Better Plants
U.S. DEPARTMENT OF ENERGY

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

Session 1
Thursday – July 16, 2026
2:00 pm – 4:30 pm ET

Welcome

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

Acknowledgments

- US Department of Energy, Industrial Technologies Office (ITO)
- Oak Ridge National Laboratory
- Dr. Beka Kosanovic
- Several industrial clients – both in the US and internationally

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Process Cooling (Chilled Water Systems) Virtual INPLT Facilitators

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Agenda – Session ONE

- Welcome and Introductions
- Safety and Housekeeping
- Agenda for Process Cooling Virtual INPLT (8 sessions)
- Today's Content:

  Industrial Process Cooling Systems Fundamentals
  - Refrigerant thermodynamics
  - Chilled water system components
  - Chilled water system overview
- Kahoot Quiz Game
- Q&A

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

Safety and Housekeeping

- Safety Moment
  - Exercise caution while working near large motor-driven systems
  - Accidents can be life-threatening
- You are welcome to ask questions at any time during the webinar

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

Process Cooling Virtual INPLT Agenda (2026)

- Session 1 (July 16) – Industrial Chilled Water Systems Fundamentals
- Session 2 (July 23) – Review of Chilled Water System Scoping Tool; Efficiency Metrics & Calculations
- Session 3 (July 30) – Introduction to Process Cooling Assessment (using MEASUR)
- Session 4 (August 6) – Using MEASUR to Quantify Energy Efficiency Opportunities – Part 1
- Session 5 (August 13) – Using MEASUR to Quantify Energy Efficiency Opportunities – Part 2
- Session 6 (August 20) – US DOE MEASUR other modules, 3EPlus, etc.; Assessment & Reporting
- Session 7 (August 27) – Case Studies; Refrigerants – Past, Present & Future; Reclamation and O&M
- Session 8 (September 3) – Industrial Process Cooling System VINPLT Wrap-up Presentations

Course Objectives

- Understand the fundamentals and become familiar with the system and components of industrial process cooling (chilled water systems)
- Use a Systems Approach to evaluate and optimize chilled water systems
- Identify the measurements required to manage chilled water systems
- Measure the individual chiller & overall plant operating efficiency
- Understand load profile on a chilled water system
- Determine annual energy consumption baseline and operating costs
- Use software tools (CRST, MEASUR, and 3EPlus) to assess, optimize and manage industrial chilled water systems

Course Objectives

- Identify and prioritize areas of chiller plant efficiency improvements
- Understand different end-uses and identify areas of end-use efficiency improvements
- Evaluate the effectiveness of thermal insulation
- Understand inter-relationships between refrigerant, oil and water
- Become familiar with future refrigerants and impacts of legislation
- Undertake field work to do a chilled water system assessment
- Start thinking out-of-the-box and continue to reduce your plant's energy footprint, reduce operating costs and enhance reliability

Participant Background / Objectives / Questions

Let's take a few minutes at a high-level and everyone can chime in

- What is your background?
- What is your day-to-day responsibility?
- What issues / concerns do you have about your chilled water systems?
- What energy efficiency projects / upgrades have you done recently in your plants?

Polling Question 1

Polling Question

1) Which industry do you belong to?

   A. Petrochemicals, Refineries, Chemicals
   B. Food and Beverage
   C. Pharmaceuticals
   D. Manufacturing Assembly plants (Automobiles, transport equipment)
   E. Electronics, specialty manufacturing
   F. Data Centers
   G. Large Commercial (Buildings, Universities, Hospitals, Malls, etc.)
   H. Other

Polling Question 2

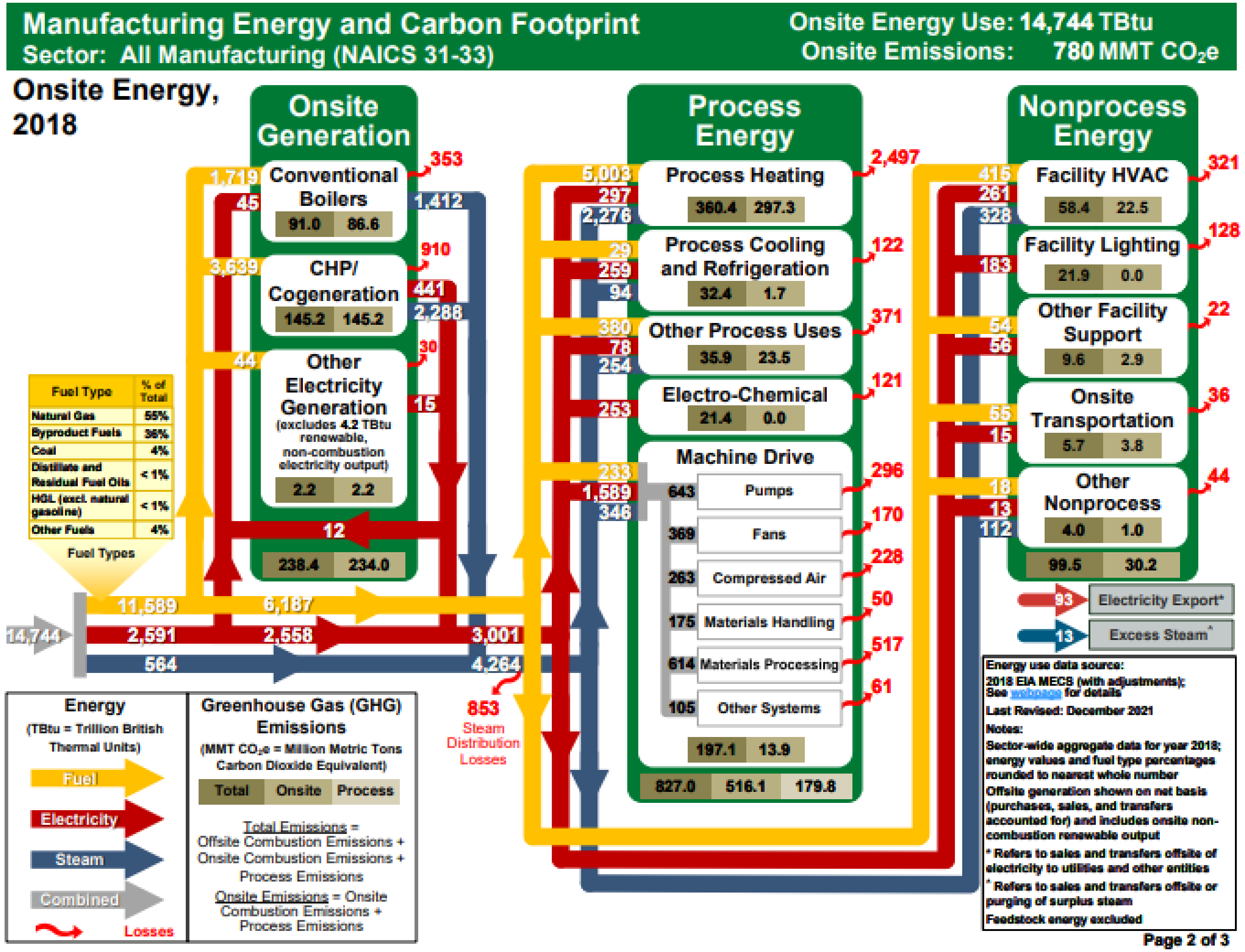
Polling Question

2) What is your major function in your current role at your plant?

A. Engineering (Design)
B. Operations & Maintenance (Engineering / Technical)
C. Operations & Maintenance (Management)
D. Plant management
E. Corporate-level management
F. Independent consultant / contractor
G. Other

Industrial Energy Overview

- Industry consumes 1/3 of U.S. energy
- Approximately 20% of industrial electricity demand is for Process Cooling, Refrigeration & Facility HVAC
- Energy is key to economic growth and maintaining U.S. jobs in manufacturing



Industrial Energy Consumption

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

- [Manufacturing Energy Footprints]

The Systems Approach

The Systems Approach

- Look at the Forests and DO NOT get lost in the individual trees
- 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 **industrial** system is unique and deserves the same level of due diligence

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”

The Systems Approach (with a simplified example)

