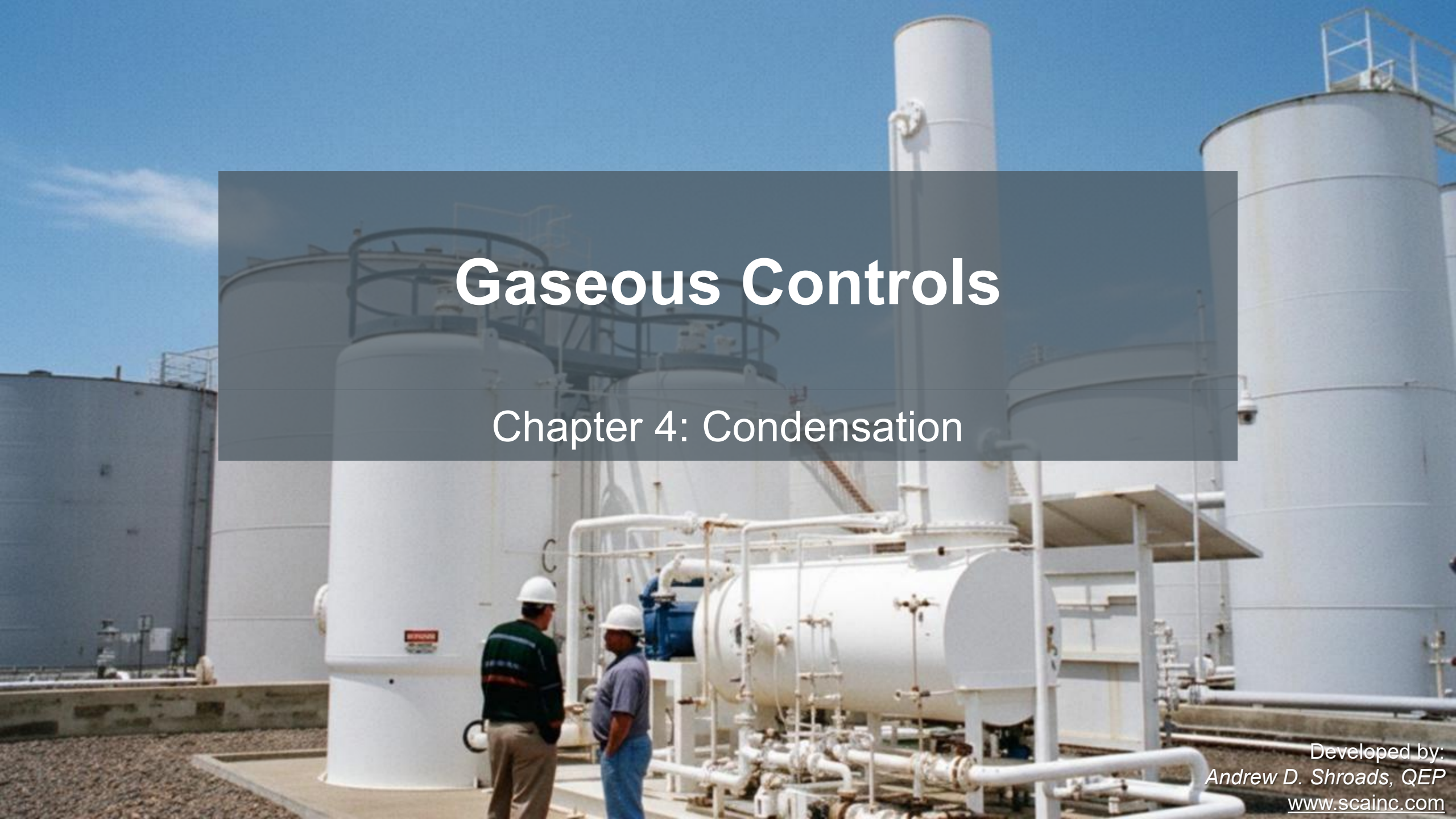


Gaseous Controls

Chapter 4: Condensation

Developed by:
Andrew D. Shroads, QEP
www.scainc.com

Chapter 4: Condensation
Objective

To improve understanding of condensation control technologies

- What are the types of condensation controls?
- How do condensation controls operate?
- How are condensation controls designed?
- What is the expected control efficiency for condensation?
- What are common problems with condensation control?
- How are condensation controls monitored?

Condensation

- VOC in exhaust are condensed from gas to liquid
  - Condensation begins at the dew point, when vapor reaches equilibrium with first condensate
  - Air pollutant condenses because it is below dew point or above its saturation vapor pressure (SVP)
    - Vapor Pressure: Pressure exerted by all components of a gas
    - Partial Pressure: Vapor pressure of an individual gas component
    - Saturation Vapor Pressure (SVP): Pressure where gas and liquid are in equilibrium
    - Dew Point: Temperature where gas becomes completely saturated
  - Useful to recover air pollutant as a product

Vapor Pressure

- Pressure of molecules evaporating to vapor
  - Total vapor pressure is sum of individual partial pressures
  - Higher vapor pressure means faster evaporation (more volatile)

