionality of CWSAT in a real-life scenario
- Start from the basics and get into details and build a “Baseline Model” for a central chilled water system
- Trainees will learn to model their own chilled water plant and develop a baseline for the energy consumption and the breakdown of energy consumed by the individual sub-systems

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Description of Chilled Water System

- **Industrial Complex – Johannesburg, SA**
  The system provides chilled water for process and air-conditioning within two facilities that manufacture plastic molded products for the semiconductor industry

Chilled Water System:

- Water-cooled
- 10 years old
- 3 Chillers
- 2 cell 1-speed Tower (1)
- Primary / Secondary Chilled Water Distribution System

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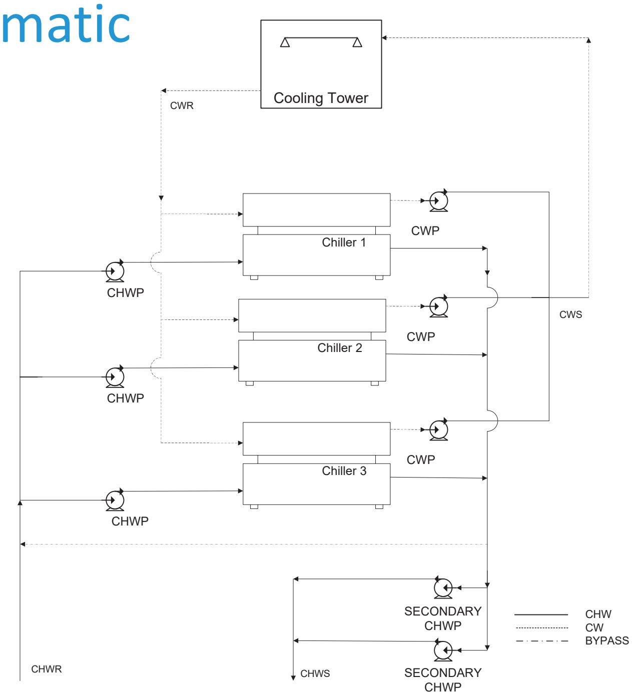
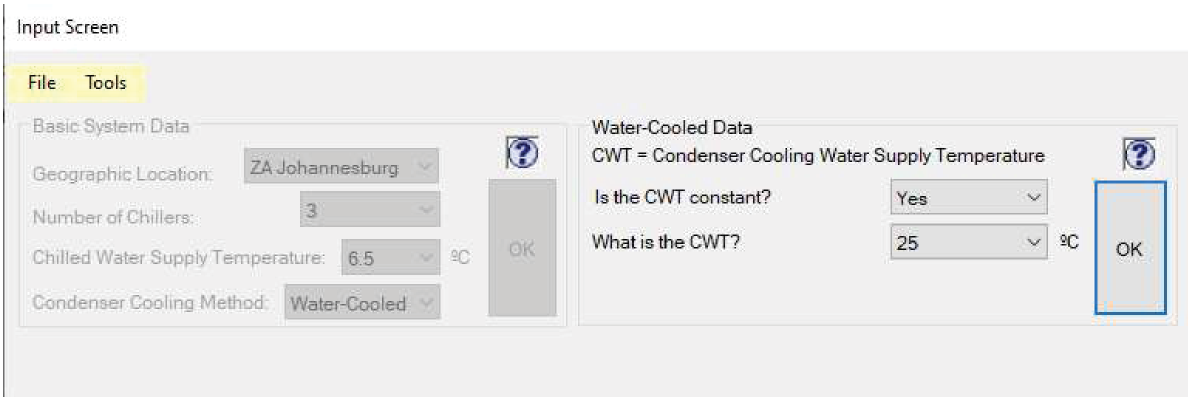
System Schematic



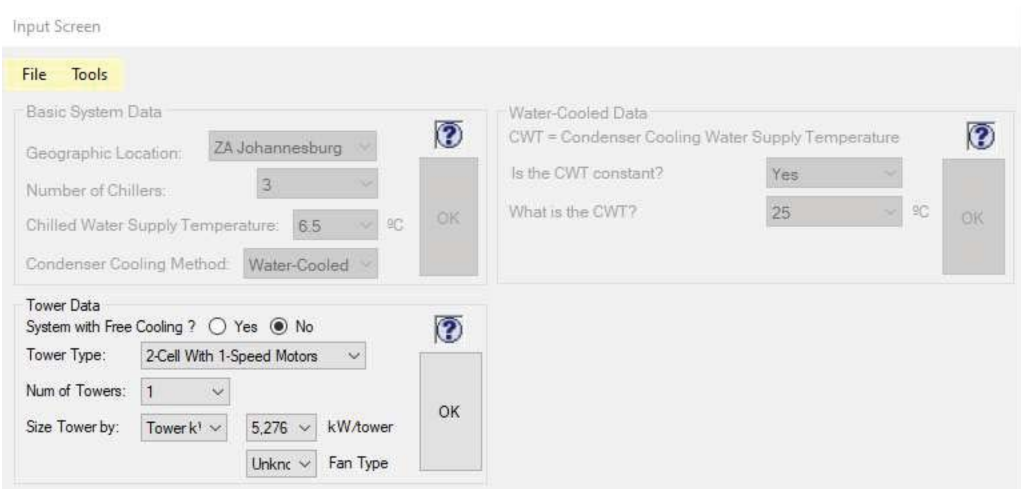
System Information

- Chillers:
  - Chilled Water Setpoint – 6.5°C
  - Condenser Water Setpoint – 25°C



System Information

- Cooling Tower
  - 1 Tower with 2 cell and 1-speed motor
  - Tower Rated Capacity - 5,276 kW



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Sub-System Information

- Chilled Water Pumps
  - Primary
    - 3 x 15 kW Constant Speed
    - Flow rate based on 0.043 l/s/kW
  - Secondary
    - 2 x 25 kW Variable Speed

- Condenser Water Pumps
  - 3 x 10 kW Constant Speed
  - Flow rate based on 0.054 l/s/kW

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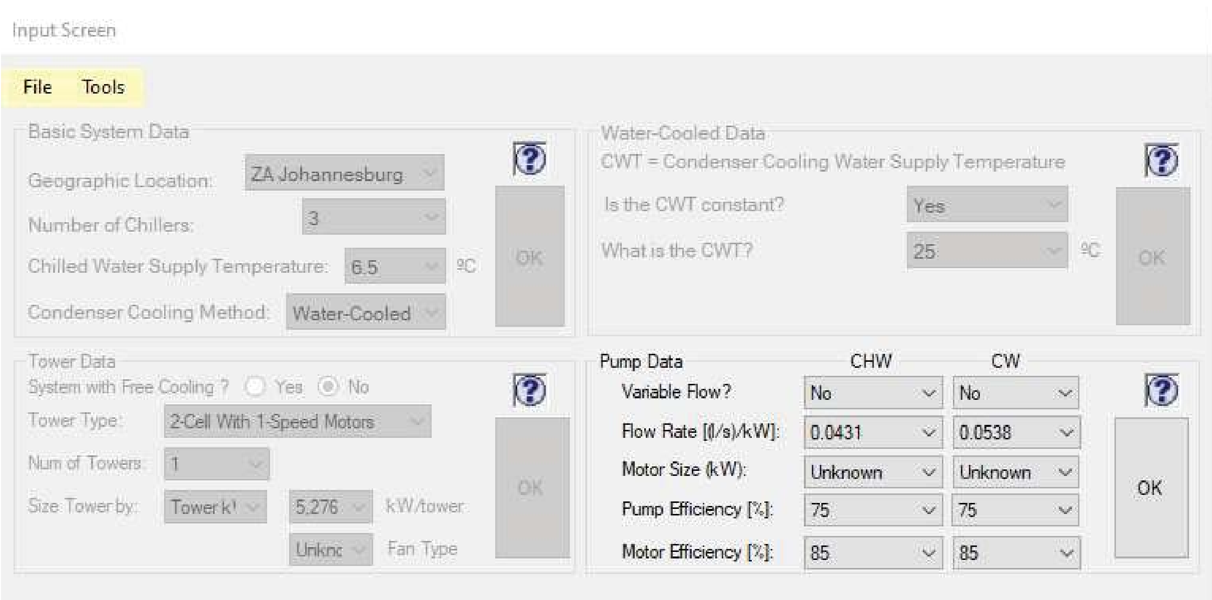
Sub-System Information



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System Information

- Chillers:
  - 2 Centrifugals and 1 Screw machine (constant speed)
    - Centrifugals - 2,640 kW each
    - Screw - 705 kW
  - Rated Full Load Efficiency (COP)
    - Centrifugals - 5.41
    - Screw – 4.69
  - Age: 10 years
  - Chilled Water Setpoint – 6.5°C
  - Condenser Water Setpoint – 25°C

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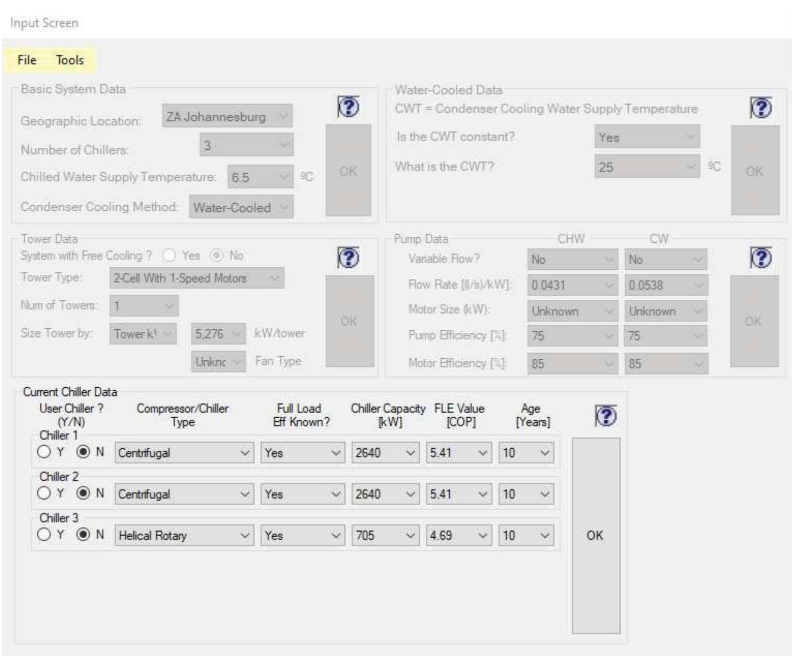
System Information



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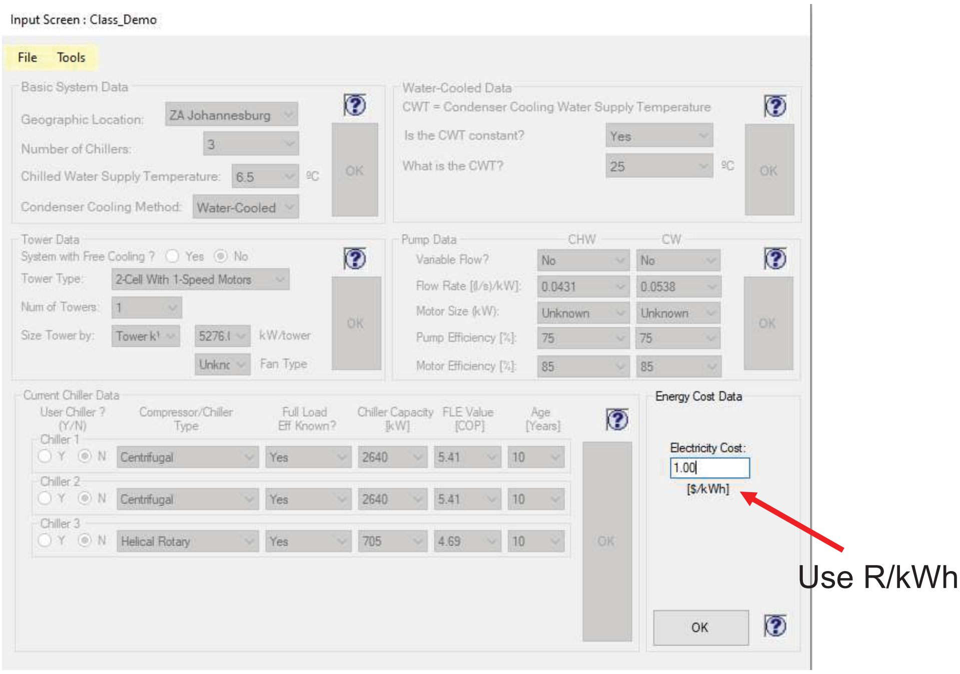
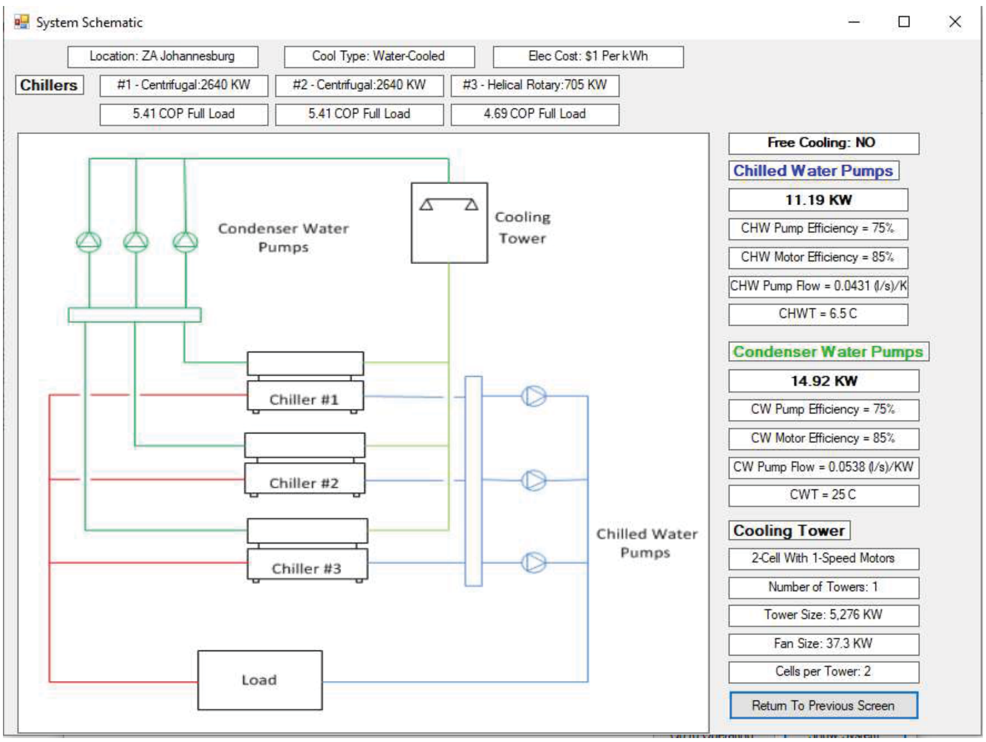
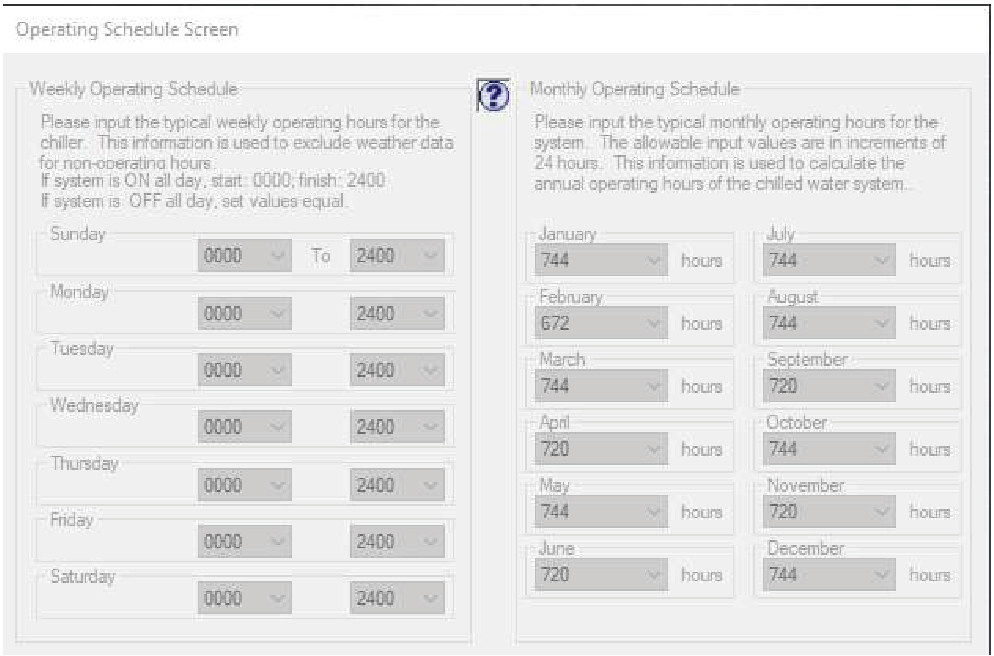
System Information



System Schematic



Operating Schedule



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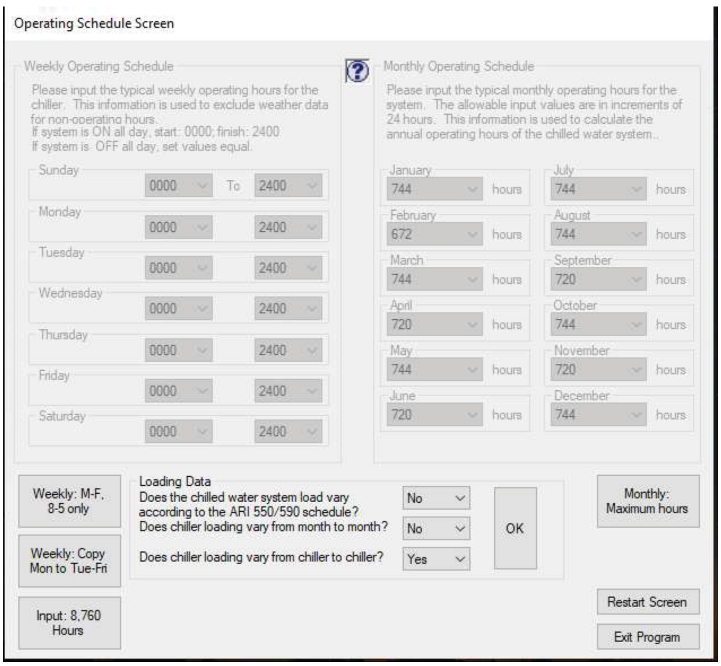
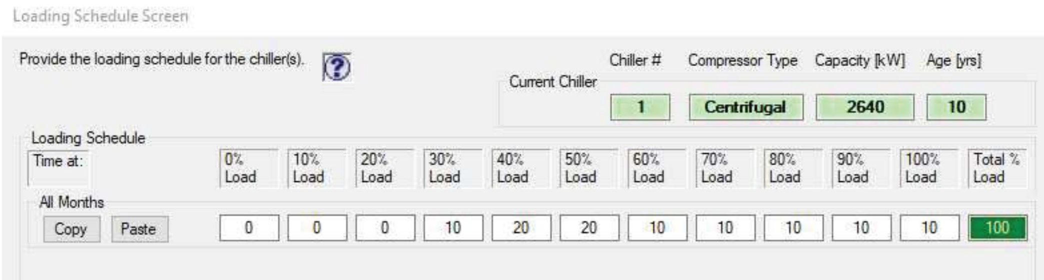
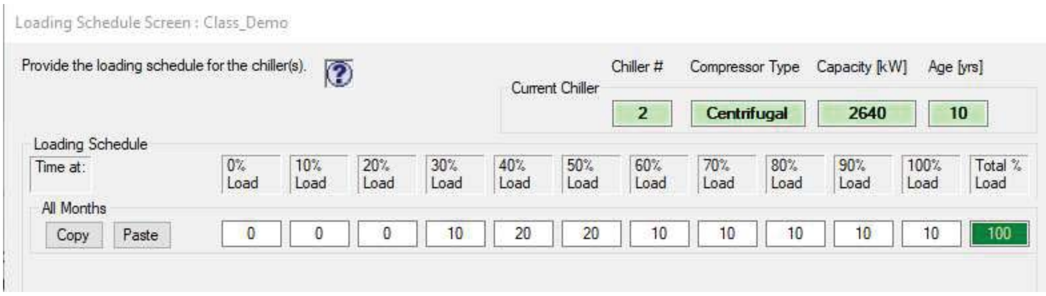
Operating Schedule

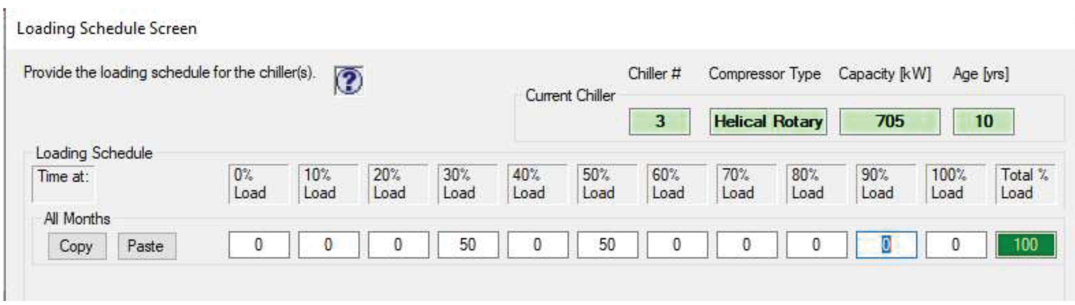


Individual Chiller Load Profile



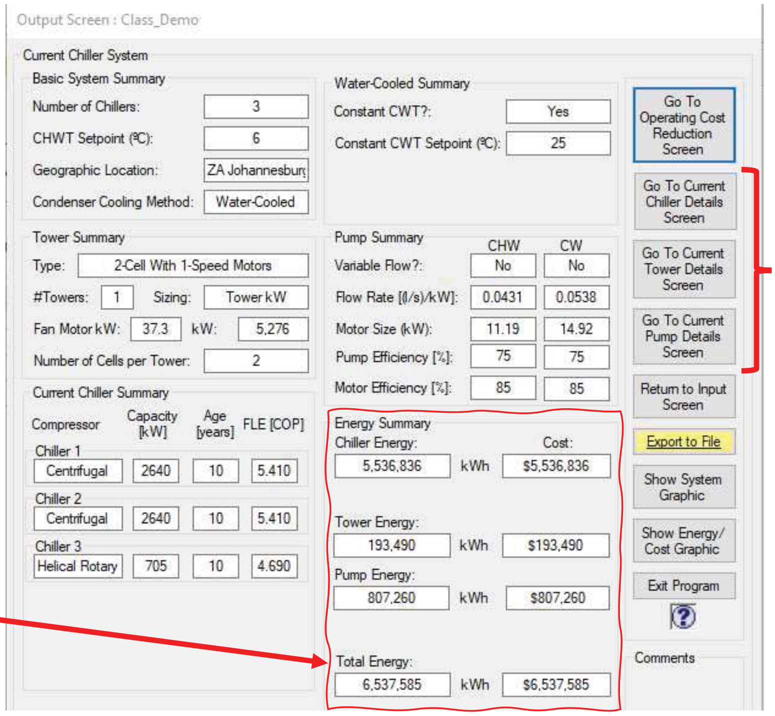


Individual Chiller Load Profile



Chiller Loading Schedule											
Chiller	0% load	10% Load	20% load	30% load	40% load	50% load	60% load	70% load	80% load	90% load	100% load
ARI	0%	0%	1%	5%	13%	23%	26%	19%	9%	3%	1%

Output Screen (Baseline)



Detail Screens

Summary Information
Cost is in ZAR

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Chiller Operating Details Screen (Baseline)

Current Chiller Details Screen : Class_Demo

	0% Load	10% Load	20% Load	30% Load	40% Load	50% Load	60% Load	70% Load	80% Load	90% Load	100% Load	Total
Chiller 1: Centrifugal (Rated Capacity: 2640 kW)												
[COP]:	∞	∞	∞	5.388	5.941	6.107	6.107	5.943	5.685	5.378	5.075	
Hours:	0	0	0	881	1,753	1,746	881	873	880	873	873	8,760
Power [kW]:	0.0	0.0	0.0	147.0	177.7	216.1	259.4	311.0	371.5	441.8	520.2	
Energy [kWh]:	0	0	0	129,512	311,590	377,373	228,523	271,463	326,922	385,697	454,122	2,485,202
Chiller 2: Centrifugal (Rated Capacity: 2640 kW)												
[COP]:	∞	∞	∞	5.388	5.941	6.107	6.107	5.943	5.685	5.378	5.075	
Hours:	0	0	0	881	1,753	1,746	881	873	880	873	873	8,760
Power [kW]:	0.0	0.0	0.0	147.0	177.7	216.1	259.4	311.0	371.5	441.8	520.2	
Energy [kWh]:	0	0	0	129,512	311,590	377,373	228,523	271,463	326,922	385,697	454,122	2,485,202
Chiller 3: Helical Rotary (Rated Capacity: 705 kW)												
[COP]:	∞	∞	∞	4.033	∞	4.585	∞	∞	∞	∞	∞	
Hours:	0	0	0	4,380	0	4,380	0	0	0	0	0	8,760
Power [kW]:	0.0	0.0	0.0	52.4	0.0	76.9	0.0	0.0	0.0	0.0	0.0	
Energy [kWh]:	0	0	0	229,677	0	336,757	0	0	0	0	0	566,433

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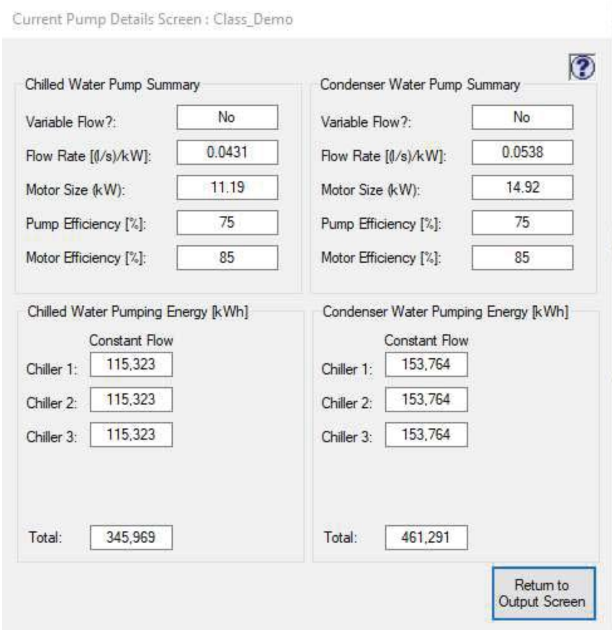
Pumps Operating Details Screen (Baseline)



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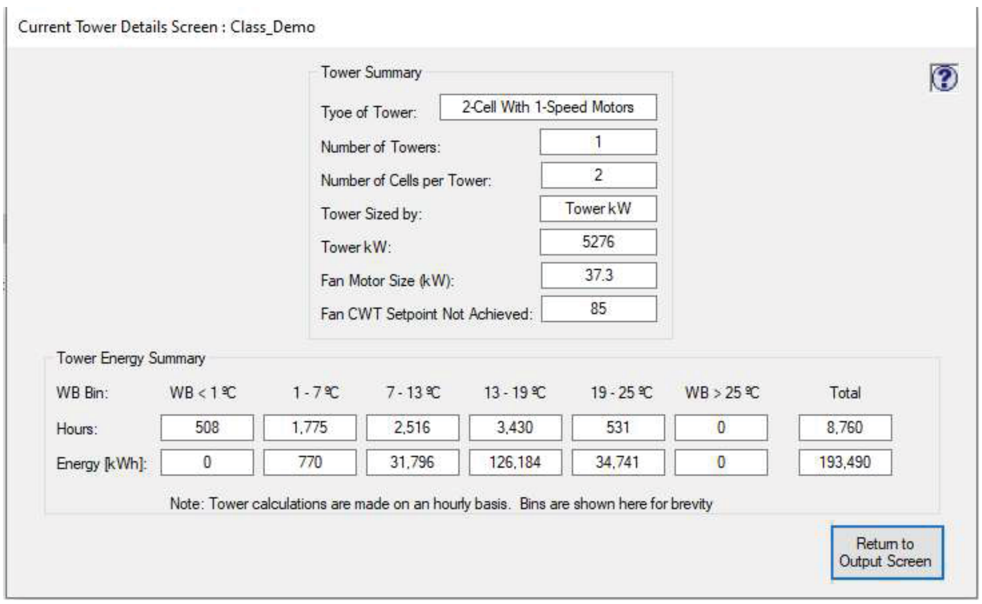
Tower Operating Details Screen (Baseline)



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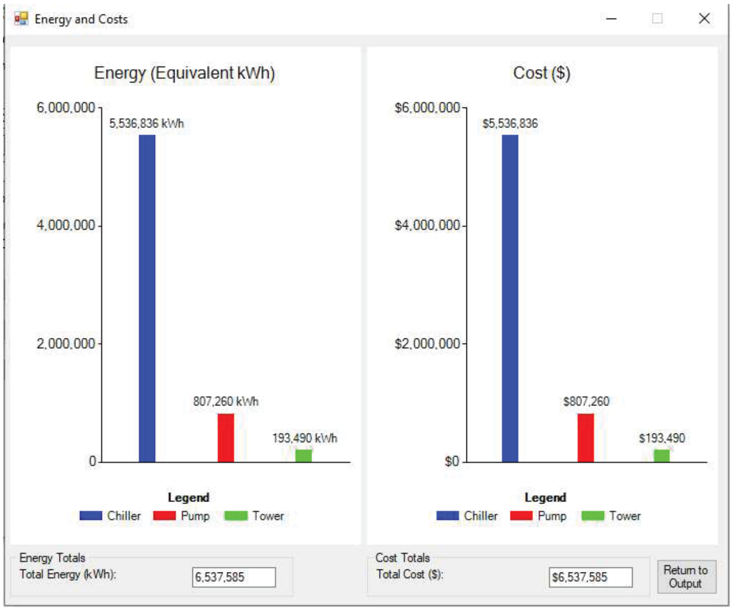
Overall Energy & Operating Costs Graphic (Baseline)



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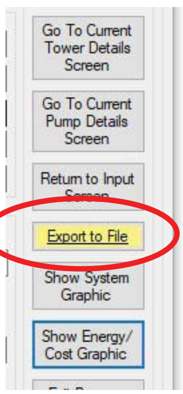
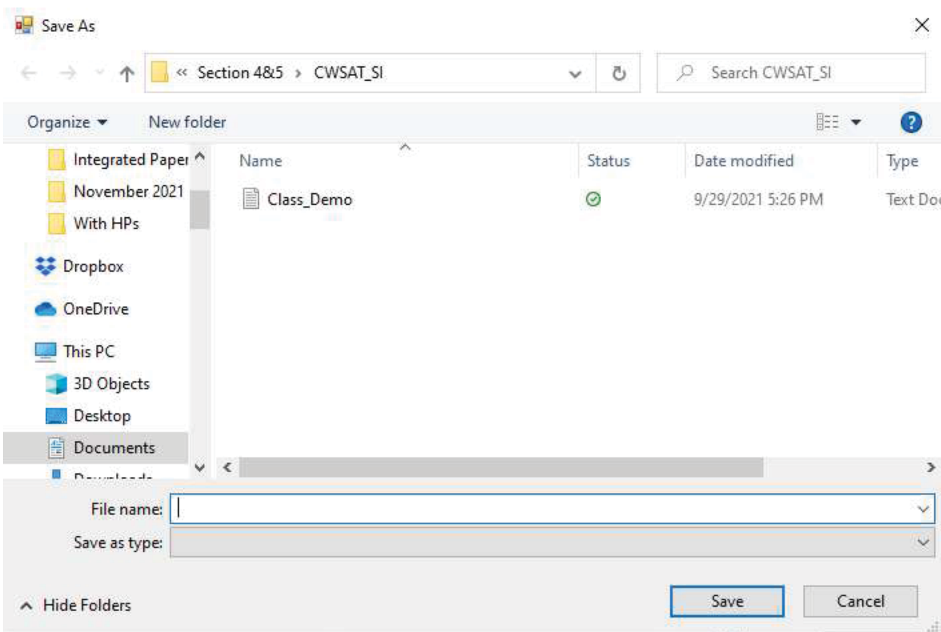
Saving the Baseline Model file





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Additional CWSAT Topics

- Installing and weather folder location / use
- Input Sensitivity
- Hourly text files output
- Detailed results screens
- Tool Benefits:
    - Energy end-use distribution
    - Identify areas to examine for conservation
    - “What-if” analyses

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1

5 ENERGY EFFICIENCY OPPORTUNITIES IN CHILLED WATER SYSTEMS

5.1 Control of Cooling Tower Set-point Temperature

5.2 Control of End-Use (Chilled Water) Set-point Temperature

5.3 Air-Cooled vs Water-Cooled

5.4 Reduction of Cooling Load

5.5 Operations Maximizing Chiller Plant Efficiency

Acknowledgments: Dr. Dragoljub (Beka) Kosanovic
University of Massachusetts, Amherst, USA

2

Methods for System Optimization

- Preventive
  - Identify problems before they become expensive (cost avoidance)
  - Maintain optimum chilled water plant efficiency
- Restorative
  - Identify heat transfer problems, i.e., off-design water flow, fouling or scaling, etc.
  - Remove non-condensable gases
  - Maintain proper refrigerant levels
- Opportunity
  - Identify optimal chilled water set points
  - Proper chiller sequencing and load balancing
  - Proper tower basin water management
  - Peak demand management
  - Condition-based maintenance versus scheduled preventive maintenance