15 kW motor
efficiency = 91%

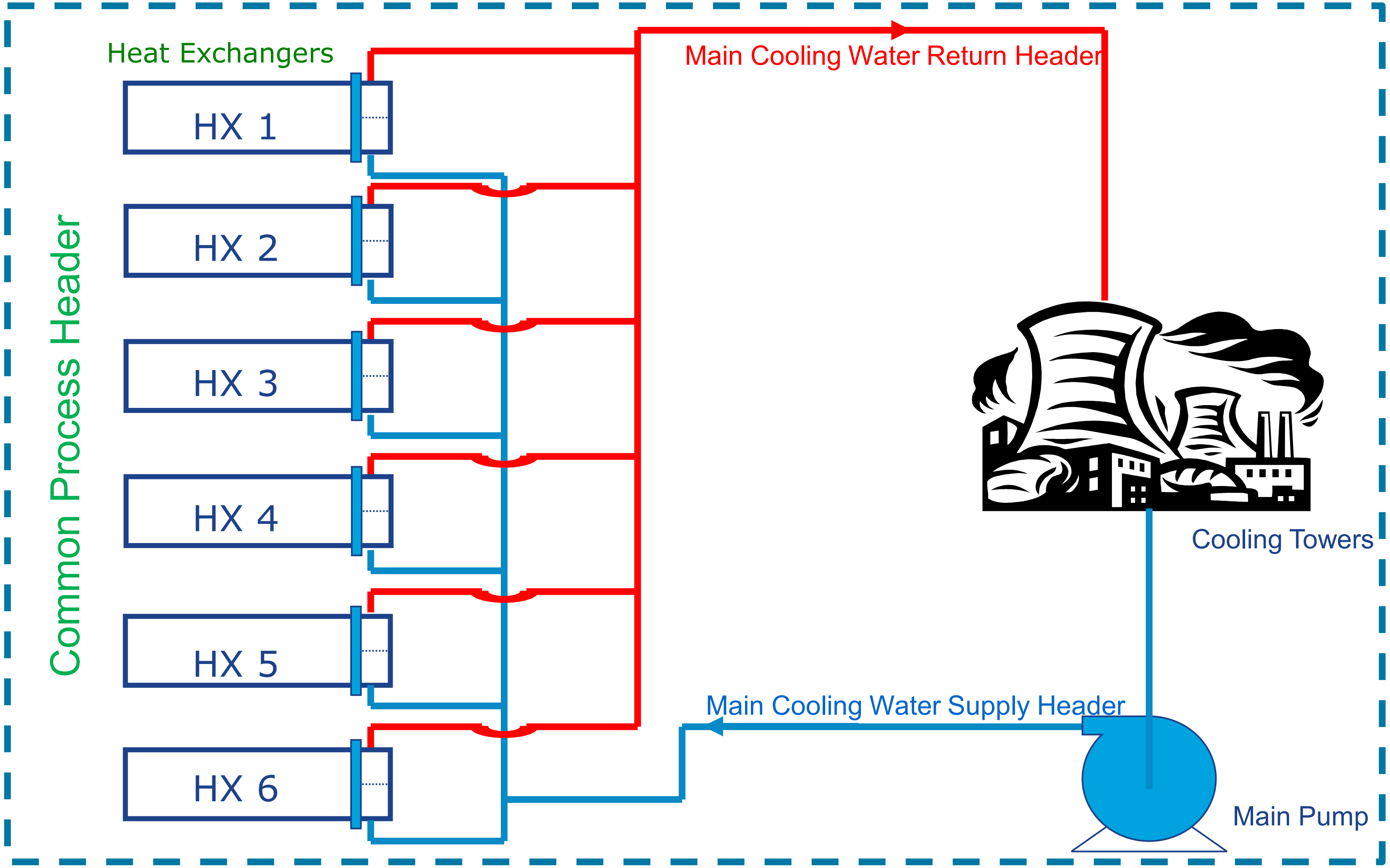
Combined motor & pump
efficiency = 59%

System efficiency = 13%

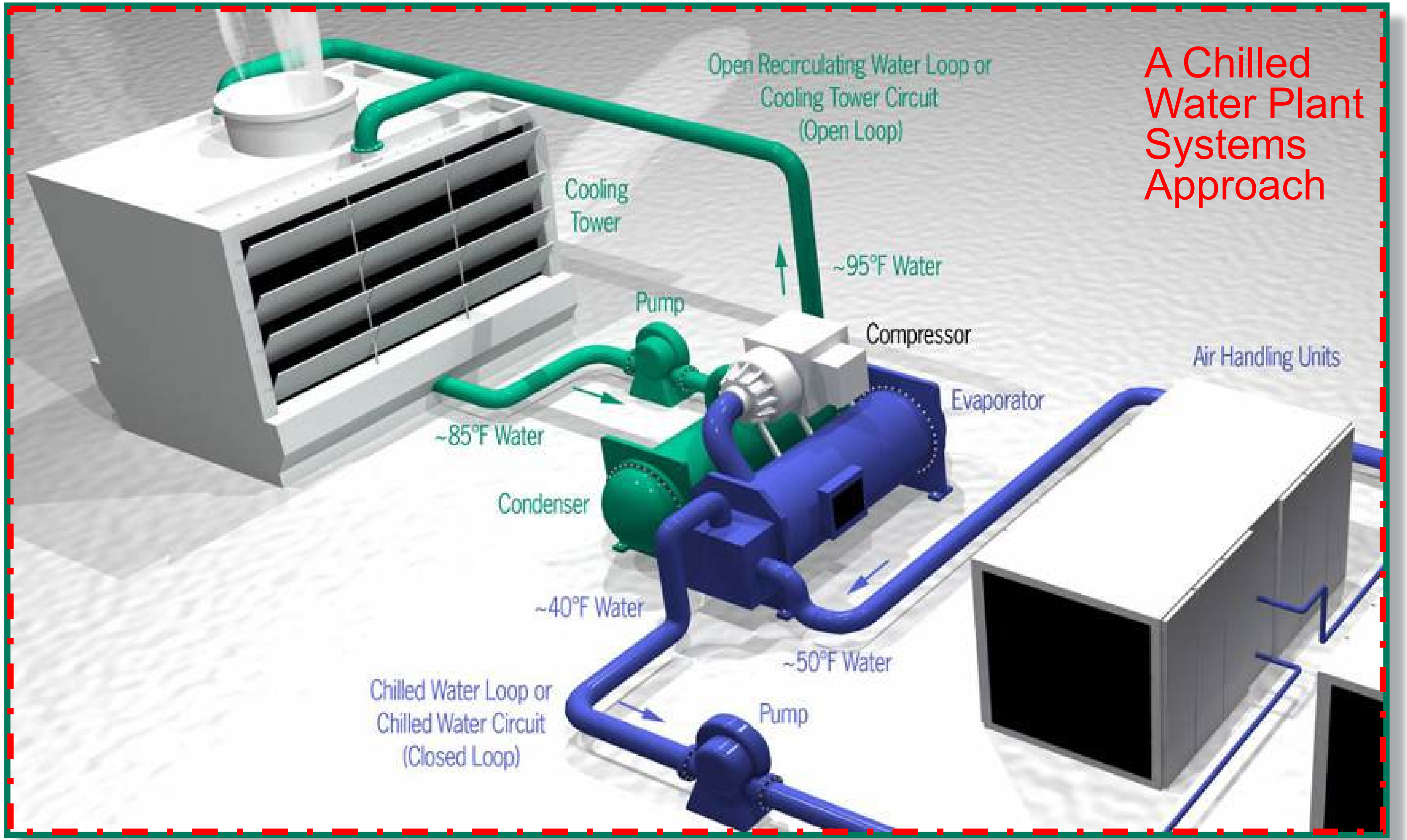
Source: US DOE Better Plants Program

Courtesy: Don Casada, PE – Diagnostic Solutions

A Cooling Water Plant Systems Approach

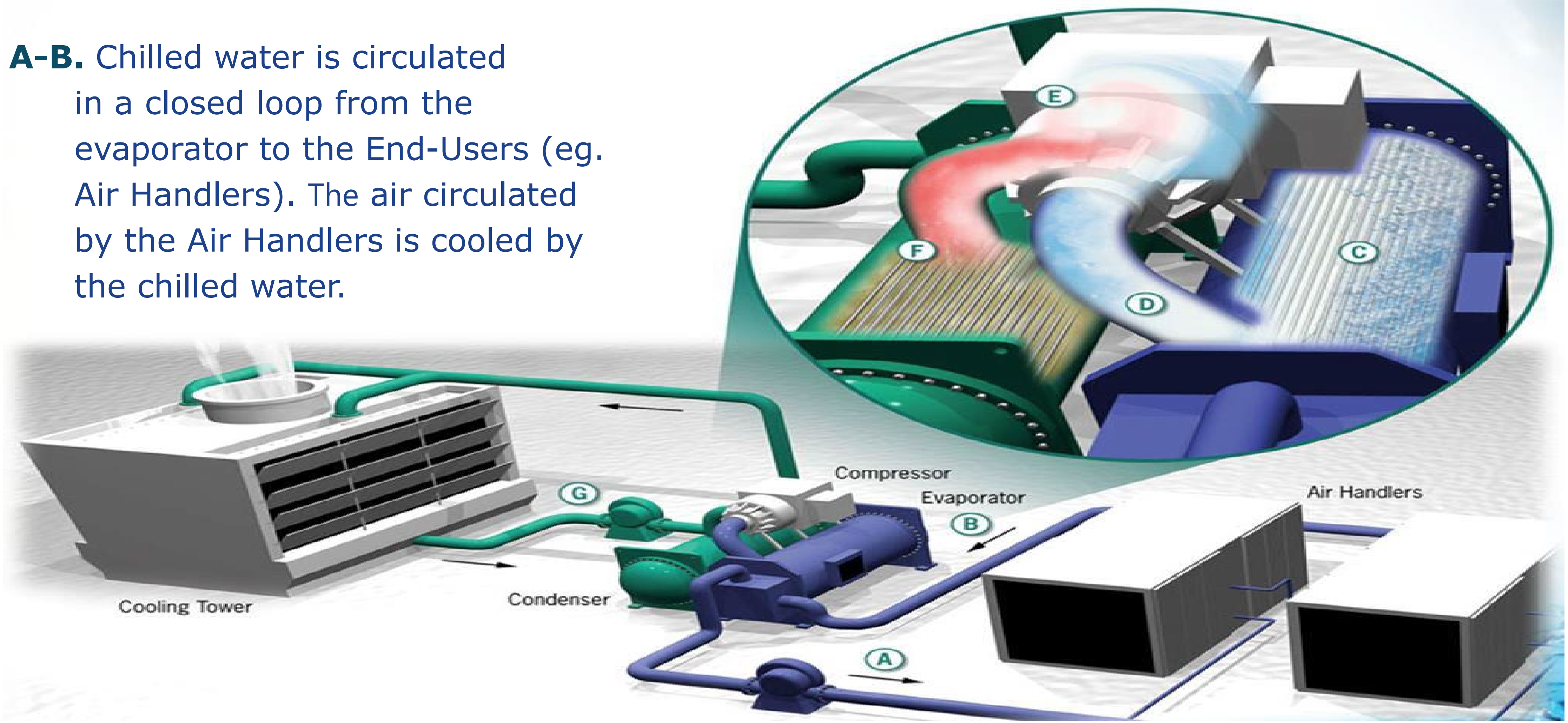


A Chilled Water Plant Systems Approach



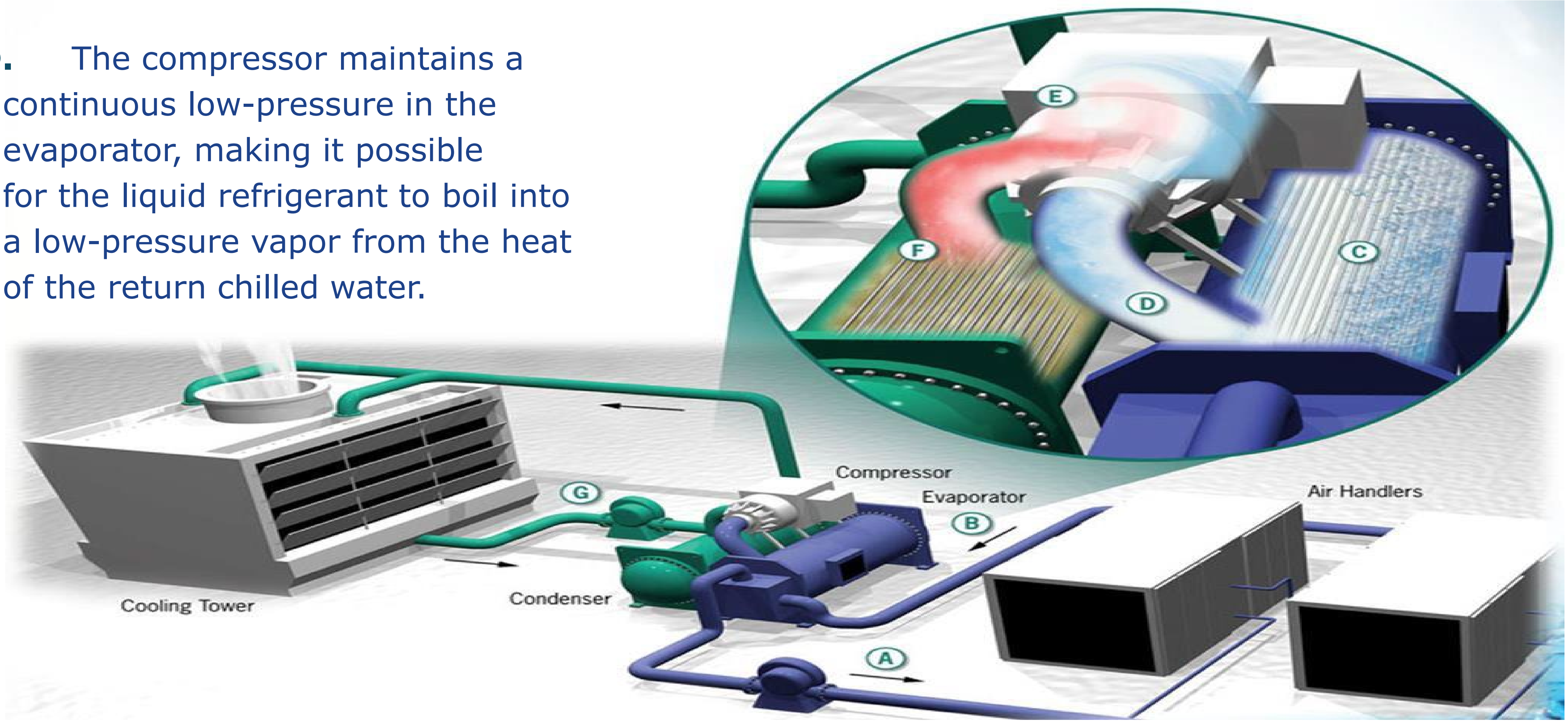
The Cooling Cycle

A-B. Chilled water is circulated in a closed loop from the evaporator to the End-Users (eg. Air Handlers). The air circulated by the Air Handlers is cooled by the chilled water.



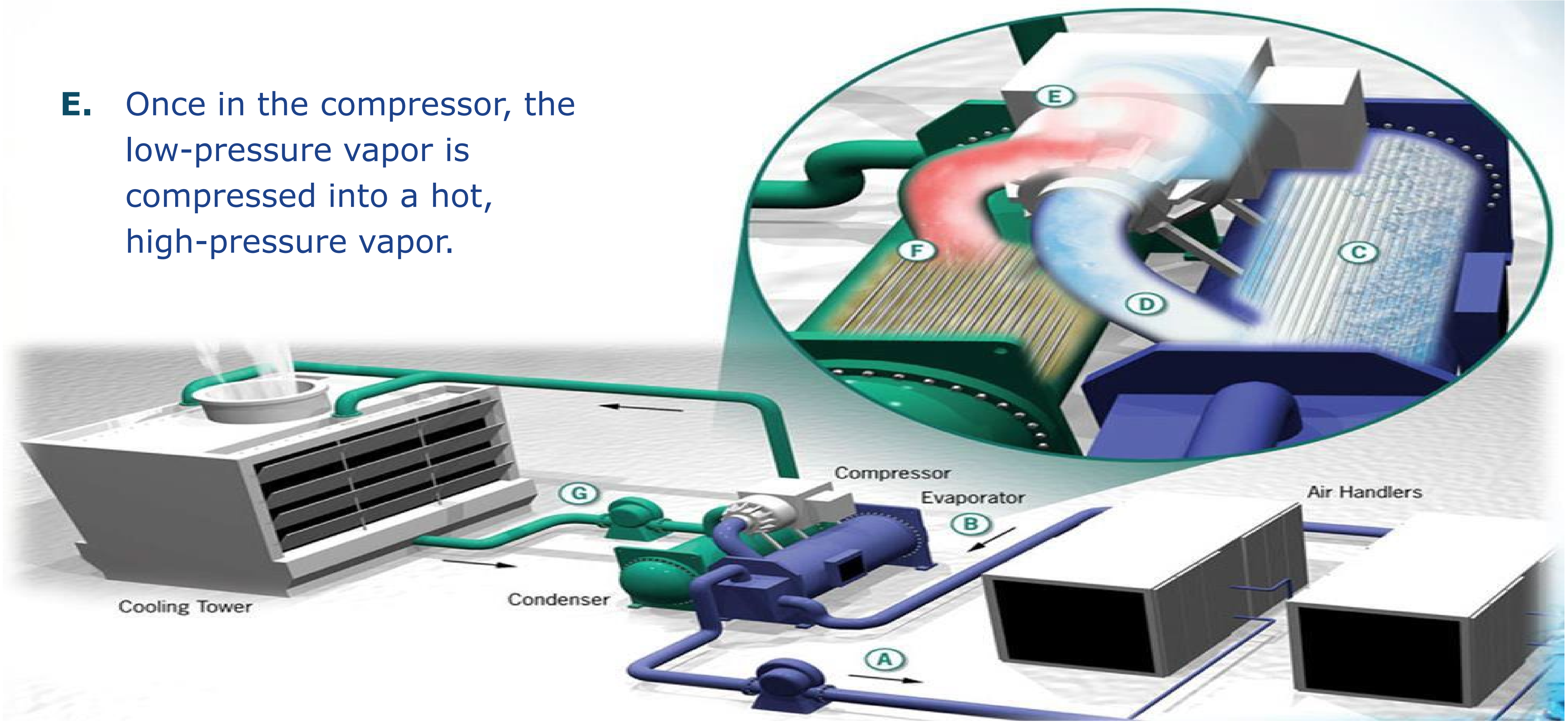
The Cooling Cycle

C-D. The compressor maintains a continuous low-pressure in the evaporator, making it possible for the liquid refrigerant to boil into a low-pressure vapor from the heat of the return chilled water.