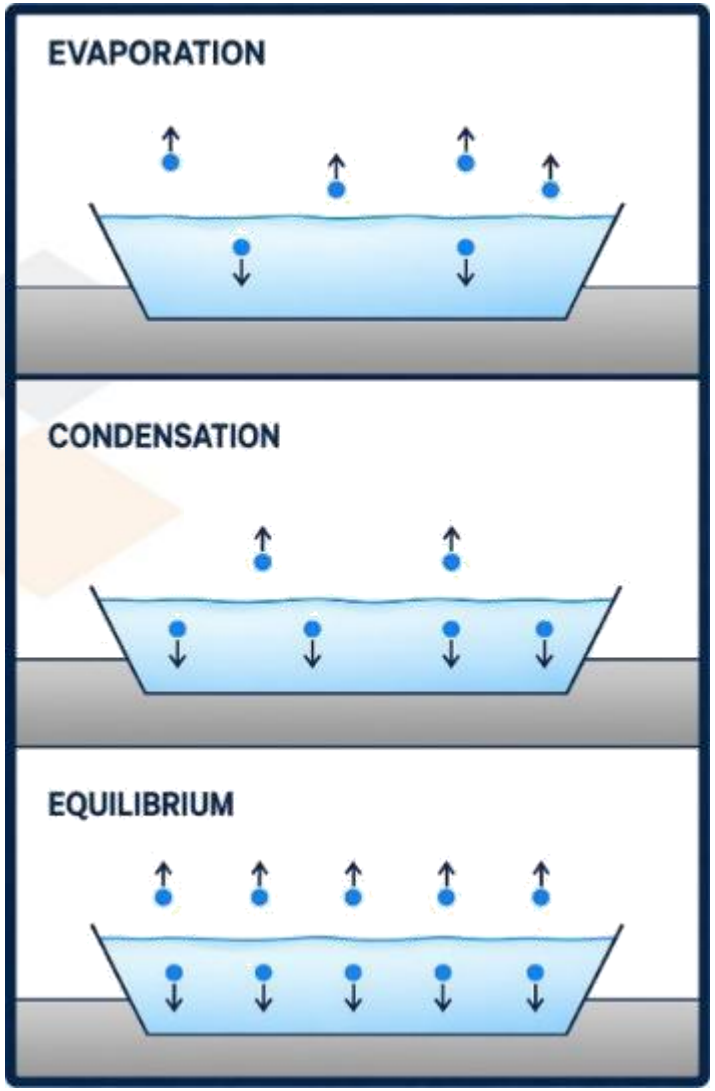


Compound	Vapor Pressure (70°F)[1]
Ethylene Glycol	0.001 psi
Ethylbenzene	0.14 psi
Water	0.35 psi
Toluene	0.55 psi
Isopropyl Alcohol	0.64 psi
Trichloroethylene	1.3 psi
Ethyl Alcohol	0.9 psi
Benzene	2.0 psi
Acetone	4.4 psi

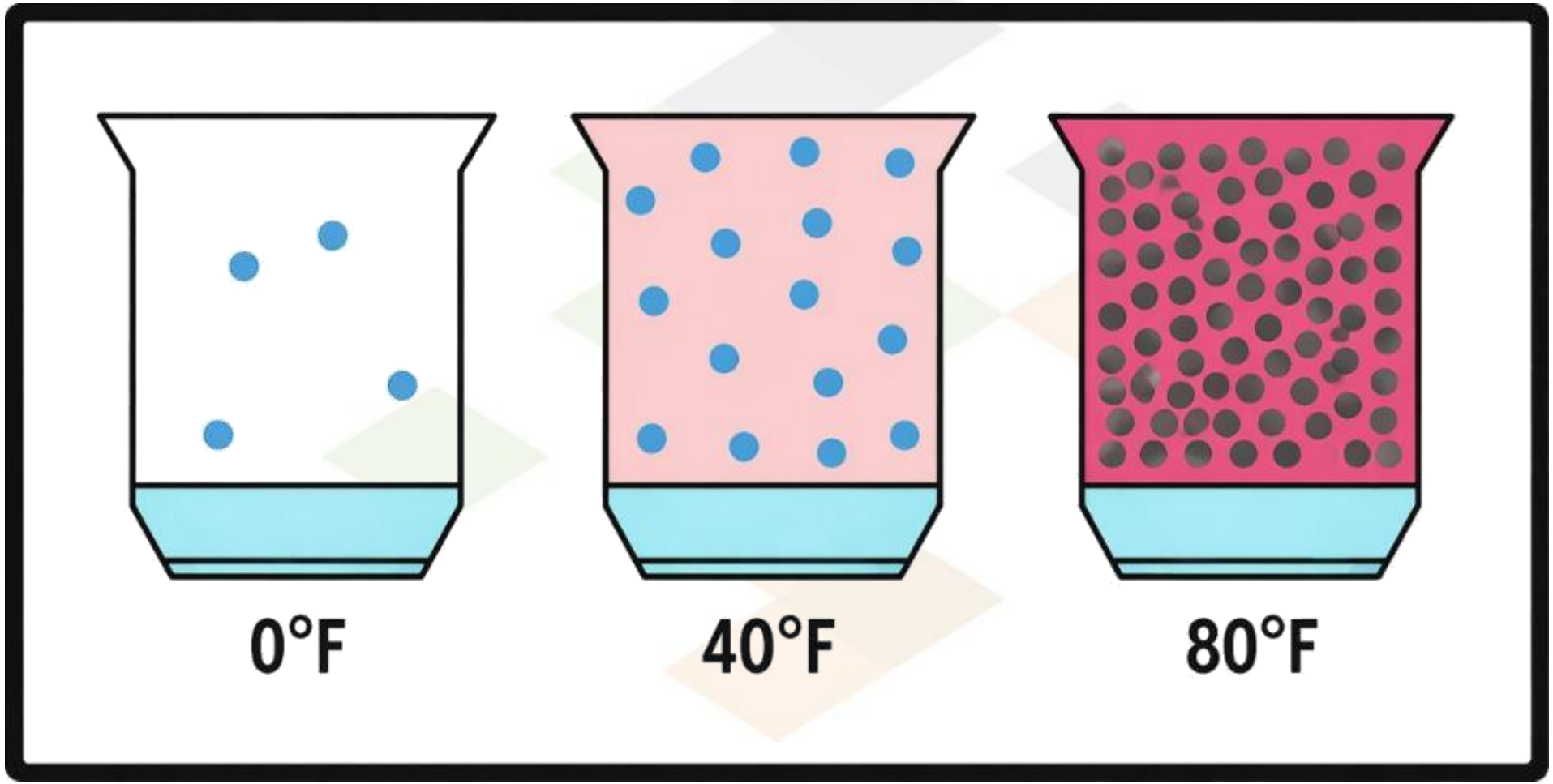
[1] From The Engineering Toolbox

Saturation Vapor Pressure (SVP)

- Gas is at equilibrium with liquid
  - Equal evaporation and condensation rates
- Gas vaporizes (evaporates), reducing temperature of remaining liquid
  - Occurs below boiling point
  - Concept behind sweat and swamp coolers
- SVP is when gas cannot vaporize any more liquid (gas is fully saturated)
  - Increasing gas pressure above SVP causes condensation