3

List of Energy Efficiency Opportunities

- Implement cooling tower water temperature management
- Optimize settings for chilled water supply temperature
- Eliminate inappropriate uses of chilled water
- Maintain optimum water flow rates in evaporator / condenser
- Clean fouled and scaled evaporator / condenser
- Implement variable frequency driven chillers, pumps, fans
- Sequence multiple chillers to optimize efficiency
- Implement free cooling, when available

4

List of Energy Efficiency Opportunities (continued)

- Evaluate water-cooled options versus air-cooled systems
- Remove non-condensable gases and moisture
- Reclaim refrigerant
- Eliminate all refrigerant leaks
- Maintain proper refrigerant levels
- Minimize compressor surging
- Maintain compressor isentropic efficiency
- Undertake peak load management strategy (thermal storage)
- Evaluate process heat integration

5

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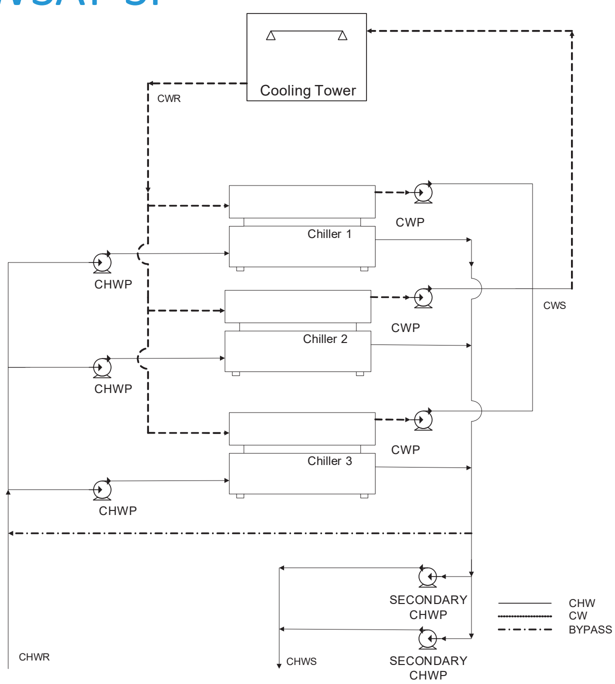
Chilled Water System – CWSAT-SI

- Open CWSAT-SI
- Load the system model file
- Review the Baseline
  - Schematic
  - Overall system energy and costs including sub-systems
- Data Validation
  - Can be done if actual energy numbers are available for the whole system and/or sub-systems
  - Aim to be within 10% of actual energy usage and costs



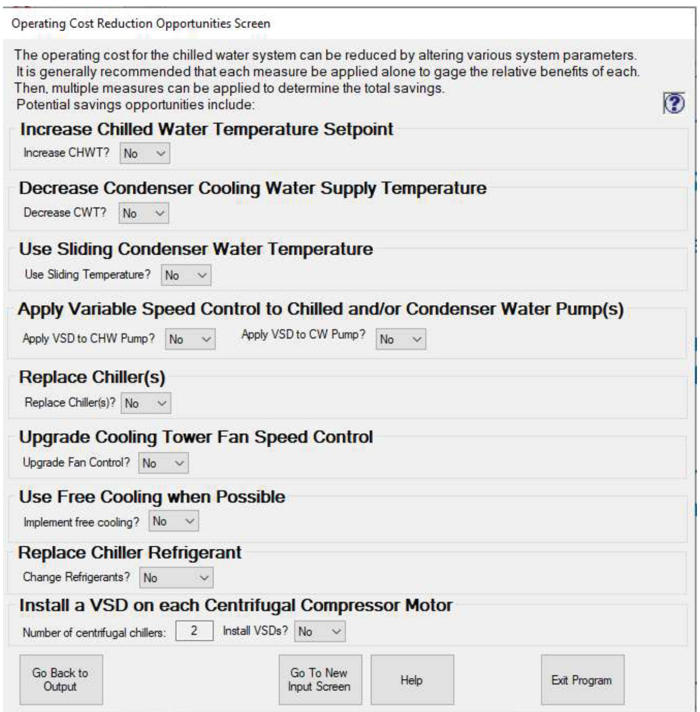
6

Next Steps with CWSAT-SI Baseline Model

- Several system optimization opportunities can be modeled using a parametric “what-if” scenario configuration
- CWSAT-SI allows for the following (“Adjusted Model” or “New Input”):
  - New Equipment Specification
    - Chillers, Towers, Pumps
  - Variable Speed Drive Installation
    - Centrifugal Chillers, Tower Fans, & Pumps
  - Various Chilled and Condenser Water Strategies
  - Air-cooled to Water-cooled system conversion
  - Using Free Cooling, when possible
  - Sequencing chillers

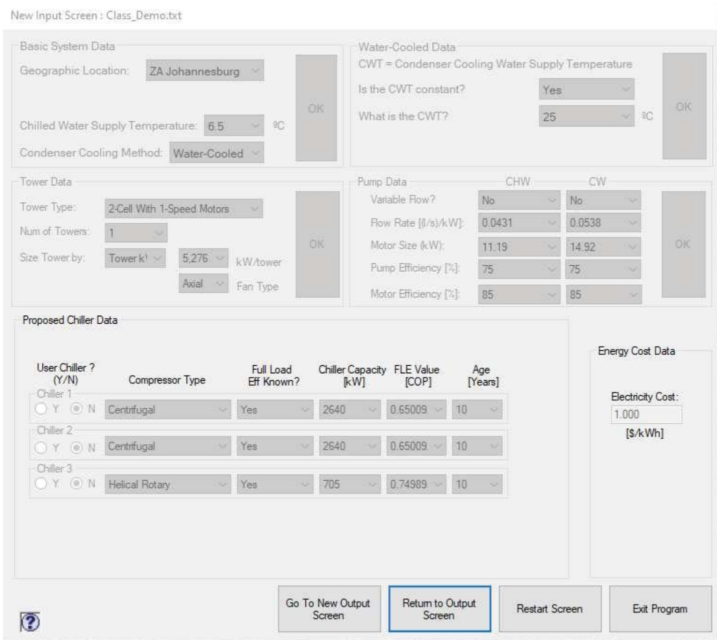
Operating Cost Reduction Screen

- Asks basic questions to allow the facility to understand gaps
- Analyze energy conservation options simply by modifying one or more of the system inputs
- This feature allows combinatorial “What-If?” analyses



"Adjusted Model" or "New Input" Screen

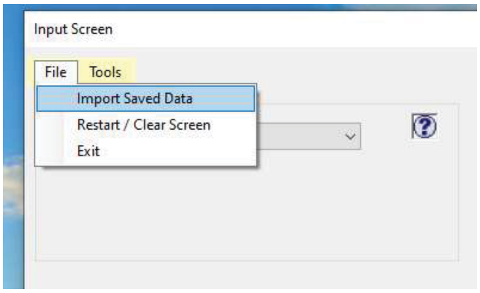
- This allows the user to make very specific and targeted modifications so that the exact quantification of the energy conservation opportunities can be done
- Multiple inputs and "What-If?" scenarios can be modeled



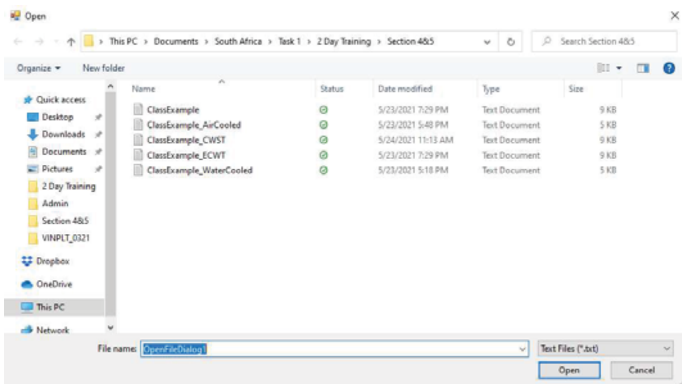
New Equipment Specification

- Within the Adjusted Model "NEW INPUT" Screen
  - Specify New Chillers
    - Optimize sizing
    - Optimize efficiency
    - Raise chilled water supply temperature
  - Specify New Cooling Tower(s)
    - Specify larger unit(s)
    - Install two-speed fans or variable speed drive-controlled fan motor(s)
    - Specify new condenser water control strategies
  - Specify New Pumps
    - Lower kW
    - Lower Liters per second / kW
    - Variable speed drives

Opening a SAVED file in CWSAT-SI



Go to the Folder, where the filed is saved and select the Text File to be opened



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5 ENERGY EFFICIENCY OPPORTUNITIES IN CHILLED WATER SYSTEMS

5.1 Control of Cooling Tower Set-point Temperature

5.2 Control of End-Use (Chilled Water) Set-point Temperature

5.3 Air-Cooled vs Water-Cooled

5.4 Reduction of Cooling Load

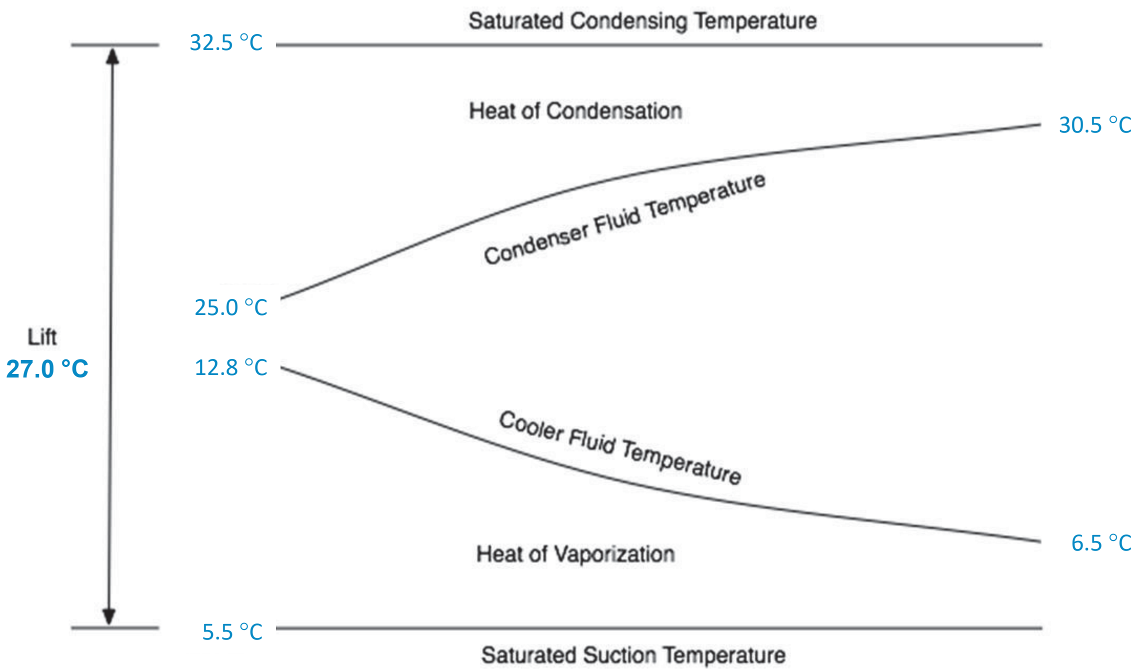
5.5 Operations Maximizing Chiller Plant Efficiency

5.1 Cooling Tower Set-Point Temperature

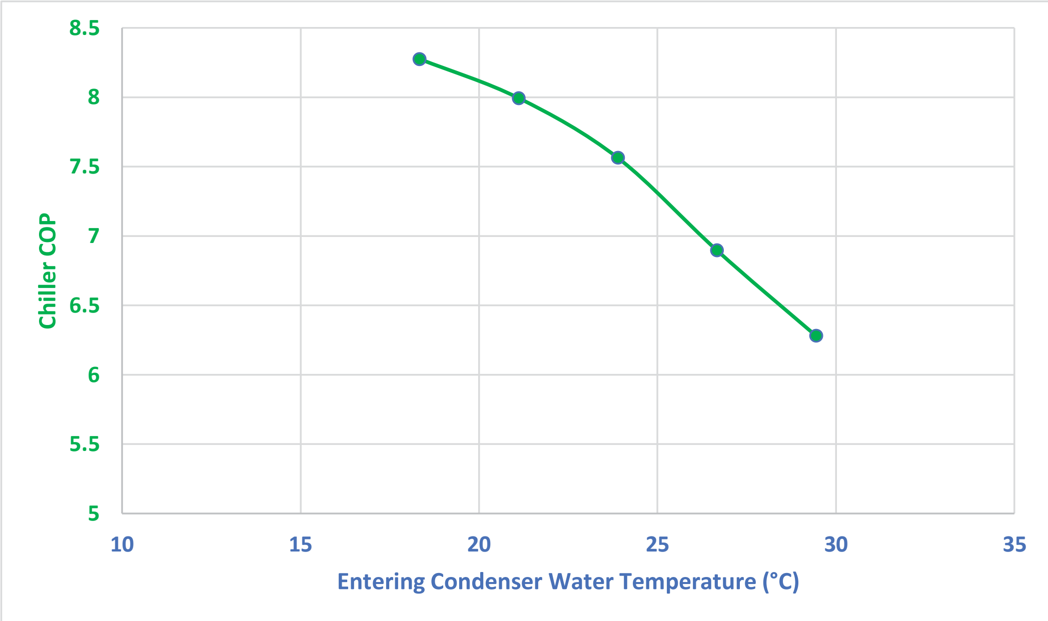
- Approach
  - The approach is the difference in temperature between the cooled-water temperature and the entering-air wet bulb temperature
  - Since the cooling towers are based on the principles of evaporative cooling, the maximum cooling tower efficiency depends on the wet bulb temperature of air

- Wet Bulb
  - Wet bulb temperature is the lowest temperature that can be reached by the evaporation of water only
  - It is determined by the atmospheric pressure, ambient temperature and the relative humidity

Remember Chiller Lift



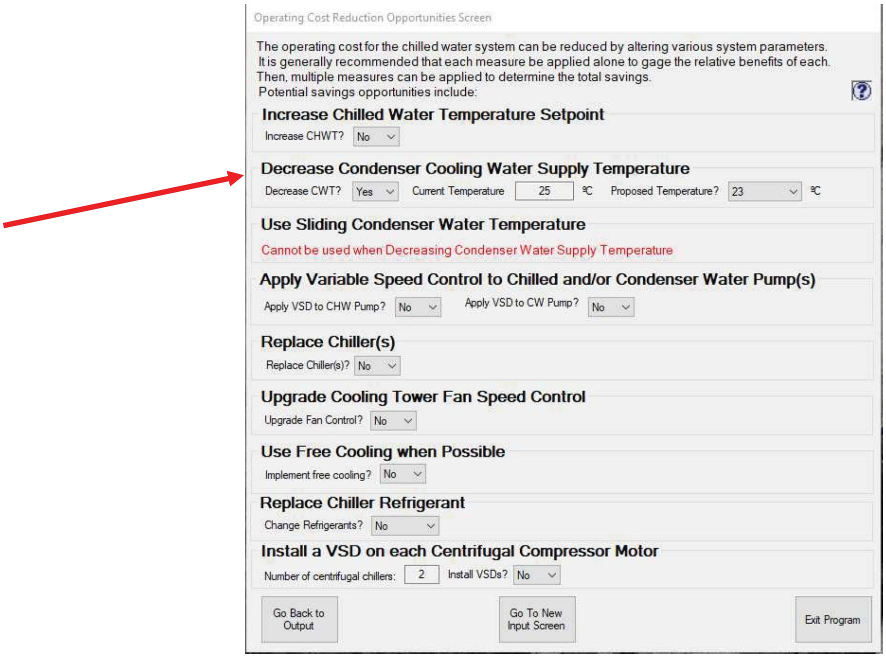
Implement ECWT Management



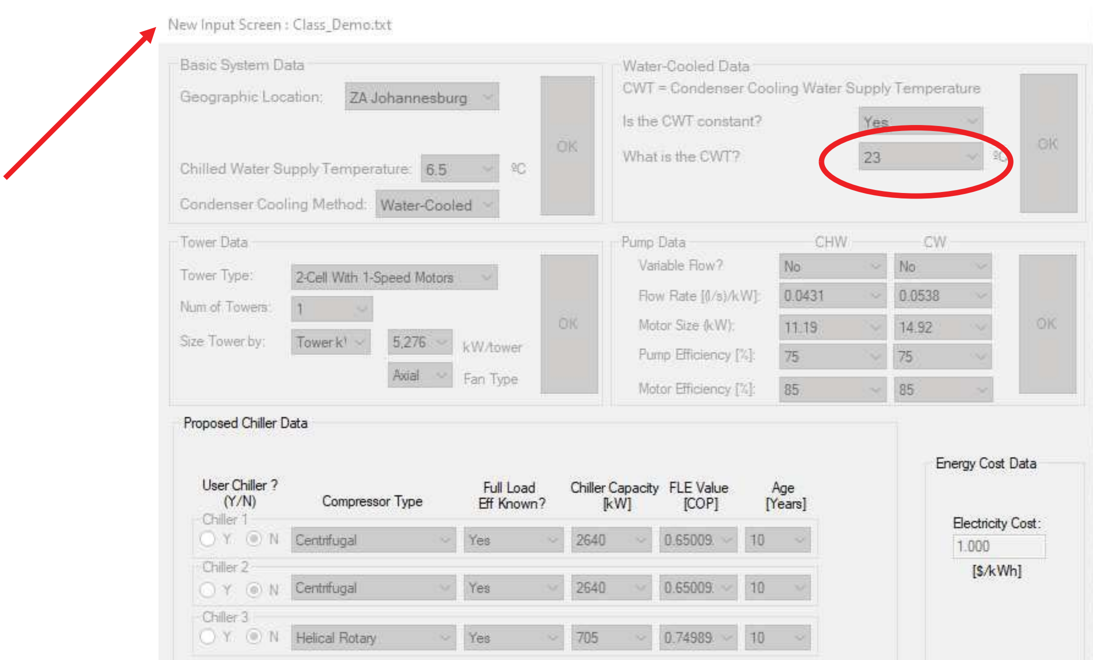
Trainee Exercise

- The industrial plant engineer recently completed a chilled water system audit and found that the cooling tower water supply temperature was fixed at 25°C.
- They wanted to determine if there would be a benefit to let the cooling tower water supply temperature be reduced by 2°C.
- Use the CWSAT model to determine how much system energy could be saved if the plant was able to reduce the cooling tower supply temperature by 2°C.
- Additionally, determine the energy and cost savings if the cooling tower water be allowed to float automatically based on the ambient conditions
- Discuss concerns and issues with the chosen option and what steps can be taken to mitigate them

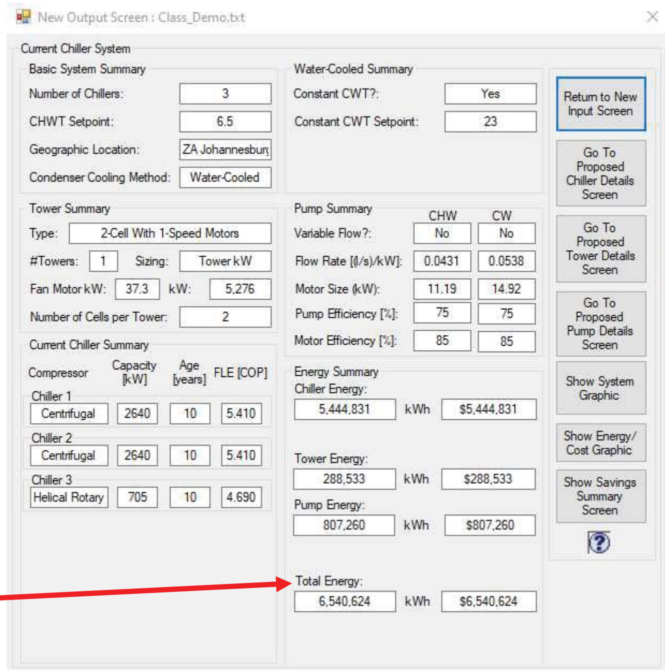
Trainee Exercise (Reduce Condenser Water Temperature)



Trainee Exercise (Reduce Condenser Water Temperature)



Trainee Exercise (Reduce Condenser Water Temperature)



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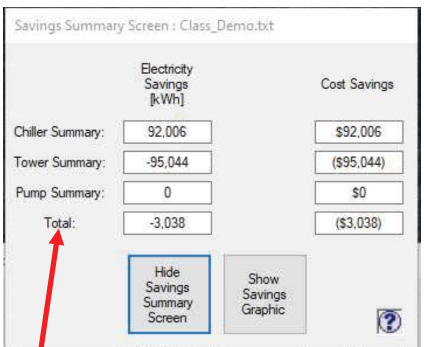
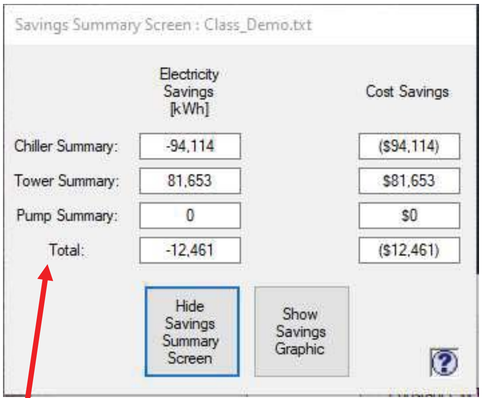
Trainee Exercise (Reduce Condenser Water Temperature)



Note: Chiller Savings get more than offset by Tower extra costs

Trainee Exercise (Increase Condenser Water Temperature)



Increased Cooling Water Temperature to 27°C

Note: Chiller Costs increase more than Tower savings

- There is an OPTIMUM cooling water temperature dependent on several system factors
- In this example, 25°C proved to be an optimum temperature for the cooling tower to minimize overall energy costs for the chiller plant

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5 ENERGY EFFICIENCY OPPORTUNITIES IN CHILLED WATER SYSTEMS

5.1 Control of Cooling Tower Set-point Temperature

5.2 Control of End-Use (Chilled Water) Set-point Temperature

5.3 Air-Cooled vs Water-Cooled

5.4 Reduction of Cooling Load

5.5 Operations Maximizing Chiller Plant Efficiency

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5.2 End-Use (Chilled Water) Set-Point Temperature

- Approach
  - The Refrigerant Approach Temperature is the difference in temperature between the chilled-water supply temperature and the refrigerant saturated temperature in the evaporator
  - It provides the driving force to transfer the heat from the water to the refrigerant
- Optimum control of End-Use (chilled water) set-point temperature
  - Chiller plants control use this as the main signal for operations
- Load control
  - Cooling required is controlled by bypassing chilled water flow
  - Alternate methodology – variable pumping

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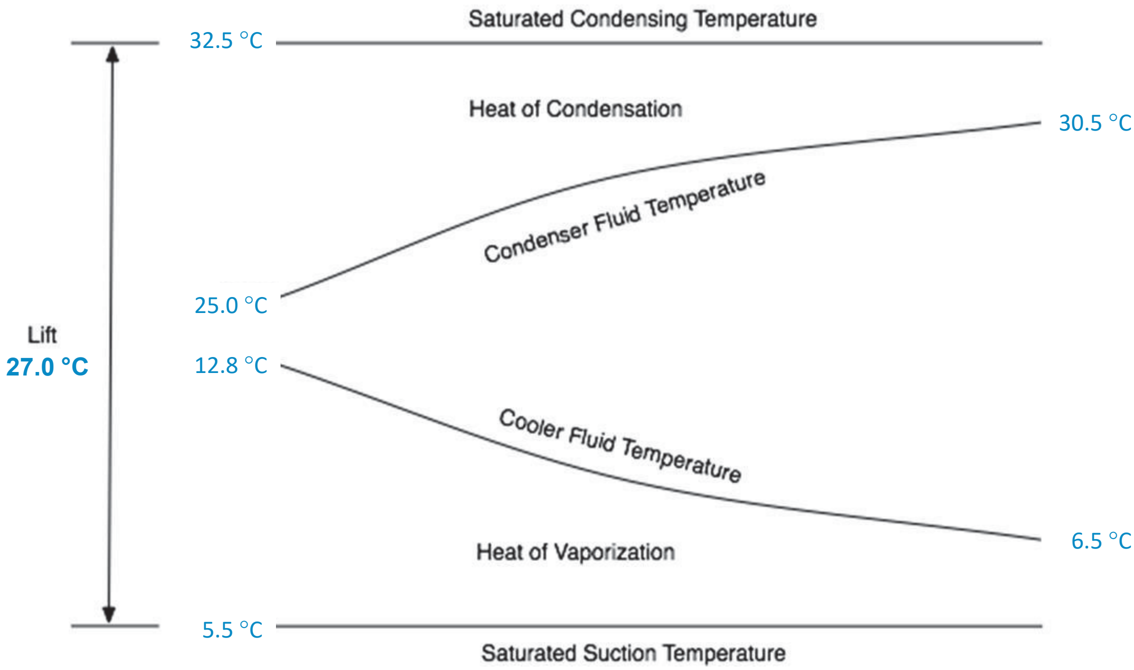
Remember Chiller Lift – Again!



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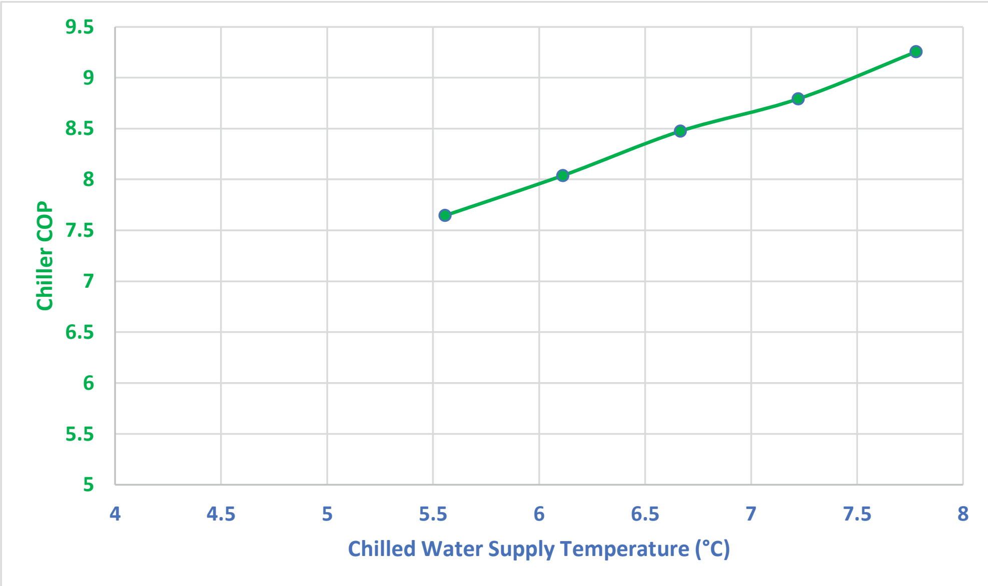
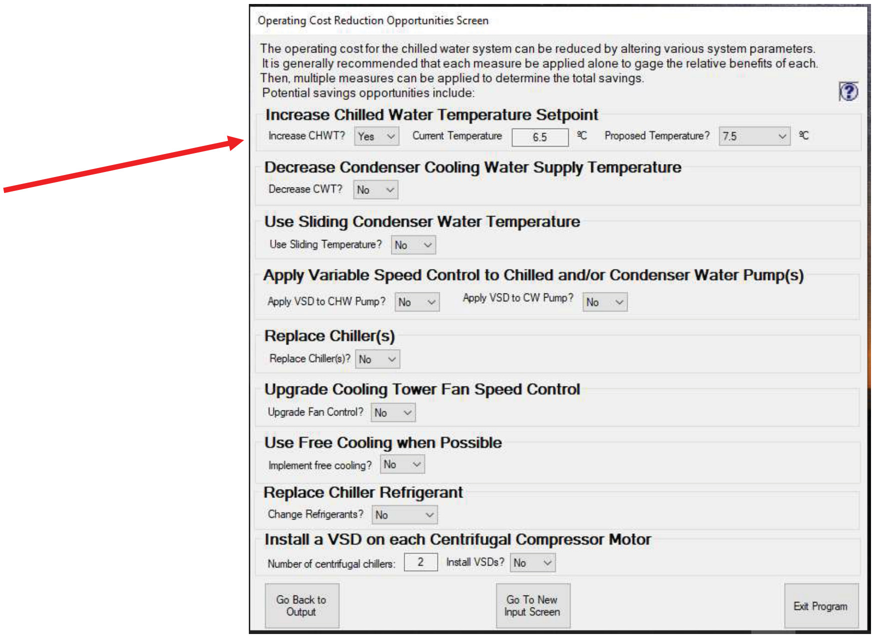
Chiller Plant Efficiency and Chilled Water Set-Point



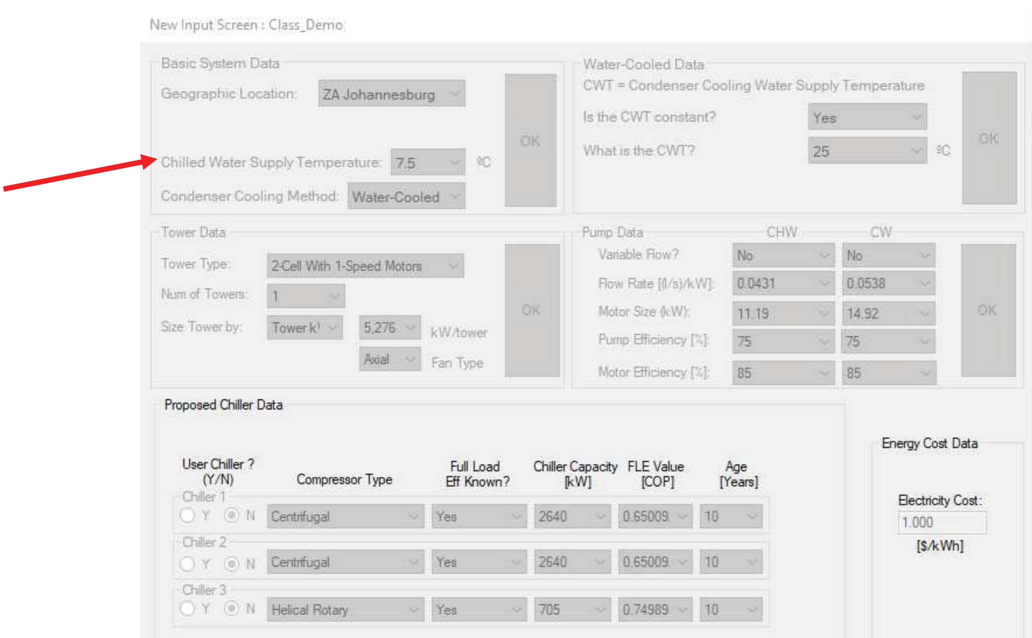
Trainee Exercise

- The industrial plant engineer recently completed a chilled water system audit and found that the chilled water supply temperature was fixed at 6.5°C.
- They wanted to determine if there would be a benefit to let the chilled water supply temperature be increased by 1°C.
- Use the CWSAT model to determine how much system energy could be saved if the plant was able to increase the chilled water supply temperature by 1°C.
- Discuss concerns and issues with the chosen option and what steps can be taken to mitigate them

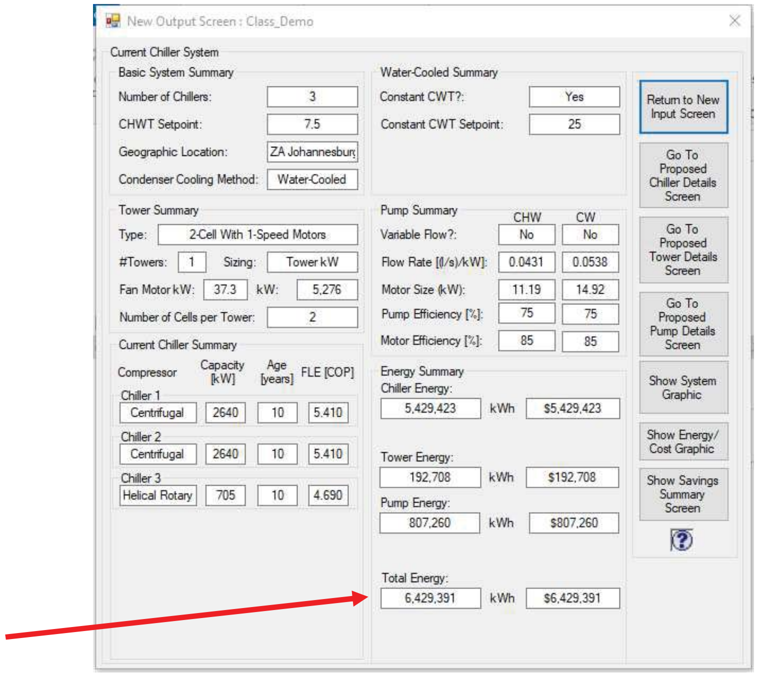
Trainee Exercise (Increase Chilled Water Supply Temperature)



Trainee Exercise (Increase Chilled Water Supply Temperature)



Trainee Exercise (Increase Chilled Water Supply Temperature)