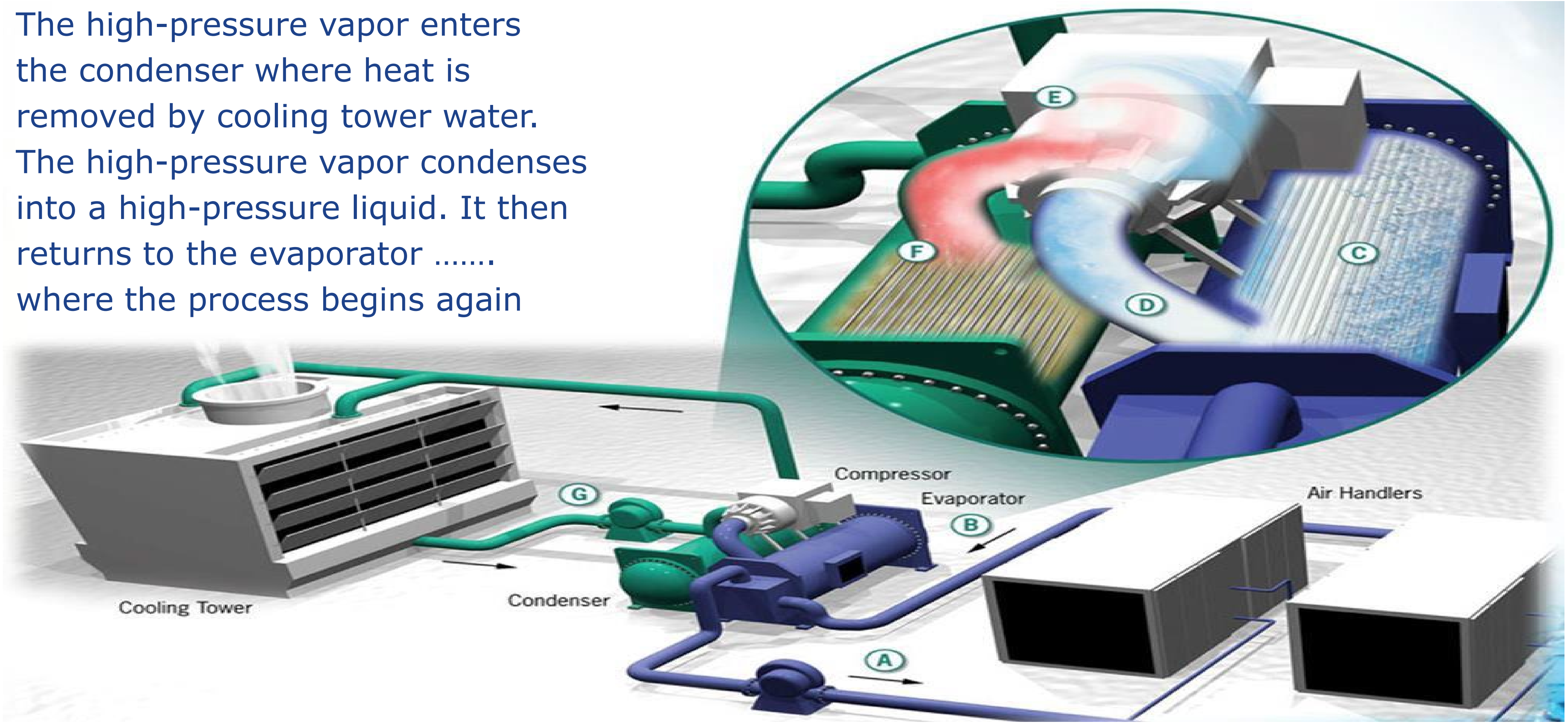
The Cooling Cycle

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



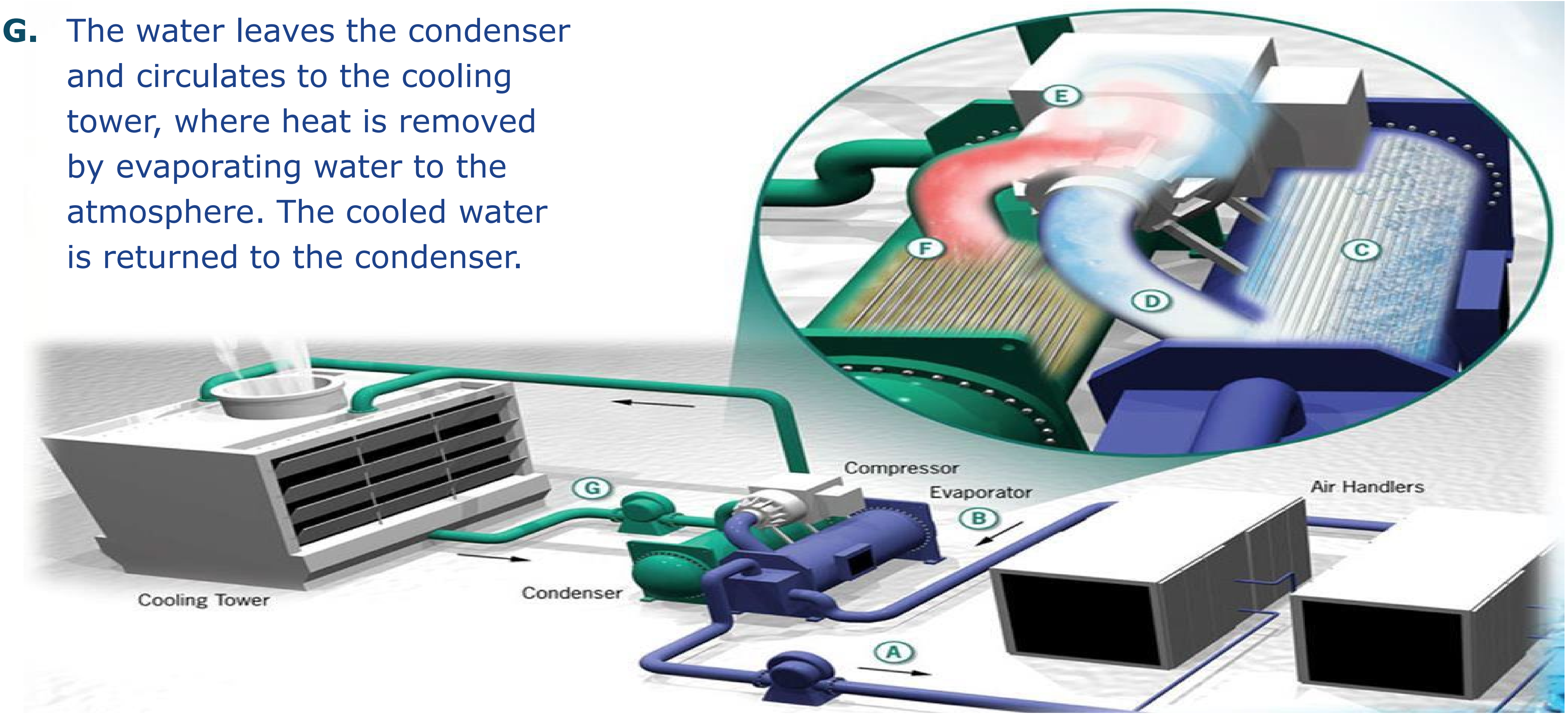
The Cooling Cycle

F. The high-pressure vapor enters the condenser where heat is removed by cooling tower water. The high-pressure vapor condenses into a high-pressure liquid. It then returns to the evaporator ……. where the process begins again

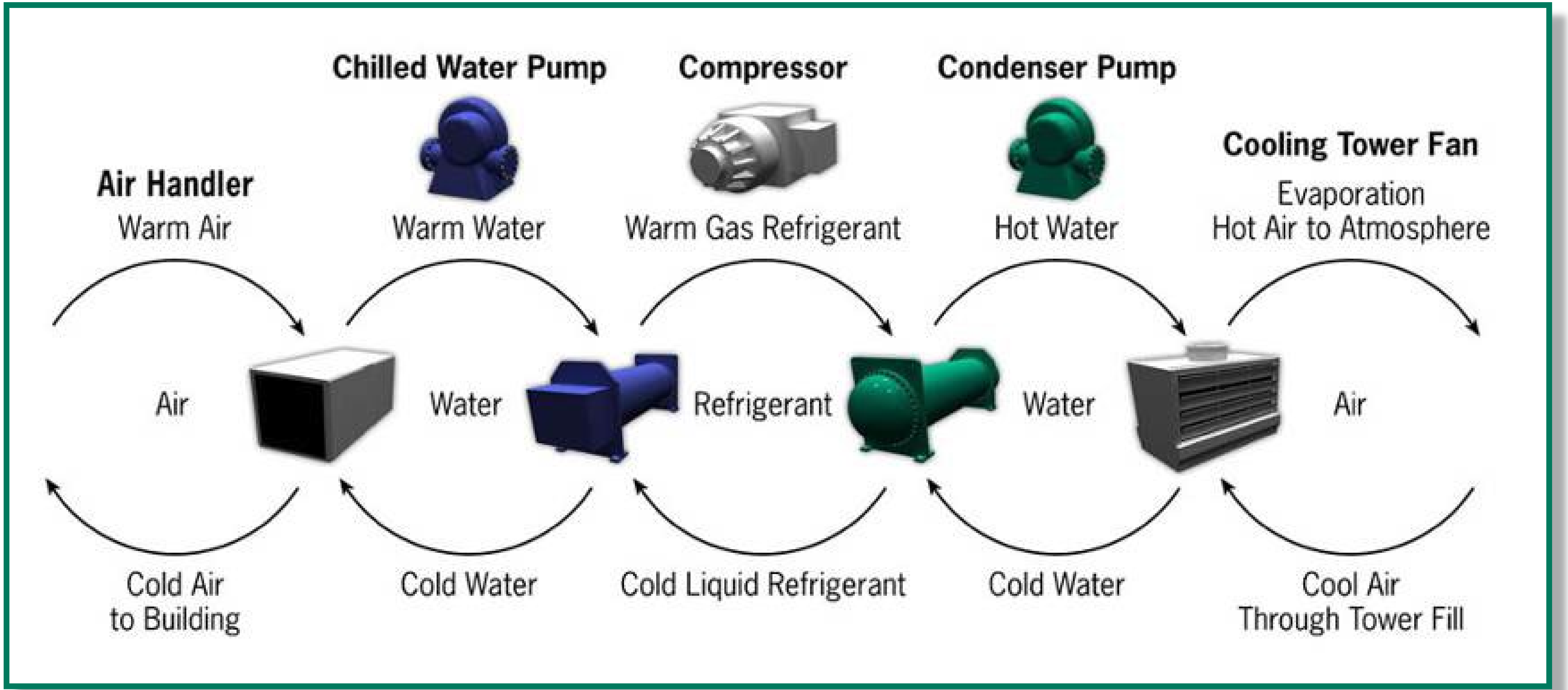


The Cooling Cycle

G. The water leaves the condenser and circulates to the cooling tower, where heat is removed by evaporating water to the atmosphere. The cooled water is returned to the condenser.



The Air, Water & Refrigerant Cycle



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

Key Points / Action Items

1. *Use a Systems Approach to optimize industrial chiller plant systems*

2. *The main function of any chiller / chiller plant is to remove heat from (or provide cooling to) an end-use and reject that heat to the ambient*

3. *Depending on the industry, end-use application different types of chiller plant systems can be designed and used*

4. *An understanding of the laws of thermodynamics, heat transfer, fluid flow and fluid properties will be required for a proper system analysis*

Refrigerants & Thermodynamics

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Refrigerants

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

- Depending on the level of due-diligence, the refrigerants' physical, thermodynamic and transport properties will be required
  - This also applies to all heat transfer fluids in the system

Refrigerants

- Refrigerants
  - 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 (glide) during phase change
  - Natural – Ammonia, Water, Carbon dioxide

- Nomenclature
  - R-number
  - Single (Double) bonds – 1-399 (1XXX)
    - Easy convention for C, H, F, Cl
  - Near Azeotropes – 400 series
  - Azeotropes – 500 series
  - Natural (Inorganic) – 700 series
    - Easy convention – 7 + Molecular wt.

Examples of Refrigerants

- CFC (Chloro fluoro carbon) Refrigerants
  - R-11 - Was used in residential, commercial and industrial applications
  - R-12 - Was used in residential, commercial and industrial applications
- HCFC (Hydro chloro fluoro carbon) Refrigerants
  - R-22 - Extensively used in residential, commercial and industrial applications
  - R-123 – commercial and industrial applications
- HFC (Hydro fluoro carbon) Refrigerants
  - R-134a - Automobile applications, commercial and industrial applications
  - R-32 – new replacement refrigerant
- HFO (Hydro fluoro olefin) Refrigerants
  - R-1234yf – new replacement refrigerant
- Refrigerant Blends (Azeotrope and Near Azeotrope)
  - R-410a - residential A/C, commercial applications
  - R-407c – commercial applications
  - R-454b - new replacement refrigerant
  - R514a – commercial and industrial applications

Refrigerant Safety
A1, A2L, A2, A3
B1, B2L, B2

Refrigerants

- Thermodynamic Properties
  - P - Pressure (psig, psia, etc.)
  - T - Temperature (°F)
    - Absolute Temperature (R)
  - X - Quality
  - ρ - Density (lb/ft^3)

- Thermodynamic Properties
  - V – Specific Volume (ft^3/lb)
  - H - Enthalpy (Btu)
    - Specific Enthalpy (Btu/lb)
  - S - Entropy (Btu/R)
    - Specific Entropy (Btu/lb-R)

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

- Thermodynamic States
  - Subcooled
    - Liquid
    - Temperature and Pressure are independent
    - Energy content $\propto$ Temperature
  - Saturated
    - Liquid / 2-Phase / Vapor
    - Temperature and Pressure relationship is fixed
    - $0 \leq$ Quality ≤ 1
  - Superheated
    - Vapor
    - Temperature and Pressure are independent
    - Energy content $\propto$ Temperature & Pressure

Refrigerants

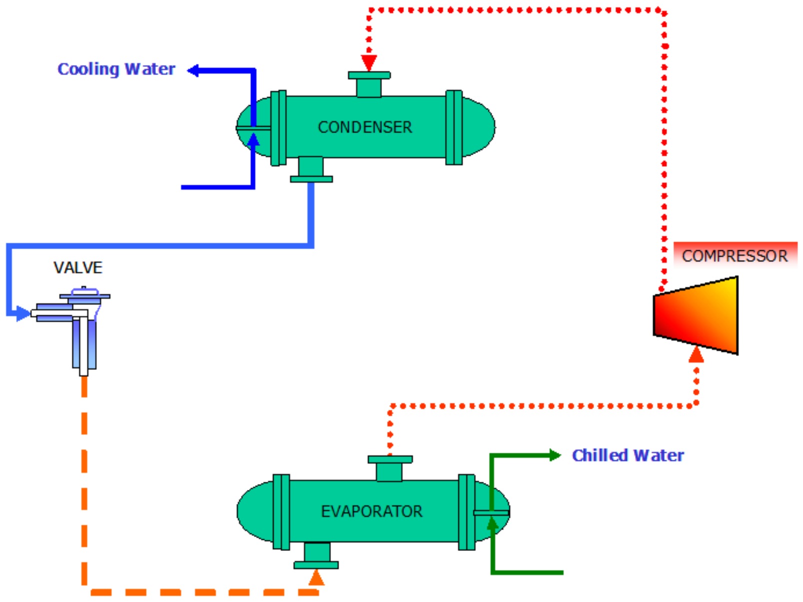
R134a Saturation Properties

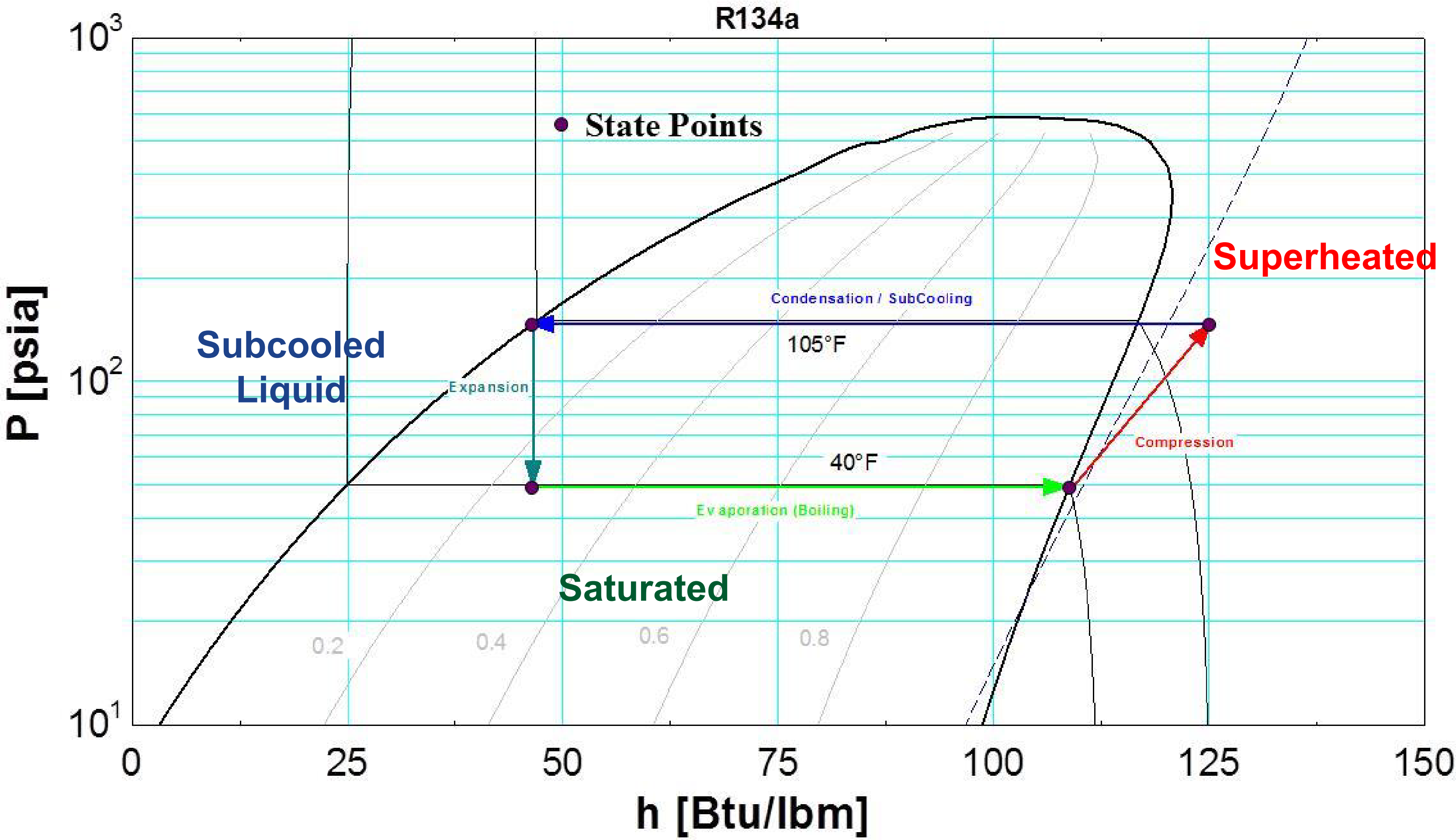
Temperature [°F]	Pressure [psig]	Liquid Density [lb/ft^3]	Vapor Volume [ft^3/lb]	Liquid Enthalpy [Btu/lb]	Vapor Enthalpy [Btu/lb]	Liquid Entropy [Btu/lb-R]	Vapor Entropy [Btu/lb-R]
(14.95)	-	85.96	3.0460	7.58	100.90	0.01752	0.22728
(5.23)	4.00	84.94	2.4270	10.57	102.30	0.02414	0.22603
2.96	8.00	84.07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