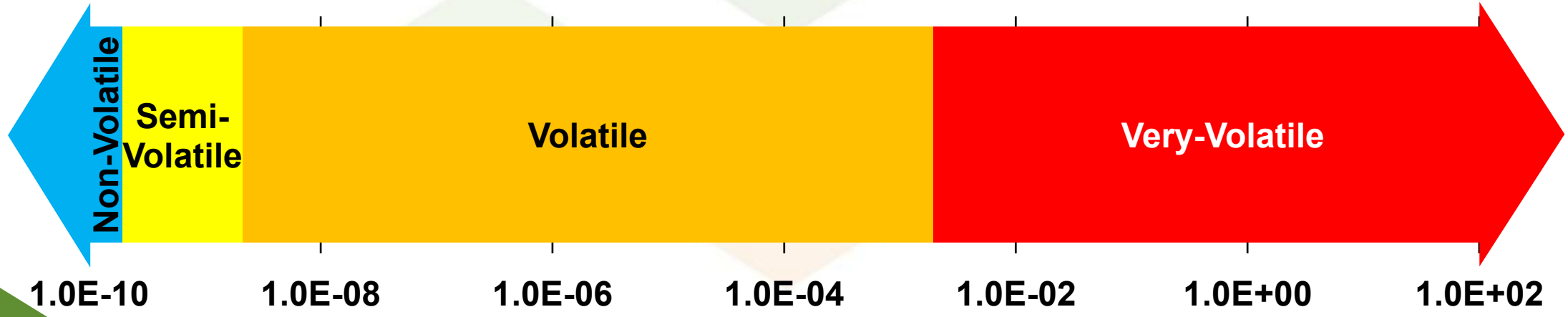


Approximate Vapor Pressure of Water by Temperature



EPA Categorization of Vapor Pressures

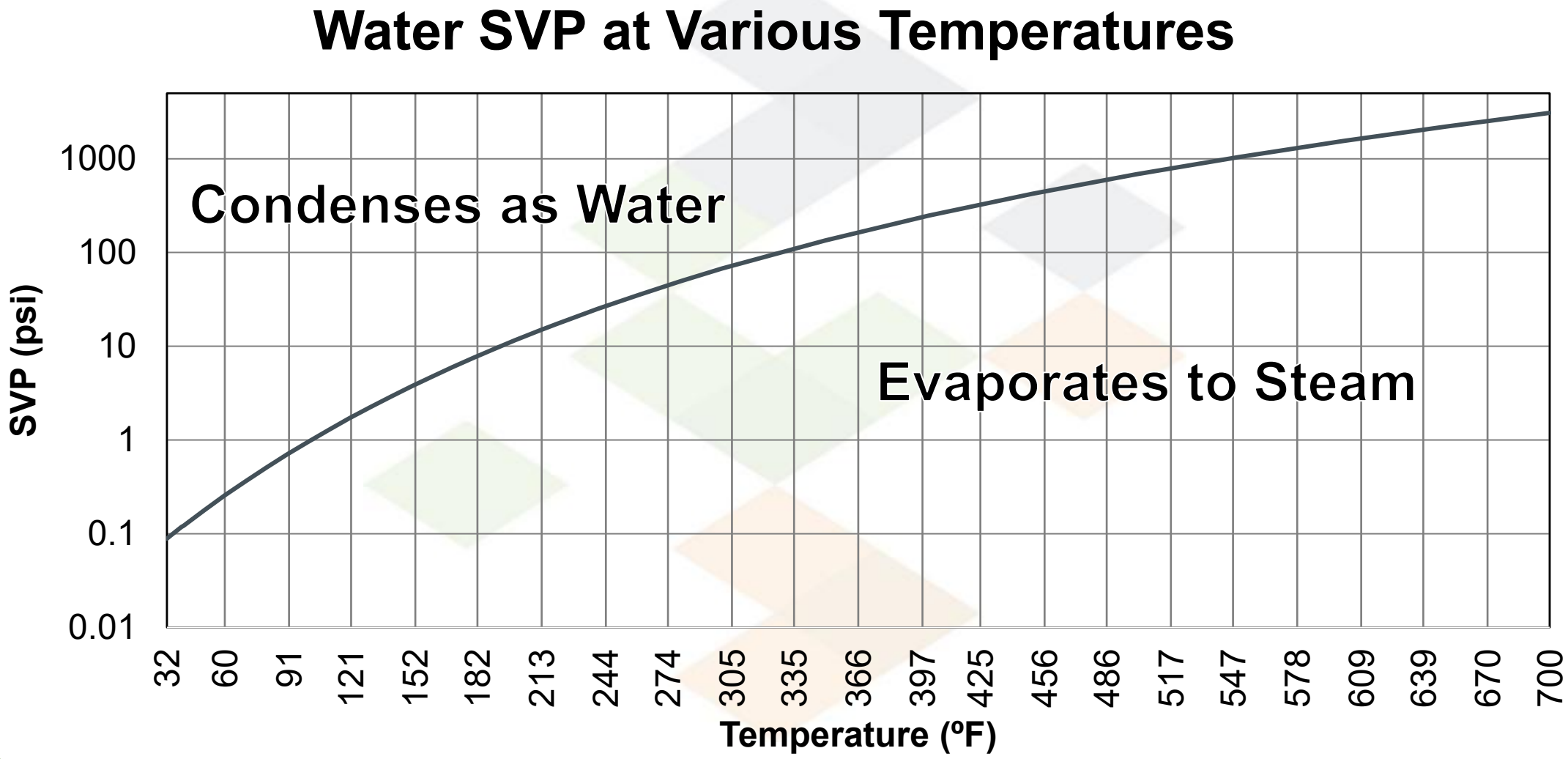
- Very Volatile Organic Compounds:
  - >380 mm Hg (7.35 psi)
- Volatile Organic Compounds:
  - >0.1 mmHg (1.9×10^{-3} psi) & <380 mm Hg (7.35 psi)
- Semi-volatile Organic Compounds:
  - >1×10^{-7} mmHg and (1.9×10^{-9}) <0.1 mm Hg (1.9×10^{-3} psi)