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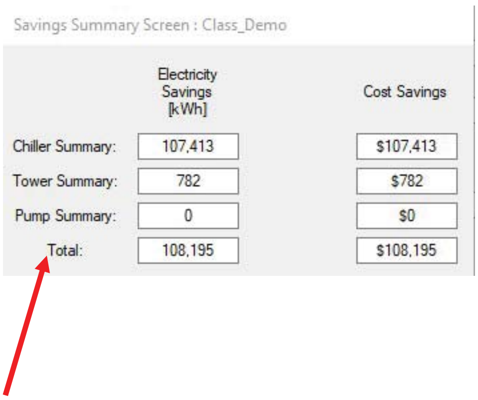
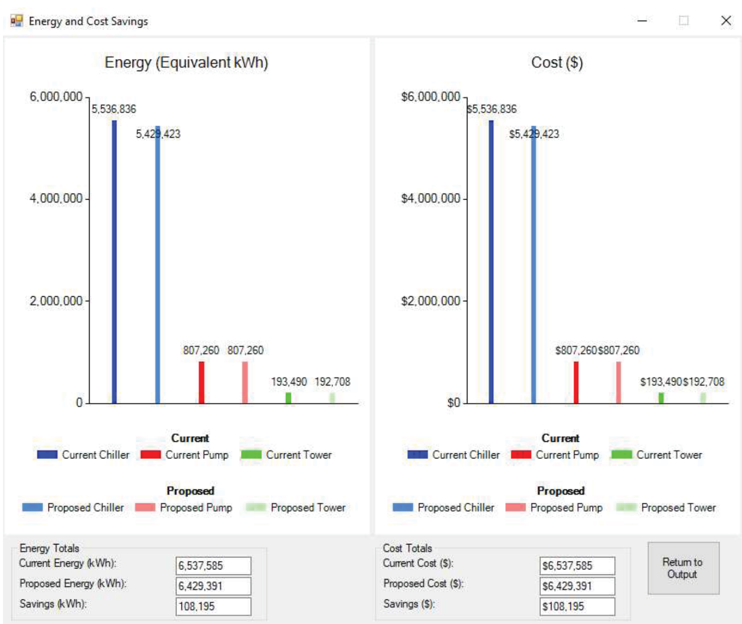
Trainee Exercise (Increase Chilled Water Supply Temperature)





5 ENERGY EFFICIENCY OPPORTUNITIES IN CHILLED WATER SYSTEMS

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5.3 Air-Cooled versus Water-Cooled

Air-Cooled

Water-Cooled

Basics of Air-Cooled Chillers

- Heat rejection mechanism
  - Direct exchange of refrigerant superheat and latent heat (condensation) with air
  - Refrigerant is inside finned tubes and large amounts of ambient air flows over the heat exchange surface to remove the heat
- Advantages
  - Compact packaged system
  - No heat rejection distribution system needed
  - Lower refrigerant charge
  - One temperature difference for heat rejection
  - Good option for applications in areas which have "scarce or restricted water"
- Disadvantages
  - Higher compressor lift – lower system efficiency – higher operating costs
  - Part-load performance limited by dry-bulb temperature

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Basics of Water-Cooled Chillers

- Heat rejection mechanism
  - Indirect exchange of refrigerant superheat and latent heat (condensation) with air
  - Use of a cooling tower and a cooling tower water pumped loop
- Advantages
  - Higher system efficiency – lower operating costs
  - Optimization opportunities by using wet-bulb temperature heat rejection
- Disadvantages
  - System design is spread out and will require detailed engineering
  - Additional water distribution system with cooling tower, pumps, valves
  - Higher first-cost and increased water operating costs
  - Two temperature differences to overcome for heat rejection

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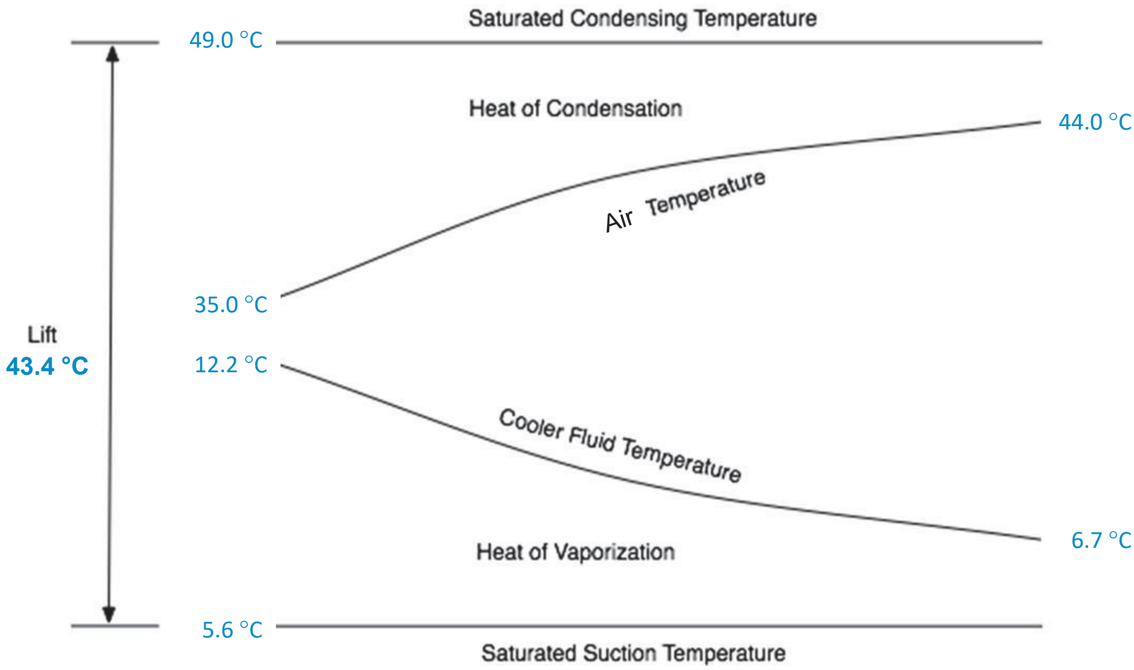
Chiller Lift – Air-Cooled Chiller



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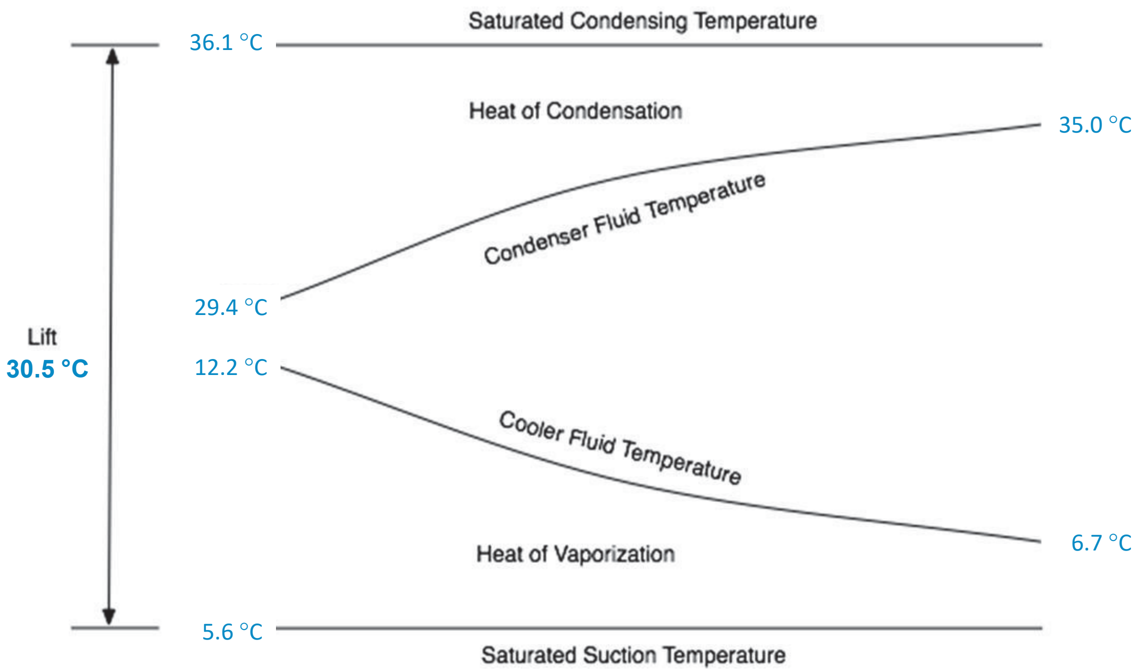
Chiller Lift – Water-Cooled Chiller



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Impact of Chiller Lift

- Crux of chiller plant / refrigeration system optimization
- Significant impact on efficiency, capacity and reliability of system
- Several optimization concepts primarily revolve around reducing chiller plant lift

- But there are lower operating limits
  - Manufacturer's recommendations
  - System design

- Geography / Climate plays a strong role
  - Humid versus Dry ambient conditions

Lowering heat rejection temperature

↓

Lowers head pressure

↓

Reduces compressor work

↓

Reduces energy consumption

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5 ENERGY EFFICIENCY OPPORTUNITIES IN CHILLED WATER SYSTEMS

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5.3 Air-Cooled vs Water-Cooled

5.4 Reduction of Cooling Load

5.5 Operations Maximizing Chiller Plant Efficiency

5.4 Reduction of Cooling Load

- Difficult to understand & implement
- Extreme caution required since a thorough understanding of the process will be required
- Very large energy and cost savings can be achieved by implementing a cooling load reduction strategy
- Several opportunities and ways exist for reducing overall cooling load (kW)
- Start by asking a simple question – why is cooling needed?

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Cooling Load

- Amount of cooling (kW) required by the process / plant
- Most chiller / refrigeration systems are designed to be Load Followers (dependent)
  - Analogous to a boiler generating steam – a boiler doesn't know how much steam is needed – it continues to produce steam until it meets the setpoint pressure
  - A chiller plant continues to produce the cooling effect until it meets the setpoint chilled water outlet (supply) temperature
- Load profile is very important for every plant
- Cooling load can vary significantly based on
  - Production rate and schedules of operation
  - Seasonality due to weather and production cycles
  - Occurrence of certain losses – distribution system loss
  - Inappropriate uses of chilled water

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Inappropriate Uses of Chilled Water

- This can be a significant optimization opportunity but will require a high-level of due-diligence and process knowledge
- Best to implement this in a gradual manner – Plan; Do; Check; Improve
- Inappropriate chilled water uses include, but not limited to:
  - Processes where cooling tower water would be adequate to remove the heat
  - Areas where cooling is not needed – scheduled-based; seasonal; decommissioned
  - Applications where no pre-cooling is done
    - Temperature pinch analysis
  - Systems where a fluid or product is cooled and then immediately heated again to bring it to ambient temperature
    - Take care to make sure that this is NOT a time-temperature process requirement
  - Processes where excessive cooling is demanded (most times is reflected in the chilled water set-point temperature)
- The energy savings potential for eliminating inappropriate uses of chilled water is very large!

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Remember Cooling (End-Use) Metrics

- Energy Metrics
  - Efficiency (COP)
  - Energy used per kW of cooling provided (unit or system-based)
  - Energy used per unit chilled water flow
    - Dependence on chilled water set-point temperature
- Cost Metrics
  - Cost per kW of cooling provided (unit or system-based)
  - Cost per unit chilled water flow
    - Dependence on chilled water set-point temperature
- Emissions Metrics

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5 ENERGY EFFICIENCY OPPORTUNITIES IN CHILLED WATER SYSTEMS

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5.5 Operations Maximizing Chiller Plant Efficiency

- Sequencing in multi-chiller plants
  - Different types of chillers, sizes, control mechanisms
- Increasing efficiency of existing chillers
  - Replacing older chillers
  - Retrofitting parts, controls, heat exchangers
- Adding Variable Frequency Drives
  - Chiller compressors
  - Pumps, Fans

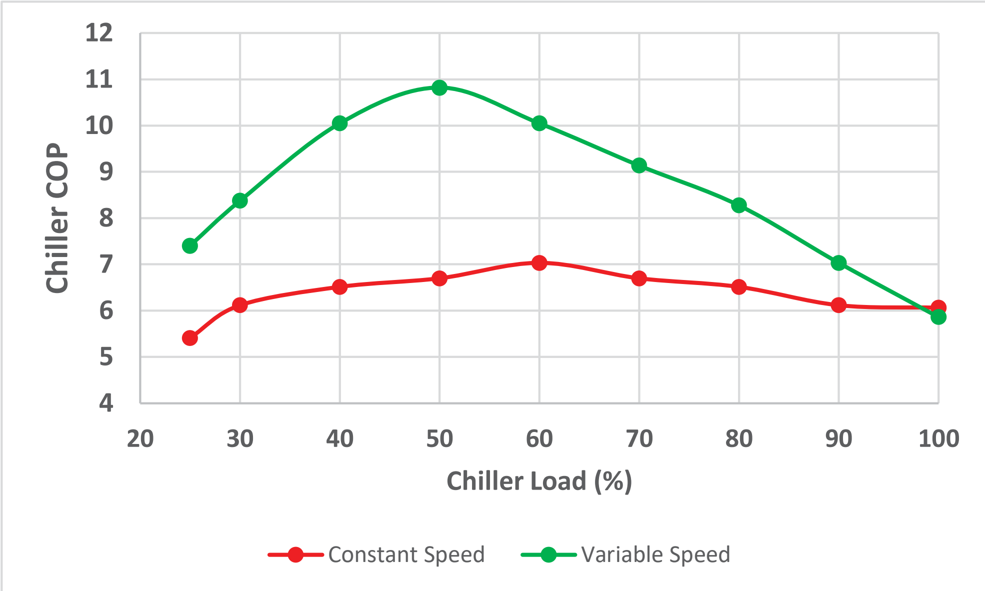
Sequence Multiple Chillers to Optimize Efficiency

- All chillers will have an optimal operating (best efficiency) point
- When multiple chillers are operating, the overall plant's composite operating curve maybe very different from the individual chiller's curve
- It is important to know how each of the chillers operate under different load conditions
- Pick the best chiller operating combination for the current operating conditions – Dynamic Optimization problem (NOT Easy)

Implement Variable Frequency Driven Chillers

- This maybe a capital-intensive Energy Efficiency Opportunity but deserves a lot of merit
- Overall chiller plant efficiency can be improved by replacing old chillers with newer energy efficient systems – most new packaged chillers will come with a VFD option
- VFD chillers take advantage of lower ambient temperatures (lower lift) and correspondingly lower cooling loads (lower refrigerant flow rates) at those conditions
- The centrifugal compressor follows the cube law
  - Flow $\propto$ Speed
  - Power $\propto$ Speed^3

Variable Frequency Driven Chillers



Improve Drive Efficiency

- Most chiller drives are constant speed electric motor drives – 3 phase AC units
- Motor efficiency is generally very high (95%) and the efficiency curve is very flat across the overall operating range
- But at very low loads (<35%), the electric motor efficiency falls off sharply and the chiller COP drops
- Main opportunity – Reduce number of operating chillers if all the chillers are operating at low loads where overall efficiency is impacted!

Improve Drive Efficiency

- New chiller packages now have the option of Variable Frequency Drives (VFD) for compressors
- VFD efficiency is extremely high (99%) and more importantly, it offers a benefit on the drive side by providing
  - Soft start capability
  - Power factor correction
- Reducing compressor speed reduces flow (tonnage) proportionately BUT reduces power by the third power – Centrifugal Law

Undertake a Peak Load Management Strategy

- Peak demand charges can become excessive depending on chiller plant management and operational strategy
- There are four ways to manage peak demand
  - Implement free-cooling / waterside economizer
    - May have limited applicability – season, geographic location
  - Thermal storage
    - Actual stratified water / ice-bank
    - Using the chilled water distribution system thermal inertia
  - Optimize chiller efficiency to lower kW usage of running chillers while meeting required cooling requirements
  - Take a chiller off-line
    - Curtail chiller plant load / production cycle dependent

Key Points / Action Items

1. *Energy Conservation Measures (ECMs) can be divided into three major categories: Preventive, Restorative and Opportunity*

2. *It is important to calculate the impact of all ECMs and then prioritize to implement the projects*

3. *Each ECM evaluation will require collection of actual chiller operating data, design information, load profile, thermodynamic chiller plant modeling*

4. *Each chiller plant analysis is unique and there are no thumb-rules*

5. *Use a Systems Approach w/Plan, Do, Check & Improve*

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Class Homework

- Sketch (line-drawing) of your plant's chilled water system. Include as much details as you can based on what you have learned today but don't get lost in the weeds / details
- Identify:
  - Older equipment
  - Throttled piping systems
  - Complaints of setpoints not being achieved
  - Maintenance problems
  - Systems designed in-house
  - Bypass piping lines
  - Fixed setpoints
  - Constant speed motors
- Build a CWSAT-SI system model and identify one energy efficiency opportunity that you can quantify and eventually implement in your system

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1

6 REFRIGERANTS – PAST, PRESENT & FUTURE

6.1 The Montreal Protocol

6.2 The Kyoto Protocol

6.3 The Paris Agreement

6.4 The Kigali Amendment

6.5 Next Generation Refrigerants

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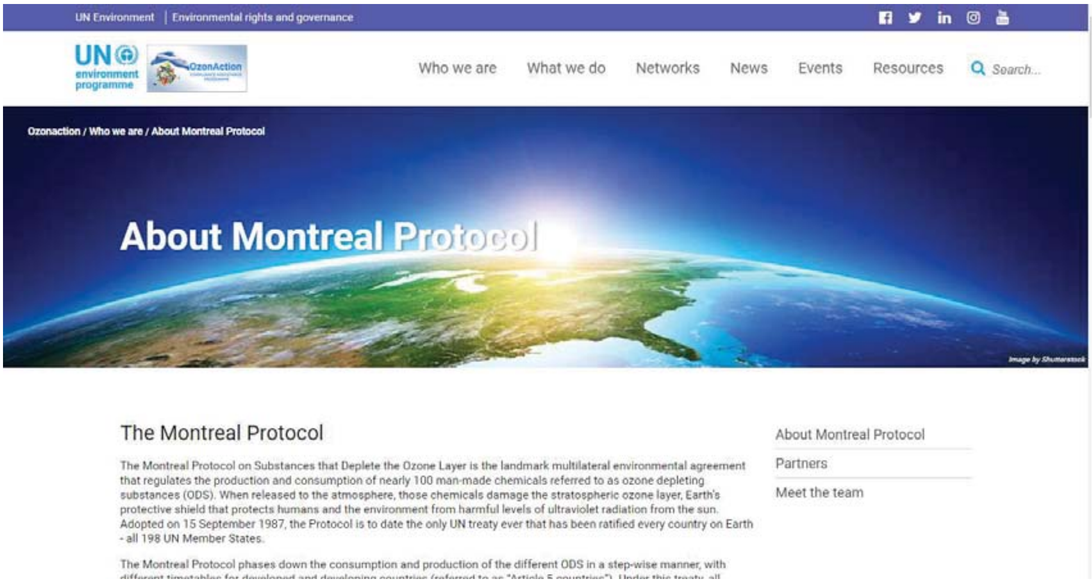
6.1 The Montreal Protocol



The Montreal Protocol - General Information

- Adopted on 15th September 1987 – ratified by every country (198 UN member States)
- Regulates the production and consumption of nearly 100 man-made chemicals known as Ozone Depleting Substances (ODS)
- When released, chlorine from these substances damages the stratospheric ozone layer
- Phasedown of different ODS substances in a step-wise manner with different time-tables for developed and developing countries
- The protocol has articles (provisions) and Annexes (for different substances – CFCs, HCFCs)
- Treaty evolves over time based on new scientific, technical and economic developments
- Annual meetings – Governance Body & Open-ended Working Group

The Montreal Protocol – United States

- Production and importation of CFC's was banned completely in 1996
- In 2010, US regulations banned the production and importation of HCFC's – R22 and R142b for use in new equipment
- www.epa.gov/ozone-layer-protection

U.S. Action to Meet the Montreal Protocol Phaseout Schedule

Year to Be Implemented	Implementation of HCFC Phaseout through Clean Air Act Regulations	Year to Be Implemented	Percent Reduction in HCFC Consumption and Production from Baseline
2003	No production or import of HCFC-141b	2004	35.0%
2010	No production or import of HCFC-142b and HCFC-22, except for use in equipment manufactured before January 1, 2010	2010	75.0%
2015	No production or import of any other HCFCs, except as refrigerants in equipment manufactured before January 1, 2020	2015	90.0%
2020	No production or import of HCFC-142b and HCFC-22	2020	99.5%
2030	No production or import of any HCFCs	2030	100.0%

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The Montreal Protocol – Vietnam

- The production and import of CFCs are completely banned.
- **Objectives and Roadmap:** Viet Nam is committed to gradually reducing HCFC consumption. By 2030, the goal is to eliminate 97.5% of the baseline consumption, retaining only a very small amount for servicing purposes.
- **Implementation progress:** Viet Nam reduced HCFC consumption by 35% during the 2020–2024 period. In 2025, Viet Nam cut HCFC import quotas by 50%. Phase II (HPMP II, 2018–2023) has been completed, with funding from the World Bank (WB).
- ***Source: https://en.mae.gov.vn/Pages/chi-tiet-tin-Eng.aspx?ItemID=8698***

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6 REFRIGERANTS – PAST, PRESENT & FUTURE

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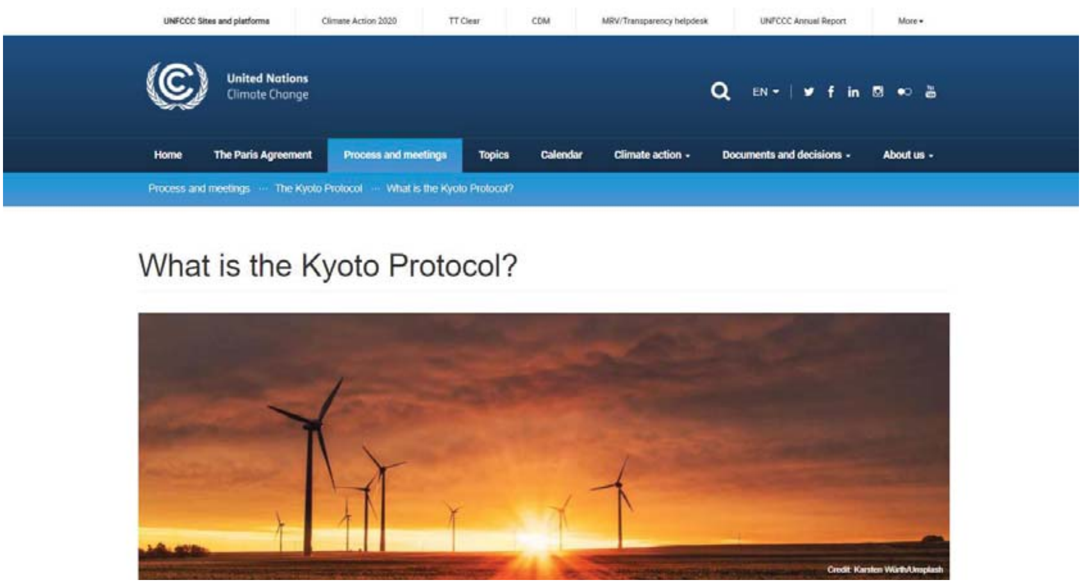
6.2: The Kyoto Protocol

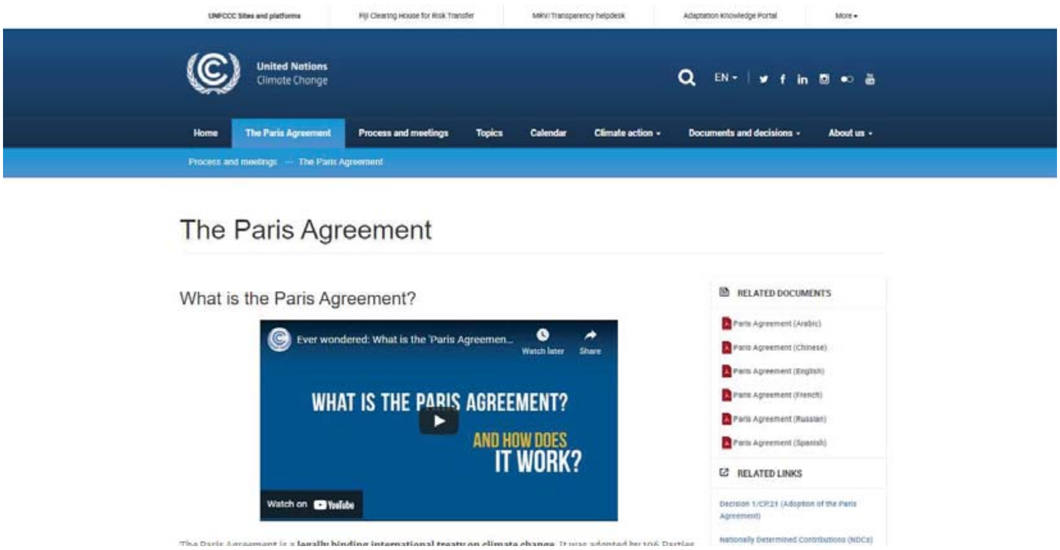


The Kyoto Protocol - General Information

- Adopted on 11th December 1997 – entered into force with 192 Parties ratifying it on 16 February 2005
- United Nations Framework Convention on Climate Change
- Commitment of industrialized countries and economies in transition to limit and reduce greenhouse gas (GHG) emissions in accordance with agreed individual targets
  - Annex B – 37 industrialized countries and the European Union
- What is the Kyoto Protocol? | UNFCCC

6 REFRIGERANTS – PAST, PRESENT & FUTURE

6.3: The Paris Agreement

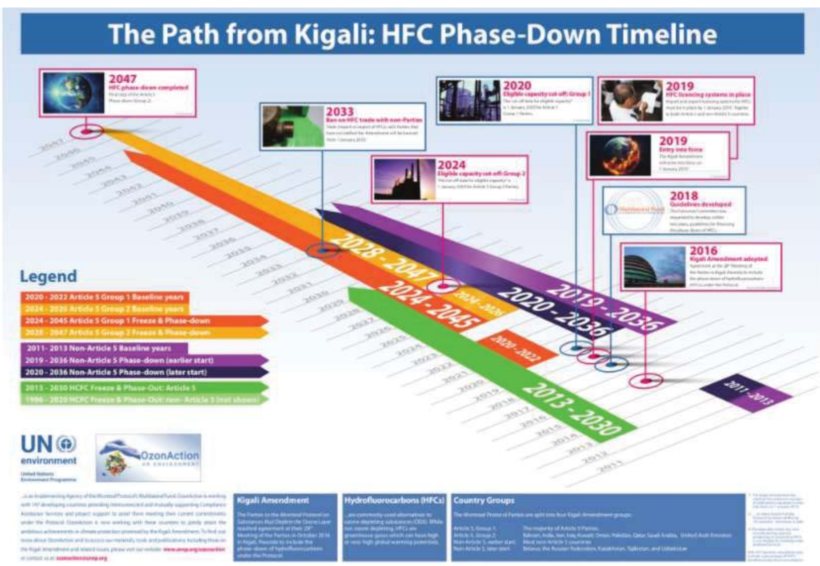


The Paris Agreement - General Information

- Adopted on 12th December 2015 by 196 parties at COP 21 in Paris
- Entered into force on 4 November 2016
- United Nations Framework Convention on Climate Change
- Its goal is to limit global warming to well below 2°C – preferably to 1.5°C, compared to pre-industrial levels
  - The Kigali amendment's full impact can be a reduction of 0.5°C
  - It is the single largest mechanism amongst all the different strategies
- 5-year cycle and plan for climate actions known as nationally determined contributions
- Enhanced transparency framework starting in 2024
- By 2030, zero-carbon solutions possible in sectors representing 70% of global emissions
- The Paris Agreement | UNFCCC

6 REFRIGERANTS – PAST, PRESENT & FUTURE

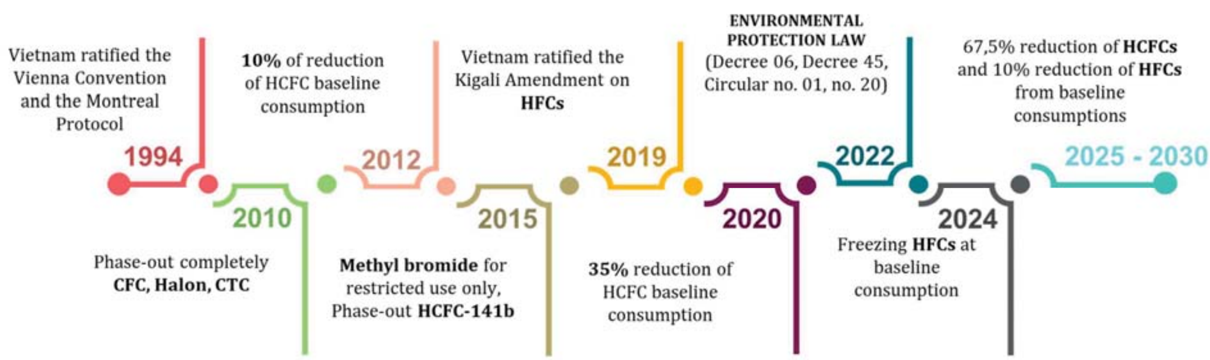
6.4: The Kigali Amendment



The Kigali Amendment - General Information

- Adopted on 15th October 2016 – 28th Meeting of the Parties
- HFC's – introduced as alternatives to ODS to support their timely phase out
- Some of these HFC's have high Global Warming Potential – 12-14,000
- HFC emissions are projected to rise to 7-19% of global CO_2 emissions by 2050
- Countries agreed to add HFC's to the list of controlled substances and approved a timeline of 80-85% reduction by 2040
- First reductions in developed countries started in 2019
- Developing countries will follow with a freeze of HFC levels in 2024-2028
- About Montreal Protocol (unep.org)
- Significant New Alternatives Policy (SNAP) Program | US EPA

The Kigali Amendment – Vietnam



- ❑ Control the import quota of **HCFCs** according to the roadmap, ending the import of HCFCs completely by **2040**
- ❑ Freezing consumption of **HFCs** in the period 2024-2029 and gradually phase-down of 80% ↓ of the HFCs consumption by

6 REFRIGERANTS – PAST, PRESENT & FUTURE

6.5: Next Generation Refrigerants

- ODP – Ozone Depletion Potential
  - A material's ability to deplete stratospheric ozone
  - A value relative to R11's value of 1.0
- GWP – Global Warming Potential
  - An index describing a GHG's relative ability to trap radiant energy compared to CO2
  - Typically, 100 years is used for calculation of GWP's
- TEWI – Total Equivalent Warming Impact
  - Direct refrigerant emissions + System's energy use emissions over the service life
- LCCP – Life Cycle Climate Performance
  - TEWI + direct and indirect emissions associated with the refrigerant manufacture and end-of-life disposal

Properties of Refrigerants

- Safety
  - Toxicity
  - Flammability
- Thermophysical
  - Boiling point
  - Critical temperature, pressure
- Refrigerant performance in a system
  - Operating pressures; Compression ratios
  - Net refrigerant effect
  - Specific heat
  - Oil handling
- Amount of refrigerant charge needed (depends on system type)

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Refrigerant Environmental Properties

Refrigerant	Atmospheric Lifetime* (years)	ODP	GWP
CFC 11	45	1	4,660
CFC 12	100	0.73	10,800
CFC 13	640	1	6,900
HCFC 22	11.9	0.034	1,760
HCFC 123	1.3	0.01	79
HCFC 142b	17.2	0.057	1980
HFC 23	222	0	12,400
HFC 32	5.2	0	677
HFC 125	28.2	0	3,170
HFC 64a	6.4	0	1,300
HFC 143a	47.1	0	4,800

* Refers to how long a molecule remains in the atmosphere without breaking down into its natural elements

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Refrigerant Environmental Properties

Refrigerant	ODP	GWP
R 404A	0.0	3,940
R 407C	0	1,620
R 410A	0	1,920
R 500	0.50	8,010
R 501	0.29	4,020
R 502	0.20	4,790
R 507A	0	3,990

The Tables are adapted from ASHRAE – Fundamentals Handbook, Chapter 29, 2017

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Refrigerant Environmental Properties

Refrigerant	Atmospheric Lifetime (years)	ODP	GWP
HCFO 1233zd(E)	0.071	0.00034	1
HFO 1234yf	0.029	0	<1
HFO 1234ze(E)	0.045	0	<1
HFO 1336mzz(Z)	0.07	0	2
HC 290	0.034	0	5
HC 600		0	4
HC 1270	0.001	0	1.8
R 717		0	
R 744		0	1

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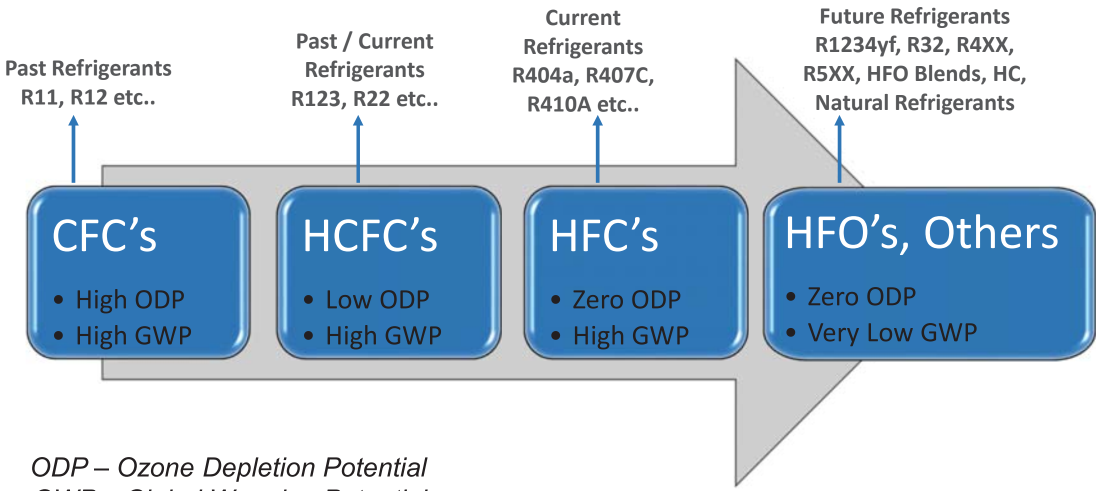
Refrigerants Trend



ODP – Ozone Depletion Potential
GWP – Global Warming Potential

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Next Generation Refrigerants

- Most focus and targets are looking at a systematic approach
  - Option 1 – a transition plan with a step-down GWP approach
    - Provides time for industry to adapt
  - Option 2 – immediate change to the zero-GWP option
    - One-time change and be done with it
- Industry is looking at “No one shirt fits all” approach
  - Application specific
  - Availability of a drop-in replacement
  - Availability of reclaimed refrigerant
- Natural refrigerants are most often the choice that industry is making provided it is feasible based on the properties of refrigerants
  - System compatibility
  - Safety
  - Cost of new system

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Key Points / Action Items

1. *There are several multi-lateral government Protocols that have been ratified and enforced – The Montreal Protocol with Kigali Amendment; The Kyoto Protocol with the Paris Climate Agreement*

2. *It is important to periodically check on the status of these protocols and South Africa's position and commitments*

3. *Refrigerant and their systems emissions (directly and indirectly) can contribute to ~0.5°C of total global warming*

4. *The industry and regulatory bodies are working diligently to develop next-generation of refrigerants*

5. *Safety (Flammability) are key concerns of some of the next-generation refrigerants*

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7 INDUSTRIAL REFRIGERATION SYSTEMS

7.1 End-Use Applications

7.2 Different Types of Industrial Refrigeration Systems

7.3 Major Components & Controls

7.4 System Performance Metrics

What is Industrial Refrigeration?