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 or a T-s 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!

The Refrigeration Cycle





Refrigerants (Worked Examples)

- 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=40°F, P=40 psig
    - T=135°F, P=124 psig
    - T=89.8°F, P=104 psig
  - For refrigerant R123, determine saturation pressure for the following operating temperatures:
    - T=37.2°F
    - T=100°F
  - For refrigerant R134a, determine liquid and vapor densities and latent heat of vaporization at the following state point:
    - P=36 psig

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.

Basic Components in a Chilled Water System

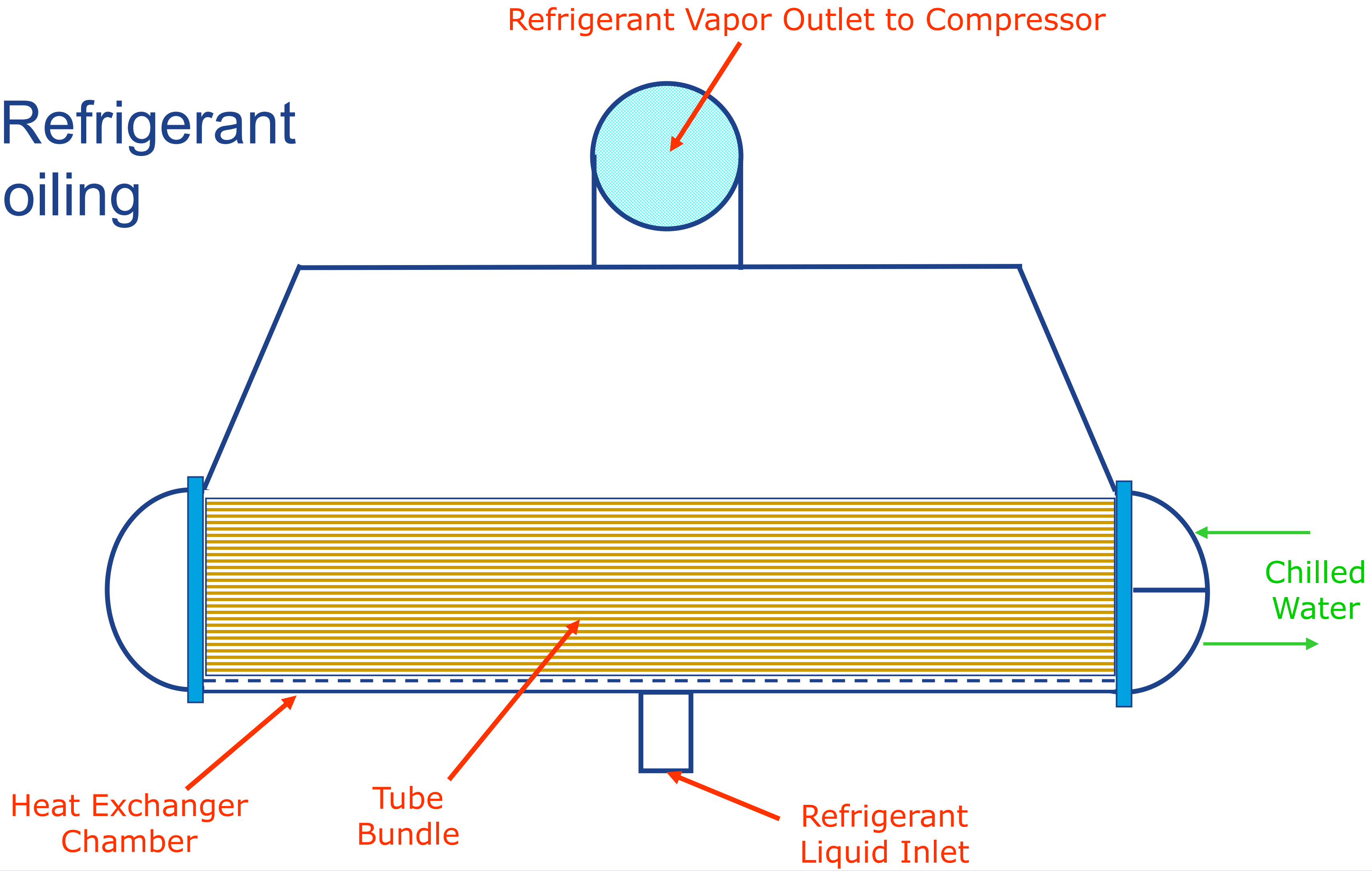
A Chiller System

- 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
  - Plate and frame common in some applications

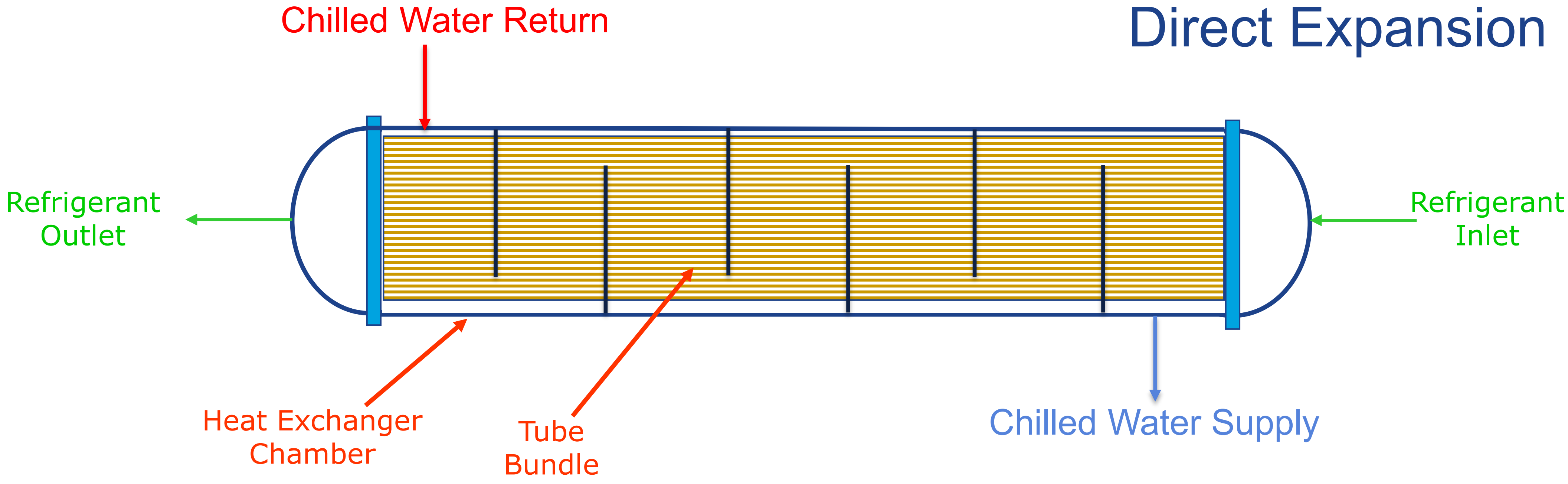
Evaporator / Cooler / Chiller Barrel

Shell side – Refrigerant
Pool Boiling

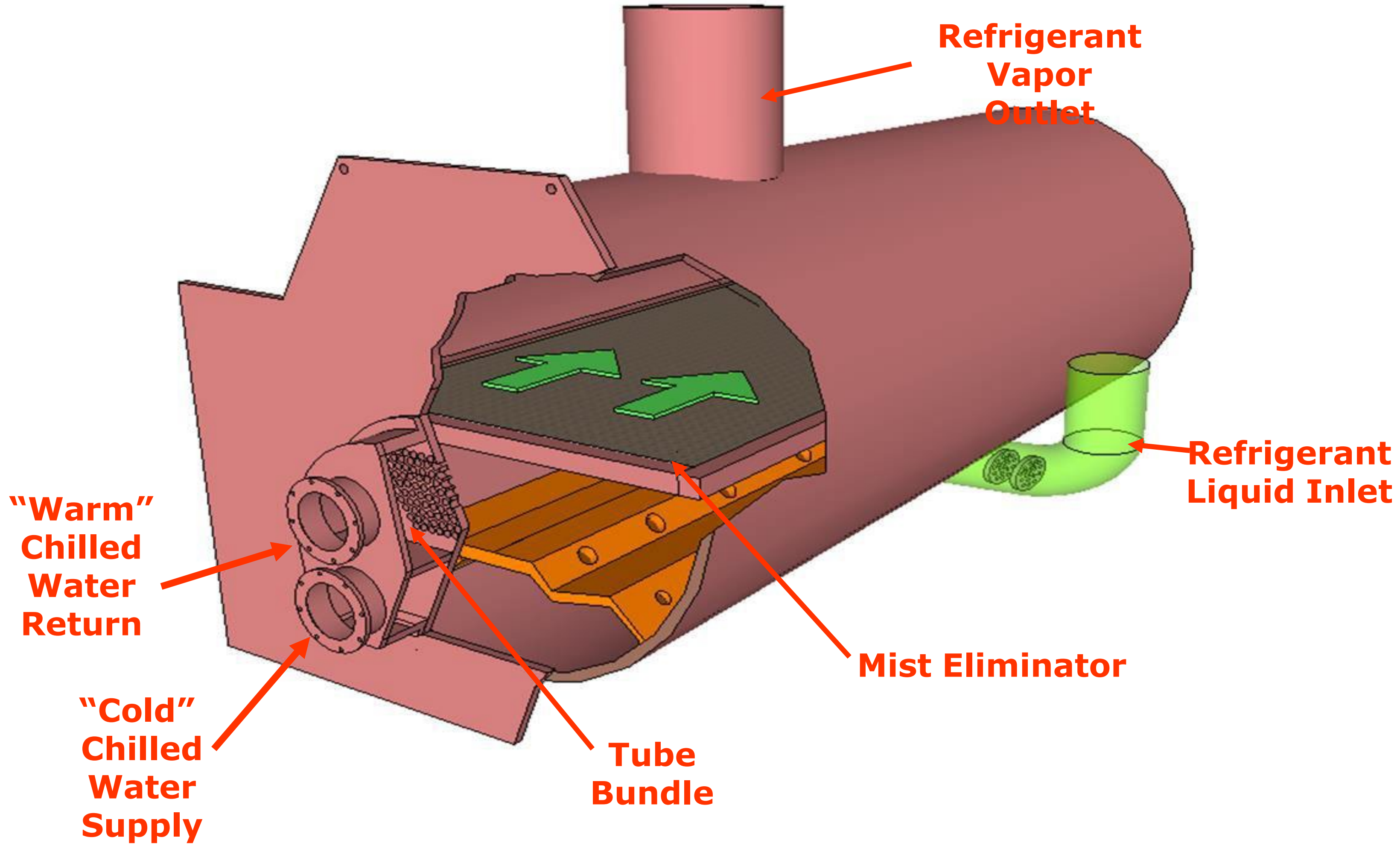


Evaporator / Cooler / Chiller Barrel

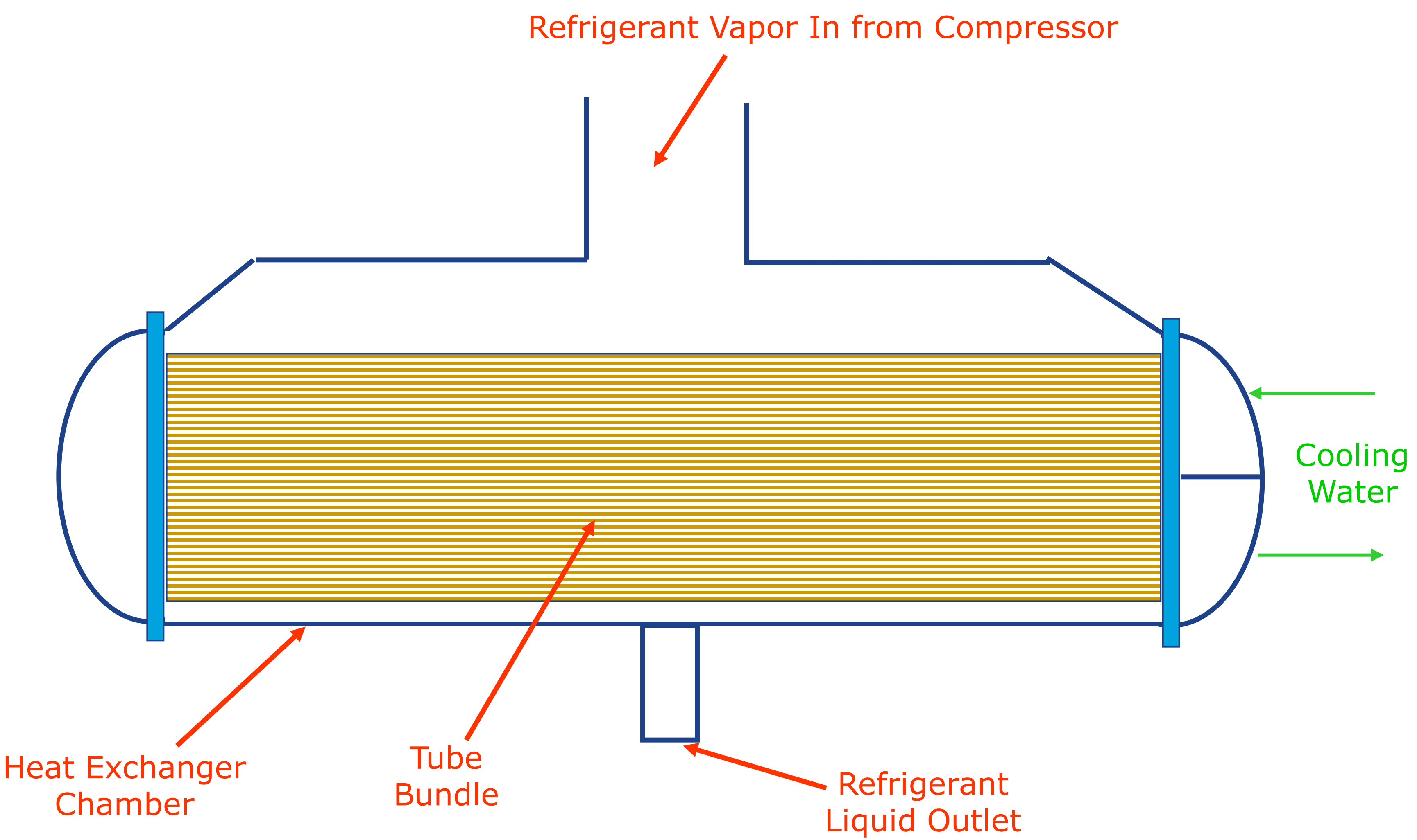
Tube side – Refrigerant Direct Expansion