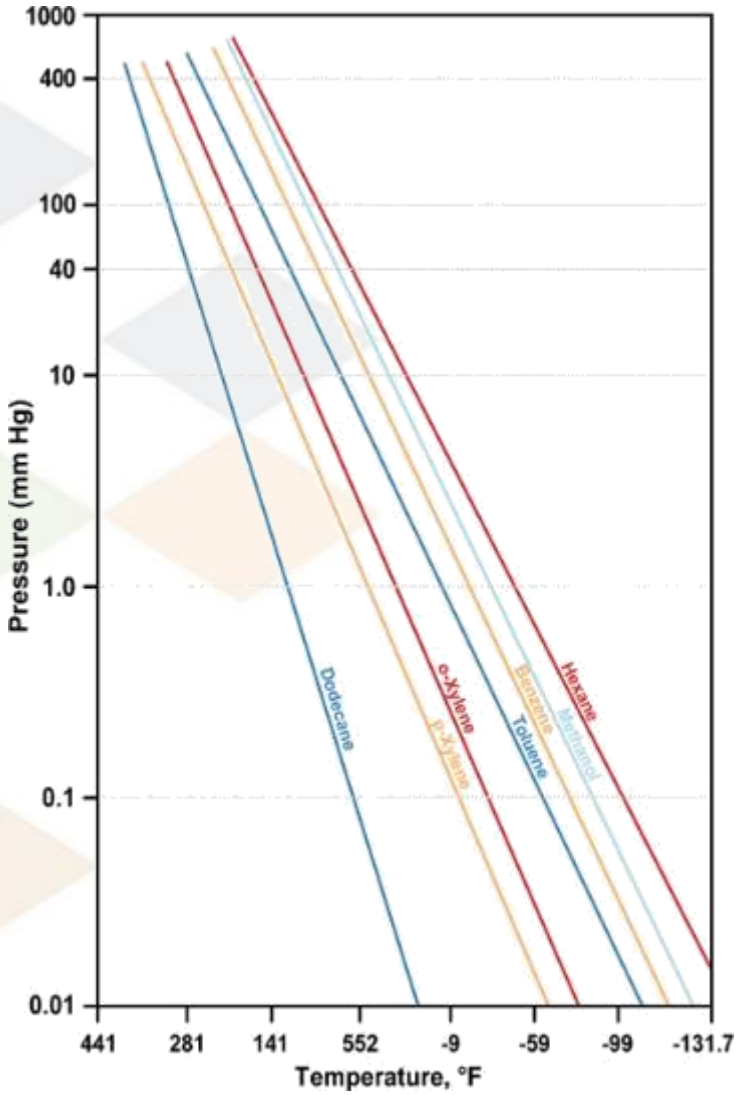
Dew Point

- Temperature where material condenses
  - When gas is at SVP, dew point is temperature at which gas will condense to liquid
  - Cooling a gas lowers the SVP, causing condensation due to lower dew point
- Liquids condense on objects that are cooler than dew point
  - On a glass of ice water, humidity condenses on outside of glass (below dew point) while water inside of glass evaporates (below SVP)



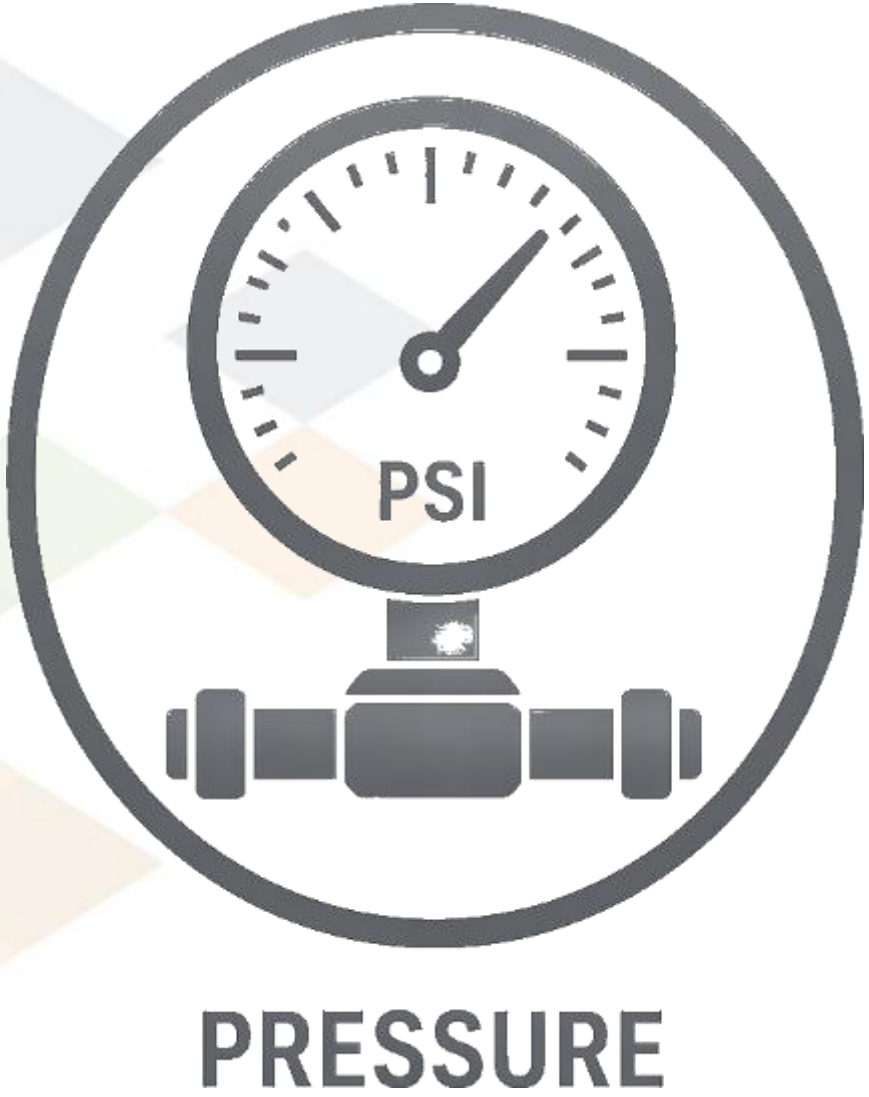

Water SVP at Various Temperatures
Condenses as Water
Evaporates to Steam
SVP (psi)
1000
100
10
1
0.1
0.01
32
60
91
121
152
182
213
244
274
305
335
366
397
425
456
486
517
547
578
609
639
670
700
Temperature (ºF)