- Temperature range primarily distinguishes industrial refrigeration from other process cooling
- Evaporation temperatures may be as high as 15°C but the range extends down to -70°C
  - Below -70°C, it is generally known as Cryogenics
- Food, Chemicals and Process Industries account for more than 75% of industrial refrigeration

3

7.1 End-Use Applications

- Industrial Refrigeration is a niche area of overall process cooling and chilling
- Almost all systems are custom-designed but the individual components may be standard catalogued items
- End-Use applications are very specific and directly integrated with process
  - Much higher level of application / industry specific knowledge is needed
- Industries that use refrigeration, generally have a large portion of their plant energy consumed by refrigeration
- Process temperature is the key

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End-use Applications

- Refrigeration is a significant (electrical) energy user in some specific industry sectors and plants

Industry sector	% of total electricity used for refrigeration
Pharmaceutical	7% to 25%
Dairy	25% to 30%
Frozen Foods	60%
Beverages	20% to 30%

Source: Sustainable Energy Authority of Ireland – Refrigeration Special Working Group

- And there is a huge energy saving potential

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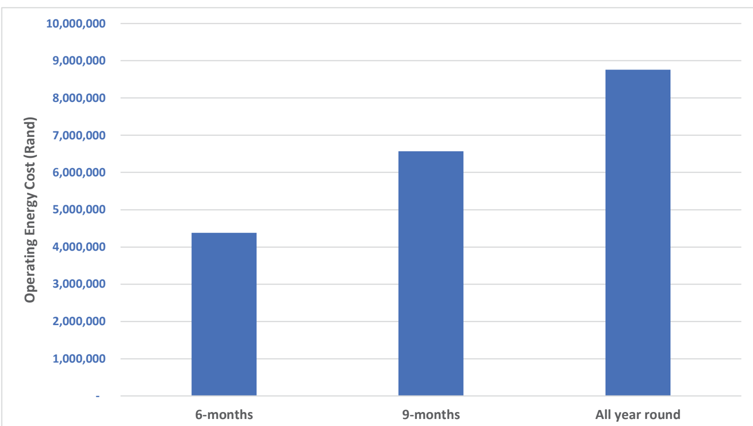
Industrial Refrigeration System Energy Cost

- 2,000 kW refrigeration plant load at -20°C
- Refrigeration System performance (COSP)= 2.0
- Bundled power cost (R/kWh)= 1.0



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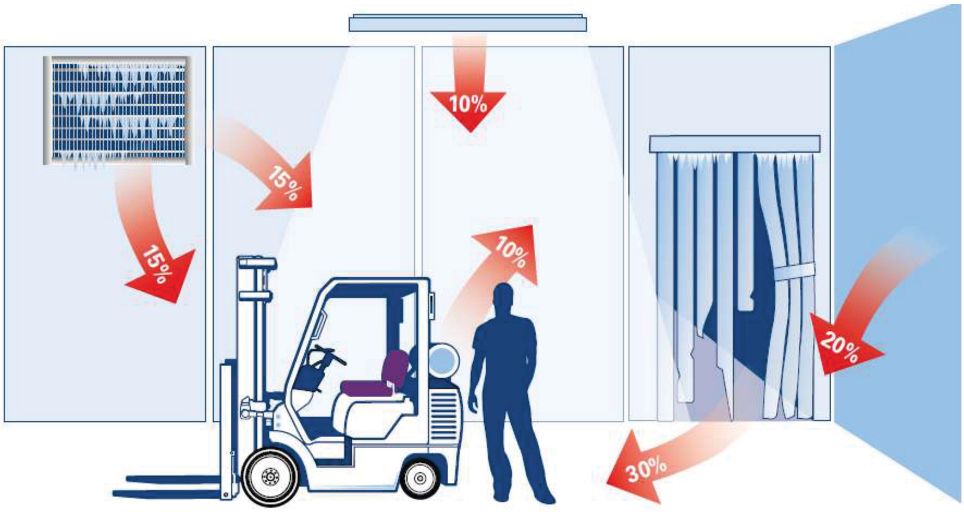
Starting point: Heat must be removed



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End-Use Applications (Food Industry)

- Precooling
  - Rapid removal of heat from freshly harvested fruits and vegetables before shipping, storage or processing
  - Requires significant energy and movement of product and refrigerated media
- Precooling methods include:
  - Hydrocooling – spray chilled water or immerse in agitated bath
    - Hydraircooling – combination of chilled water and air
    - Direct contact w/freezing media – brine (23%) solution
    - Benefits of hydrocooling – very efficient, no water loss from product
  - Forced air cooling
    - Forcing air through stacked serpentine patterns with product in direct-contact

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End-Use Applications (Food Industry)

- Precooling methods include:
  - Package icing – finely crushed ice used in containers
  - Vacuum cooling
    - Water is the refrigerant which vaporizes and provides cooling
    - Limited to 0°C
  - A combination of the above methods
- Refrigeration used in processing of food is very specific and follows a strict time-temperature curve
  - Every fruit and vegetable has specific cooling coefficients and half-cooling times that determine the pre-cooling methodology to be used and designed
- Refrigerated storage of unfrozen food
- Freeze drying applications both in food and pharmaceuticals

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End-Use Applications (Food Industry)

- Most frozen food products (fruits, vegetables, meat, poultry, fish) are stored between -18 to -35°C
- Methods of freezing
  - Blast freezing – forced convection with very cold air circulated over the product
  - Contact freezing – conduction with surface being chilled by refrigerant or circulating media
  - Liquid immersion – convection and conduction (special methods)
  - Cryogenic freezing – convection and/or conduction by spraying liquid nitrogen or liquid carbon dioxide
  - Cryomechanical freezing – series process of cryogenic freezing followed by mechanical refrigeration

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End-Use Applications (Chemicals Industry)

- Almost always, one-of-a-kind systems
  - Commercially available equipment is unacceptable
- Most applications are continuous but batch scenarios can be found occasionally
- Main applications include:
  - Removing the heat of exothermic reactions
  - Condensing overhead vapors
  - Controlling the process temperature/pressure to form specific products (monomer/polymer conversion, etc.) and/or storage
  - Separation of one gas from another by liquefaction
  - Separation by solidification of a product
  - Humidity control for hygroscopic products
  - Pre-cooling/chilling specific reactant/product streams

Key Points / Action Items

1. *A significant portion of the plant's energy can be consumed by its refrigeration system – sometimes as much as 50%!*
2. *Industrial refrigeration systems are mainly used by the food and chemicals industry but there are several process industries which have a definite need for refrigeration*
3. *The food industry requires pre-cooling of unfrozen foods and then temperatures between -18 to -35°C for storage*
4. *Applications ranging from convective cooling to contact freezing and variations with selective equipment can be in various food and process industries*
5. *The efficiency of the industrial refrigeration system is a direct driver of operating costs and should be managed*

7 INDUSTRIAL REFRIGERATION SYSTEMS

7.1 End-Use Applications

7.2 Different Types of Industrial Refrigeration Systems

7.3 Major Components & Controls

7.4 System Performance Metrics

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7.2 Different Types of Systems

- Industrial refrigeration systems are unique
- Custom-designed
- Several differentiating characteristics exist in these systems
- Nomenclature and comparison between each of the systems can be a challenge

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Thermodynamics - Refrigeration

- **Differentiation could be made on:**
  - Refrigerants (e.g. R22, R134a, R407C, R404A, R507, R717, R744, HFOs)
  - Compressor type (scroll, screw, reciprocating, centrifugal)
    - Compressor drive (electric motor – open or hermetic, steam turbine)
  - Type of condenser heat rejection (air or water cooled)
  - Construction of condenser and evaporator (plate heat exchanger, shell and tube, fin and coil)
  - Type of expansion device (thermal / electronic expansion valve, orifice, capillary tube)

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Thermodynamics - Refrigeration

- **Differentiation could be made on:**
  - Type of evaporator
    - direct expansion - Split System, cold room refrigeration (coolant is the refrigerant itself)
    - indirect expansion (coolant is in most cases glycol or brine)
  - Construction of evaporator (plate heat exchanger, shell and tube, fin and coil)
  - Construction of refrigerant cycle (compact stand-alone, compressor evaporator unit with external condenser, compressor with external evaporator and external condenser, condensing unit with external evaporator)

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The Basic Refrigeration Cycle

- All of the different kinds of refrigeration machines have basically the same concept – all of them use these main components:
  - at least one compressor
  - at least one condenser
  - at least one expansion device
  - at least one evaporator
  - all components are connected with piping
  - it is always a closed system
  - they all incorporate the latent heat of the refrigerant as the cooling effect
  - all refrigeration machines have a high and a low-pressure side

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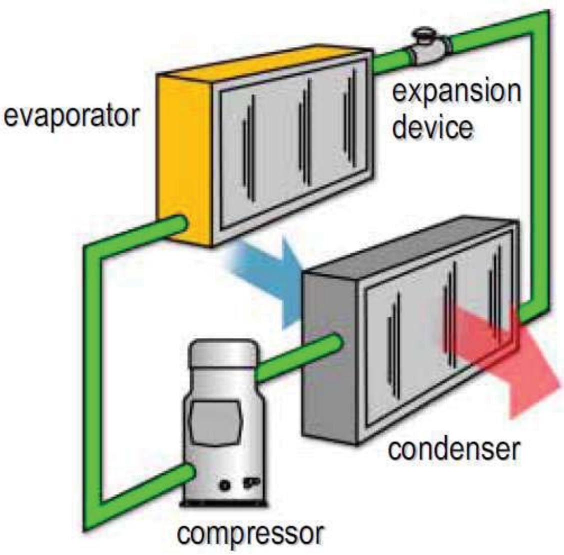
The Vapor Compression Cycle



- Thermodynamically, the vapor compression cycle always looks the same compressor – condenser – expansion device – evaporator

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Complex Industrial Refrigeration Systems

- Multistage systems
  - Most common
  - Chemical plant systems
    - Hydrocarbons - Ethylene, Propylene, Propane, Isobutane
    - R22, Ammonia
- Cascade systems
  - Ammonia (high-stage) / Carbon dioxide (low-stage)
  - R22 (high-stage) / R23 (low-stage)
- Liquid Overfeed systems
  - Ammonia, R22, R134a
- Absorption systems
  - Ammonia - water

7 INDUSTRIAL REFRIGERATION SYSTEMS

Multistage Systems

- This is the most common industrial refrigeration system and can be used very effectively to supply refrigeration, process cooling and chilled water through the same system
- Industrial refrigeration systems have very high lifts
- Compression is done in two or more stages given the limitations of the compressor pressure ratios
- Each stage represents a temperature level and most often in multiple temperature levels with multiple evaporators, the system is designed such that intermediate pressure serves the higher temperature evaporator
- A multistage system uses ONLY one refrigerant

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Halocarbon Refrigeration Systems

- Refrigerants used - R22, R134a, R404a, R407c, R507
- Types of evaporators
  - Flooded fluid coolers
  - Direct Expansion (DX) coolers
- All types of compressors
- Type of condensers
  - Water-cooled
  - Evaporative
  - Air-cooled
- Receivers
- Subcoolers – flash-type, closed type
- Liquid Suction heat exchangers
- Oil separators
- Surge drums or Accumulators

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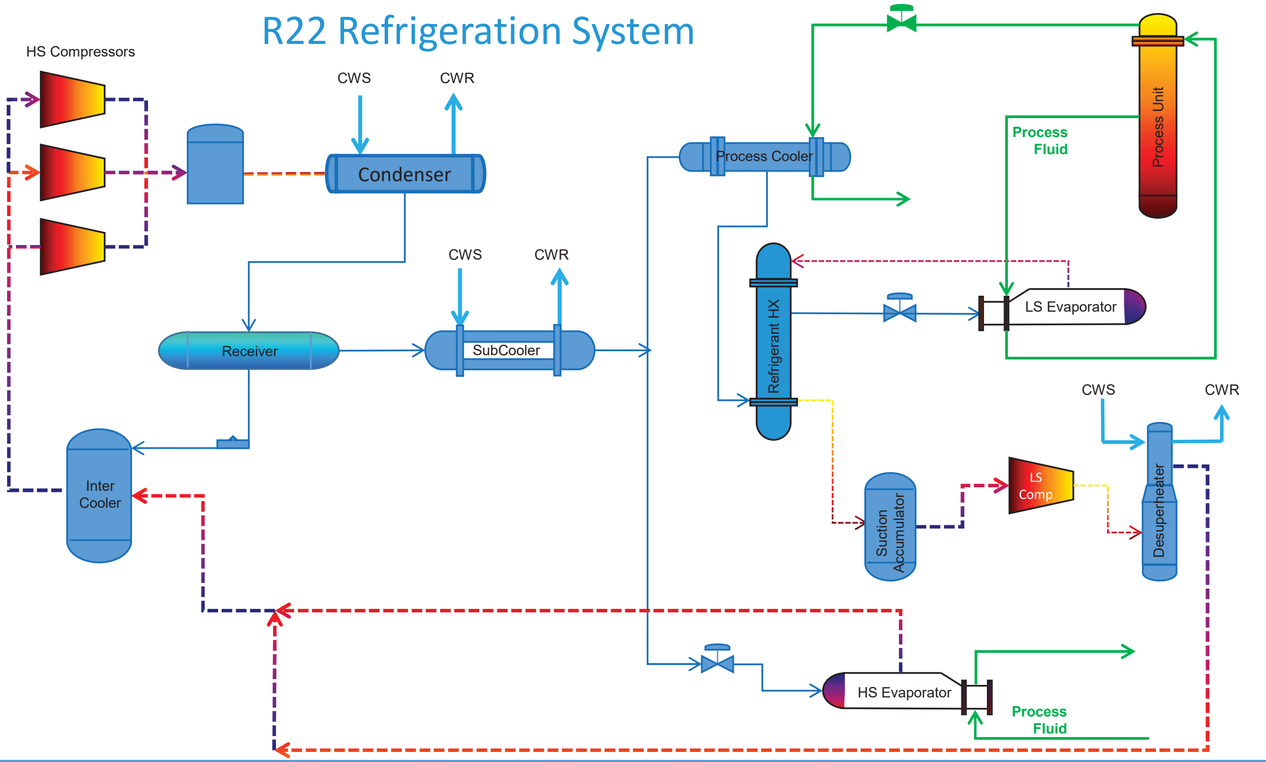
R22 Refrigeration System



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R22 Refrigeration System

Cooling Towers

Evaporator

Water-Cooled Condenser

Reciprocating Compressor

Intercooler

Ammonia Refrigeration Systems

- Type of condensers
  - Horizontal shell-and-tube w/through-type receiver
  - Evaporative
- Type of evaporators
  - Fan-coil direct expansion (above -18°C)
  - Fan-coil w/recirculation or overfeed (very efficient)
  - Flooded shell-and-tube evaporators w/secondary coolants
  - Spray shell-and-tube w/secondary coolants
- High pressure receiver
- Intercoolers
  - Vertical shell and coil
  - Flash
- Float control – High side (one evaporator), Low side (multiple evaporators)

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Ammonia Refrigeration Systems

- Type of compressors – rotary vane, reciprocating and screws
  - Rotary vane – low stage, booster applications
  - Reciprocating – less than 75 kW
  - Screw – greater than 75 kW
- Helical screws – V_i (volume index)
  - Ratio of suction volume to discharge volume
- Capacity control by slide valve, bypass ports and speed (VFD)
- Oil flooded screw compressors – paraffinic or naphthenic, synthetic
  - Oil is used for sealing, lubrication and slide valve control
  - Lubricant cooling done by external HX
- Receivers
- Subcoolers – flash-type, closed type
- Liquid Suction heat exchangers
- Oil separators
- Surge drums or Suction Accumulators

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Ammonia Refrigeration System


Refrigerant Piping & Pipe Rack


Thermosyphon Cooler/Separator


Evaporative Condensers & Receiver

A large poultry meat processing facility


Freezer DX Coils & Air Handler


Screw Compressor

Carbon Dioxide Refrigeration Systems

- Applications – cold storage, plate freezers, ice makers, spiral and belt freezers, freeze drying and supermarkets
- Large industrial systems - CO_2 (low stage) in cascade w/ammonia or R507a
- Transcritical cycle – CO_2 is the sole refrigerant (small systems)
- Cascade heat exchanger
  - CO_2 condenser & other refrigerant evaporator
  - Large systems: shell-and-tube; plate-and-frame; plate-and-shell
  - Commercial: brazed-plate; coaxial; tube-in-tube

Carbon Dioxide Refrigeration Systems

- Evaporators - air coils, plate freezers
- Control with liquid overfeed or electronic expansion valves
- Open-style belt-driven compressors (rotary screw and reciprocating)
- Lubricants – mineral oils, alkyl benzene, PAO, POE, PAG
- Stainless steel – preferred material of construction for CO_2
- Water is extremely critical for CO_2 systems – icing in control valves, carbonic acid formation (above saturation)

7 INDUSTRIAL REFRIGERATION SYSTEMS

7.1 End-Use Applications

7.2 Different Types of Industrial Refrigeration Systems

7.2.1 Multistage Systems

7.2.2 Cascade Systems

7.2.3 Liquid Overfeed Systems

7.2.4 Absorption Systems

7.3 Major Components & Controls

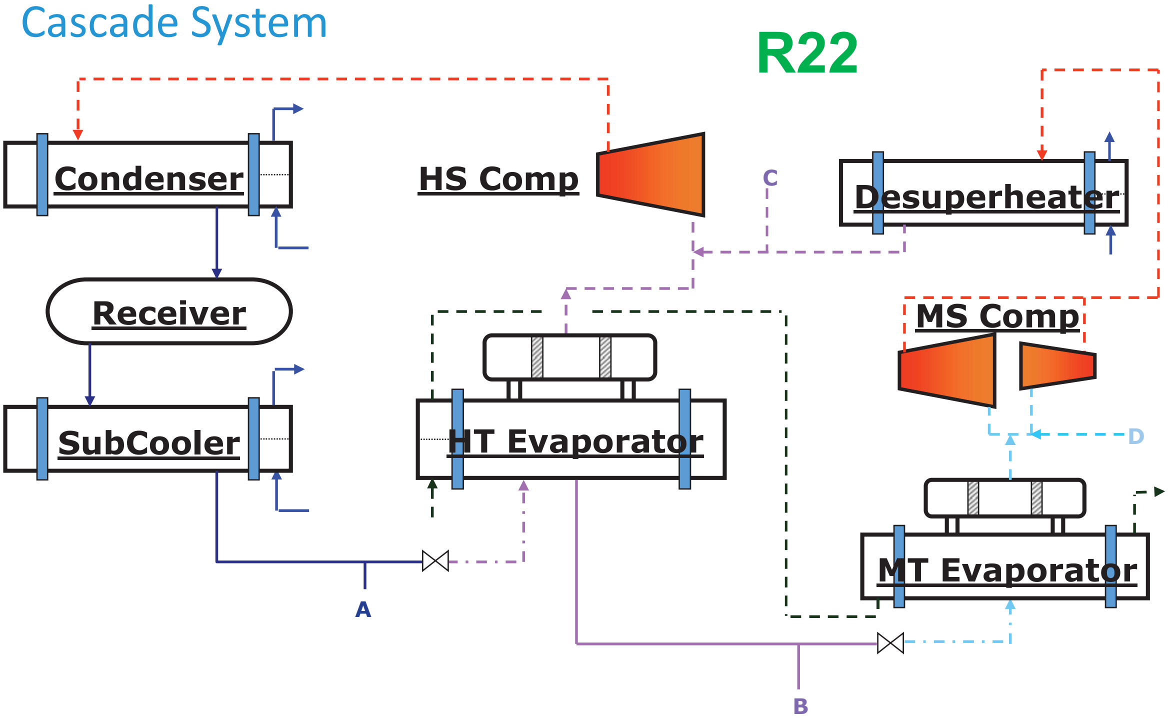
7.4 System Performance Metrics

Cascade Systems

- Cascade systems
  - Excessive temperature lifts and/or other system benefits and designs allow the implementation of two refrigerant systems
  - Excellent capabilities to eliminate low pressure (vacuum) conditions at low temperature levels
    - Economies in equipment (CAPEx)
    - Operating benefits – lower operating costs
  - Examples include:
    - Ammonia or R507 or R404 (high stage) and CO_2 (low stage)
    - R22 (high stage) and R23 (low stage)

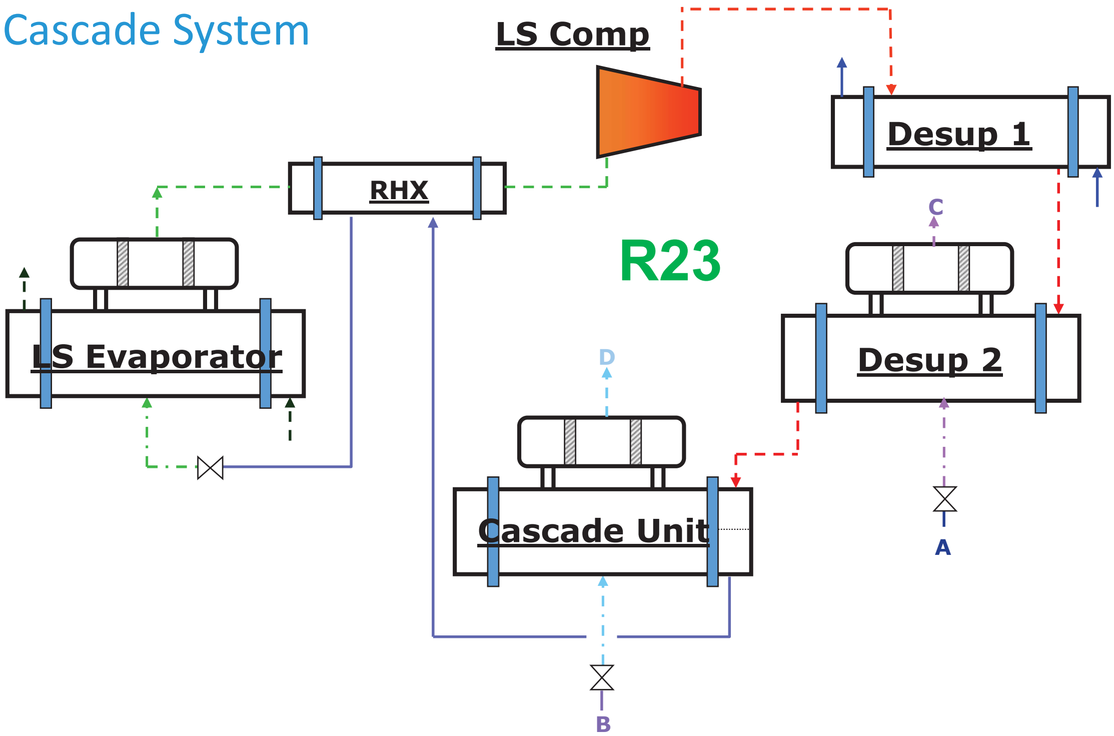
31

Cascade System



32

Cascade System



7 INDUSTRIAL REFRIGERATION SYSTEMS

Liquid Overfeed Systems

- Force liquid in excess of the amount evaporated either mechanically or by gas pressure through evaporators, then separate the vapor and return the liquid back to the evaporator
- Advantages
  - High system efficiency
  - Easy expandability
  - Reduced operating costs
- Disadvantages
  - Higher refrigerant charge
  - Piping insulation
  - Higher installed cost
  - Mechanical pumps needed + maintenance
- More the number of evaporators better the economics

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Liquid Overfeed Systems

- Metering devices regulate flow to the individual evaporators – valves, orifices
- Circulation rate
  - Ratio of mass of liquid pumped to the amount of vaporized liquid
- Overfeed rate
  - Ratio of mass of liquid to the amount of vapor returning to receiver
- Low pressure receiver (several different names)
  - Separate liquid and vapor
  - Allow for shrink and swell
  - Allow for enough liquid volume to accommodate load changes in the system
  - Internal baffles, mist eliminators help separation

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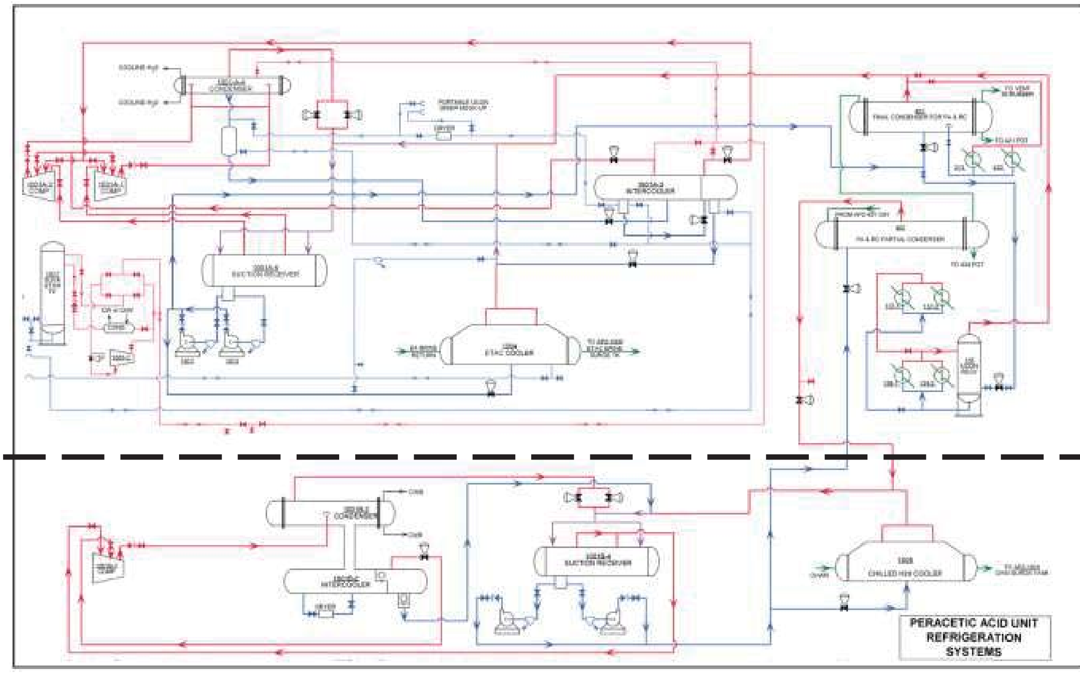
Liquid Overfeed System



7 INDUSTRIAL REFRIGERATION SYSTEMS

7.1 End-Use Applications

7.2 Different Types of Industrial Refrigeration Systems

- 7.2.1 Multistage Systems
- 7.2.2 Cascade Systems
- 7.2.3 Liquid Overfeed Systems
- 7.2.4 Absorption Systems

7.3 Major Components & Controls

7.4 System Performance Metrics

Absorption Refrigeration Systems

- Ammonia (Refrigerant) and Water (Absorbent) pair used in industrial refrigeration systems
- Main components
  - Evaporator
  - Condenser
  - Absorber
  - Generator
  - Rectifier
- Additional components include: solution pumps, refrigerant heat exchanger, solution heat exchanger, etc.
- Most often driven by waste heat in industrial plants
  - Low pressure steam (or hot water)
  - Available process heat

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A Waste Heat fired Ammonia Absorption Refrigeration System

Evaporators, Absorbers & Pumps on Skid

Generator, Rectifier & Solution HX

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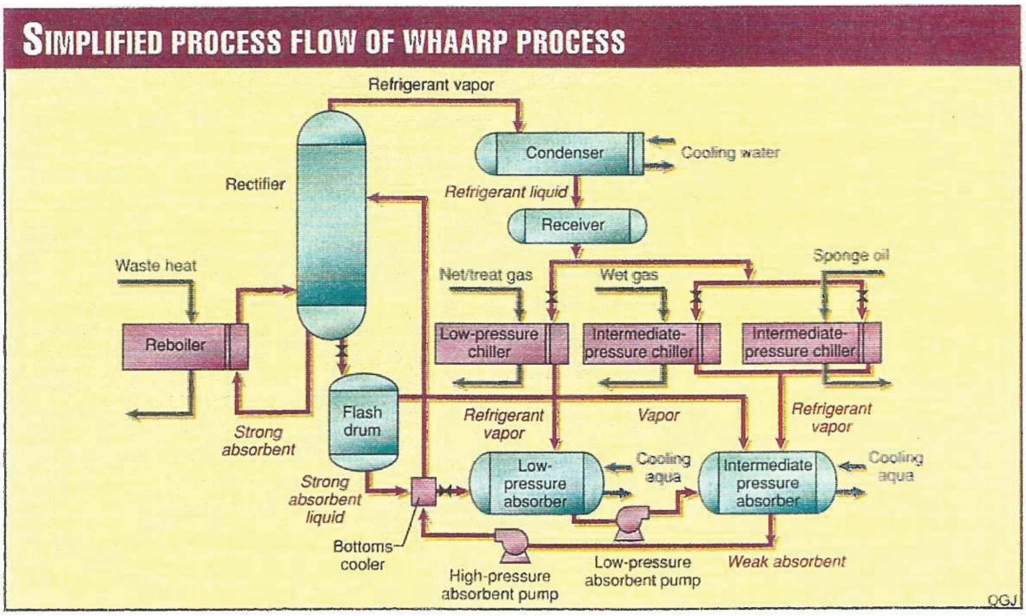
A Waste Heat fired Ammonia Absorption Refrigeration System



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Key Points / Action Items

1. *Industrial refrigeration systems can be differentiated in many ways but most times the refrigerant used is the primary differentiation – halocarbon, ammonia, carbon dioxide, etc.*
2. *Multistage, liquid overfeed systems, cascade systems, absorption systems provide another differentiation method*
3. *Majority of industrial refrigeration systems are based on the vapor compression cycle but there are a few industrial systems that are based on heat-driven absorption systems*
4. *Applications drive the need for a certain type of system*
5. *Almost always, there are multiple temperature levels supported by industrial refrigeration systems*

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7 INDUSTRIAL REFRIGERATION SYSTEMS

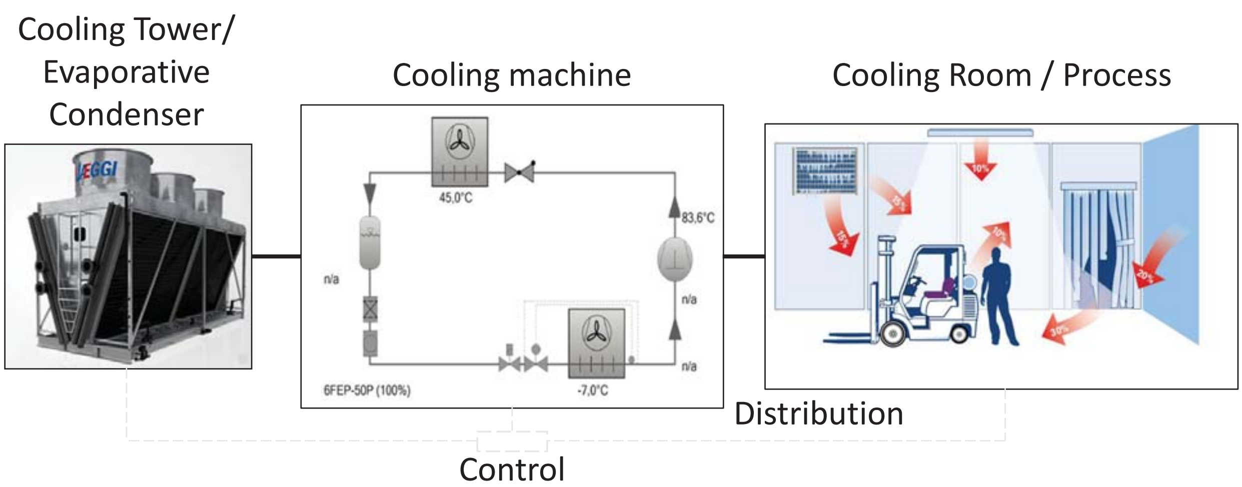
7.1 End-Use Applications

7.2 Different Types of Industrial Refrigeration Systems

7.3 Major Components & Controls

7.4 System Performance Metrics

7.3 Major Components & Controls



Energy performance – wet evaporation heat rejection provides high COP

Cooling Tower

Evaporative Condenser

Evaporative Condensers

- A heat exchanger (condenser) built into the cooling tower
- Advantages
  - Excellent heat transfer coefficient
  - Saturation temperature approaches wet-bulb (eliminate water ΔT)
  - Reduced pumping costs
  - Thermosyphon cooling can be easily accommodated
- Disadvantages
  - Initial cost maybe higher (but depends on system design)
  - Heat exchanger fouling could become an issue
- Evaporative condenser should be run at full capacity to take advantage of the wet-bulb and thereby reduce the compressor lift as much as possible