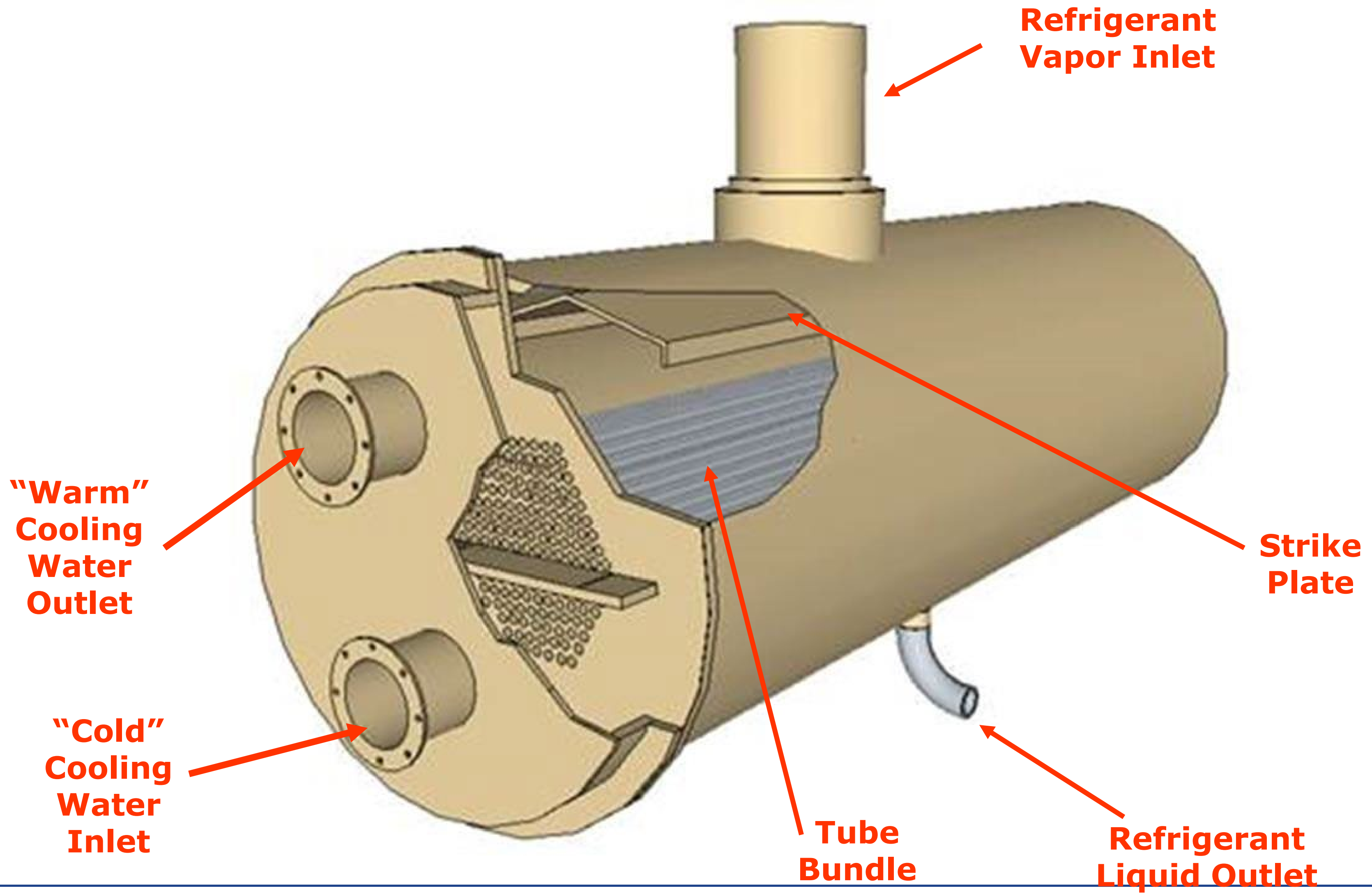
Evaporator / Cooler



Condenser


Refrigerant Vapor In from Compressor
Cooling Water
Heat Exchanger Chamber
Tube Bundle
Refrigerant Liquid Outlet

Condenser



Refrigerant
Vapor Inlet
"Warm"
Cooling
Water
Outlet
Strike
Plate
"Cold"
Cooling
Water
Inlet
Tube
Bundle
Refrigerant
Liquid Outlet

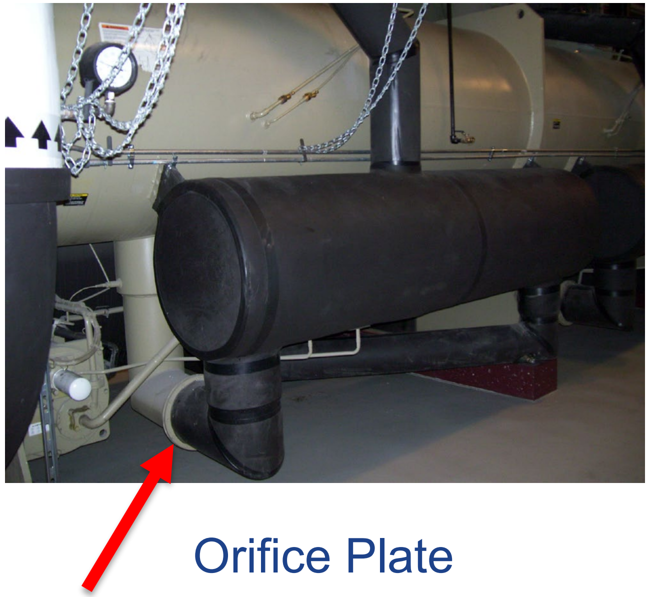
Compressor

- 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

Expansion Device

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

Electronic Expansion Valve



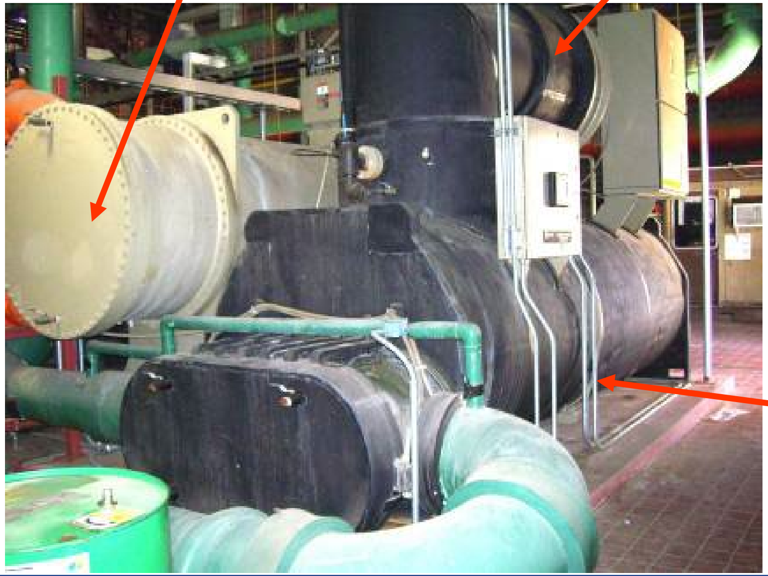
Orifice Plate

Flow / Level Control Valve

A Field Chiller

Condenser

Compressor



Evaporator (Chiller Barrel)

Other (Auxiliary) Components

- SubCooler
  - Internal / External
- Heat Recovery Equipment
- Receiver (or Refrigerant Storage Tank)
- Oil Filter, Cooler, Sump
- Purge Unit
- Pump Out unit

Process End-Users

Shell-and –tube Heat Exchangers

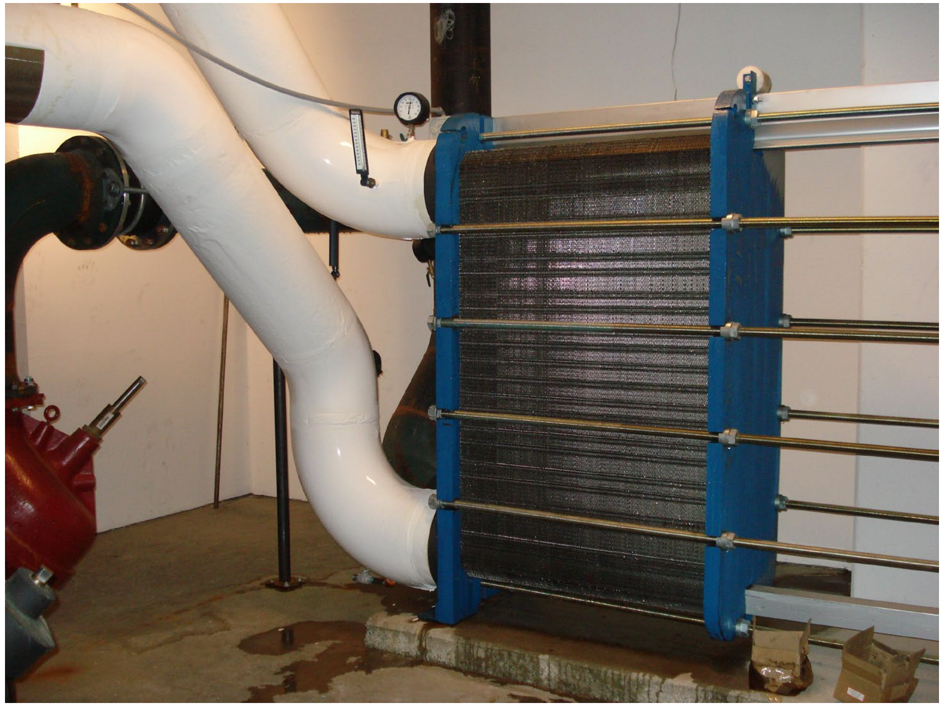


Plate and Frame Exchangers

End-Use can be very specific to industrial applications and will vary from one plant to another based on the products manufactured

End Use - Air Handling Unit

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

Heat Rejection Mechanism

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

Water-Cooled Condenser
Using Cooling Tower (Open Loop)

Heat Rejection Mechanism

- Indirect heat exchange - cooling towers have a closed loop heat exchanger
- Excellent to avoid fouling issues on the condenser of the chiller or other process heat exchangers
- Can be operated dry in colder ambients – to take advantage of air cooling and saving water

Water-Cooled Condenser
Using Indirect Cooling (Closed Loop)

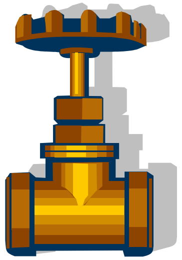
Heat Rejection Mechanism

- 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 20°F of the ambient dry-bulb temperature
- Not as efficient as water-cooled, BUT simple installation, easier to maintain, have a higher reliability, and can be more easily operated in freezing temperatures than cooling towers

Air-Cooled Condenser

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)