- Pressure Condensers
  - Increasing pressure raises gases above SVP
- Temperature Condensers
  - Decreasing temperature lowers dew point for gases at SVP
  1. Chilled Water (40 to 80ºF)
  2. Brine (0 to 80ºF)
  3. Refrigeration (-50 to -150ºF)
  4. Cryogenic (-100 to -320ºF)



Pressure Condensers

- Compression raises VOC partial pressure and heat removal allows condensation
  - Very uncommon control device



Pressure Condenser

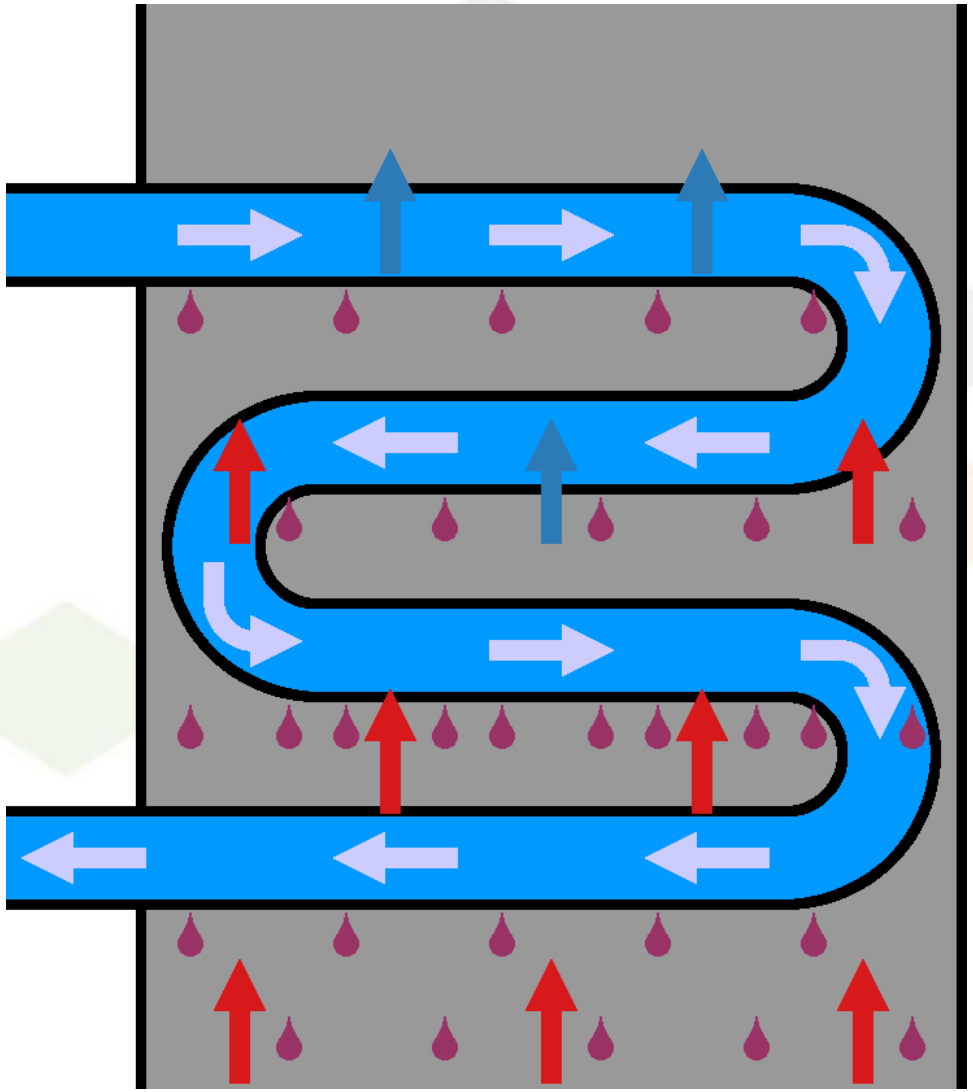


Refrigerated Condensers

- Temperature of exhaust is reduced below VOC dew point
  - Useful to recover air pollutant as a product
  - Must have high VOC concentration in process gas

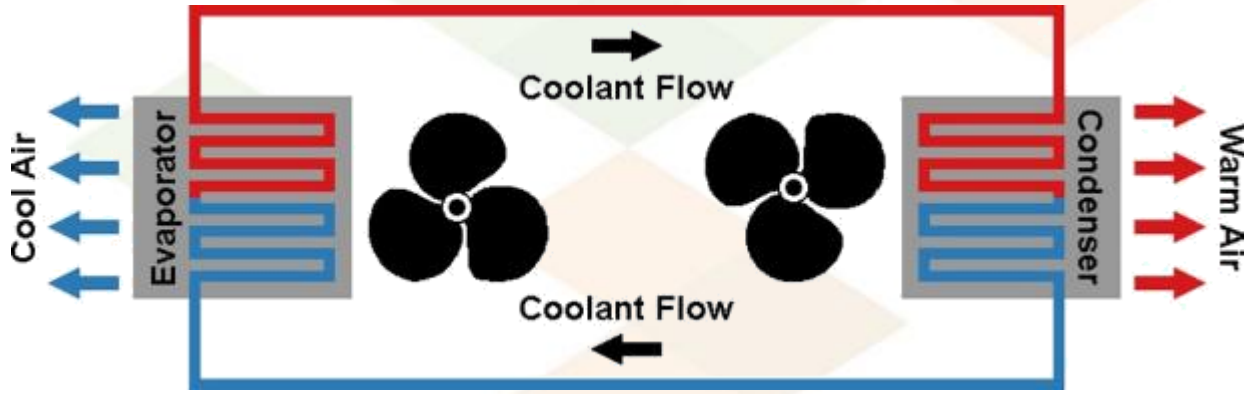


Chapter 4: Condensation
Principles of Operation



Refrigeration Cycle

- Evaporator: VOC in exhaust are cooled from gas to liquid
  - Gas must be brought below VOC dew point
- Condenser: Releases waste heat to ambient air
  - Returns chilled refrigerant back to evaporator