Compressors

- Two main types of compressors for industrial refrigeration skids
  - Reciprocating
  - Screw
- Very large low temperature industrial refrigeration systems will have centrifugal compressors
- Compressor control follows the same logic
  - Control the pressure of the low-temperature evaporator by pumping capacity of the low stage compressor
  - Control the intermediate pressure by pumping capacity of the high stage compressor
- Control mechanisms depend on the compressor type and have the most significant impact on energy consumed by the compressors
- Compressor efficiency is another important metric for operations

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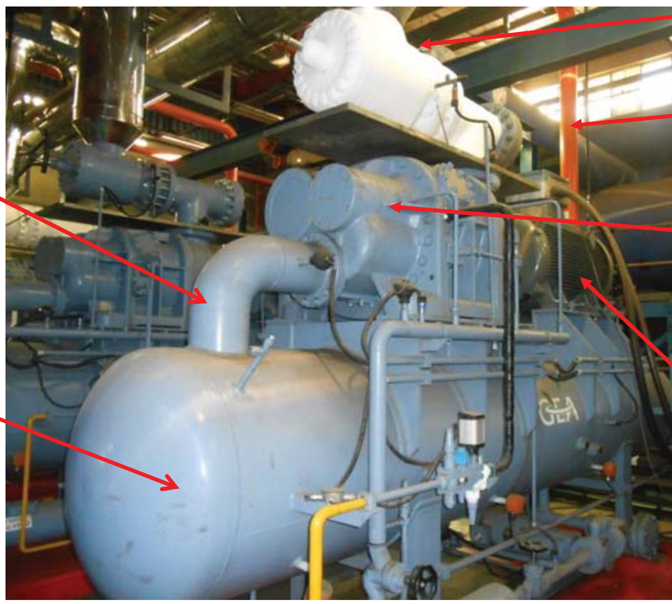
Screw Compressor Skid Package



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Oil Cooling Technologies

- As oil passes through the compressor, it picks up a lot of heat of compression from the refrigerant
- This heat has to be rejected after the oil is separated from the refrigerant and before it is reinjected
- There are four methods of heat rejection
  - Direct injection of liquid refrigerant
  - External thermosyphon heat exchanger
  - External cooling water heat exchanger
  - Adding liquid refrigerant into the refrigerant/oil mixture at compressor discharge
- Different manufacturers offer different options
- Some options have higher first cost but minimal operating costs and capacity penalties

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InterCoolers

- Cooling refrigerant vapor discharge from the low-stage compressor before the suction of the high-stage
- Best configuration is flashing a small amount of the high pressure refrigerant liquid in the intercooler to provide the cooling needed
- It improves the system efficiency without any loss in capacity

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Other Components

- High pressure receivers
- Flash tank / Subcooler
- Desuperheater
- Low pressure receiver
- Surge drum
- Suction line accumulator
- Thermosyphon receiver
- Refrigerant heat exchangers
- Other heat exchangers
- Float / control valves
- Oil pots and heaters
- Skimmers

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Key Points / Action Items

1. *Evaporative condensers are the preferred choice of heat rejection mechanism in industrial refrigeration system*
2. *Reciprocating and Screw compressors are the work horses of the refrigeration systems*
3. *Part-load operation should be carefully evaluated especially since screw compressors can have a significant detriment to efficiency when using slide valves to control capacity*
4. *Variable Frequency Drives should be considered*
5. *There are several important sub-systems whose operations are critical for industrial refrigeration*

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7 INDUSTRIAL REFRIGERATION SYSTEMS

7.4 System Performance Metrics

- Industrial Refrigeration consume a significant amount of energy and being very complex and process integrated require a much higher-level of due diligence for define performance metrics
- Several industrial refrigeration systems have multiple temperature levels and different loads at these temperatures
- Basic thermodynamics and fundamentals do remain the same
  - Individual component efficiencies (compressors) get more emphasis

System Energy Performance Metrics

- Temperatures, Pressures
- Lift
- Refrigeration Load
- COP, COSP, SCOSP
- HX performance
- Compressor performance

55

General COP Ranges for Refrigeration Systems

- This is just a high-level comparison – should be used as a guide ONLY
- Air-cooled condensing systems
  - Evaporation temperature range (-15 to 7°C)
    - Reciprocating: 1.6 – 3.2
    - Screw: 1.9 – 4.2
  - Evaporation temperature range (-45 to -30°C)
    - Reciprocating: 1.0 – 1.5
    - Screw: 1.2 – 1.7

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General COP Ranges for Refrigeration Systems

- This is just a high-level comparison – should be used as a guide ONLY
- Water-Cooled (Evaporative) condensing systems
  - Evaporation temperature range (-15 to 7°C)
    - Reciprocating: 2.0 – 5.2
    - Screw: 2.3 – 6.1
  - Evaporation temperature range (-45 to -30°C)
    - Reciprocating: 1.2 – 1.8
    - Screw: 1.4 – 2.1

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Key Points / Action Items

1. *It is important to identify unit and system performance metrics for your specific industrial refrigeration system*
2. *Trend system performance and compare operation metrics at similar loads, ambient and seasonal production conditions*
3. *COP, COSP are the most commonly used system metrics in industrial refrigeration systems but compressor efficiency can also be evaluated*
4. *COP ranges depend on compressor type, heat rejection mechanism, ambient conditions, system load, control mechanism, etc.*
5. *No two systems are identical and comparison between systems should be made carefully*

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1

8 MODELING AN INDUSTRIAL REFRIGERATION SYSTEM

8.1 Revisiting CRST

8.2 Overview of Software - CoolPack

8.3 A Simple Food Industry System Model w/CoolPack

Acknowledgments: Team CoolPack; Department of Mechanical Engineering, Technical University of Denmark

2

8.1 Revisiting CRST

- There are specific sections in the Chiller & Refrigeration Scoping Tool (CRST) that pertain to industrial refrigeration systems
- The questions help to qualify the refrigeration system
  - Operational BestPractices
  - Profiling and maintenance BestPractices
- It will NOT quantify the savings opportunities but it's a great first step to understand the overall system

Intended CRST Users

- Industrial manufacturers
  - Plant managers
  - Utility managers
  - Plant process engineers
- Energy consultants
  - Energy efficiency experts (high-level)
  - System-focused experts

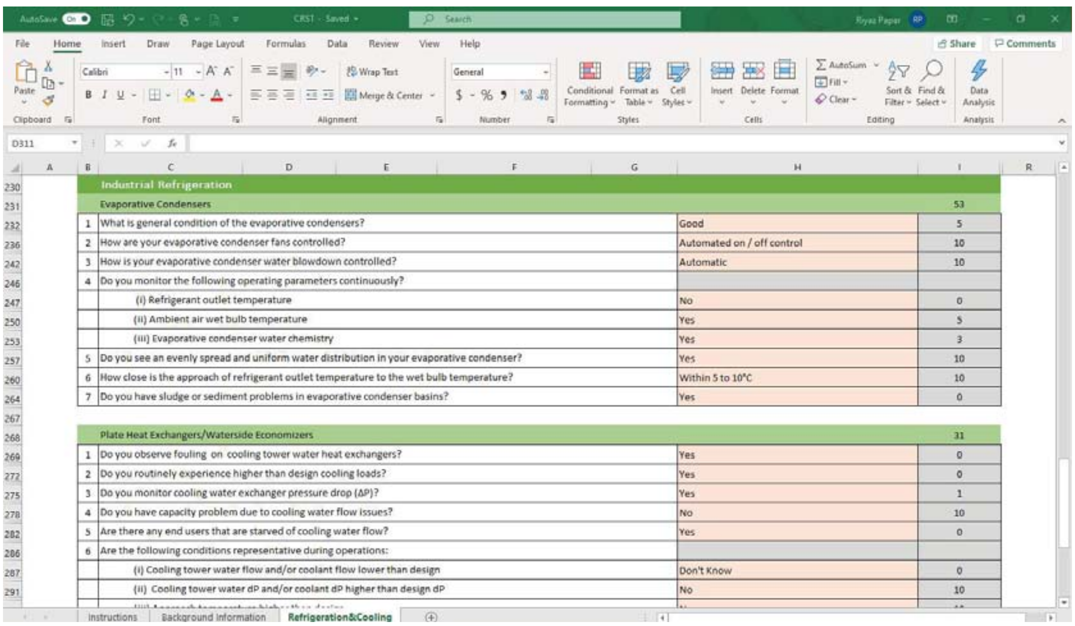
Obtaining Data for CRST Input

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

- Expected time: 1.5 hours (90 minutes)

5

CRST – CR System Scorecard – Industrial Refrigeration



230		**Industrial Refrigeration**		
231		**Evaporative Condensers**		53
232	1	What is general condition of the evaporative condensers?	Good	5
236	2	How are your evaporative condenser fans controlled?	Automated on / off control	10
242	3	How is your evaporative condenser water blowdown controlled?	Automatic	10
246	4	Do you monitor the following operating parameters continuously?		
247		(i) Refrigerant outlet temperature	No	0
250		(ii) Ambient air wet bulb temperature	Yes	5
253		(iii) Evaporative condenser water chemistry	Yes	3
257	5	Do you see an evenly spread and uniform water distribution in your evaporative condenser?	Yes	10
260	6	How close is the approach of refrigerant outlet temperature to the wet bulb temperature?	Within 5 to 10°C	10
264	7	Do you have sludge or sediment problems in evaporative condenser basins?	Yes	0
267				
268		**Plate Heat Exchangers/Waterside Economizers**		31
269	1	Do you observe fouling on cooling tower water heat exchangers?	Yes	0
272	2	Do you routinely experience higher than design cooling loads?	Yes	0
275	3	Do you monitor cooling water exchanger pressure drop (ΔP)?	Yes	1
278	4	Do you have capacity problem due to cooling water flow issues?	No	10
282	5	Are there any end users that are starved of cooling water flow?	Yes	0
286	6	Are the following conditions representative during operations:		
287		(i) Cooling tower water flow and/or coolant flow lower than design	Don't Know	0
291		(ii) Cooling tower water dP and/or coolant dP higher than design dP	No	10

6

8 MODELING AN INDUSTRIAL REFRIGERATION SYSTEM

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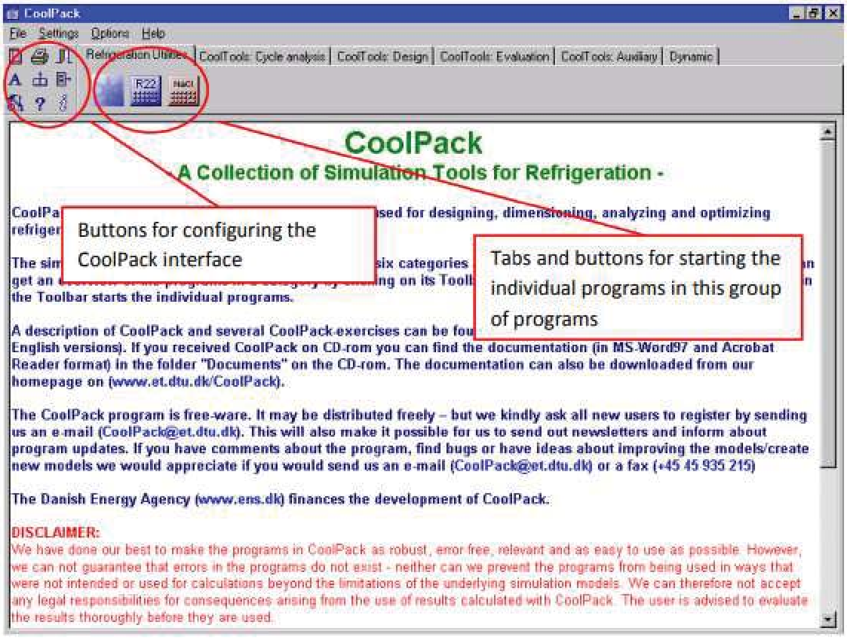
8.2 CoolPack / CoolTools

- Free downloadable software from www.ipu.dk
  - Technical University of Denmark
- CoolPack was developed starting in 2000 and continued to be updated and modified until recently
- CoolTools (beta version) is now the modern adaptation of CoolPack
- These are simulation programs for evaluating actual COPs of different refrigeration systems
- These tools will help quantify the savings opportunities

CoolPack Version 1.50



CoolPack Version 1.50

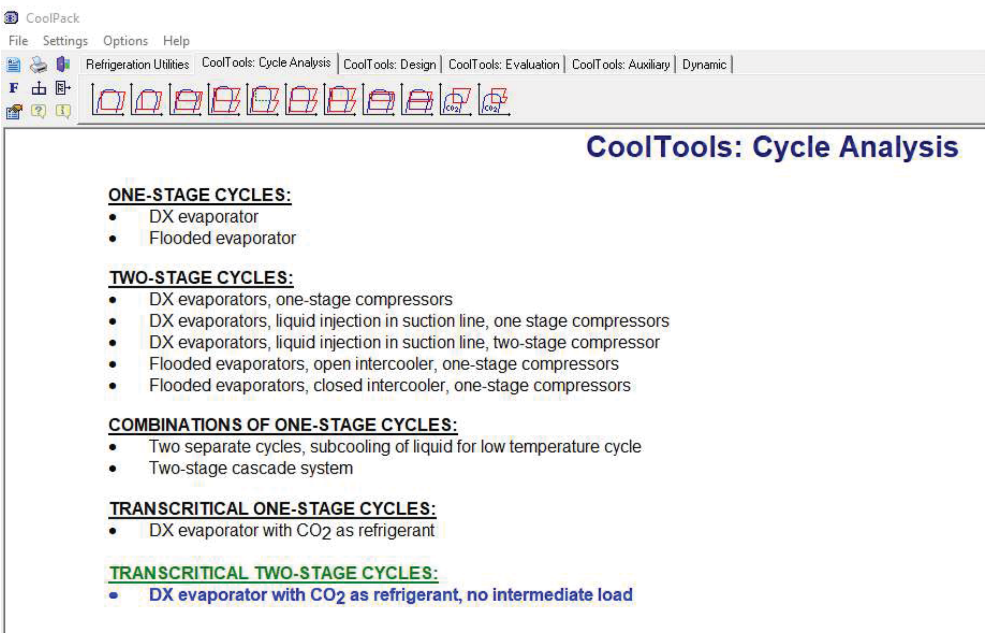
- Refrigeration Utilities
  - P-h diagrams
  - T-s diagrams
  - H-s diagrams

  } 45 refrigerants including R400 and R500 series
  - Thermodynamic properties for saturated and superheated refrigerant
  - Tables for thermophysical properties
  - Psychrometric moist air properties
- Refrigerant Calculator
  - It could be very useful in the field for immediate state-point calculations, data collection, etc.
- Secondary Fluids for Heat Transfer
  - Calculator for secondary fluids – transport properties, pressure drop calcs

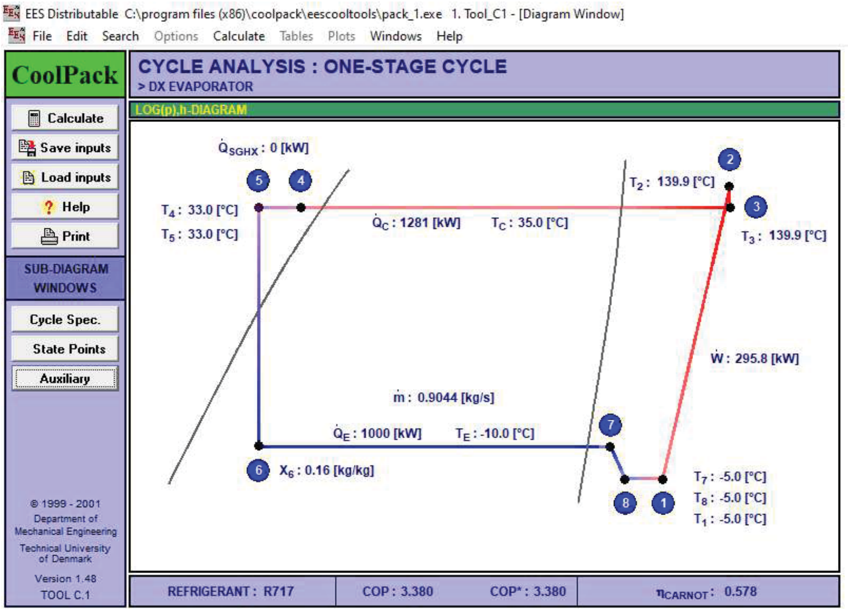
CoolPack Version 1.50

Description of function	Button and icon
Return to main diagram window	
Calculate, corresponds to pressing the F2-key	- CALC -
Save inputs in a file	- SAVE -
Load inputs from a file	- LOAD -
Activate the help-function	- HELP -
Go to sub-diagram window with cycle specification	Cycle Spec.
Go to sub-diagram window with auxiliary calculations	Auxiliary
Go to sub-diagram windows with overview of state points	State Points

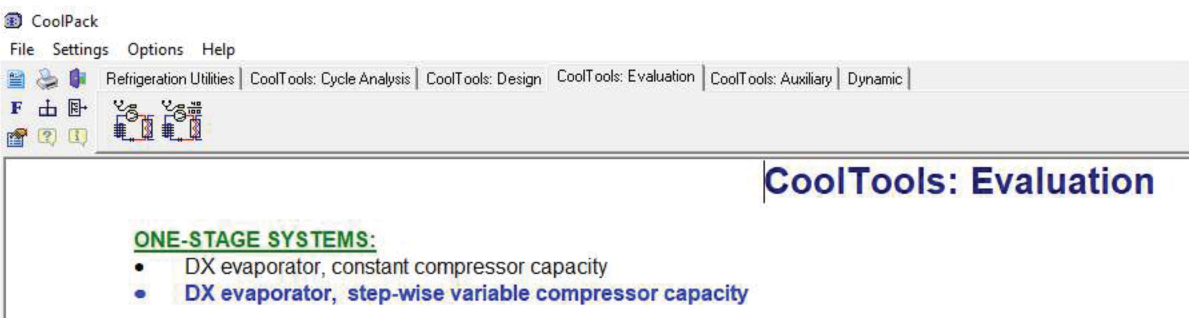
CoolPack Version 1.50



Cycle Analysis

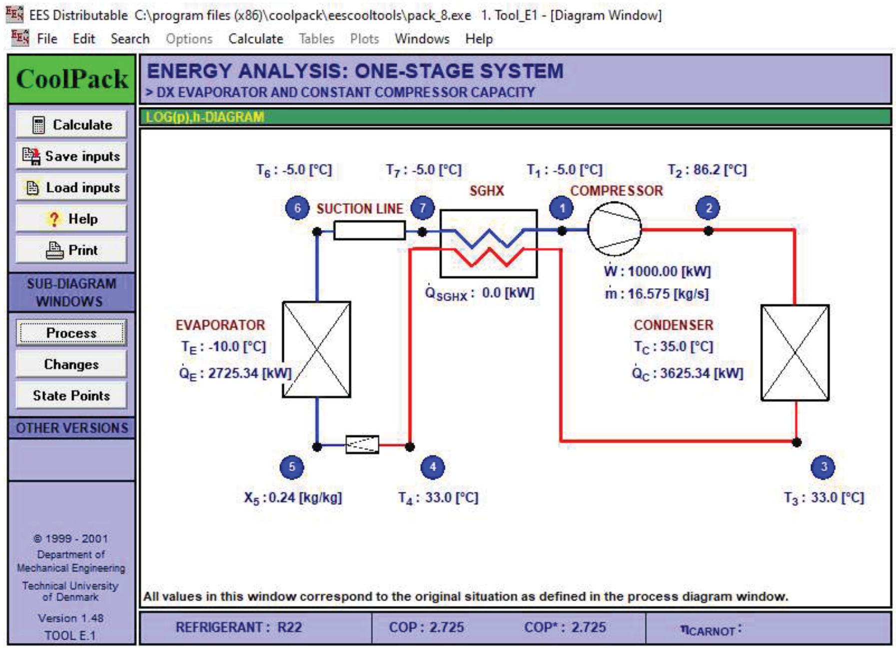


Evaluation



- The intent of this section is to model the refrigeration system as closely as possible
- Undertake a "what-if" Consequence analysis on energy and economy
  - Base Case
  - Change of Parameters

Evaluation



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Evaluation

EES Distributable C:\program files (x86)\coolpack\eescooltools\pack_8.exe 1. Tool_E1 - [Change of parameters]

File Edit Search Options Calculate Tables Plots Windows Help

CHANGE OF PARAMETERS: CONSEQUENCES FOR ENERGY AND ECONOMY

CHANGE OF PARAMETERS

CHANGES OF COMPONENTS [+/-]

Reduction of $\dot{Q}_E$ [%] : 0
Isentropic efficiency [%] : 0
Evaporator UA-value [%] : 0
Condenser UA-value [%] : 0

CHANGES ON SECONDARY SIDE OF EVAPORATOR

Temperature of fluid on secondary side is increased by [K] : 2.0

CHANGES ON SECONDARY SIDE OF CONDENSER

Ambient temperature for condenser is decreased by [K] : 2.0

ENERGY

OVERALL VIEW OF OPERATION (PRESENT & NEW SITUATION)

	$\dot{Q}_E$ [kW]	$\dot{W}$ [kW]	COP [-]	T_E [°C]	T_C [°C]
Present	2725.34	1000.00	2.725	-10.0	35.0
New	2725.34	879.23	3.100	-8.0	32.7
% Changes	0.0	-12.1	13.74	-	-

COMPRESSOR

Change of compressor capacity : -8.58 [%]

ECONOMY

COST OF ENERGY AND HOURS OF OPERATION

Cost of one kWh : 0.1 $
Hours of operation [h] : 8760

ANNUAL SAVINGS WITH NEW PARAMETERS

Savings : 1.058E+06 [kWh]
Savings : 105790 [$]

Calculate | Print | Help | Home | State Points | Process | COP : 2.725 | COP* : 2.725

Evaluation – Step-wise Compressor Capacity

EES Distributable C:\program files (x86)\coolpack\eescooltools\pack_8.exe 2. Tool_E2 - [Process Specification]

File Edit Search Options Calculate Tables Plots Windows Help

PROCESS SPECIFICATION FOR PRESENT SITUATION

EVAPORATOR

Evaporating temperature (T_E) [°C]: -10.0 ΔT_{SH} [K]: 5

Temperature of air or water entering evaporator [°C]: 2

$T_{E,A}$: -10.0 [°C] $p_{E,A}$: 354.0 [kPa] UA-value: 227.112 [kW/K]

$T_{E,B}$: -5.3 [°C] $p_{E,B}$: 416.5 [kPa]

NOTE: Evaporating pressure = suction pressure

CONDENSER

Condensing temperature (T_C) [°C]: 35 ΔT_{SC} [K]: 2

Temperature of air or water entering condenser [°C]: 25

$T_{C,A}$: 35.0 [°C] $p_{C,A}$: 1354.0 [kPa] UA-value: 362.580 [kW/K]

$T_{C,B}$: 30.7 [°C] $p_{C,B}$: 1214.0 [kPa]

NOTE: Condensing pressure = discharge pressure

SUCTION GAS HEAT EXCHANGER (SGHX)

No SGHX: 0.0 $T_{4,A}$: 33.0 [°C] η_T: 0.00 [-]

REFRIGERANT

R22

CYCLE CAPACITY

Volumetric efficiency (η_{VOL}) [-]: 0.8

$\dot{Q}_{E,A}$: 2725.34 [kW] $\dot{m}_A$: 16.58 [kg/s] $\dot{V}_{S,A}$: 4000.000 [m³/h] η_{VOL}: 0.800 [-]

$\dot{Q}_{E,B}$: 1663 [kW] $\dot{m}_B$: 9.68 [kg/s] $\dot{V}_{S,B}$: 2000.400 [m³/h]

COMPRESSOR PERFORMANCE

Isentropic efficiency (η_{IS}) [-]: 0.572 η_{IS}: 0.572 [-] $\dot{W}_A$: 1001 [kW] $\dot{W}_B$: 461.1 [kW]

Compressor displacement ($\dot{V}_D$) [m³/h]: 5000

CONDITION A	Capacity [%]: 100.0	$\dot{V}_{D,A}$: 5000 [m³/h]	Relative operation time [%]: 50
CONDITION B	Capacity [%]: 50.0	$\dot{V}_{D,B}$: 2501 [m³/h]	Relative operation time [%]: 50

COMPRESSOR HEAT LOSS

Heat loss factor (f_Q) [%]: 10 f_Q: 10.0 [%]

$T_{2,A}$: 86.3 [°C] $\dot{Q}_{LOSS,A}$: 100.051 [kW]

$T_{2,B}$: 72.6 [°C] $\dot{Q}_{LOSS,B}$: 46.112 [kW]

SUCTION TEMPERATURE

$T_{1,A}$ [°C]: -5.0 $\Delta T_{SH,SL}$: -0.0 [K] $\Delta T_{SH,SL}$ does not include superheat in SGHX

Calculate | Print | Help | Home | State Points | Changes | COP: 2.724 COP*: 2.724

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Evaluation – Step-wise Compressor Capacity

EES Distributable C:\program files (x86)\coolpack\eescooltools\pack_8.exe 2. Tool_E2 - [Change of parameters]

File Edit Search Options Calculate Tables Plots Windows Help

CHANGE OF PARAMETERS: CONSEQUENSES FOR ENERGY AND ECONOMY

CHANGE OF PARAMETERS

CHANGES OF COMPONENTS [+/-]

Reduction of $\dot{Q}_E$ [%]: 0

Isentropic efficiency [%]: 0

Evaporator UA-value [%]: 0

Condenser UA-value [%]: 0

CHANGES ON SECONDARY SIDE OF EVAPORATOR

Temperature of fluid on secondary side is increased by [K]: 2

CHANGES ON SECONDARY SIDE OF CONDENSER

Ambient temperature for condenser is decreased by [K]: 2

ENERGY

WEIGHTED AVERAGE OF A+B AND CONTINUOUS OPERATION

	$\dot{Q}_E$ [kW]	$\dot{W}$ [kW]	Cap. [%]	COP [-]	T_E [°C]	T_C [°C]
A+B	2194	730.8	100.0 50.0	3.002	-10.00 -5.32	35.00 30.73
Continuous	2194	702.6	72.8	3.123	-7.66	32.80
% Change		-3.86		4.02		

WEIGHTED AVERAGE ("A+B" - PRESENT AND NEW SITUATION)

	$\dot{Q}_E$ [kW]	$\dot{W}$ [kW]	Cap. [%]	COP [-]	T_E [°C]	T_C [°C]
Present A+B	2194	730.8	100.0 50.0	3.002	-10.00 -5.32	35.00 30.73
New A+B	2194	638.6	91.4 45.9	3.436	-8.00 -3.32	32.70 28.57
% Change		-12.62		14.44		

ECONOMY

ENERGY COST AND HOURS OF OPERATION

Cost of one kWh: 0.1 $

Hours of operation [h]: 8760

ANNUAL SAVING WITH NEW PARAMETERS

Savings: 807964 [kWh]

Savings: 80796 [$]

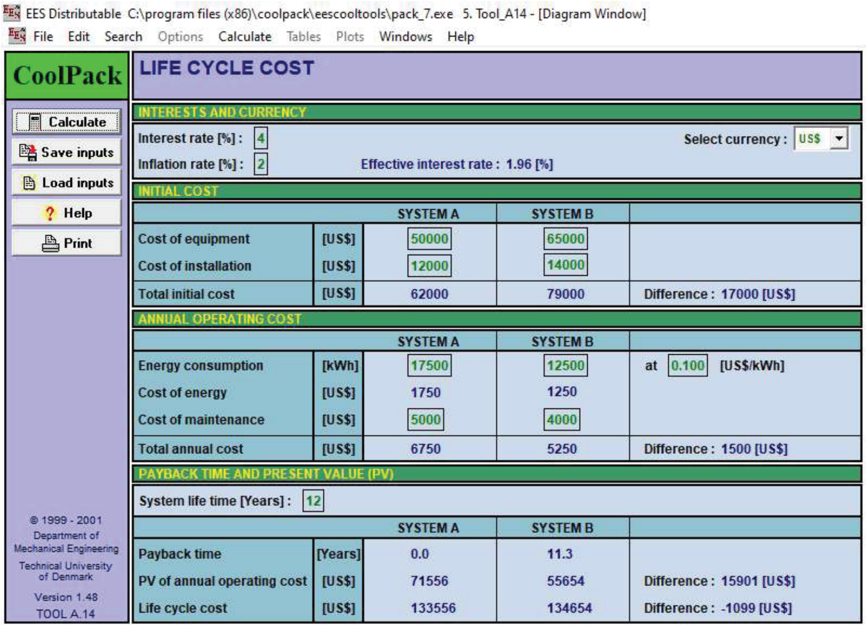
ANNUAL SAVING WITH CONTINUOUS OPERATIONS

Savings: 247397 [kWh]

Savings: 24740 [$]

Calculate | Print | Help | Home | Process | State Points | COP: 2.724 COP*: 2.724

Auxiliary – Life Cycle Cost Comparison



EES Distributable C:\program files (x86)\coolpack\eescooltools\pack_7.exe 5. Tool_A14 - [Diagram Window]

File Edit Search Options Calculate Tables Plots Windows Help

CoolPack — LIFE CYCLE COST

Calculate | Save inputs | Load inputs | Help | Print

INTERESTS AND CURRENCY

Interest rate [%] : 4 — Select currency : US$

Inflation rate [%] : 2 — Effective interest rate : 1.96 [%]

INITIAL COST

		SYSTEM A	SYSTEM B	
Cost of equipment	[US$]	50000	65000	
Cost of installation	[US$]	12000	14000	
Total initial cost	[US$]	62000	79000	Difference : 17000 [US$]

ANNUAL OPERATING COST

		SYSTEM A	SYSTEM B	
Energy consumption	[kWh]	17500	12500	at 0.100 [US$/kWh]
Cost of energy	[US$]	1750	1250	
Cost of maintenance	[US$]	5000	4000	
Total annual cost	[US$]	6750	5250	Difference : 1500 [US$]

PAYBACK TIME AND PRESENT VALUE (PV)

System life time [Years] : 12

		SYSTEM A	SYSTEM B	
Payback time	[Years]	0.0	11.3	
PV of annual operating cost	[US$]	71556	55654	Difference : 15901 [US$]
Life cycle cost	[US$]	133556	134654	Difference : -1099 [US$]

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8

MODELING AN INDUSTRIAL REFRIGERATION SYSTEM

8.1 Revisiting CRST

8.2 Overview of Software - CoolPack

8.3 A Simple Food Industry System Model w/CoolPack

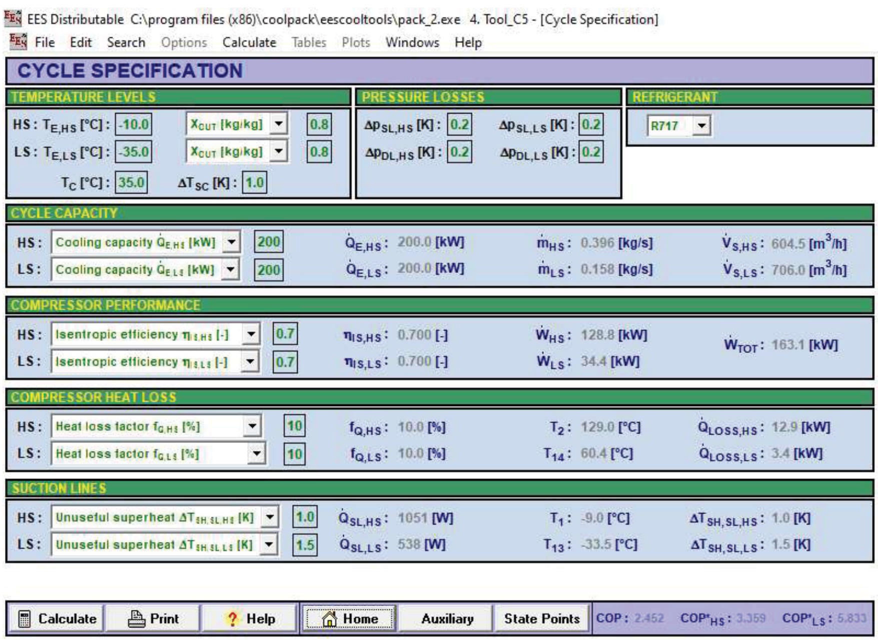
8.3 CoolPack 1.50

- CoolPack will be actively demonstrated and the functionalities highlighted while modeling a system