Types of Chillers

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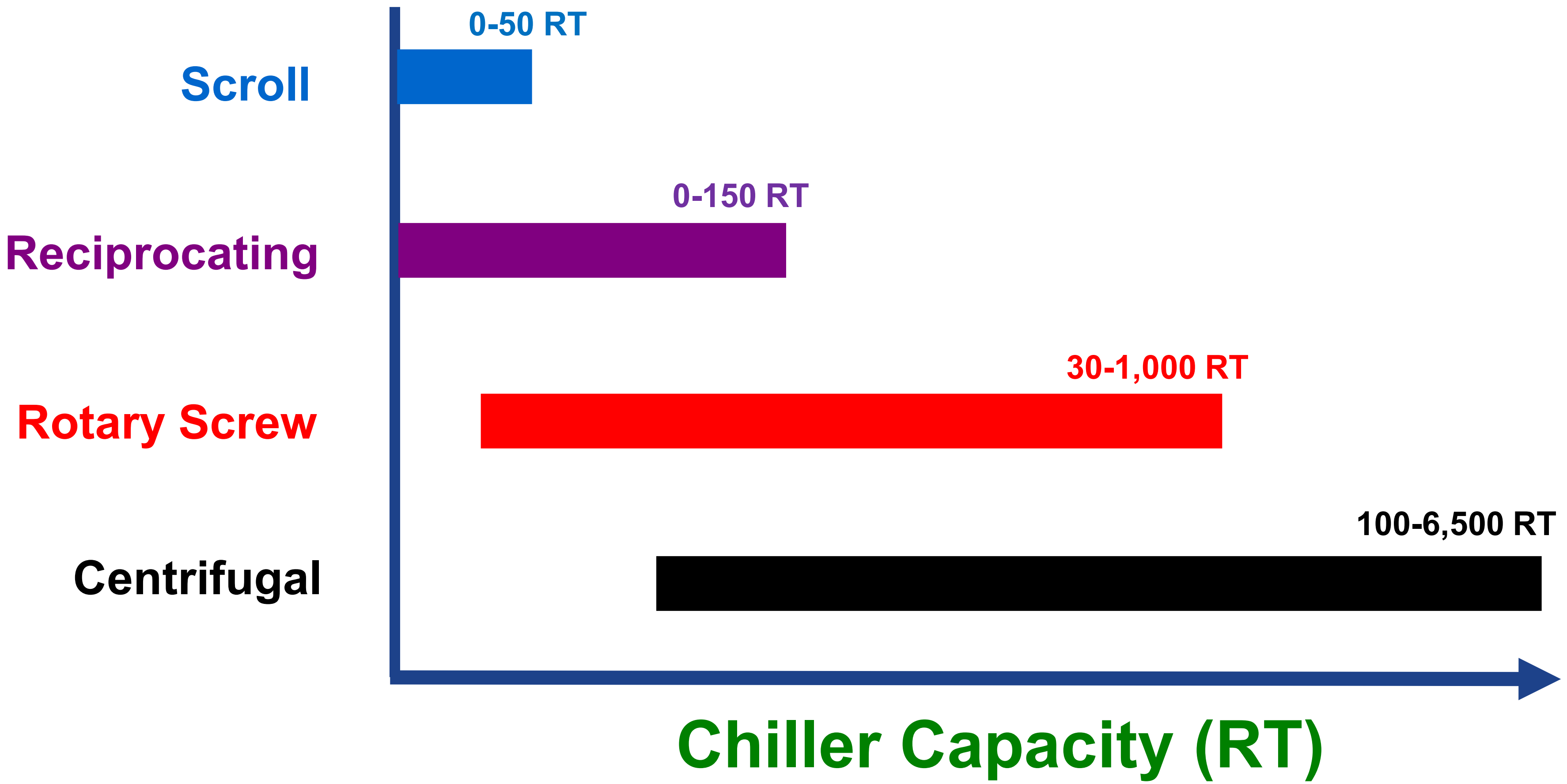
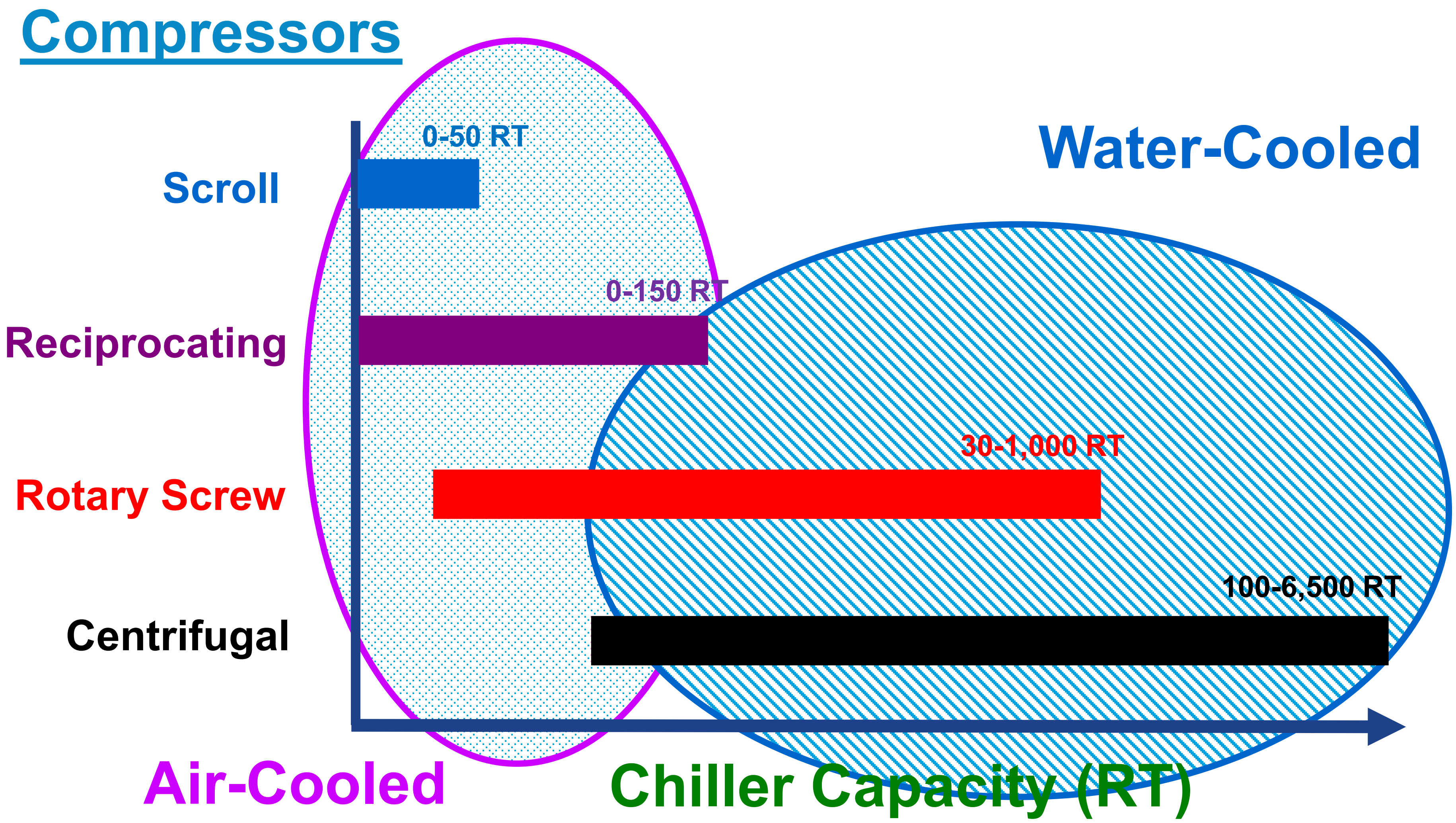
Different Compressor Types & Sizes

Compressors



Different Compressor Types, Sizes & Heat Rejection Mechanism



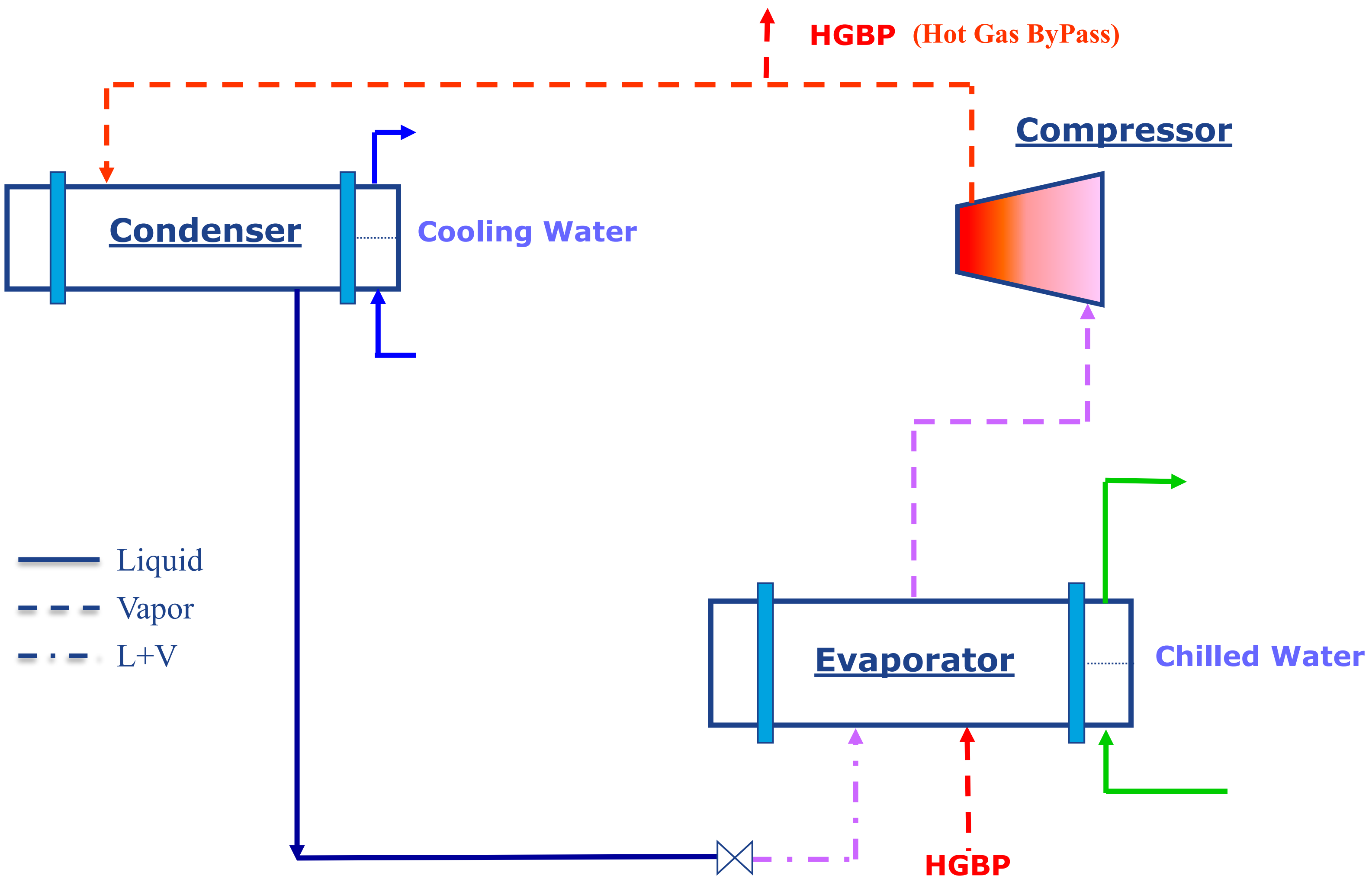
Polling Question 3 and 4

Polling Questions

3) What type of a chiller plant system(s) do you have?
   A. Water-cooled
   B. Air-cooled
   C. Both
   D. Don't know

4) What type of chiller compressors do you have in your chiller system(s)?
   A. Centrifugal
   B. Screw
   C. Reciprocating
   D. Scroll
   E. Combination of some of the above
   F. Don't know

Single Stage Chiller System



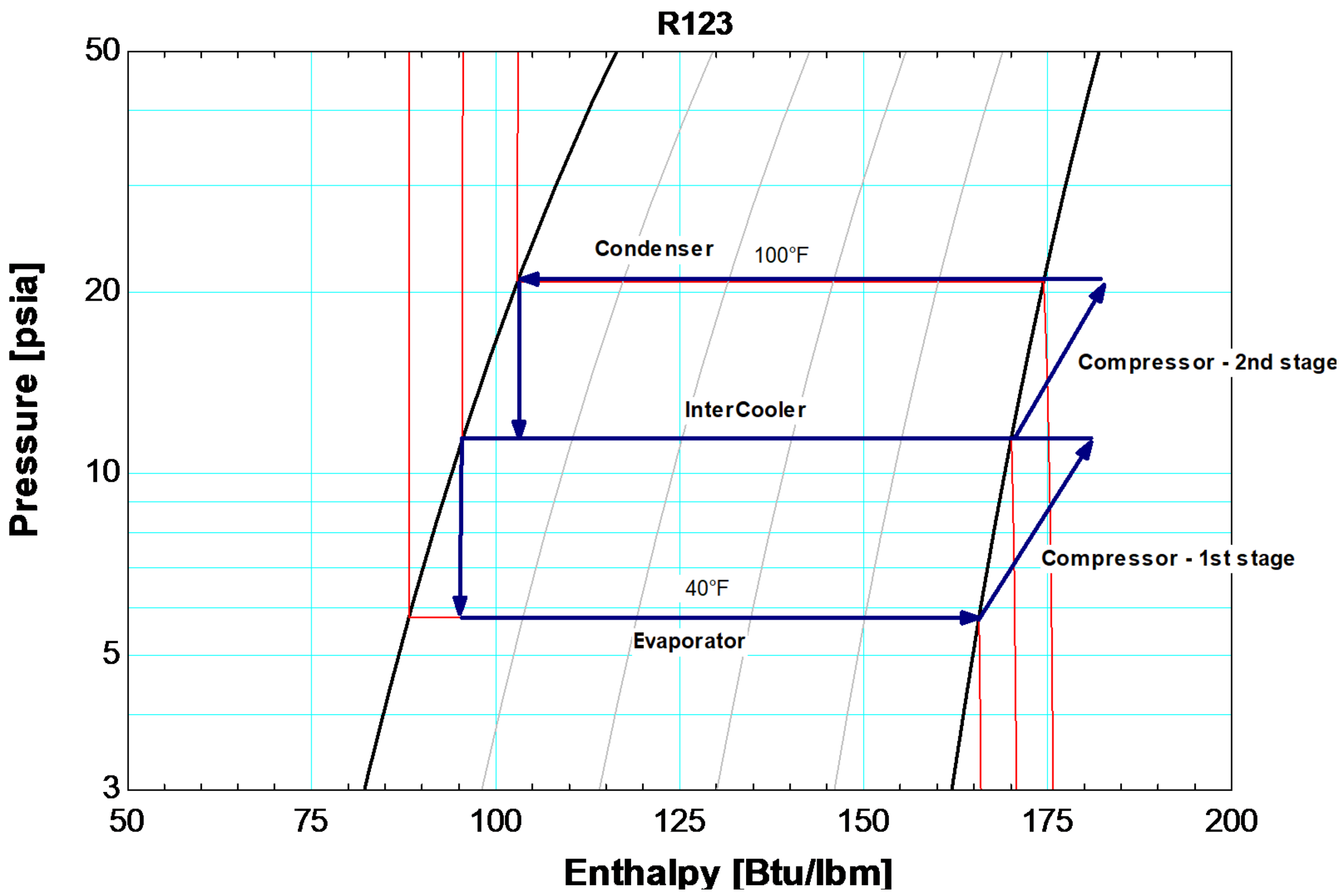
Multi Stage Chiller System

- The need for multistage systems
  - Compressor size limitations
  - For a specific refrigerant, 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 reduce sensible heat losses
- The downside
  - Requires additional components
  - May have higher first costs