Chapter 4: Condensation
Video

VOC 2.0 - Condensation Intro.mp4

VOC 2.1 - Condensation Conventional.mp4

VOC 2.2 - Condensation Refrigeration.mp4

VOC 2.3 - Condensation Cryogenic.mp4

Chapter 4: Condensation Controls





Condenser

- Process Gas Temperature
- Process Gas Pressure
- Coolant Temperature
- VOC Dew Point
- VOC / PM Concentration
- Residence Time
  - Maximize to cool below dew point
- Surface Area (Surface Condenser)

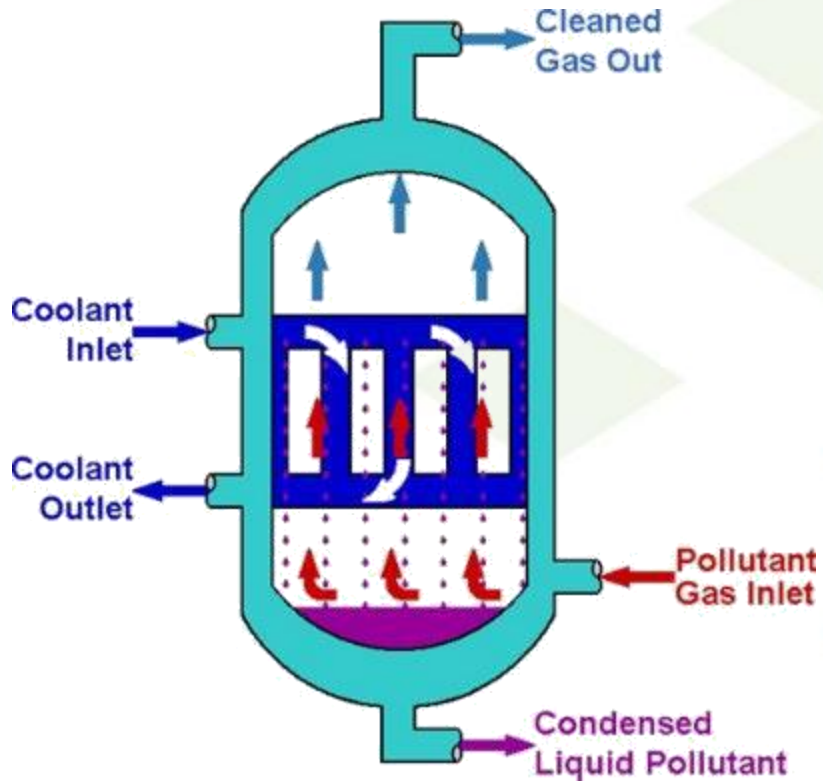


Conventional Condenser

- Operate 40 to 80ºF on water or 0 to 80ºF on brine (saltwater)
- Normally use water or air to cool exhaust stream and condense VOC
  1. Surface (No Contact): Gas condenses on surface chilled by coolant
  2. Direct Contact: Mixing of coolant and gas (wet scrubber)
- Air condensers may be used where water is not recommended
  - Larger than water condensers due to reduced heat transfer efficiency