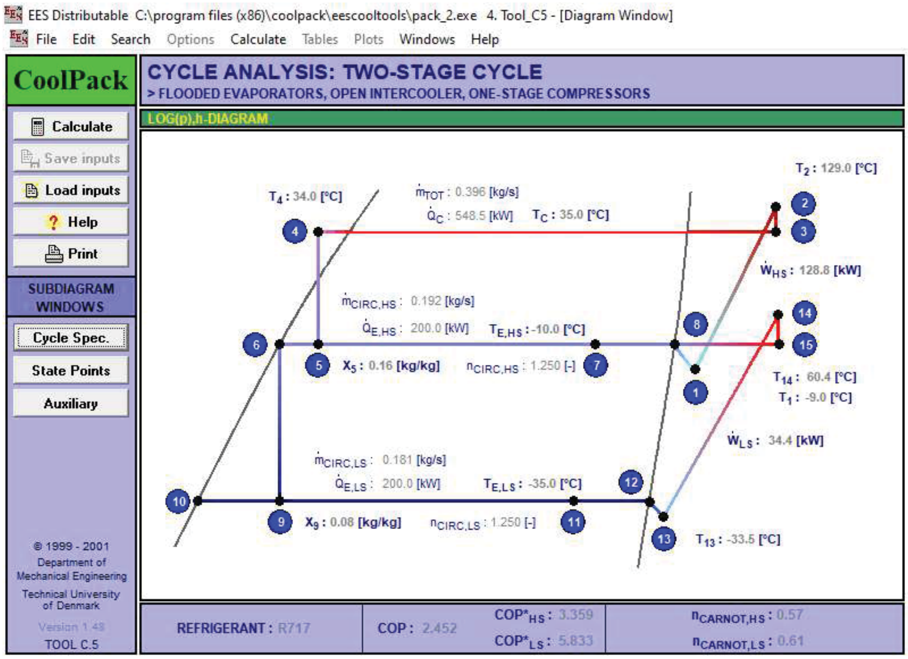
- A simple (and small) refrigeration system in a Food industry is being used as an example
  - Refrigerant is Ammonia (R717)
  - Flooded system with two temperature levels
  - Both low stage and high stage require 200 kW each of cooling capacity
  - System effects – subcooling, suction lines heat gains, isentropic efficiencies, etc. – are considered and can be modified/improved

- Convergence issues and initial guess values are important

Food Industry Refrigeration System



Food Industry Refrigeration System



Food Industry Refrigeration System

EES Distributable C:\program files (x86)\coolpack\eescooltools\pack_2.exe 4. Tool_C5 - [State Points]

File Edit Search Options Calculate Tables Plots Windows Help

STATE POINTS

	STATE POINT	TEMPERATURE [°C]	PRESSURE [kPa]	ENTHALPY [kJ/kg]	DENSITY [kg/m³]
HIGH PRESSURE	2	129.0	1361.7	1729.2	7.3
	3	129.0	1353.9	1729.4	7.2
	4	34.0	1353.9	345.4	588.9
INTERMEDIATE PRESSURE	5	-10.0	290.9	345.4	-
	6	-10.0	290.9	133.2	651.9
	7	-10.0	290.9	1173.9	-
	8	-10.0	290.9	1434.1	2.4
	1	-9.0	288.6	1436.8	2.4
	15	60.4	290.9	1598.1	1.8
	14	60.4	293.3	1598.0	1.8
LOW PRESSURE	9	-35.0	92.9	133.2	-
	10	-35.0	92.9	21.3	683.4
	11	-35.0	92.9	1123.3	-
	12	-35.0	92.9	1398.8	0.8
	13	-33.5	92.0	1402.2	0.8

Additional information

$p_{OPTIMUM} = \sqrt{p_2 \cdot p_{13}}$

$p_{OPTIMUM}$: 353.9 [kPa]

$T_{SAT,OPTIMUM}$: -5.1 [°C]

Pressure ratio (p_2 / p_1) : 4.719

Pressure ratio (p_{14} / p_{13}) : 3.189

$T_{2,IS}$: 103.6 [°C]

$T_{2,W}$: 141.8 [°C]

$T_{14,IS}$: 41.5 [°C]

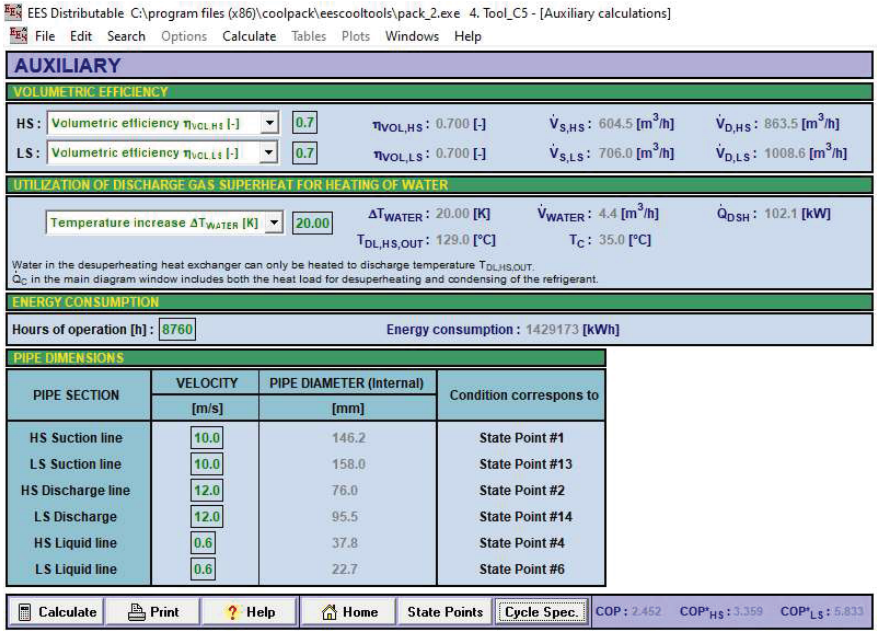
$T_{14,W}$: 70.0 [°C]

T_{IS} is the temperature of the discharge gas assuming reversible and adiabatic compression

T_W is the temperature of the discharge gas assuming real and adiabatic compression

Calculate | Print | Help | Home | Cycle Spec. | Auxiliary | COP : 2.452 | COP*HS : 3.359 | COP*LS : 5.833

Food Industry Refrigeration System



25

Key Points / Action Items

1. *CoolPack 1.50 is a free downloadable software from Technical University of Denmark (Department of ME)*
2. *It has tremendous abilities to model industrial refrigeration systems and allow simulations of operations at steady state*
3. *It has built libraries of 45 refrigerants that can be accessed via a pull-down menu and the software's interface is extremely user-friendly*
4. *CoolPack is divided into several sections and sub-sections for ease of use and provides energy and cost comparisons*
5. *CoolTools is the new home eventually for all the CoolPack algorithms and models*

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1 FUNDAMENTALS
2 LARGE SCALE COOLING & INDUSTRIAL REFRIGERATION SCOPING TOOL (CRST)
3 CALCULATIONS OF UNIT & SYSTEM EFFICIENCY
4 CHILLED WATER SYSTEM ASSESSMENT TOOL (CWSAT)
5 ENERGY EFFICIENCY (EE) OPPORTUNITIES IN CHILLED WATER SYSTEMS
6 REFRIGERANTS – PAST, PRESENT & FUTURE
7 INDUSTRIAL REFRIGERATION SYSTEMS
8 MODELING AN INDUSTRIAL REFRIGERATION SYSTEM
9 EE OPPORTUNITIES IN INDUSTRIAL REFRIGERATION SYSTEMS
10 CR SYSTEM OPTIMISATION CASE STUDIES
11 OTHER EE SOFTWARE TOOLS FOR CR SYSTEMS
12 NEXT GENERATION CR SYSTEMS
13 CONCLUSIONS

1

Some measures to reduce energy consumption for refrigeration and to improve system efficiency

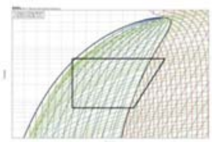
- Reduction of the cooling load
- Raise evaporating temperature
- Lower condensing temperature
- Optimize compressor control
- Efficiency and control of fans
- Use of waste heat – heat recovery
- Avoid and repair leakages

2

Most important question: How can we determine the energy/cost savings accurately?

- Option 1: Measure before and after the implementation
  - “Real” savings
  - Expensive and time consuming

- Option 2: Use software tools to calculate the theoretical savings
  - Quick solution
  - Good basis for decision
  - Result is only theoretical



3

9 ENERGY EFFICIENCY OPPORTUNITIES IN INDUSTRIAL REFRIGERATION SYSTEMS

Acknowledgments: Team CoolPack; Department of Mechanical Engineering, Technical University of Denmark

9.1 Reducing Refrigeration System Load

- The refrigeration load is the "leader" and the system is the "follower"
- Reducing system load directly reduces energy consumption, operating costs and GHG emissions
- Reducing load can enhance system reliability and also improve redundancy and available capacity
- Minimize refrigeration load and then improve operations
- Some load reduction measures are covered in this section and savings are quantified using Coolpack

5

Reducing Refrigeration System Load

- Switch off unused places – warehouses, freezers, refrigerators - and deep-freeze rooms when not in use for extended periods / seasons
- Reduce heat load caused by product temperature
  - Activity of storing
  - Activity of moving
- Evaluate pre-cooling before storage – ambient air, chilled water/glycol
  - Make step changes (ideally linear) to lowest temperature level
- Minimize air infiltration from doors, ramps, conveyors, etc.
  - Ensure proper seals

6

Reducing Refrigeration System Load

- Improve building envelope insulation – check material, emissivity, leaks
  - Reduce heat gain via doors
  - Improve Insulation of the shell
- Reduce human activity, lighting and machines in the refrigerated areas
  - Reduce heat input by persons
  - Reduce heat input by lighting
  - Reduce heat input by machines
  - Optimize regulatory frame heaters
- Optimize the demand-based defrost heater control

7

Food Industry Refrigeration System

- Reduction of Low Stage Refrigeration Load by 75 kW (from 750 kW to 675 kW) and Increase of High Stage Refrigeration Load by 75 kW (from 1,000 kW to 1,075 kW)
  - Base Case Energy Usage – 686.4 kW
  - New Case Energy Usage – 670 kW
  - Energy Savings – 16.4 kW
  - Annual Energy Savings ~ 144,000 kWh (based on 8,760 hours of operation)
  - Annual Cost Savings ~ R 144,000 (based on 1 R/kWh)
- This is the more realistic case in industry and maybe the first step to optimize and reduce overall refrigeration load of the system

8

Key Points / Action Items

1. *Industrial refrigeration system load is the single direct factor for energy costs*

2. *There are several opportunities to reduce the refrigeration system load but all of them will require a thorough process know-how*

3. *There are several opportunities of reducing industrial refrigeration load which is based on parasitic and human activity – low hanging fruit*

4. *Using a software such as CoolPack allows theoretical modeling and a good quantification level for savings*

5. *Eventually a bin analysis can be done with much more detailed load profile and ambient conditions*

9

9 ENERGY EFFICIENCY OPPORTUNITIES IN INDUSTRIAL REFRIGERATION SYSTEMS

9.1 Reducing Refrigeration Load

9.2 Optimising Evaporator Temperature Setpoints

9.3 Optimising Condenser Pressure / Operating Setpoints

9.4 Compressor Operations

10

What major factors influence the efficiency of refrigeration systems ?

- Evaporating temperature
- Condensing temperature
- Pressure drop due to:
  - pipework including valves
  - heat exchanger
- Variable flow of:
  - fluids (water, water/glycol, others)
  - vapor and gases (air, refrigerant)
- Control system (quality of control design)
- Service and maintenance

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9.2 Optimizing Evaporator Temperature Setpoints

- Evaporator temperature limits should be optimized
  - For different products
  - Segregation of products by temperature levels
  - Permissible temperature limits
- The evaporator temperature has a significant impact on
  - Energy usage and efficiency
  - Capacity
- Other factors that impact evaporator temperature
  - Fouled heat exchanger – internal, external
  - Air flow issues
  - Electronic Expansion valves

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Food Industry Refrigeration System

- Increase of Low Stage Evaporator Temperature (from -35 °C to -30 °C)
  - Base Case Energy Usage – 686.4 kW
  - New Case Energy Usage – 648.6 kW
  - Energy Savings – 37.8 kW
  - Annual Energy Savings ~ 330,000 kWh (based on 8,760 hours of operation)
  - Annual Cost Savings ~ R 330,000 (based on 1 R/kWh)
- This is almost the same savings as reducing the low stage load by 10%!

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Additional Investigative Opportunities

- Clean the evaporator heat exchanger on a regular basis
- On low-temperature applications avoid ice build-up
  - Tightness should be emphasized
  - Doors should also open and close fast
- Figure out the highest possible temperature needed to satisfy the load without loss in quality
- Based on applications and demand requirements, shift loads to higher temperatures
- Maintain approach temperatures as small as possible – focus on air/liquid flow

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Key Points / Action Items

1. *Increasing evaporator temperature improves refrigeration system efficiency and capacity*
2. *Optimize systems to operate the evaporator temperature as high as possible without violating any process constraints*
3. *There are no thumb rules – each system is unique and use CoolPack to get a very quick quantification at a theoretical level for the opportunities*
4. *Work to ensure that the approach between the evaporator system temperature is as small as possible*
5. *Operations and Maintenance can play a huge role in ensuring highest evaporator temperatures*

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9 ENERGY EFFICIENCY OPPORTUNITIES IN INDUSTRIAL REFRIGERATION SYSTEMS

9.1 Reducing Refrigeration Load

9.2 Optimising Evaporator Temperature Setpoints

9.3 Optimising Condenser Pressure / Operating Setpoints

9.4 Compressor Operations

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9.3 Optimizing Condenser Pressure Operating Setpoints

- Condensing temperature (and pressure) play a key role in system efficiency and operations
- Impact of dry-bulb, wet-bulb on condenser performance
- Floating condenser head pressure – limitations and advantages
- Fouled heat exchanger
- Air/Water flow distribution
- Location
- Non-condensable gases

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Float Condenser Head Pressure

- All refrigeration systems are designed for peak operations – full load at 35°C ambient or other specific design
- But this occurs for less than 3% of the operating hours of the system in a year
- Cooling tower fans, water pumps are controlled to artificially maintain a set-point pressure (by managing the condensing temperature)
- This causes a higher LIFT for the compressor to overcome than needed
- Opportunity can be targeted in a step-wise manner with concurrence from the manufacturer, O&M manuals, etc.

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Food Industry Refrigeration System

- Reduce Condensing Temperature (from 35 °C to 32 °C)
  - Base Case Energy Usage – 686.4 kW
  - New Case Energy Usage – 642.9 kW
  - Energy Savings – 43.5 kW
  - Annual Energy Savings ~ 380,000 kWh (based on 8,760 hours of operation)
  - Annual Cost Savings ~ R 380,000 (based on 1 R/kWh)
- This may not be the NET savings since there maybe additional fan power needed to achieve the higher heat transfer rate and lower temperature

Float Condenser Head Pressure - Issues

- Traditions and Misperceptions
- Defrosting capabilities due to lower hot gas temperatures
- Oil cooling – liquid injection
- Performance of oil separator, oil return, etc.
- Operations of control valves – not enough driving force to get liquid refrigerant to the load
- Refrigerant stacking
- Increased fan and pumping power

Additional Investigative Opportunities

- Clean the condenser heat exchanger on a regular basis
- During cold season set the condensing temperature as low as possible – check for low pressure cut out - change of set point could be made manually or by use of external control
  - Condensing temperature setpoint range for colder season – 20 - 23 °C
- Instead of On / Off control for fans use Variable Frequency Drives
- If space is available - add a dry cooler or condenser, a cooling or evaporating tower
  - This will significantly reduce the condensing temperature

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Key Points / Action Items

1. *Floating condenser (head) pressure improves refrigeration system efficiency and capacity*
2. *Optimize systems to operate the condenser temperature as low as possible without violating any process constraints*
3. *There are no thumb rules – each system is unique and use CoolPack to get a very quick quantification at a theoretical level for the opportunities*
4. *Work to ensure that the approach between the condensing system temperature and wet-bulb is as small as possible*
5. *Operations and Maintenance can play a huge role in ensuring lowest condensing temperatures*

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9 ENERGY EFFICIENCY OPPORTUNITIES IN INDUSTRIAL REFRIGERATION SYSTEMS

- 9.1 Reducing Refrigeration Load
- 9.2 Optimising Evaporator Temperature Setpoints
- 9.3 Optimising Condenser Pressure / Operating Setpoints
- 9.4 Compressor Operations

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9.4 Optimizing Compressor Operations

- The compressor is the heart of every industrial mechanical vapor compression system
- Optimizing compressor operations requires significant due-diligence
- Current operating conditions and understanding control and response of compressors is very important
- Load Profile (typical annual or seasonal) required

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Optimizing Compressor Operations

- Depends on compressor type, size and load profile
  - Unloading in reciprocating machines
  - Staging compressors to run an optimal number of compressors
  - Slide valve – constant and variable Vi - for screw compressors
  - Stepped operation
  - Variable Frequency Drives
- Compressor oil cooling in screw compressors can impact capacity and efficiency
- Bottom line – compressor efficiency degrades at lower loads

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Food Industry Refrigeration System

- Improve Compressor Isentropic Efficiency (from 70% to 75%)
  - Base Case Energy Usage – 686.4 kW
  - New Case Energy Usage – 638.5 kW
  - Energy Savings – 47.9 kW
  - Annual Energy Savings ~ 420,000 kWh (based on 8,760 hours of operation)
  - Annual Cost Savings ~ R 420,000 (based on 1 R/kWh)
- Improving compressor isentropic efficiency may require several system changes including newer adaptive controls, new screw, etc.

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Additional Investigative Opportunities

- Pressure drops in suction and discharge lines has to be overcome by compressor work
  - Minimize long piping runs; reduce number of elbows; etc.
- Liquid injection cooling adds load on the compressor and reduces capacity and system efficiency
- Use of Variable Frequency Drives on select (or all) compressors
- Routine and predictive maintenance of compressors
  - Reduce friction
  - Reduce leakage

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Key Points / Action Items

1. *Every compressor has an efficiency and it does vary based on load, age of system, controls and maintenance practices*
2. *These efficiencies are a strong function of pressure ratio and in screw compressors a function of volume ratio also*
3. *Reducing heat generated by proper maintenance of compressors and matching compressors to meet load profile can provide significant benefits*
4. *Investigate thermosyphon oil cooling in screw compressors versus liquid injection*
5. *Operations and Maintenance can play a huge role in ensuring highest compressor efficiencies*

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Other Investigative Opportunities in Industrial Refrigeration Systems

- Proper control of evaporator fans
- Use of high efficiency motors and variable frequency drives, where applicable
- Recover waste heat from compressor discharge for process
- Repair leaks
- Eliminate Non-Condensables

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Other Investigative Opportunities in Industrial Refrigeration Systems

- Reduce moisture from entering the freezers
  - Door sealing
  - Product staging and dehumidification
- Defrosting should be done in the cheapest way possible
  - Electric maybe most expensive
  - Hot gas defrosting does have a cost – it is not free
- Maintain proper defrost frequency based on demand control
  - Fin spacing reduced by 20%
  - Load-based

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1

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10 CR SYSTEMS OPTIMIZATION CASE STUDIES

10.1 Case Study 1 – Food Plant

10.2 Case Study 2 – Food Plant

2

10.1 Case Study 1 – Del Monte Foods

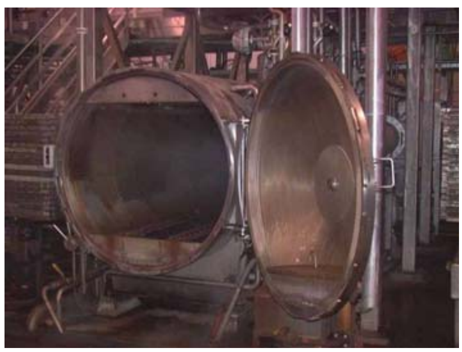
- Utilities Integration
  - Cooling & Heating
  - Cogeneration (Topping cycle)
  - Free Cooling (Water-side Economizer)
- High Repeatability
- Minimal Risk

- Acknowledgments – Del Monte Foods, California Energy Commission, Lawrence Berkeley National Laboratory

3

Del Monte Foods – Fruit To Go & Gel Cups

- System uses 4 Barriquand retorts and circulates 6,000 litres/min of water
- Each retort cycle consists of:
  - Controlled heating
  - Sterilization
  - Controlled cooling
- Steam produced at 10 barg – used in retorts at 3 barg
- Cooling is done by two air-cooled chillers (535 kW and 385 kW)
- One cooling tower for process cooling (170 m^3/hr)



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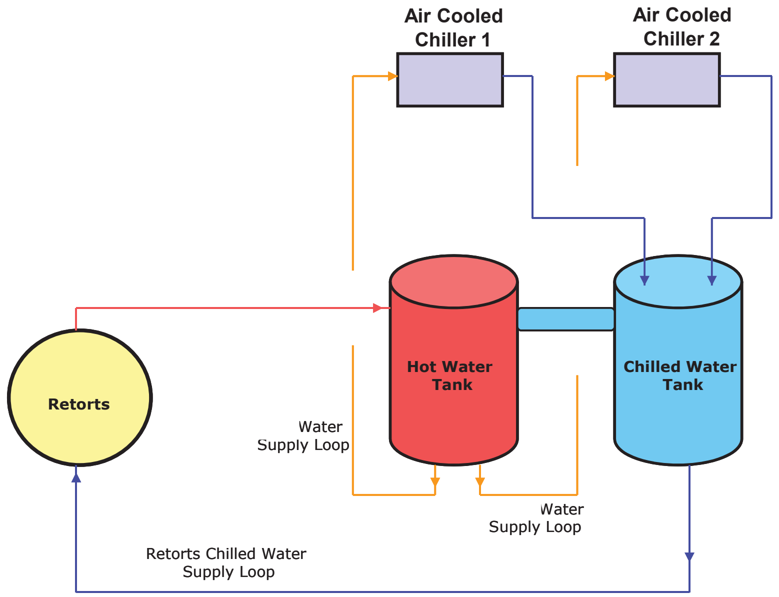
Circulating Chilled Water System



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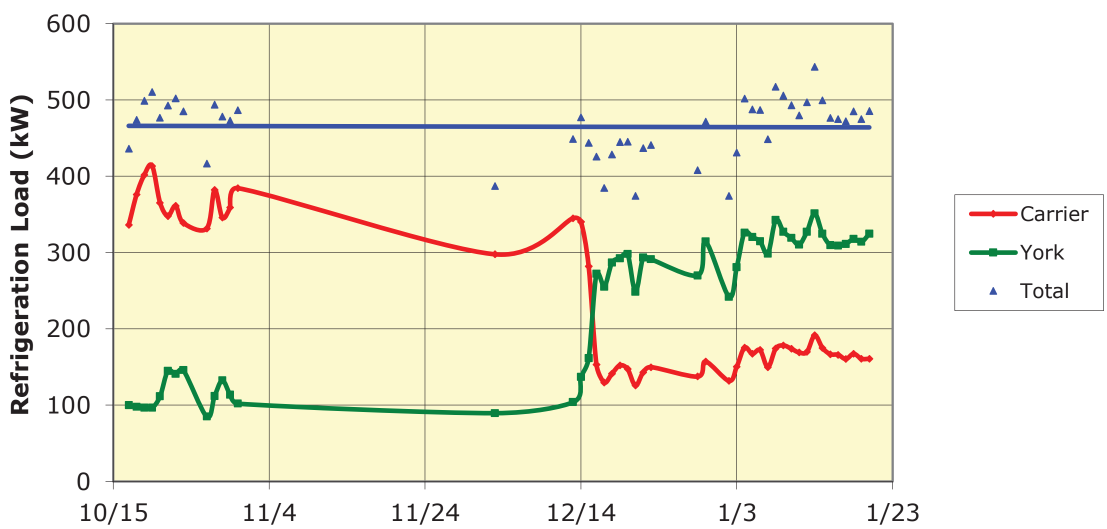
Load Profiles



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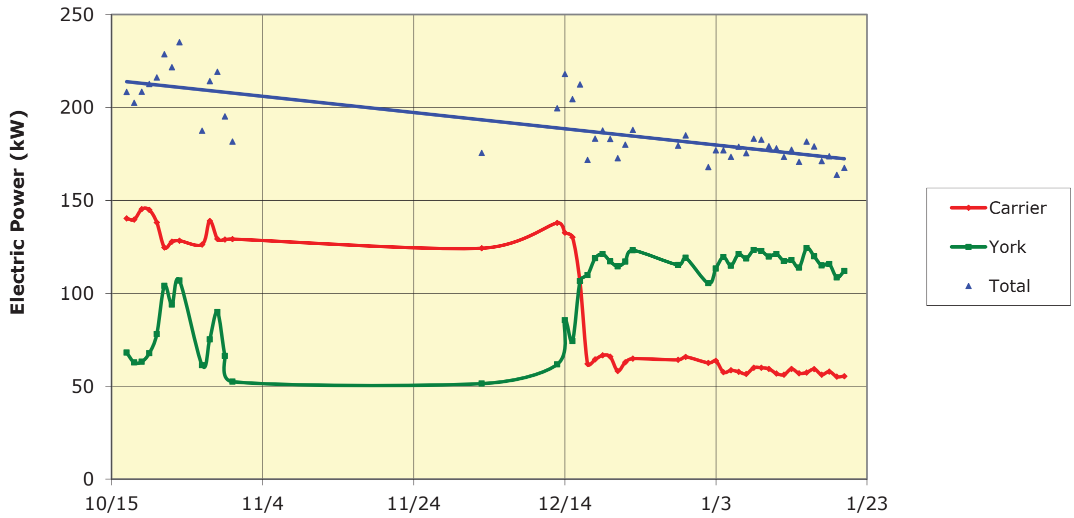
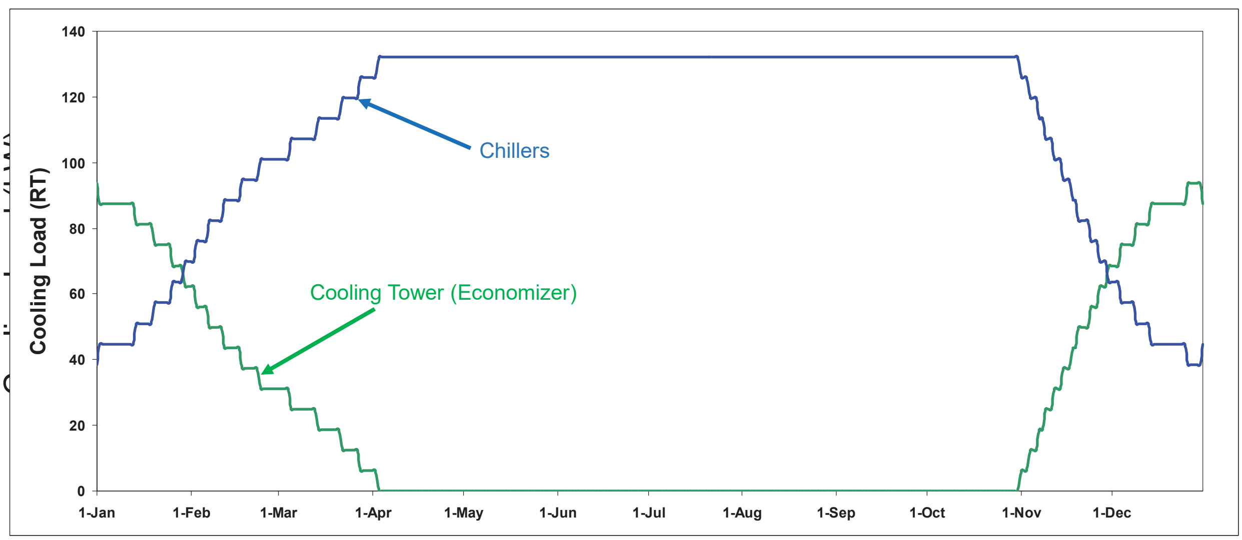
Load Profiles



Cooling Tower (Economizer) Load Sharing



Energy Optimization Options Analysis

- Cooling Tower Only
  - Supplemental cooling load by air-cooled chiller
- Cooling Tower + Water Cooled Chiller
  - Supplemental cooling load by air-cooled chiller
- Cooling Tower + Steam-Turbine driven Water Cooled Chiller
  - Supplemental cooling load by air-cooled chiller
  - Large reduction in electrical energy costs
  - Partly offset by increase in fuel cost of Natural gas

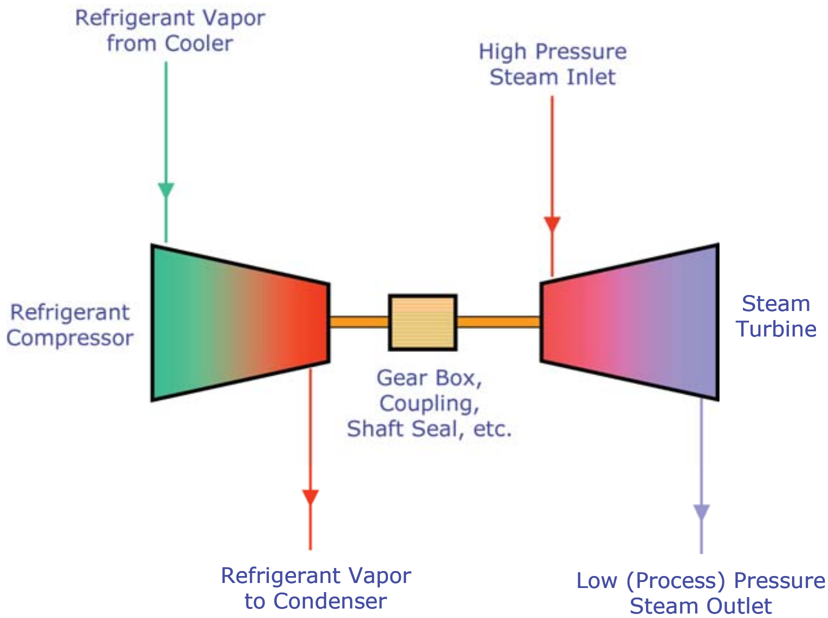
9

Energy Optimization Quantitative Analysis

- Current Baseline
  - Energy – 1,833,192 kWh; Peak Demand – 227 kW
- Cooling Tower Only
  - Energy – 1,790,937 kWh; Peak Demand – 214.3 kW
- Cooling Tower + Water Cooled Chiller
  - Energy – 1,371,415 kWh; Peak Demand –145.2 kW
- Cooling Tower + Steam-Turbine driven Water Cooled Chiller
  - Electrical Energy – 910,995 kWh; Peak Demand – 84.6 kW;
  - Fuel Energy – 3,100 GJ

10

Energy Optimized Solution



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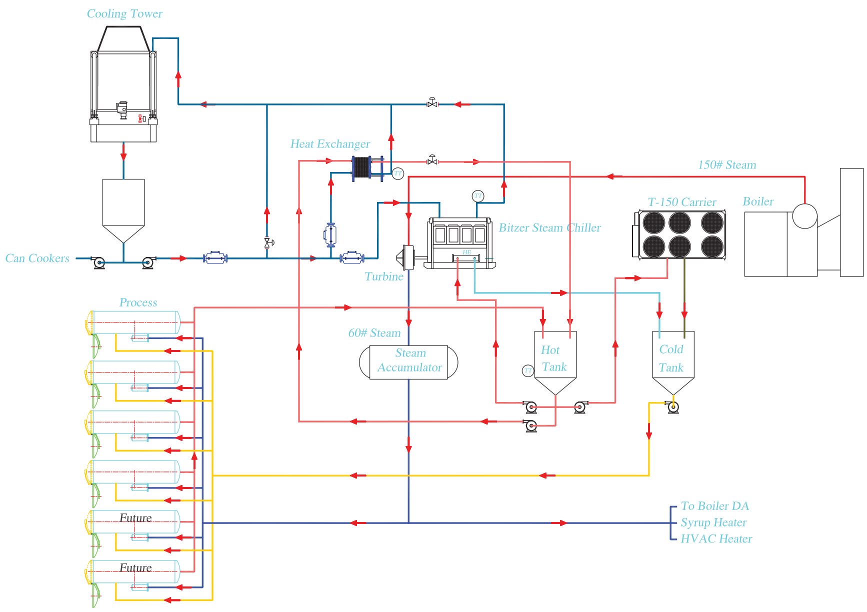
Energy Optimized Solution

Topping Cycle (TC) Definition: In a steam turbine topping cycle system, boiler-generated steam will operate a steam turbine application such as a chiller, The exhaust steam from the turbine is used for low pressure steam applications such as process heating requirements.

Del Monte Foods-Modesto Topping Cycle Application

1. A steam turbine (Elliott: 65 kW; 4000 RPM; 5 Tph) is directly coupled to a screw chiller (Bitzer 300 kW refrigeration capacity).
2. Plant boiler (10 barg) will provide steam to turbine with the low pressure exhaust (3 barg) providing steam to operations and retorts.