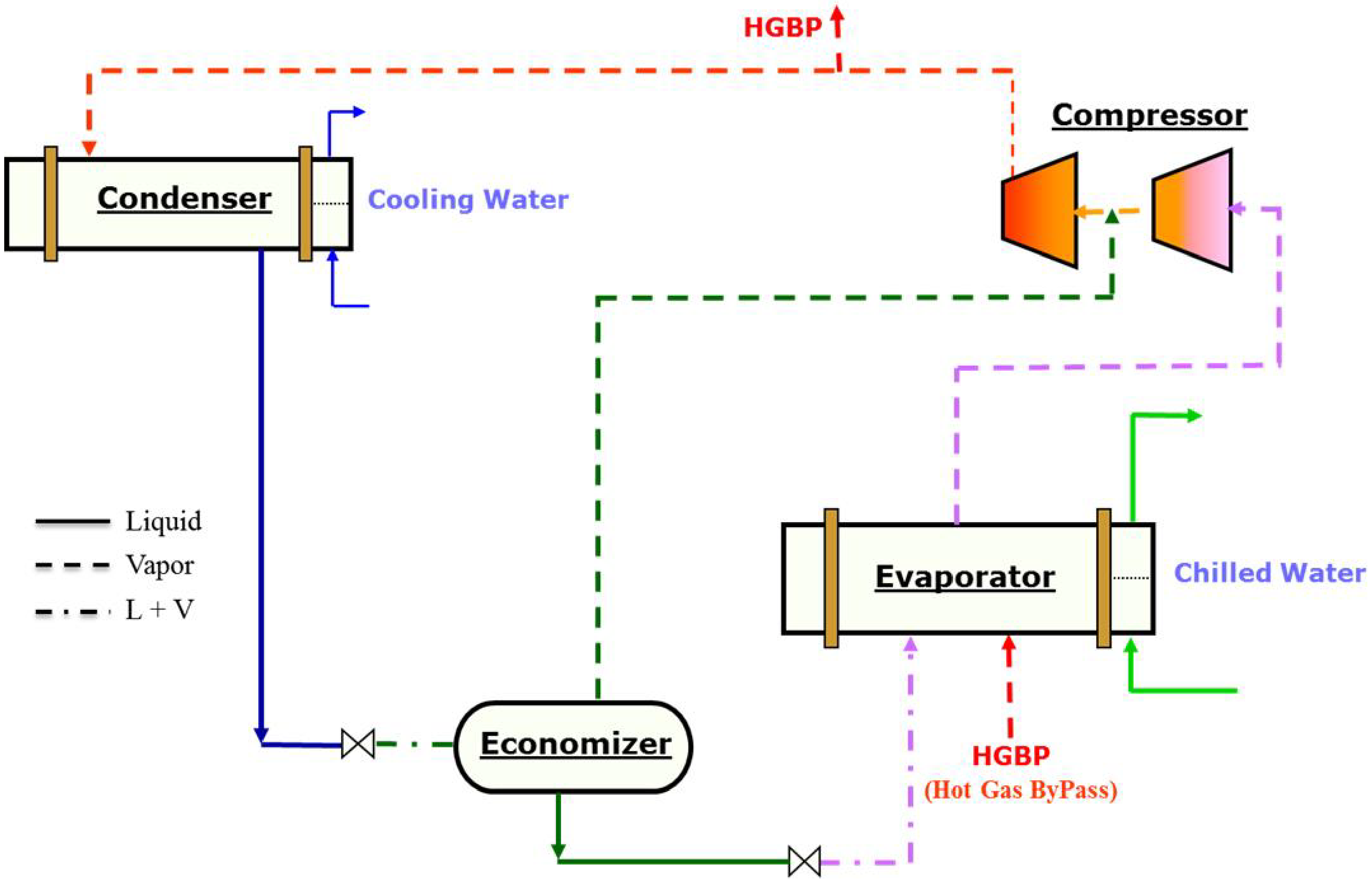
Multi Stage Chiller System

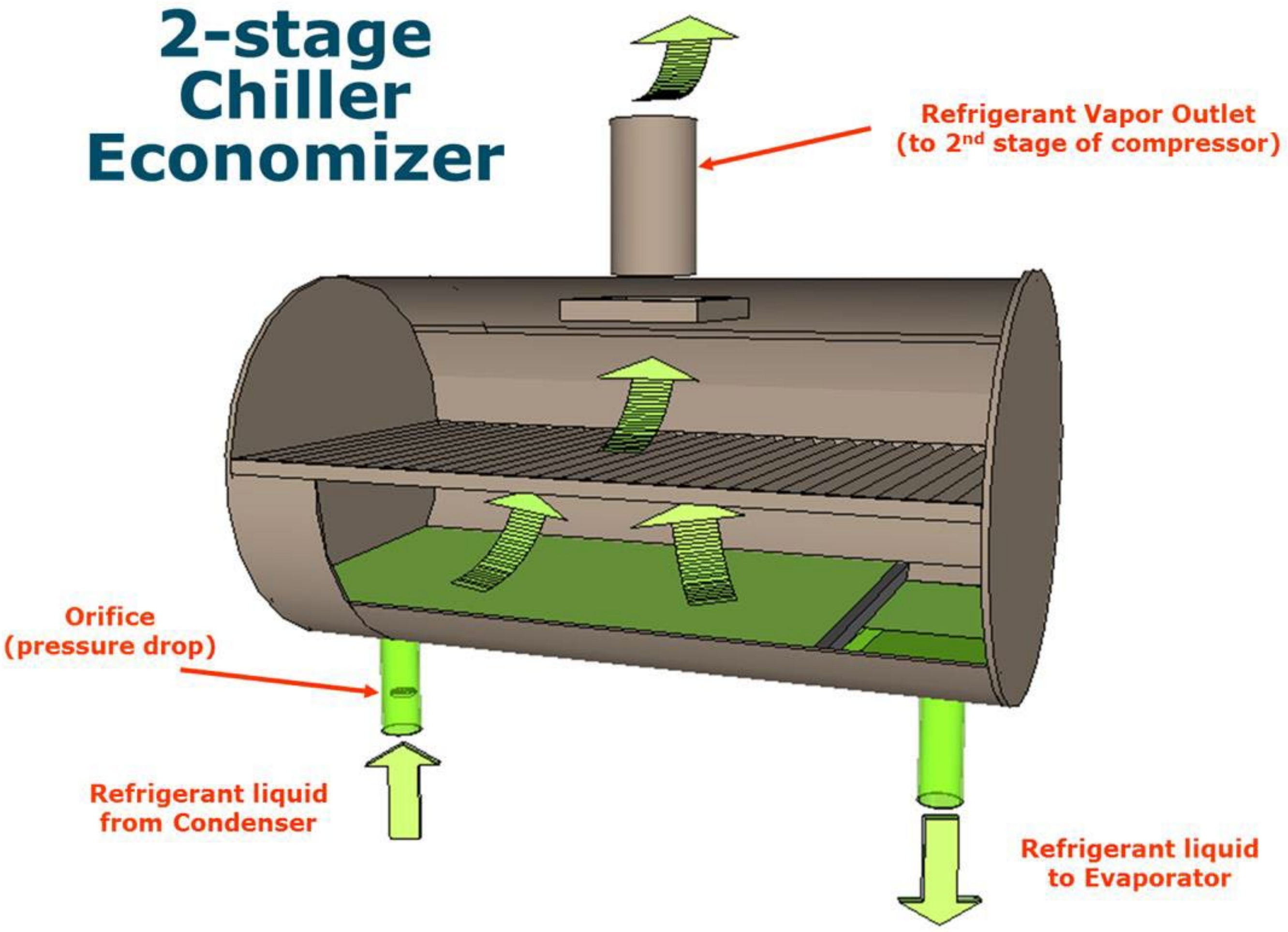
- InterCooler / Economizer / Flash Chamber
  - Thermodynamically
    - Warm saturated liquid flashes at intercooler pressure
    - Saturated cooler liquid (@ intercooler pressure) continues to the evaporator / lower stage intercooler
    - Saturated cooler vapor (@ intercooler pressure) continues to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

Economizer (InterCooler) Operation

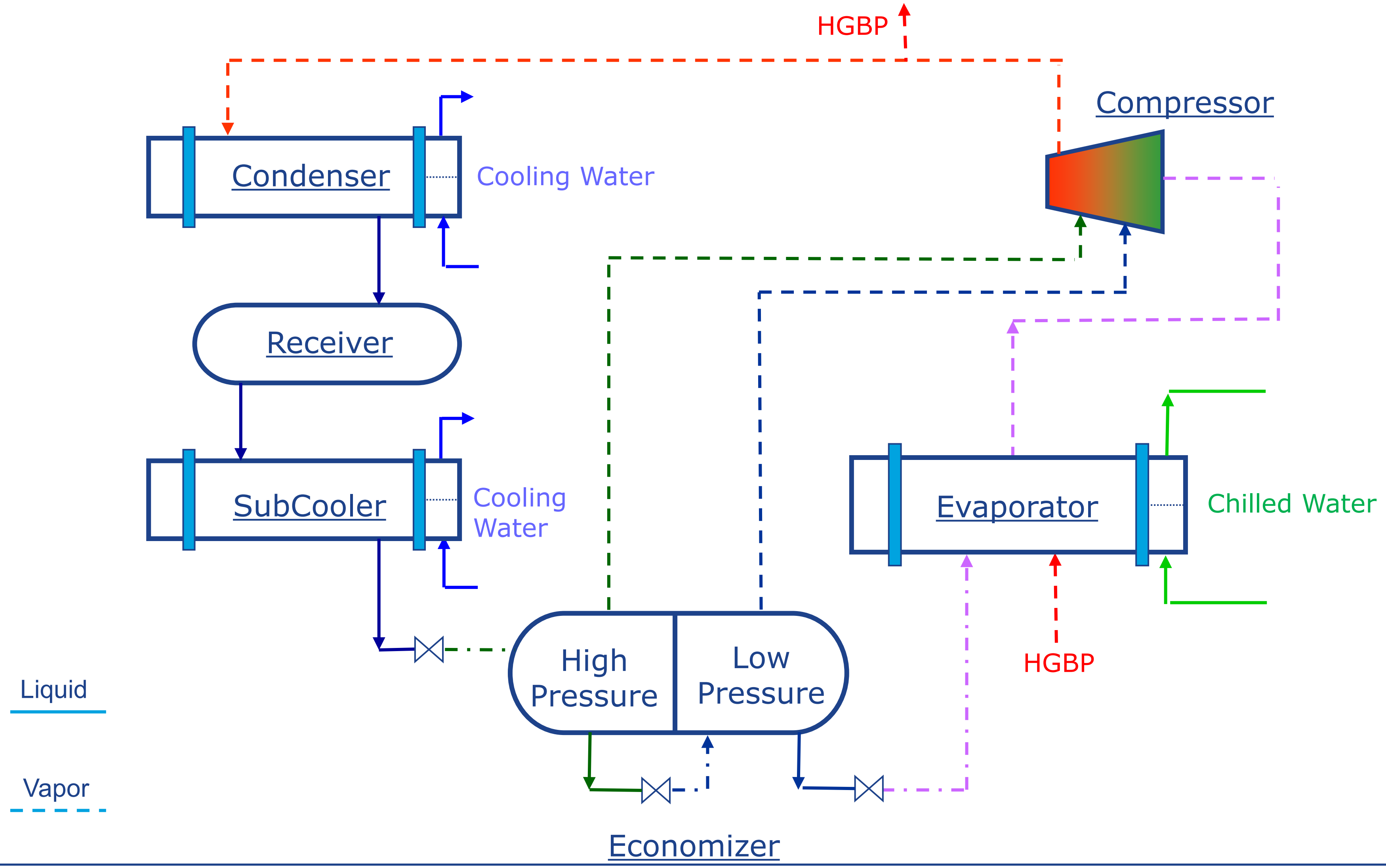


Two Stage Chiller System

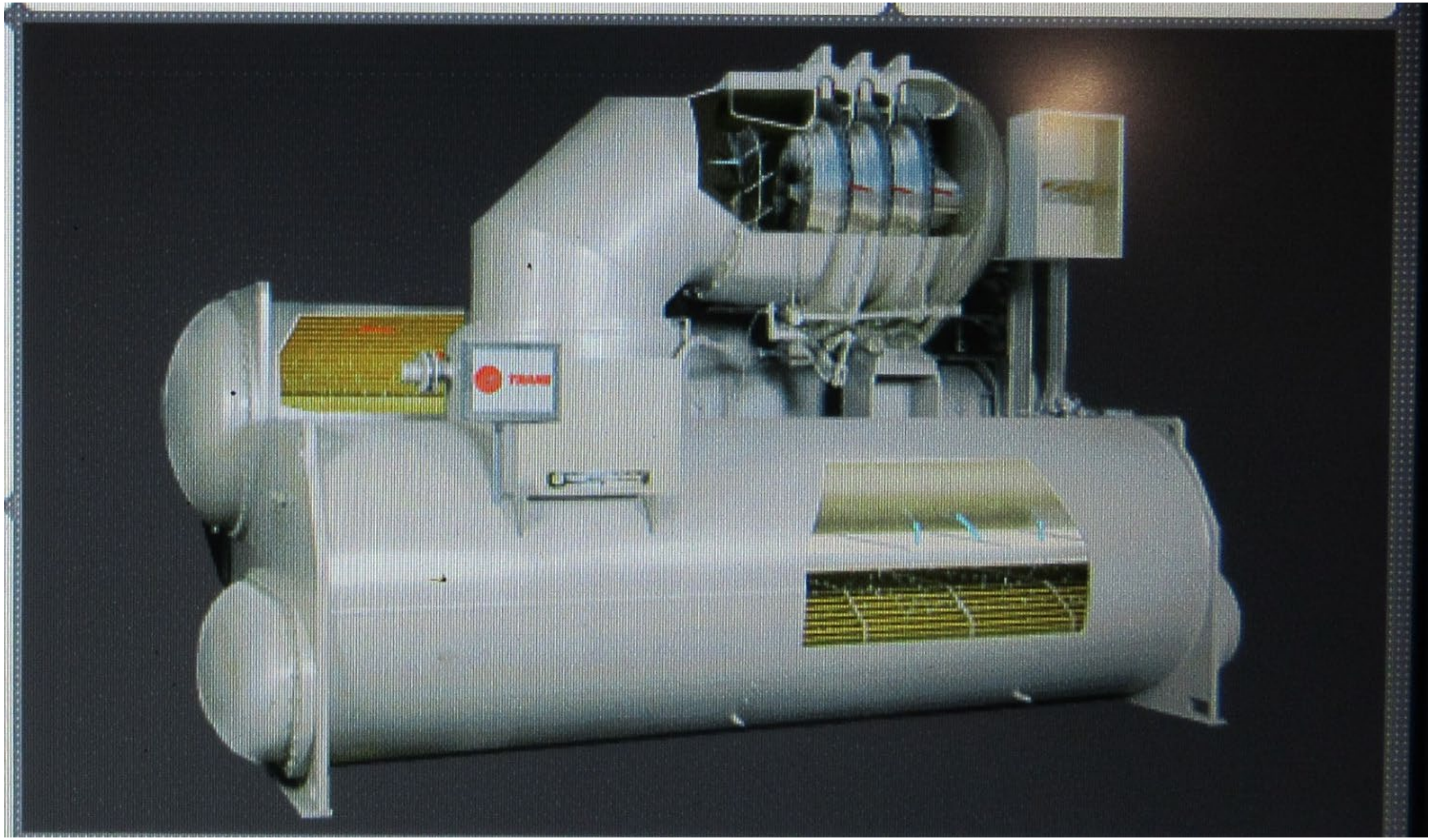



2-stage
Chiller
Economizer
Refrigerant Vapor Outlet
(to 2nd stage of compressor)
Orifice
(pressure drop)
Refrigerant liquid
from Condenser
Refrigerant liquid
to Evaporator

Three Stage Chiller System

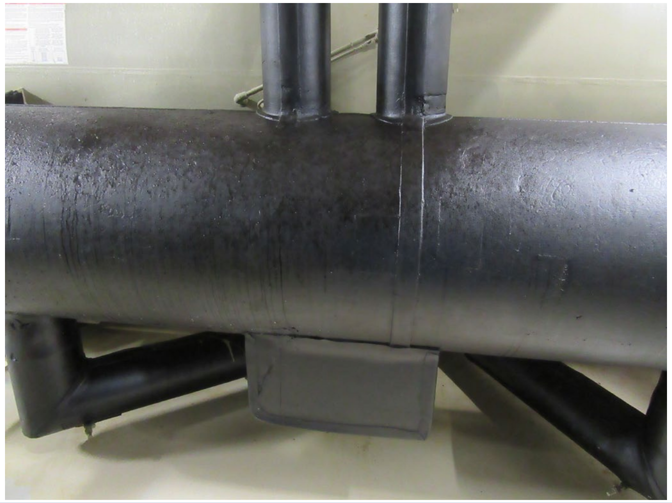


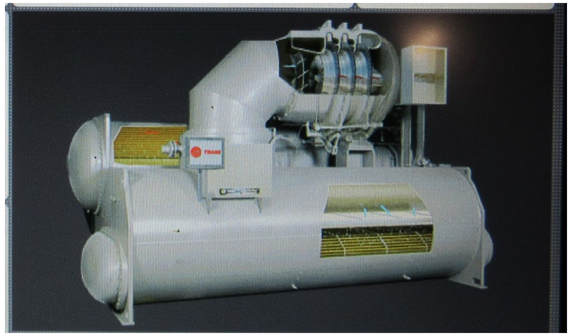
Large Three-stage Chiller



With permission from industrial customer. Operating dashboard picture

Large Three-stage Chiller





Pictures are courtesy of industrial customer.