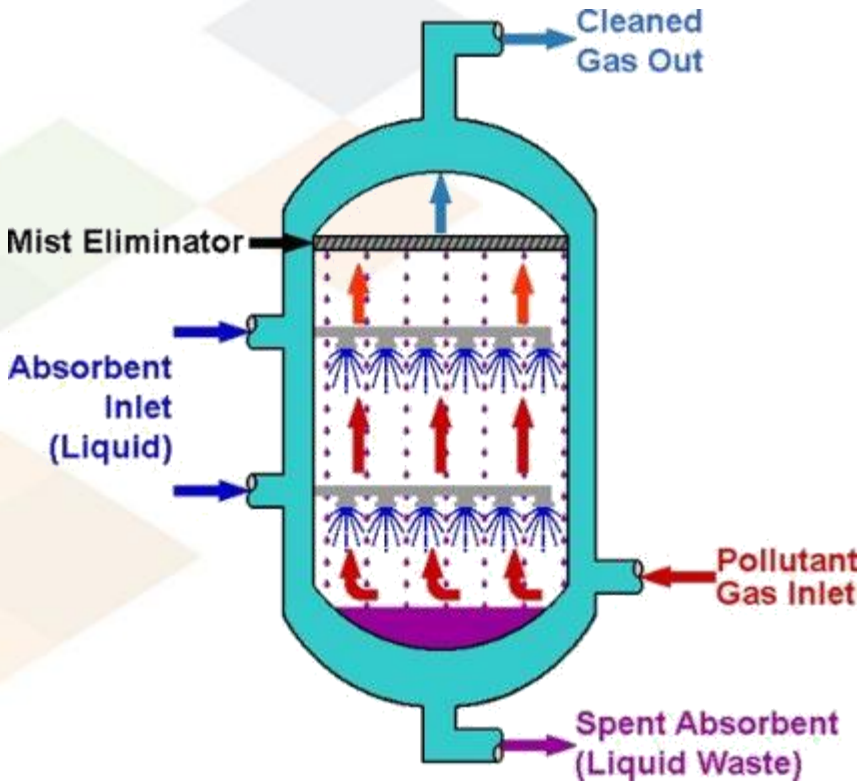
Surface Condenser

Coolant flows within tubes, does not contact air pollutant

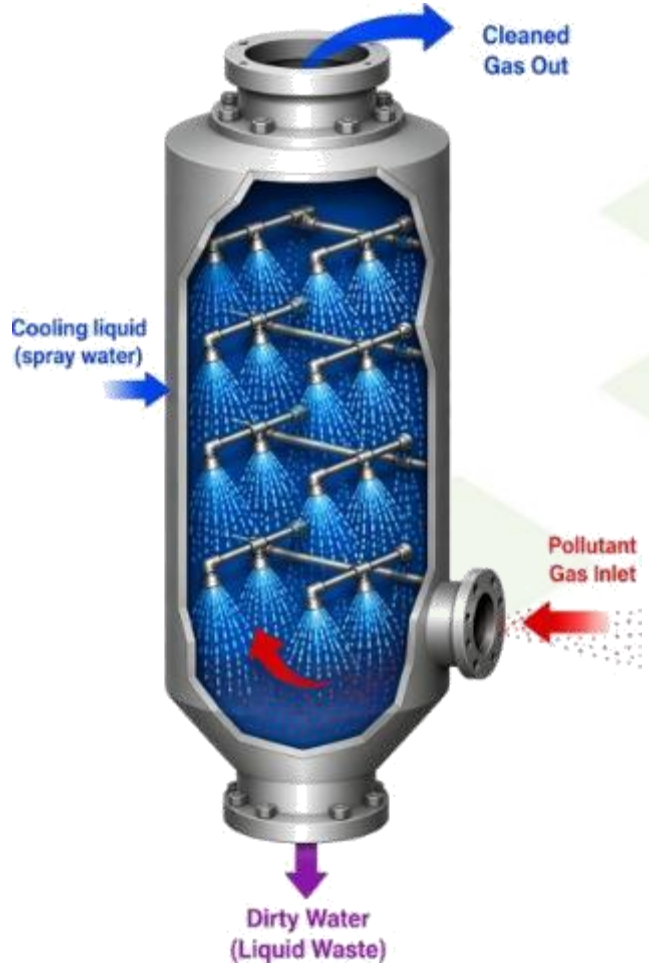


Contact Condenser

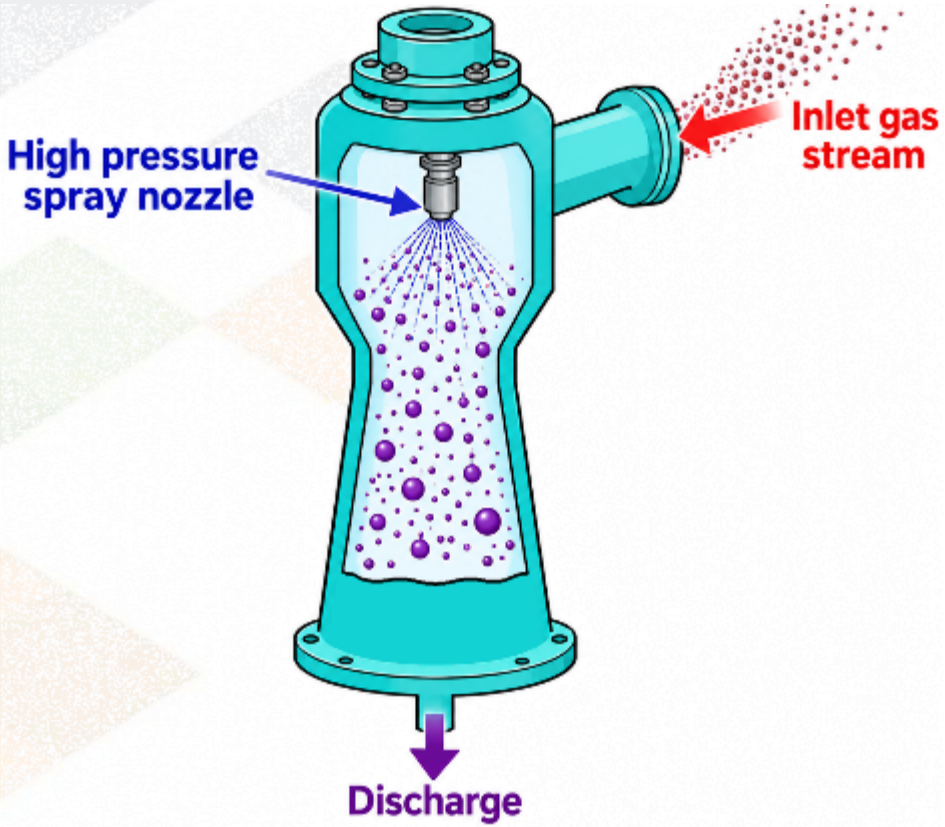
Coolant sprayed into gas stream, contacts air pollutant



Contact Condenser (Spray)



Contact Condenser (Ejector)



Surface Condenser

- Heat exchanger (heat pump) for moving heat from process gas
  - Absorbs heat from process gases in evaporator (causing condensation) and releases heat to ambient air in chiller
  - Water, brine, refrigerants, and cryogenic liquids are used as heat transfer fluids

Surface Condenser

- Coolant separate from VOC
- Commonly used for air pollutants
- Reduced waste disposal problems
- Size based on cooling surface area
- More costly

Contact Condenser

- More flexible
- Less repair time
- Wet waste disposal problem
- Size based on temperature / flow of liquid
- Cheaper