Energy Optimized Solution



Project Cost-Benefits Summary

Cost Summary

Steam turbine and controls: $30,000
Bitzer Chiller and Controls: $56,000

Savings Summary

Steam chiller vs electric unit: 104 kW and 540,000 kWh (in-season)
Natural gas net increase of 2,000 GJ due to an increase in steam generation to offset the steam enthalpy change across the steam turbine.
Net annual savings: $45,000

Simple payback: 1.9 years

10

CR SYSTEMS OPTIMIZATION CASE STUDIES

10.1 Case Study 1 – Food Plant

10.2 Case Study 2 – Food Plant

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10.2 Case Study 2 – Fish Factory, SA

- Results of Refrigeration System Energy Assessment
  - Fish processing distributors in SA
  - Completed in January 2020
  - Two-stage ammonia refrigeration system
- High Repeatability
- Minimal Risk

- **Acknowledgments**
  - **CSIR-NCPC**
  - **Danie van Zyl, Matthew Howard - CoolCheck (Pty) Ltd, Cape Town, SA**

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The Refrigeration System

- Eight ammonia compressor skids
- Two temperature levels
  - High Stage @ -10°C (two skids) – 2 MW
  - Low Stage @ -40°C (six skids) – 3.1 MW
- Two of the LS skids are single-stage compressors
- Two LS single-stage and both HS compressors use liquid injection as means of cooling while others use water-cooling
- All screw compressors with mechanical slide valve control
- Four evaporative condensers
- One cooling tower for oil-cooling system

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The Ammonia Refrigeration System

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End-Users

- Low temperature users – from -18°C to -30°C
- Medium temperature users – from 14°C to 0°C

- Receiving
- Sorting of raw products
- Cold storage
- Product processing and fileting
- Packaging
- Blast freezing
- Quick freezing of fish
- Palletizing
- Storage of frozen goods

End-Users

Compressor Control & Load Profile

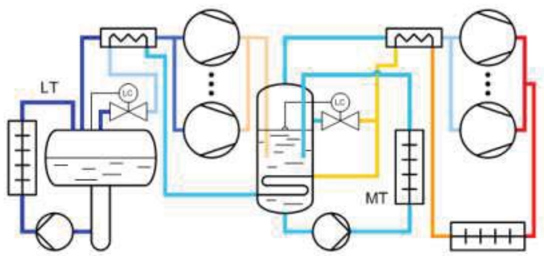
Load Utilization - Low stage				
	Comp2	Comp3	Comp5	Comp6
Chiller off	11%	1%	1%	36%
Load: 1 - 25%	0%	0%	0%	0%
Load: 25 - 50%	0%	2%	0%	0%
Load: 51 - 75%	2%	90%	47%	12%
Load: 76 - 100%	*87%*	*7%*	*52%*	*51%*

Load Utilization - High stage		
	Comp 7	Comp 8
Chiller off	28%	1%
Load: 1 - 25%	0%	0%
Load: 25 - 50%	53%	31%
Load: 51 - 75%	18%	46%
Load: 76 - 100%	0%	21%

- Screw compressors
  - Mechanical slide-valve control
  - Poor efficiency at part-load conditions
- Compressor 2 & 3 – Booster compressors (Low stage)
- Compressor 5 & 6 – Single-stage (Low stage)
- Compressor 7 & 8 – High stage

Energy Efficiency Opportunities

- Implementing floating head-pressure control
  - Common evaporative condensers for both temperature levels
  - Using a fixed differential between the condensing pressure and wet-bulb
- Add a VFD to a condenser fan



- Some capital (~R 650,000) needed but easy to implement
- Expected 10% energy savings - ~650,000 kWh annually
- Expected operating savings - ~R 1,000,000 annually

Energy Efficiency Opportunities

- Replace liquid injection with an external oil cooling system
  - A significant heat load is added to the compressors for oil cooling
  - There are several methods to reduce (or eliminate) this oil cooling load from the refrigeration system
    - Thermosyphon cooling
    - External water cooling
  - It is recommended to install an external oil cooling system
- Change operation of single-stage to LS booster compressor
  - Convert from single-stage to multi-stage operation

- Will require capital investment ~ R 1,500,000
- Expected energy savings (~12%) ~ 880,000 kWh annually
- Expected operating savings ~ R 1,500,000 annually
- Simple payback – 1 year

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Energy Efficiency Opportunities

- Improve part-load performance of LS and HS compressors
  - Performance of the screw compressor degrades at low loads when using mechanical slider control valves
  - Install VFD on the part-loaded low-stage and high-stage compressors (one each)
  - Will need to identify the trim compressor or maybe install the VFD on the larger machine and run that as the lead machine to collect maximum hours of operation

- Will require capital investment ~ R 800,000
- Expected energy savings (~5%) ~ 260,000 kWh annually
- Expected operating savings ~ R 470,000 annually

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Other Recommendations

- Repair all damaged insulation
- Defrost cycle control modifications needed
- Install possible dehumidifiers
- Repair and replace door heaters
- Daily inspections of evaporators
- Implement a continuous monitoring and energy optimizer
- Reduce pressure losses by investigating lines, components, etc
- Reclaim ammonia refrigerant by eliminating contaminants and water (moisture) from the system
- Perform a leak test on the whole system

- Monetary benefits are difficult to quantify from the above

1

11 OTHER ENERGY EFFICIENCY SOFTWARE TOOLS FOR CR SYSTEMS

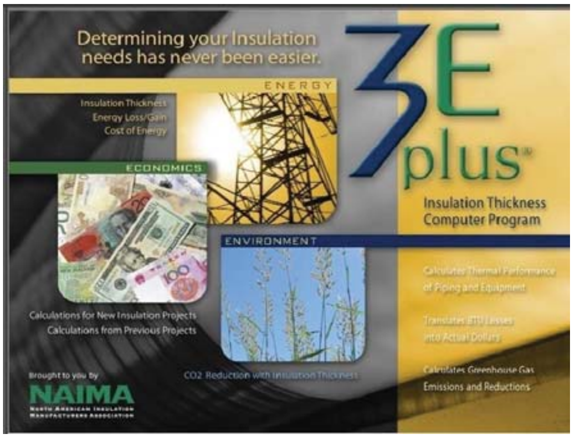
11.1 3E Plus – Insulation Evaluation Software

11.2 US DOE MEASUR Tool (PSAT & FSAT)

2

11.1 3EPlus Insulation Evaluation Software

- Purpose
  - Evaluation of Heat Gain
  - Condensation Issues
- Heat Transfer Model
- Download free from website
- Customizable for Insulation materials
- Pipe Insulation | Calculate Thickness | 3E Plus Software (insulationinstitute.org)



Chilled Water & Refrigeration System Insulation

- Why is insulation necessary on CR systems?
  - Personnel safety – very low temperatures
  - Minimize energy gain and reduce system cooling load
  - Protection from ambient conditions
  - Preserve system integrity
  - Avoid condensation on equipment, pipes, etc.
- Typical areas of insulation improvement opportunities
  - Distribution headers
  - Compressor suction lines
  - Evaporators
  - Inspection man-ways
  - Valves
  - End-use equipment
  - Storage tanks, vessels, etc.
  - Building envelope

CR System Insulation

- There are several reasons for damaged or missing insulation and hence, energy savings opportunities in the insulation area
  - Missing insulation due to maintenance activities
  - Missing / damaged insulation due to abuse
  - Damaged insulation due to accidents
  - Normal wear and tear of insulation due to ambient conditions
  - Damaged insulation due to condensation and ice-formation
  - Valves and other components not insulated

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CR System Insulation

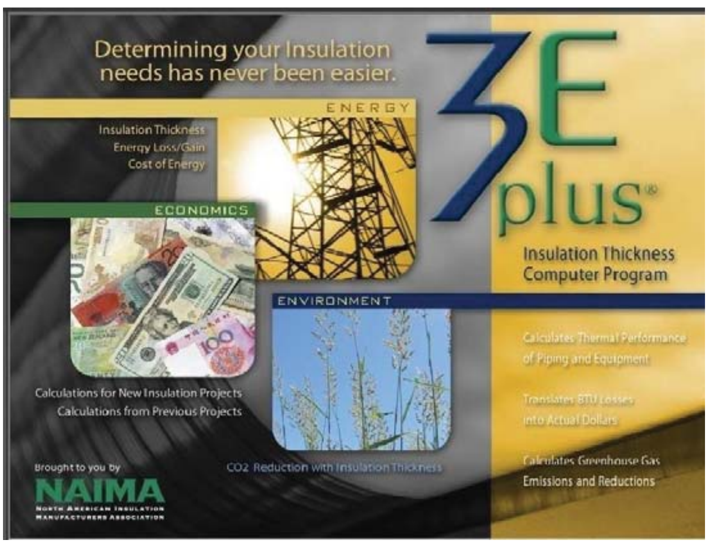
- Some basic instruments, software and basic data required to quantify the economic impact of insulation
  - Infra-red thermography camera
  - Infra-red temperature gun
  - Measuring tape
  - 3E Plus insulation evaluation software
  - Operating information
    - Hours per year
  - Ambient conditions
    - Temperature
    - Wind

Insulation Tool – 3EPlus

- North American Insulation Manufacturers Association (NAIMA) developed 3EPlus - determines optimum insulation thickness for a wide variety of insulating materials

- Software outputs include:
  - Surface heat transfer gain
  - Insulation surface temperature
  - Minimum insulation thickness to avoid condensation
  - Simple payback of an insulating project

Insulation Evaluation Software



- Free Program available from NAIMA
- **E**nergy
  - Heat Gain
  - Cost Impact
- **E**nvironment
- **E**conomic Insulation Thickness
  - Life Cycle Cost Analysis

http://www.pipeinsulation.org/

Example CR System - Missing Insulation

- During the walk through of the industrial refrigeration system at the food plant, it was found that there are several sections on the -10°C recirculation loop header that have damaged and / or are observed to be un-insulated.


9

Example CR System - Missing / Damaged Insulation

- During the walk through of the industrial refrigeration system at the food plant, it was found that there are several sections on the -10°C recirculation loop header that have damaged and / or are observed to be un-insulated.
  - 150 mm (6-inch) nominal diameter
  - 20 m total length of pipe which is uninsulated / damaged insulation
  - Insulation to be selected as follows:
    - Polystyrene pipe insulation
    - 5o mm (2-inch) thick insulation
    - All service jacket
- Estimate the heat gain and the economic impact on system operations
  - Chiller plant COP (High-stage) = 3.36 (based on CoolPack simulation)
  - Unit cost of electricity = 1.0 R/kWh

10

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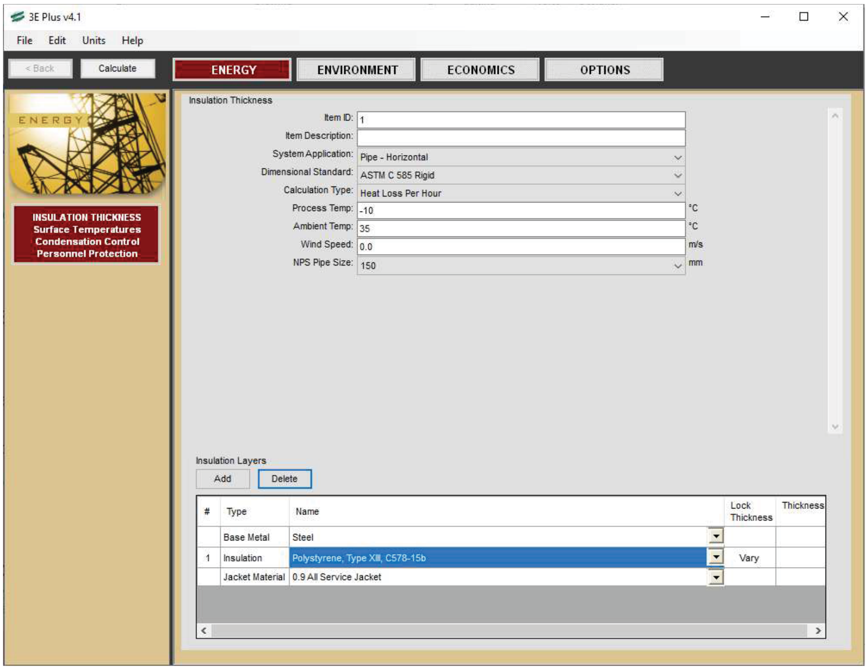
Insulation Evaluation



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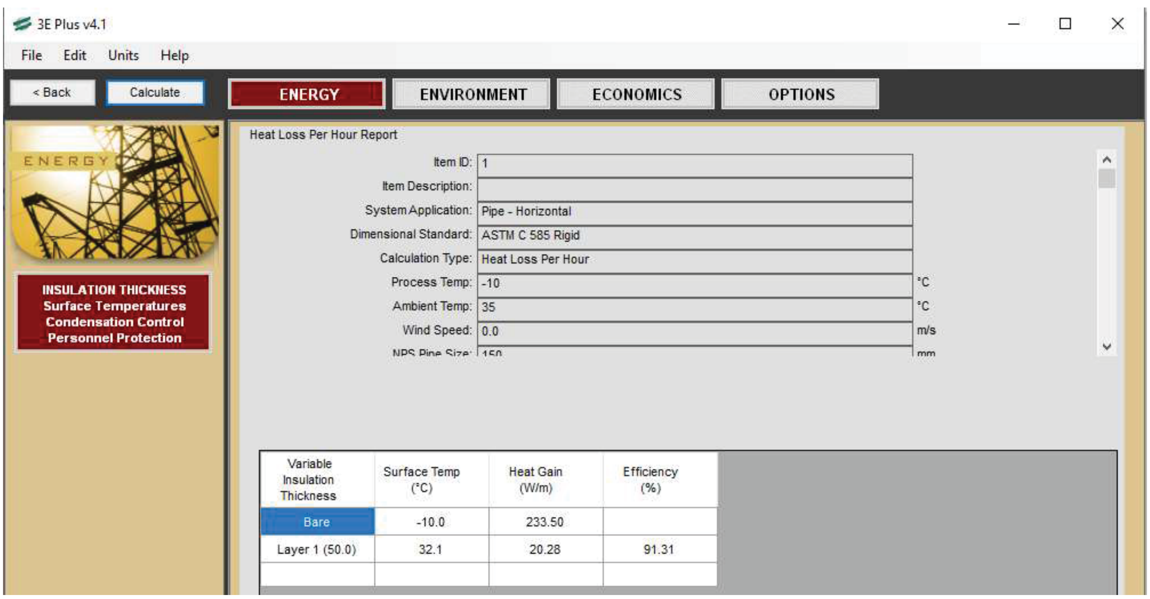
Insulation Evaluation



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Insulation Evaluation

$$Q_{saved} = (233.5 - 20.3) \times 20 = 4{,}740\ W$$

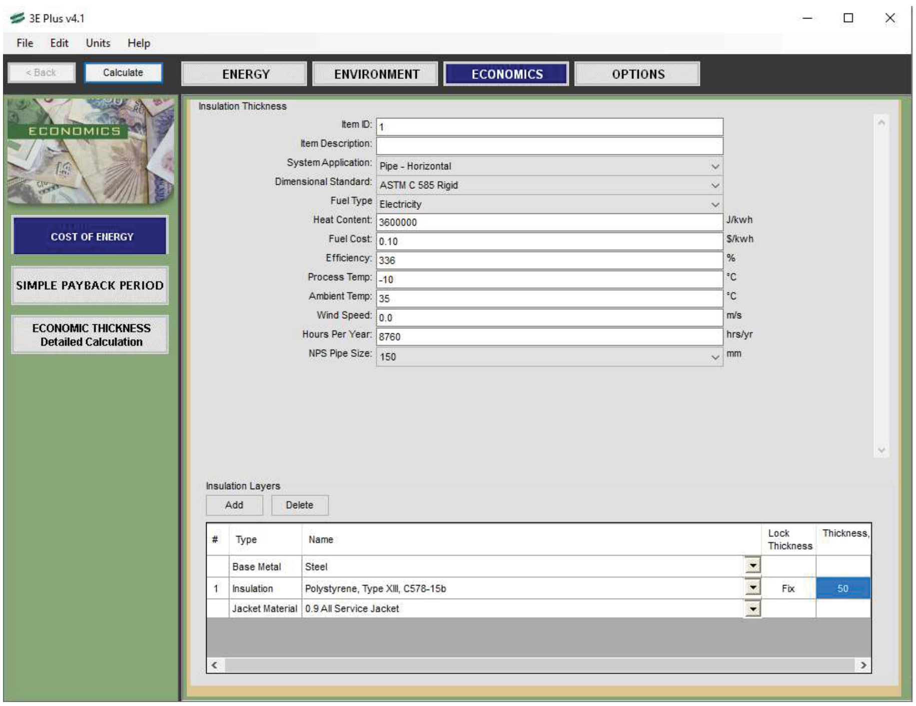
$$Electricity_{saved} = \frac{Q_{saved}}{COP}$$

$$Electricity_{saved} = 4.74\ kW \times 8{,}760\frac{hr}{yr} \times \frac{1}{3.36} = 12{,}350\ kWh/yr$$

$$Cost\ Savings = 12{,}350\frac{kWh}{yr} \times 1.0\frac{R}{kWh} = 12{,}350\frac{R}{yr}$$

13

Insulation Evaluation



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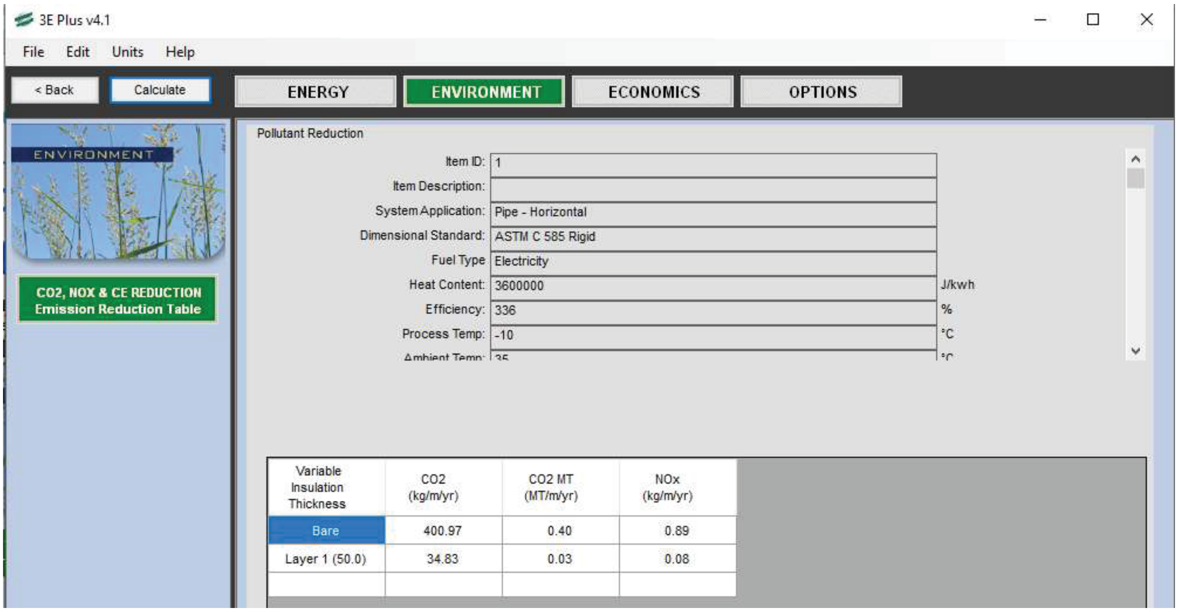
Insulation Evaluation



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Example CR System – Condensation Control

- A 1 m section of -35°C suction header in an ammonia refrigeration system is observed to be un-insulated
  - 150 mm nominal diameter
  - Existing insulation on the remainder of the header is as follows:
    - 50 mm thick insulation
    - All service jacket
- Estimate the minimum insulation thickness required to eliminate condensation issues on this suction header.

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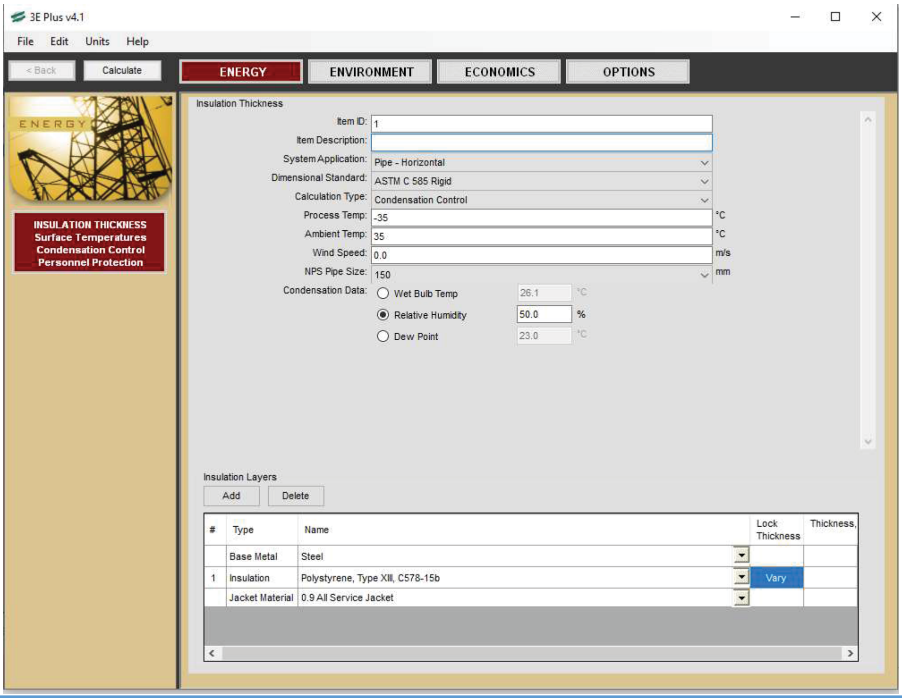
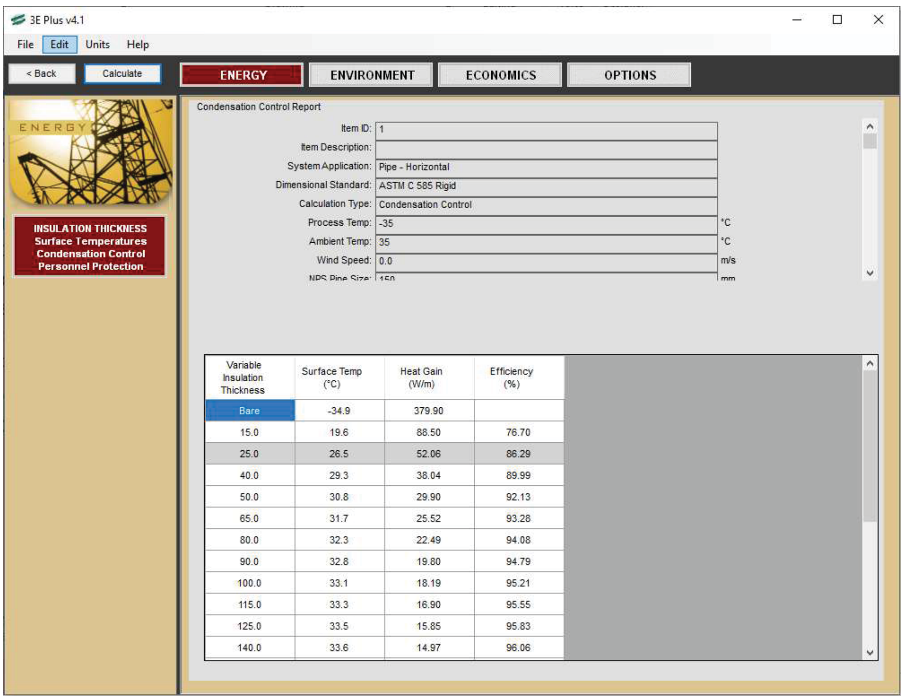
Condensation Control



Condensation Control



Variable Insulation Thickness	Surface Temp (°C)	Heat Gain (W/m)	Efficiency (%)
Bare	-34.9	379.90	
15.0	19.6	88.50	76.70
25.0	26.5	52.06	86.29
40.0	29.3	38.04	89.99
50.0	30.8	29.90	92.13
65.0	31.7	25.52	93.28
80.0	32.3	22.49	94.08
90.0	32.8	19.80	94.79
100.0	33.1	18.19	95.21
115.0	33.3	16.90	95.55
125.0	33.5	15.85	95.83
140.0	33.6	14.97	96.06

Key Points / Action Items

1. *There are several reasons for damaged or missing insulation*

2. *These areas result in significant heat gain, condensation, icing and excessive load on the CR system*

3. *A continuous improvement type insulation appraisal (audit) program should be implemented in industrial plants*

4. *Some basic instruments, heat transfer models and process data are required to quantify the economic impact of missing or damaged insulation*

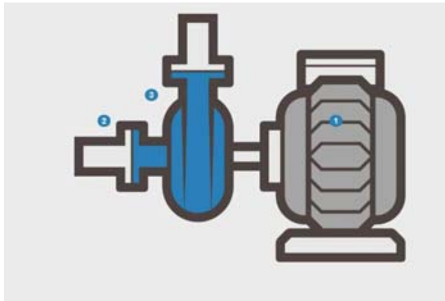
11 OTHER ENERGY EFFICIENCY SOFTWARE TOOLS FOR CR SYSTEMS

11.1 3E Plus – Insulation Evaluation Software

11.2 US DOE MEASUR Tool (PSAT & FSAT)

11.2 US DOE MEASUR Tool (for Pumps)

- Significance of Pumping Systems
  - CR systems can be spread across the plant and can require significant distribution
  - There are several different pumps required in a CR system
  - Pumping system energy can be a significant fraction of the CR system energy usage



- Download free from the US DOE website – MEASUR
  - https://www.energy.gov/eere/amo/measur

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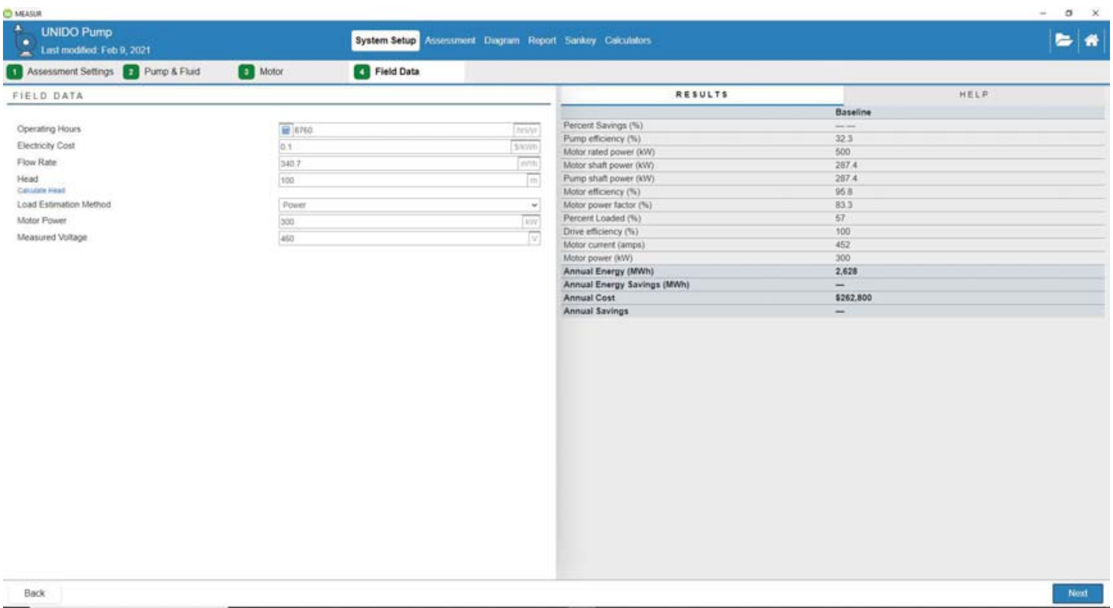
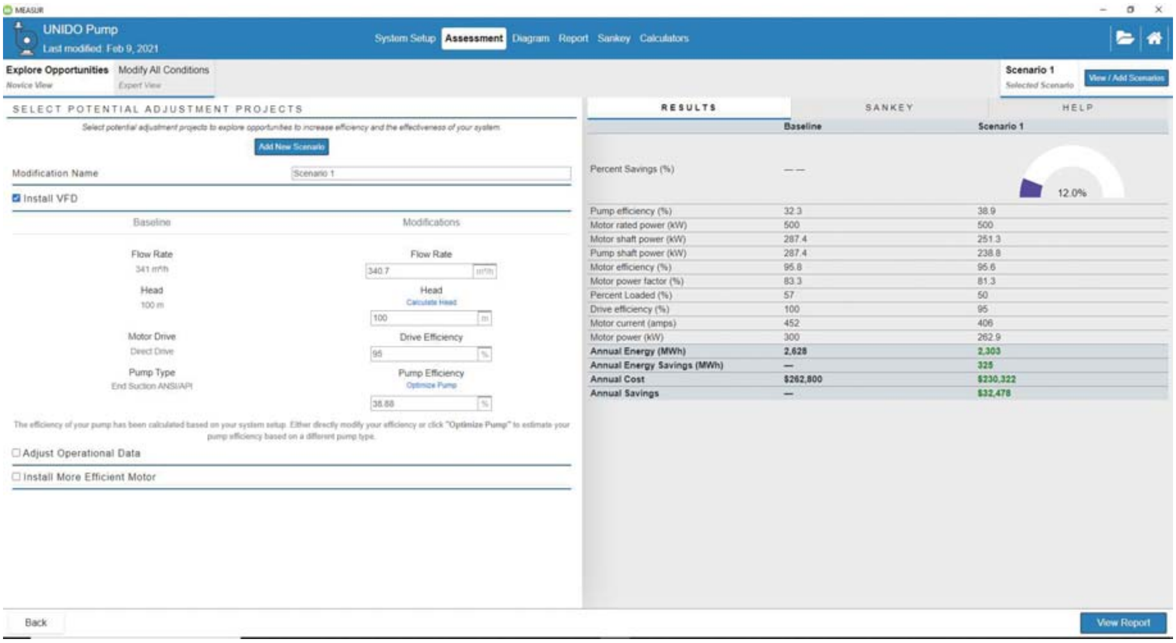


Assessment Page



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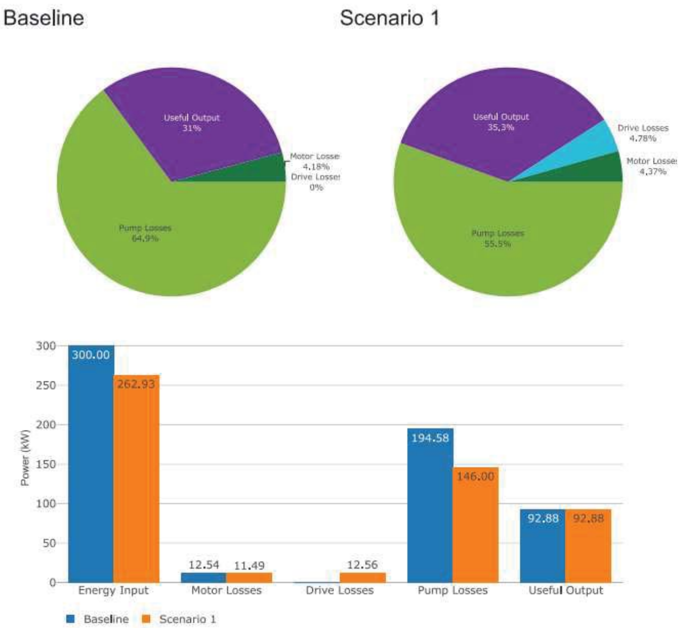
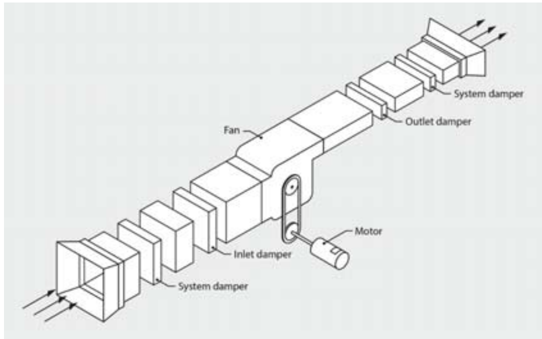
Sankey Plot, Reporting Page



11.2 US DOE MEASUR Tool (for Fans)

- Significance
  - Fans are an integral part of a CR system
  - Different types of fans and control mechanisms are used
  - Depending on the industry and application, fans can consume a significant fraction of the CR system energy



- Download free from US DOE website - MEASUR

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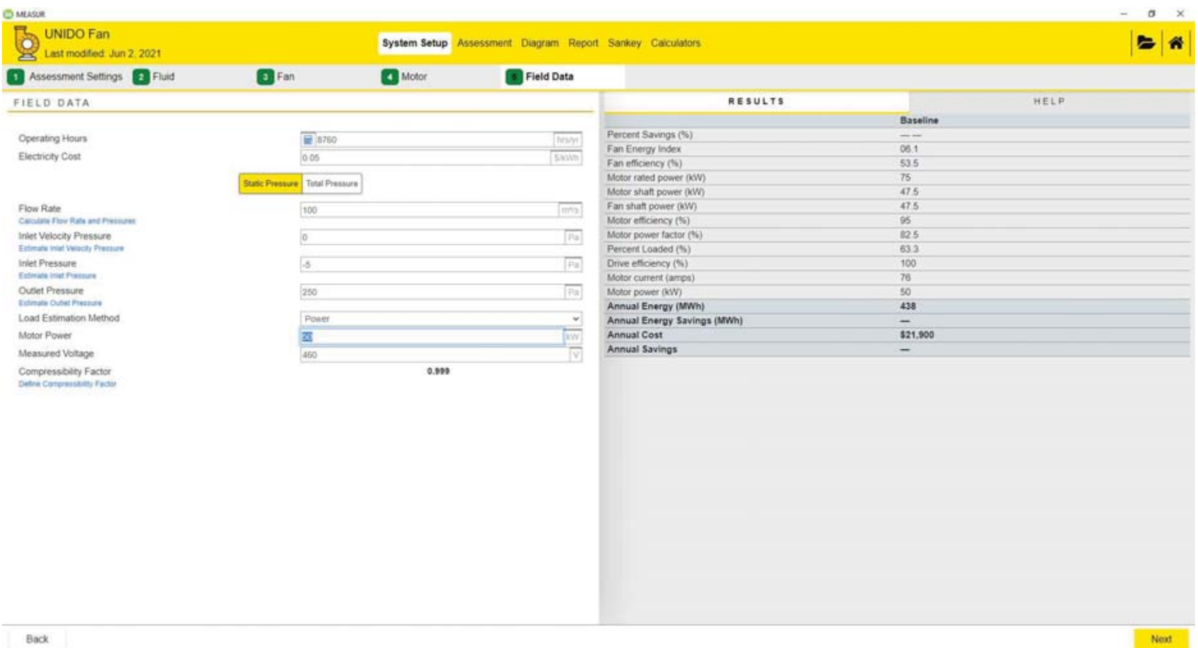