Absorption Chiller Systems

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

Absorption Chiller Systems

- Absorption systems have minimal electrical load compared to conventional electric vapor compression chillers
- Applications
  - Waste heat recovery
  - Low pressure (temperature) exhaust steam
- Less moving parts
- Lower maintenance cost

Absorption Chiller Systems

- Evaporation and Condensation

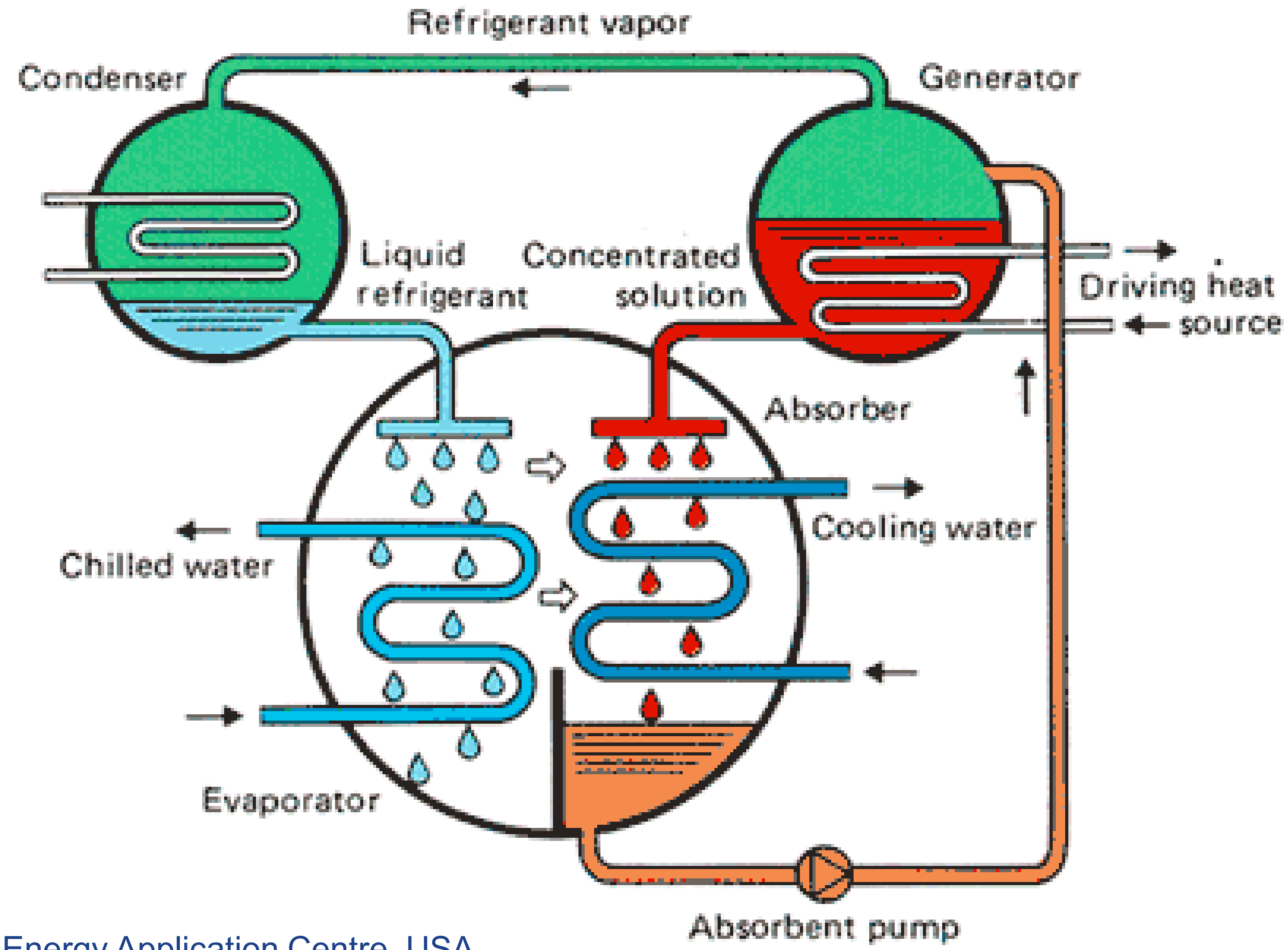
- Generation (Desorption)
  - Refrigerant vapor rich solution is heated to remove the refrigerant vapor
  - Temperature and solution concentration changes but pressure remains the same
  - Significant increase in the enthalpy
  - Heat input can take several different forms
  - Refrigerant vapor travels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

Absorption Chiller 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

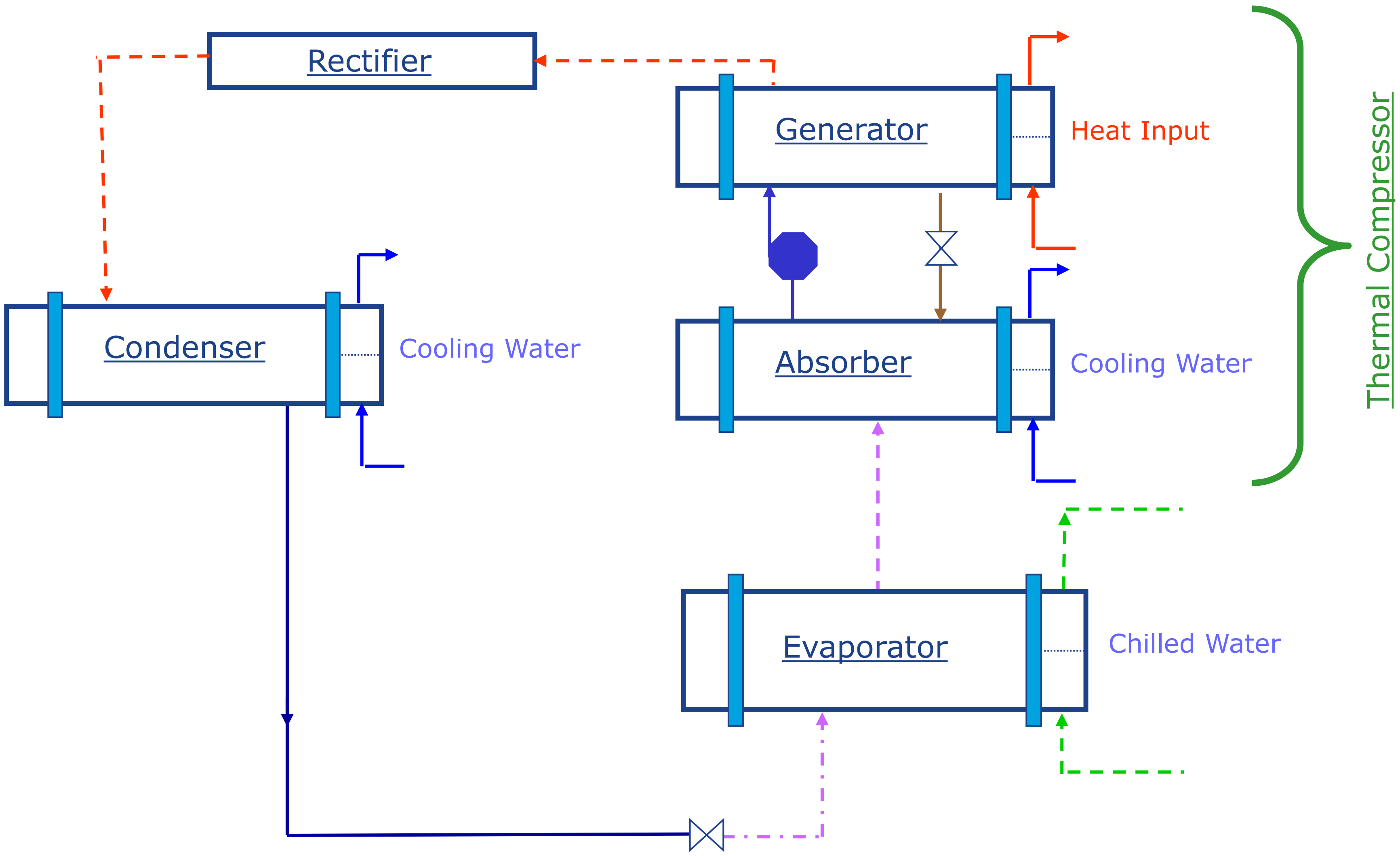
- Sensible Heat Exchange
  - Hot refrigerant depleted solution from the Generator exchanges sensible heat with refrigerant rich solution from the Absorber
  - Temperature changes but concentration and pressure remains the same

LiBr-Water Absorption Chillers



Courtesy: Midwest Clean Energy Application Centre, USA

Ammonia Water Absorption Chiller / Refrigeration System



Polling Question 5

Polling Questions

5) Do you have absorption chiller(s) in your plant?

A. Yes
B. No
C. Don’t know

Key Points / Action Items

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

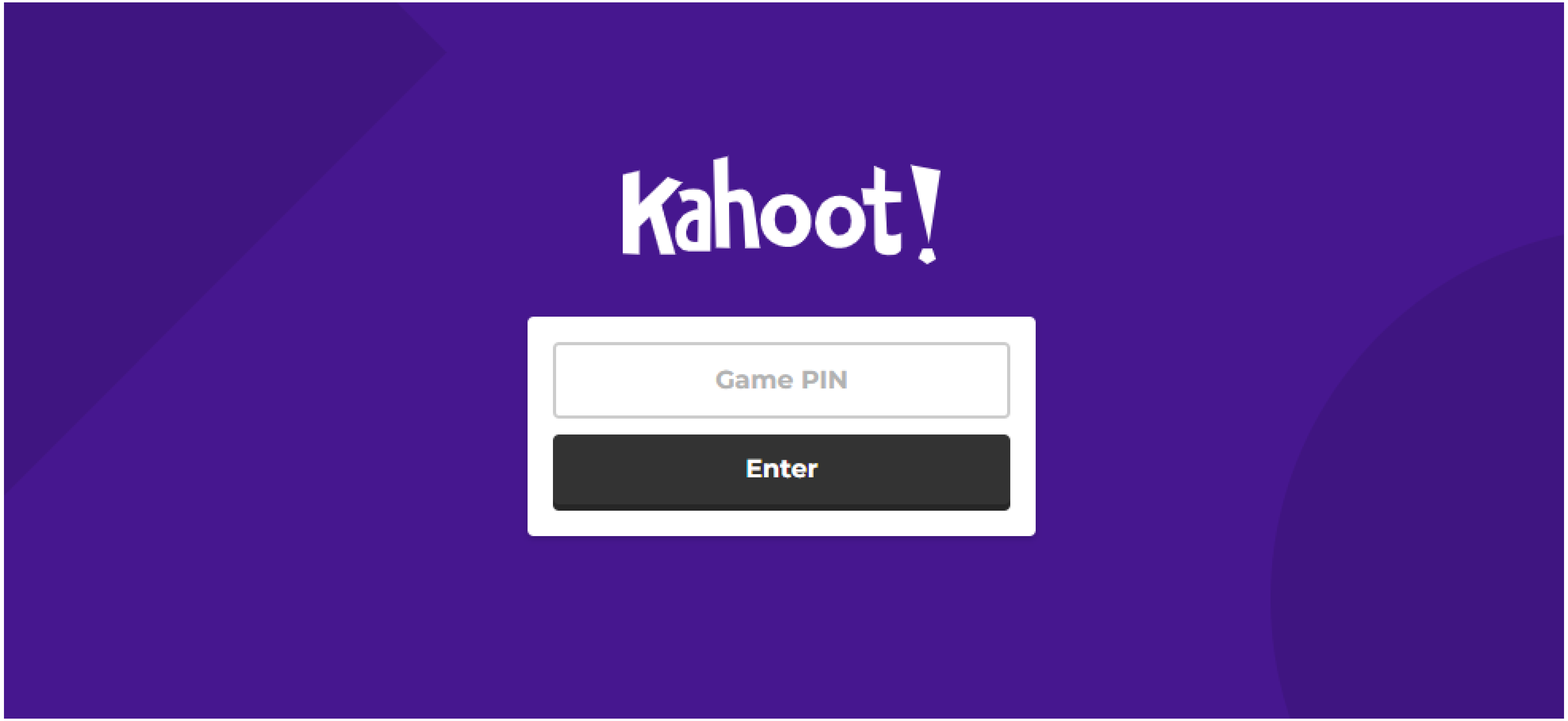
2. Two-stage and Three-stage systems will require one and two economizers (intercoolers), respectively

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

Homework #1

- Develop a high-level system understanding of your chilled water plant
- Collect nameplate / design-level information for the major components of your chilled water system
  - Chillers
  - Cooling Towers
  - Pumps
  - End-Users (will be a challenge but an approximate idea is good for now)
  - Other
- Make a high-level schematic drawing (one slide) for your distribution system

Kahoot Quiz Time



Thank You all for attending today’s webinar.

See you all next Thursday – July 23, 2026 – 2:00 pm ET

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

Alternately, you can email questions to us at paparra@ornl.gov or g@greensystemio.com

U.S. DEPARTMENT OF ENERGY