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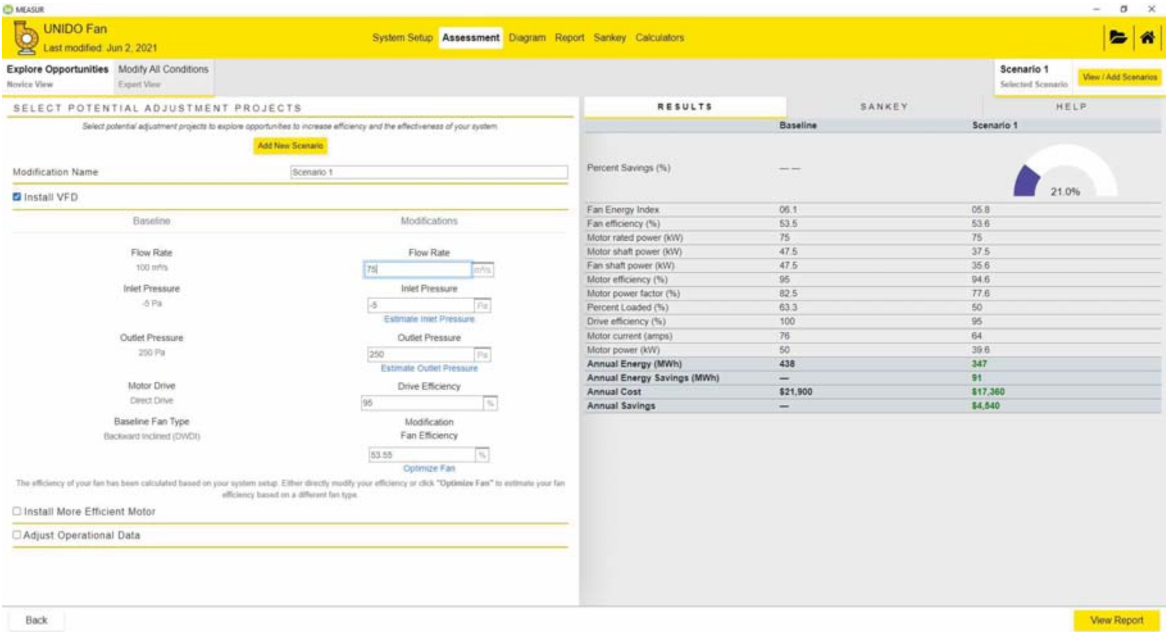

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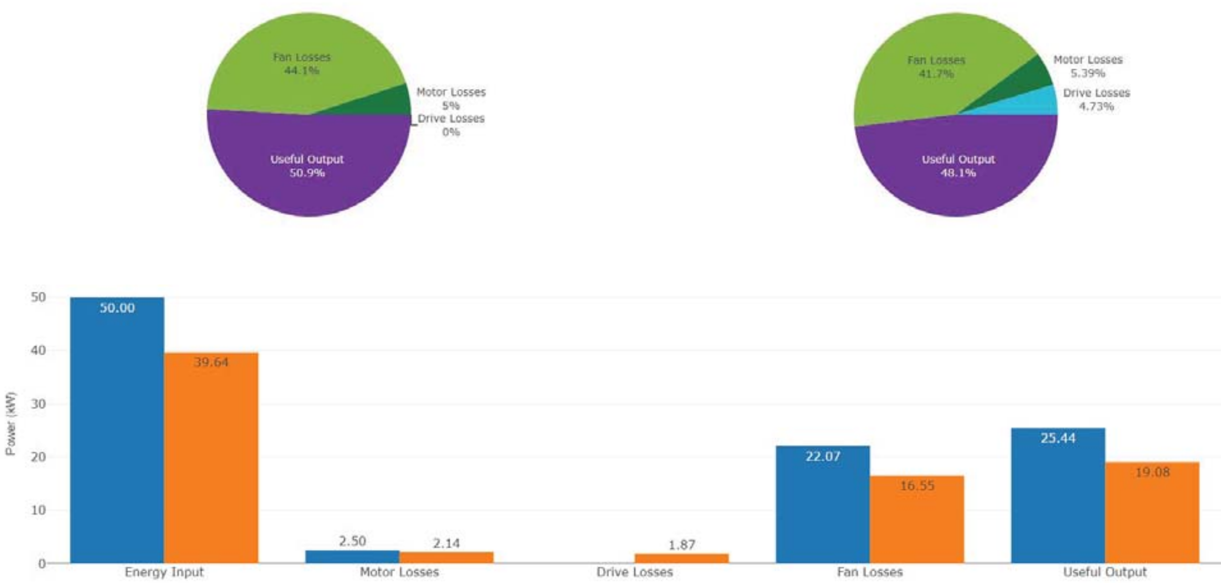
Sankey Plot, Reporting Page



Key Points / Action Items

1. *Distribution (Pumps, Fans, etc.) can consume a significant portion of the overall system energy*

2. *Most times these get overlooked or get a component-based assessment*

3. *Use a systems approach to understand the impact and performance of these systems on the overall optimization of CR systems*

4. *Some basic instruments, hydraulic models (USDOE Tools – MEASUR) and process data are required to quantify the economic impact of an unoptimized distribution system*

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1

12 Next Generation CR Systems

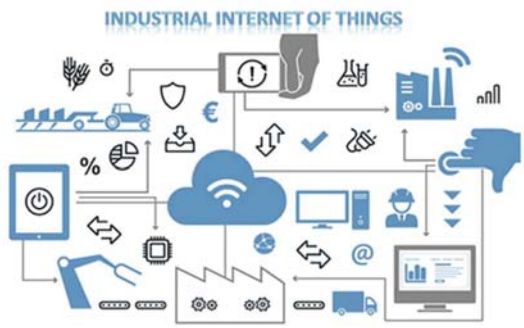
12.1 SMART CR Systems with FD&D

12.2 CR Systems with Thermal Storage

2

12.1 SMART CR Systems with FD&D

- SMART refers to the state-of-the-art Industrial Internet of Things (IIOT) managed intelligent systems
- Technology has advanced with Artificial Intelligence and Machine Learning
- Fault Detection & Diagnostics (FD&D) leads to Real-Time Optimization
- Continuous Commissioning



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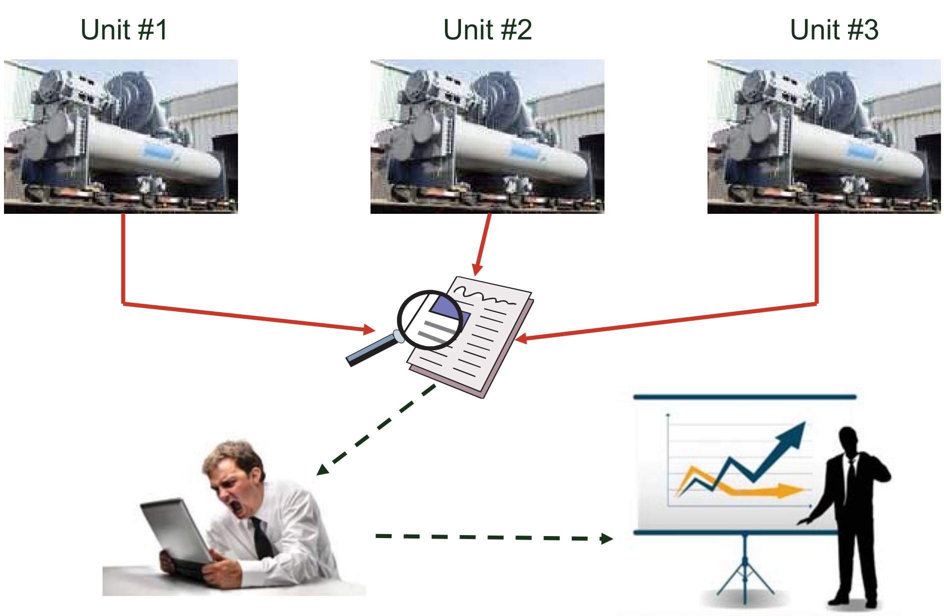
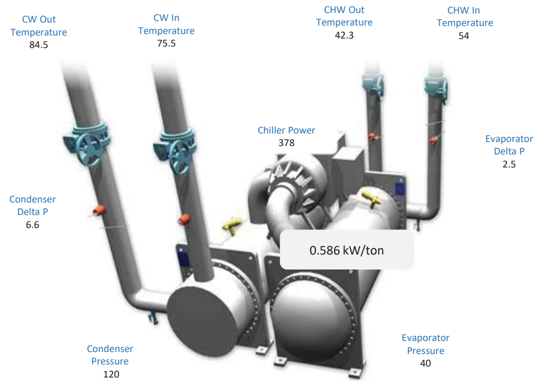
Where did we Start?



Basic Ingredients of SMART CR Systems

- Continuous monitoring of key data
- Trending of performance metrics
- Cloud-based CR system analytics
- Performance gap quantification with part load simulation (digital twin)
- Fault Detection & Diagnostics
- Seamless integration with plant's DCS
- Closed loop feedback control for optimizing CR system
- Ability to benchmark operations and verify energy savings
- Multiple chiller optimization
- Cyber-security



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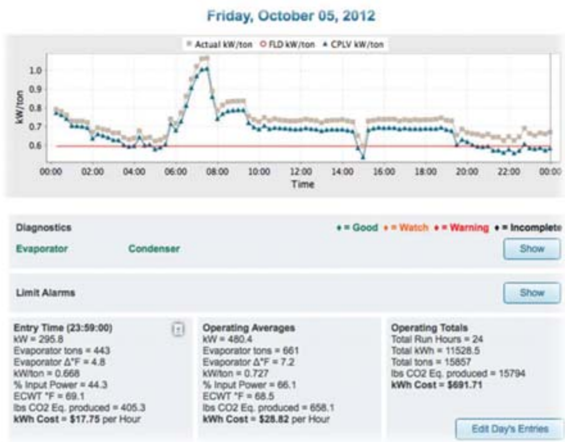
Easy to Understand CR System Dashboard

6

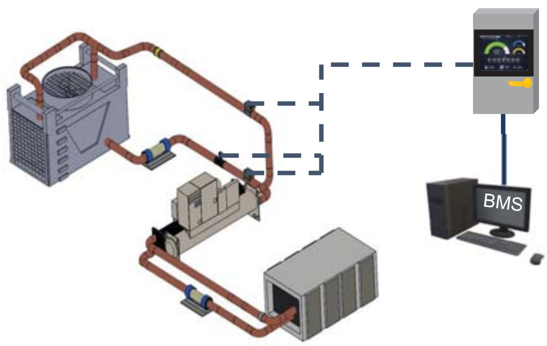
Fault Detection & Diagnostics 101

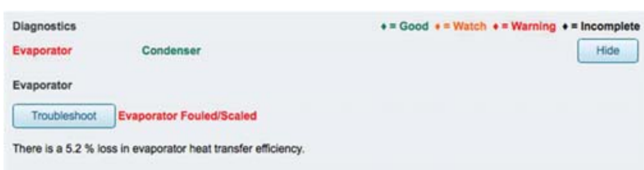
- Critical data provide the ability to run diagnostics on system operations
- Main objective is to ensure that faults, inefficiencies and issues can be identified as soon as they occur
- Saves significant money, time and effort
- Increases system reliability
- Ensures optimum performance
- Cornerstone for Predictive & Preventative Maintenance



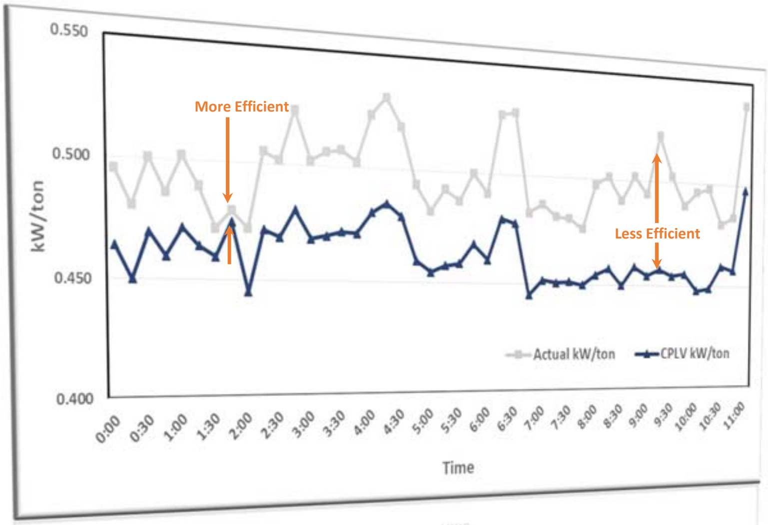
Applying FD&D on CR Systems

- Every CR system is unique
- "Critical" and "Necessary" data is specific to each individual CR system
- Common faults do exist
  - HX fouling / scaling
  - Flow issues
  - Amount of refrigerant in system
  - Non-condensable gases
  - Refrigerant stacking / migration
  - System hunting
- Strength of FD&D – true (+ve) identification of faults

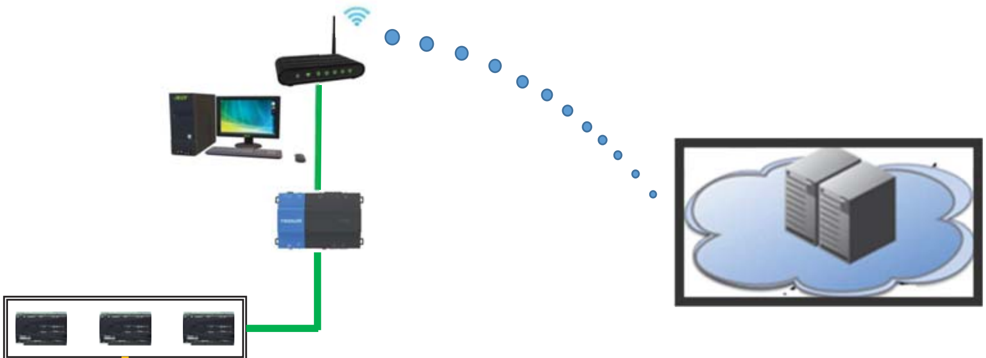


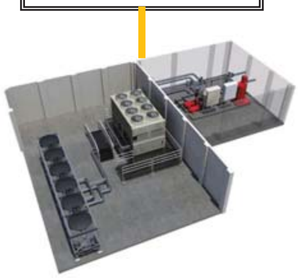


Performance Gap – Identify & Quantify



Seamless Integration w/Plant's SCADA & Historian





- Edge Control
- Very remote equipment can also be monitored easily
- Elimination of long cabling, wires and conduits – no maintenance

CR System Optimization

- Optimize CR Operating setpoints
  - Chilled water / coolant temperatures
  - Cooling tower water temperatures
  - Pressure levels
  - Flow rates
    - Bypass valves
    - Variable speed drives on pumps/fans
  - Compressor control
  - Defrost control
- Chiller / Compressor sequencing
- Closed-loop feedback control and/or Supervisory/Advisory levels
- Fault Detection & Diagnostics for Predictive Maintenance

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Key Points / Action Items

1. *IIOT, Artificial Intelligence leading to Machine Learning to train the system to continuously minimize energy costs and enhance reliability significantly*
2. *Several different layers are possible*
3. *Costs will vary based on several factors – age of system and level of instrumentation are primary drivers*
4. *Select what is best for your CR system and not someone else*

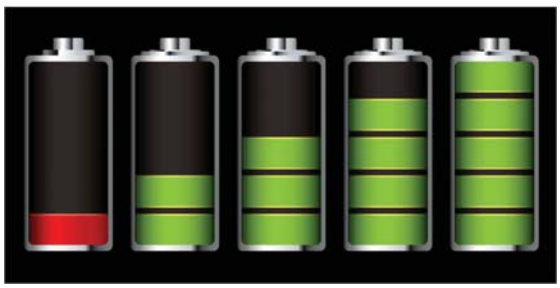
12 Next Generation CR Systems

12.1 SMART CR Systems with FD&D

12.2 CR Systems with Thermal Storage

12.2 CR Systems with Thermal Storage

- Thermal Energy Storage is NOT new and neither NEXT GENERATION
- Its application is what makes it unique
- Its impacts are system-wide



What is Thermal Energy Storage (TES)?

- It is a battery which serves as a source or sink for energy
- Thermal storage
  - Cold – to be covered in this class
  - Hot – out of scope here
- Several different methods of thermal energy storage and can be used very effectively to
  - Minimize both operating and capital costs
  - Reduce electrical / thermal demand
  - Reduce overall energy consumption & increase system efficiency
  - Reduce greenhouse gas emissions (w/renewables mix)

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Benefits of TES

- Energy cost savings
  - Reduce peak on-time electricity demand
  - Decouple time-of-use (load) and pricing
  - Higher system efficiency – constant set-point operations
- Decarbonization benefit
  - Use of renewables – solar and wind
  - Elimination of fast-acting electric grid and peaker plant response
- Reduced equipment size
  - Systems can be designed for average year-round load rather than peak loads which occur for less than 5% of the operating hours

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Benefits of TES

- Capital cost savings
  - Downsizing large chillers and cooling equipment at design-level
  - Smaller systems and equipment – pumps, fans, transformers, etc.
- System benefits
  - Optimization of system assets – eliminate part-load operations
  - Operate systems at favorable conditions allowing for higher system efficiency
- Increased reliability and redundancy
  - TES can provide additional capacity always and N+1 redundancy
  - Primary equipment operations are more stable enhancing reliability
  - Ability to do periodic and preventive maintenance to enhance reliability

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Classification of TES

- Type of storage medium
  - Sensible heat
  - Latent heat
- Sensible thermal storage (types)
  - Horizontal tanks
  - Thermal stratification (vertical tanks)
    - Multiple compartments
    - Multiple tanks
    - Labyrinth tanks
  - Underground concrete structures
  - Aquifers
- Sensible thermal storage (materials used) – chilled water; aqueous (brines, glycols) and non-aqueous fluids; Low Temperature Fluids (LTFs)

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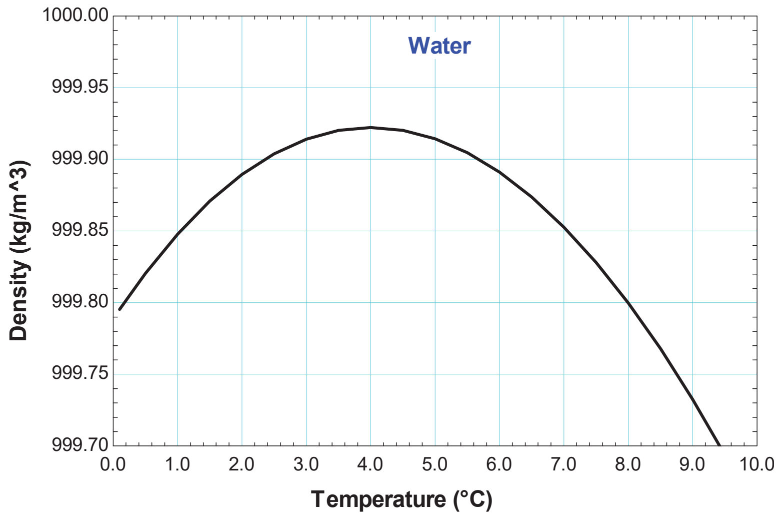
Thermal Stratification in Chilled Water Tanks

- Water has the highest density at 4°C
- Chilled water is returned to the bottom of the tank
- Warmer water is supplied to chiller from top of the tank



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Classification of TES

- Latent thermal storage
  - Water / Ice
    - Internal Melt Ice-On-Coil
    - External Melt Ice-On-Coil
    - Encapsulated ice
    - Ice harvesting
    - Ice slurry
  - Other phase-change materials
    - Salt hydrates
    - Anhydrous salt eutectics

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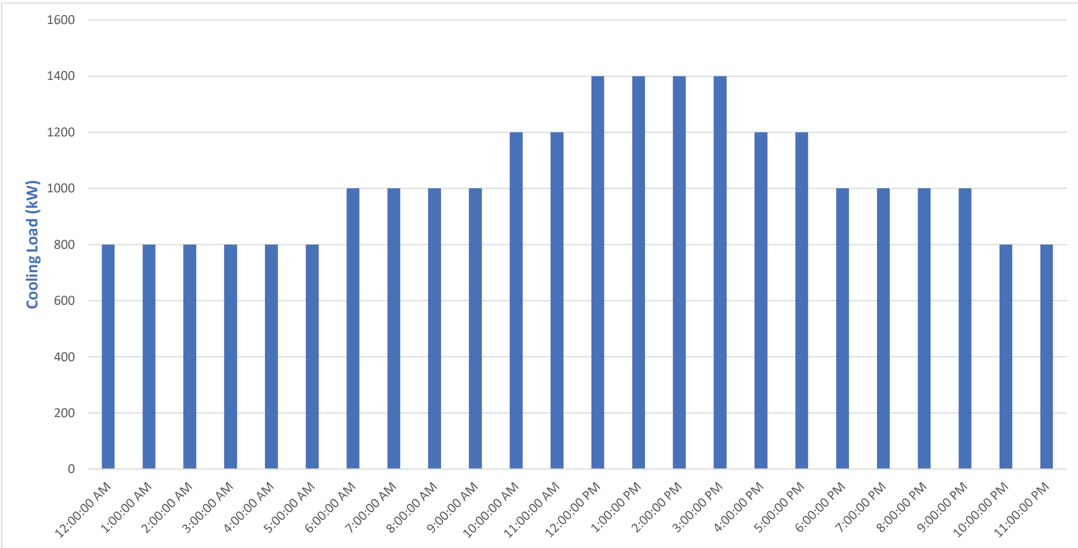
Daily Load Profile (an example)



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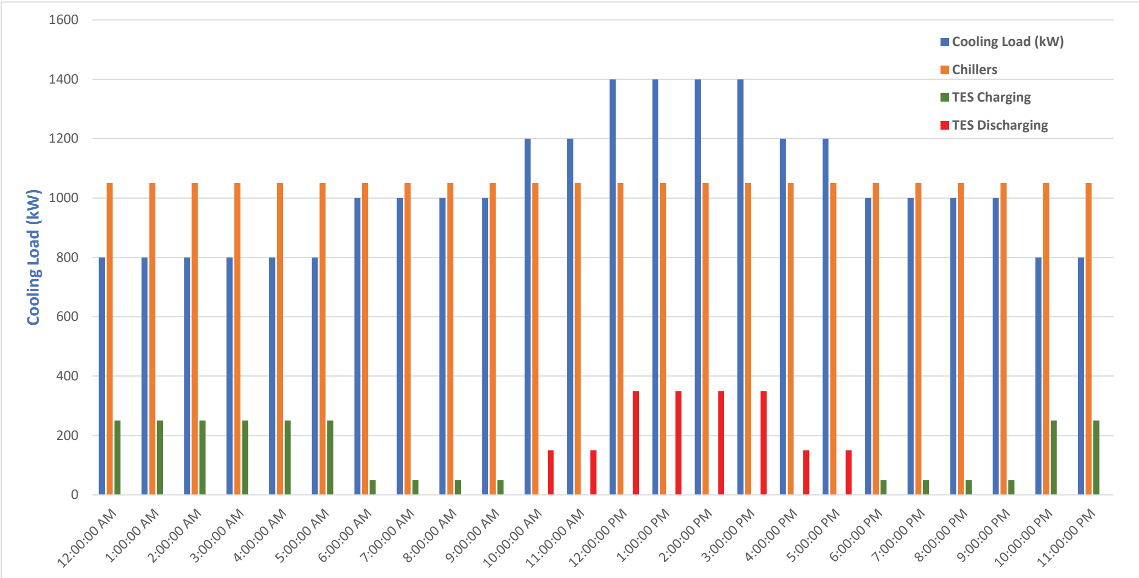
Daily Operations (an example)

- Option 1
  - Chiller Plant Size – 1,400 kW
  - Daily cooling load – 24,800 kWh
- Option 2
  - Chiller Plant Size – 1,050 kW
  - Daily cooling load – 24,800 kWh + Circulating losses
  - TES size – 2,400 kWh

Daily Load Profile w/TES (an example)



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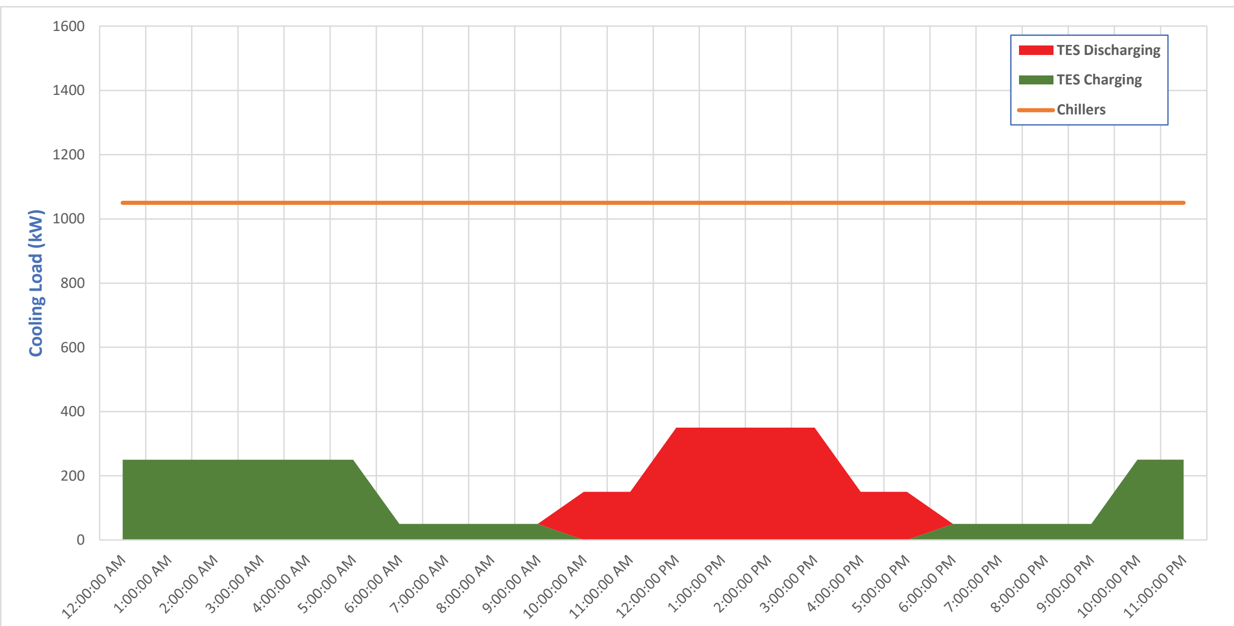
Daily Load Profile w/TES (an example)



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Most Favorable Scenarios for TES

- High (or very high) chilling load of relatively short duration
  - Think of cooling demand having a compressed air system profile
- High electric power demand charges
- Low (or very low or negative) electrical energy during off-peak hours
- Expansion on a very limited budget
- Mission critical systems that still need to operate with minimal backup generation capability
- Industry looking to decarbonize and use higher amounts of renewables mix when available

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Key Points / Action Items

1. *Thermal Energy Storage (TES) is a very effective technique for achieving several conflicting goals*
2. *Every application has to be individually evaluated*
3. *Several favorable factors can be used as screeners to evaluate 1st level feasibility*
4. *Understanding the plant's load profile is critical – especially, variations based on weather, production rates and system capabilties*
5. *Chilled water storage and Ice-banks are the most common forms of TES*

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1

13 CHILLED WATER & REFRIGERATION SYSTEM OPTIMISATION CONCLUSIONS

13.1 Conclusions

13.2 Next Steps

13.3 Tools & Resources

2

Conclusions / Summary / Wrap-Up

- Use a Systems Approach in chiller plants and refrigeration systems to identify potential energy saving opportunities, optimize and manage them
- Understanding refrigerants and their thermodynamic properties is fundamental when analyzing chillers
- A refrigeration / chiller system will have the following basic processes: Evaporation, Condensation, Compression and Expansion (throttling)
- A systems approach in a cooling cycle will include end-use (cooling load to be provided), chiller(s), cooling towers (heat rejection to ambient), pumps, fans, etc.
- Single-stage mechanical vapor compression chiller systems are most common but refrigeration systems will typically be multistage to allow for higher temperature lifts, multi-temperature levels, etc.

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Conclusions / Summary / Wrap-Up

- There are several control mechanisms to control the compressor operation
- Part-load operation can be very inefficient and several state-of-the-art technologies are available including VFDs to improve efficiency
- Simple chiller plants can have fixed / variable primary loops but complex chiller plant systems have fixed and variable primary, secondary and tertiary chilled water distribution systems
- Coefficient of Performance (COP) is used for a unit but System COP includes power consumed by the chiller compressor motor, chilled water pumps, cooling tower pumps, fans and other parasitic users
- Load profile is very important to understand the year-round system cooling / refrigeration demand

Conclusions / Summary / Wrap-Up

- Chiller plant operating cost calculation will require load profile, operating hours, COP and electric utility cost
- Seasonal COP (SCOP) is most commonly used to determine average rating
- Actual operating performance calculations for CR systems will require temperatures, pressures, flows and power information
- The other chiller plant efficiency metrics include: Compressor lift, Isentropic compressor efficiency, Heat Exchanger effectiveness, etc.
- Fouling impact in heat exchangers has to be determined and related to reduction in COP and increase in operating costs

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Conclusions / Summary / Wrap-Up

- A significant portion of the plant's energy can be consumed by its refrigeration system – sometimes as much as 50%!
- Applications range from convective cooling to contact freezing and variations with selective equipment can be in various food and process industries
- Industrial refrigeration systems can be differentiated in many ways but most times the refrigerant used is the primary differentiation – halocarbon, ammonia, carbon dioxide, etc.
- Multistage, cascade systems, liquid overfeed systems, absorption systems provide another differentiation method
- Evaporative condensers are the preferred choice of heat rejection mechanism in industrial refrigeration system
- Reciprocating and Screw compressors are the work horses of the refrigeration systems

Conclusions / Summary / Wrap-Up

- Part-load operation should be carefully evaluated especially since screw compressors can have a significant detriment to efficiency when using slide valves to control capacity
- Variable Frequency Drives should be considered
- Optimize systems to operate the evaporator temperature as high as possible without violating any process constraints
- Optimize systems to operate the condenser temperature as low as possible without violating any process constraints
- Investigate thermosyphon oil cooling in screw compressors versus liquid injection
- Operations and Maintenance can play a huge role in ensuring highest compressor efficiencies

Conclusions / Summary / Wrap-Up

- IIOT, Artificial Intelligence leading to Machine Learning to train the system to continuously minimize energy costs and enhance reliability significantly
- Thermal Energy Storage (TES) is a very effective technique for achieving several conflicting goals
- There are several multi-lateral government Protocols that have been ratified and enforced – The Montreal Protocol with Kigali Amendment; The Kyoto Protocol with the Paris Climate Agreement
- It is important to periodically check on the status of these protocols and South Africa’s position and commitments
- Safety (Flammability) are key concerns of some of the next-generation refrigerants

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13 CHILLED WATER & REFRIGERATION SYSTEM OPTIMISATION CONCLUSIONS

9

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List of Energy Efficiency Opportunities

- Implement cooling tower water temperature management
- Optimize settings for chilled water supply temperature
- Eliminate inappropriate uses of chilled water
- Maintain optimum water flow rates in evaporator / condenser
- Clean fouled and scaled evaporator / condenser
- Implement variable frequency driven chillers, pumps, fans
- Sequence multiple chillers to optimize efficiency
- Implement free cooling, when available

10

List of Energy Efficiency Opportunities (continued)

- Evaluate water-cooled options versus air-cooled systems
- Remove non-condensable gases and moisture
- Reclaim refrigerant
- Eliminate all refrigerant leaks
- Maintain proper refrigerant levels
- Minimize compressor surging
- Maintain compressor isentropic efficiency
- Undertake peak load management strategy (thermal storage)
- Evaluate process heat integration

11

Some measures to reduce energy consumption for industrial refrigeration and to improve system efficiency

- Reduction of the cooling load
- Raise evaporating temperature
- Lower condensing temperature
- Optimize compressor control
- Efficiency and control of fans
- Use of waste heat – heat recovery
- Avoid and repair leakages

12

Other Investigative Opportunities in Industrial Refrigeration Systems

- Proper control of evaporator fans
- Use of high efficiency motors and variable frequency drives, where applicable
- Recover waste heat from compressor discharge for process
- Repair leaks
- Eliminate Non-Condensables

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Other Investigative Opportunities in Industrial Refrigeration Systems

- Reduce moisture from entering the freezers
  - Door sealing
  - Product staging and dehumidification
- Defrosting should be done in the cheapest way possible
  - Electric maybe most expensive
  - Hot gas defrosting does have a cost – it is not free
- Maintain proper defrost frequency based on demand control
  - Fin spacing reduced by 20%
  - Load-based

13 CHILLED WATER & REFRIGERATION SYSTEM OPTIMISATION CONCLUSIONS

13.1 Conclusions

13.2 Next Steps

13.3 Tools & Resources

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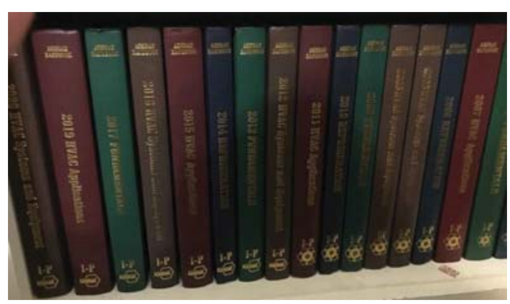

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Tools

- CWSAT – SI Metric version
  - CWSAT – US (IP) version
- CoolPack 1.50
- 3EPlus Insulation Evaluation Software
- US DOE Better Plants MEASUR
  - Pumping Systems
  - Fan Systems
  - Calculators

Thank You

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