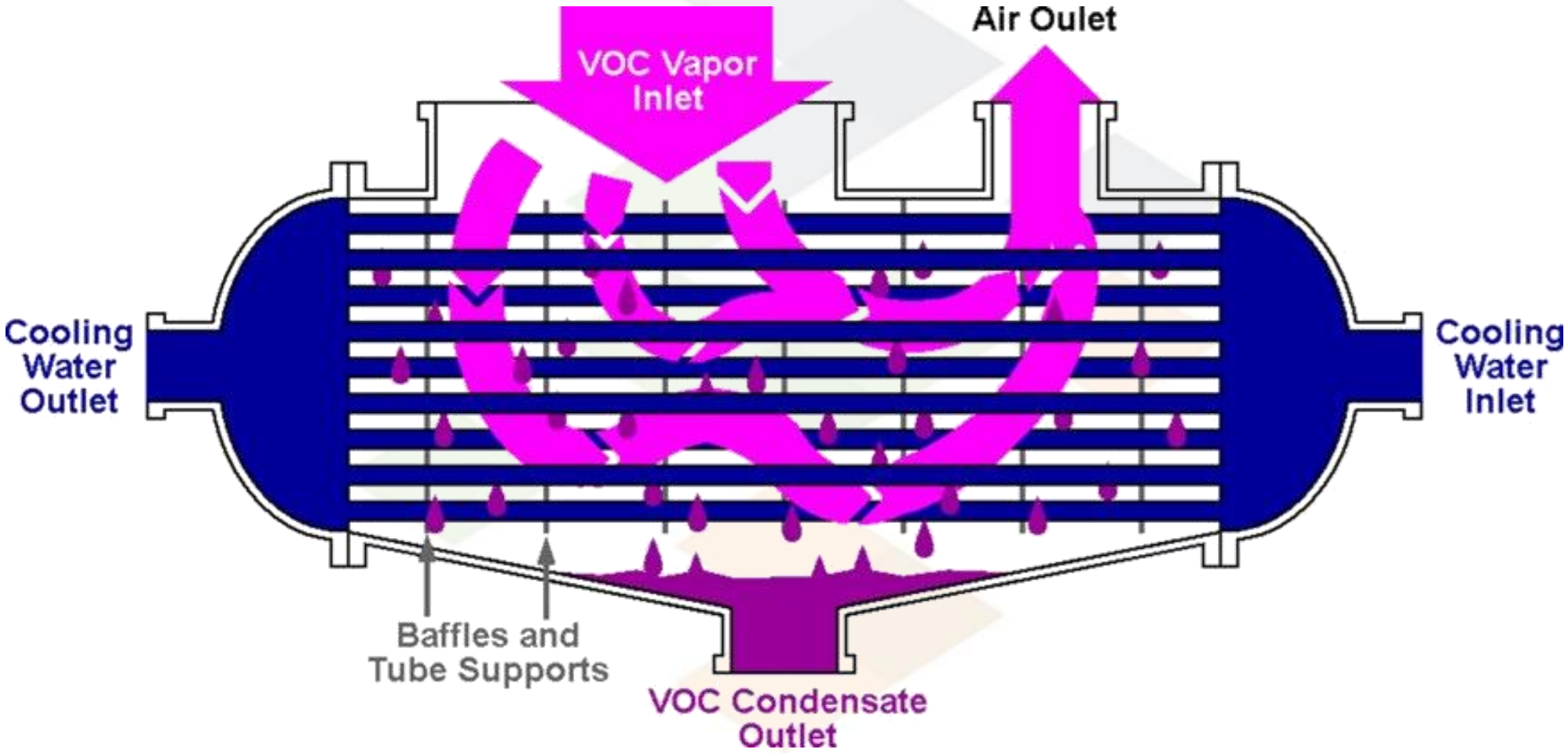
Air Refrigerated Condenser



Shell and Tube Heat Exchanger

- Circular or oval cylindrical shell into which exhaust flows
  - Numerous small tubes through with coolant flowing through
- Coolant flows through tubes; vapors condense into condensate
  - Requires large number of tubes and low process gas velocity to provide adequate heat transfer (cooling)
  - Temperature of cooling tubes varies over length of heat exchanger
- Used when exhaust VOC is a single recoverable product (reclaimed VOC can be reused in process / sold)
  - If used for VOC mixture, reclaimed VOC can be separated (fractionation column) or disposed of as a waste

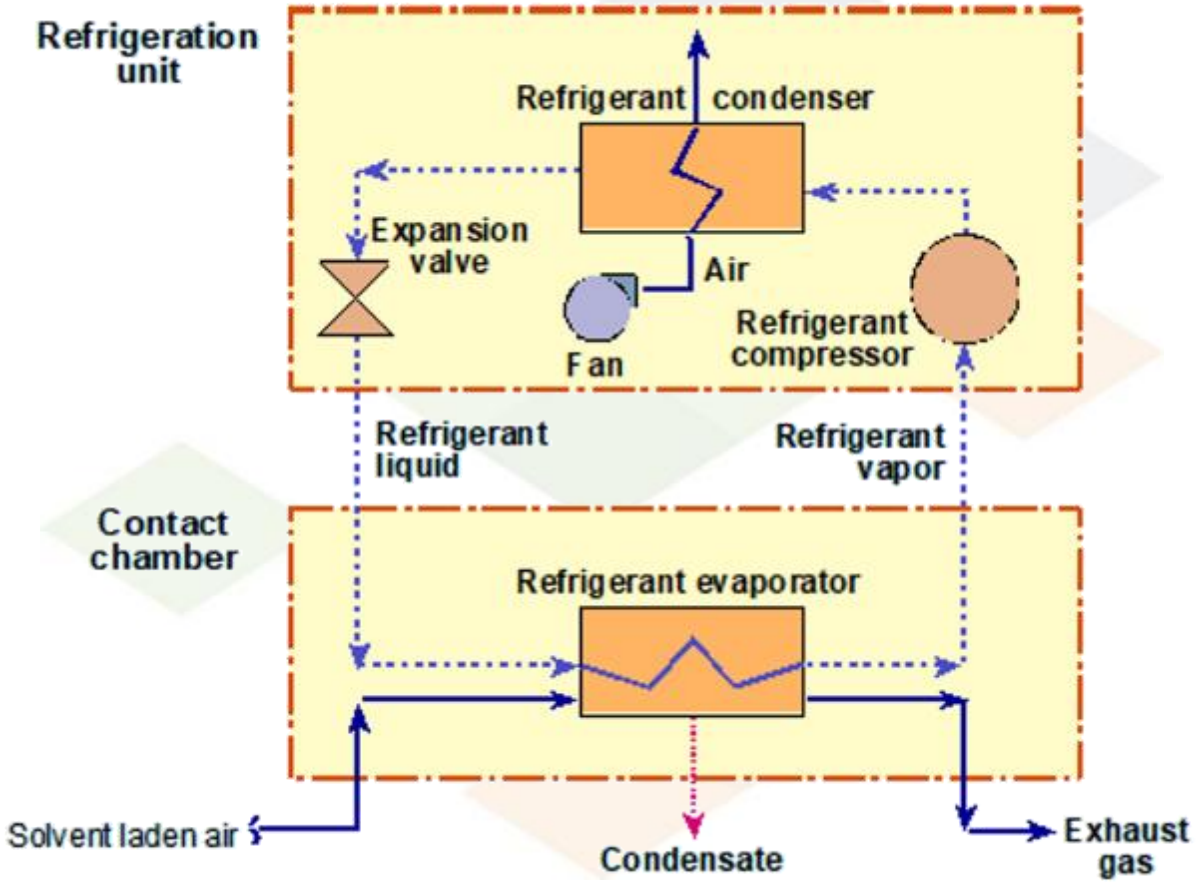
Chapter 4: Condensation Controls



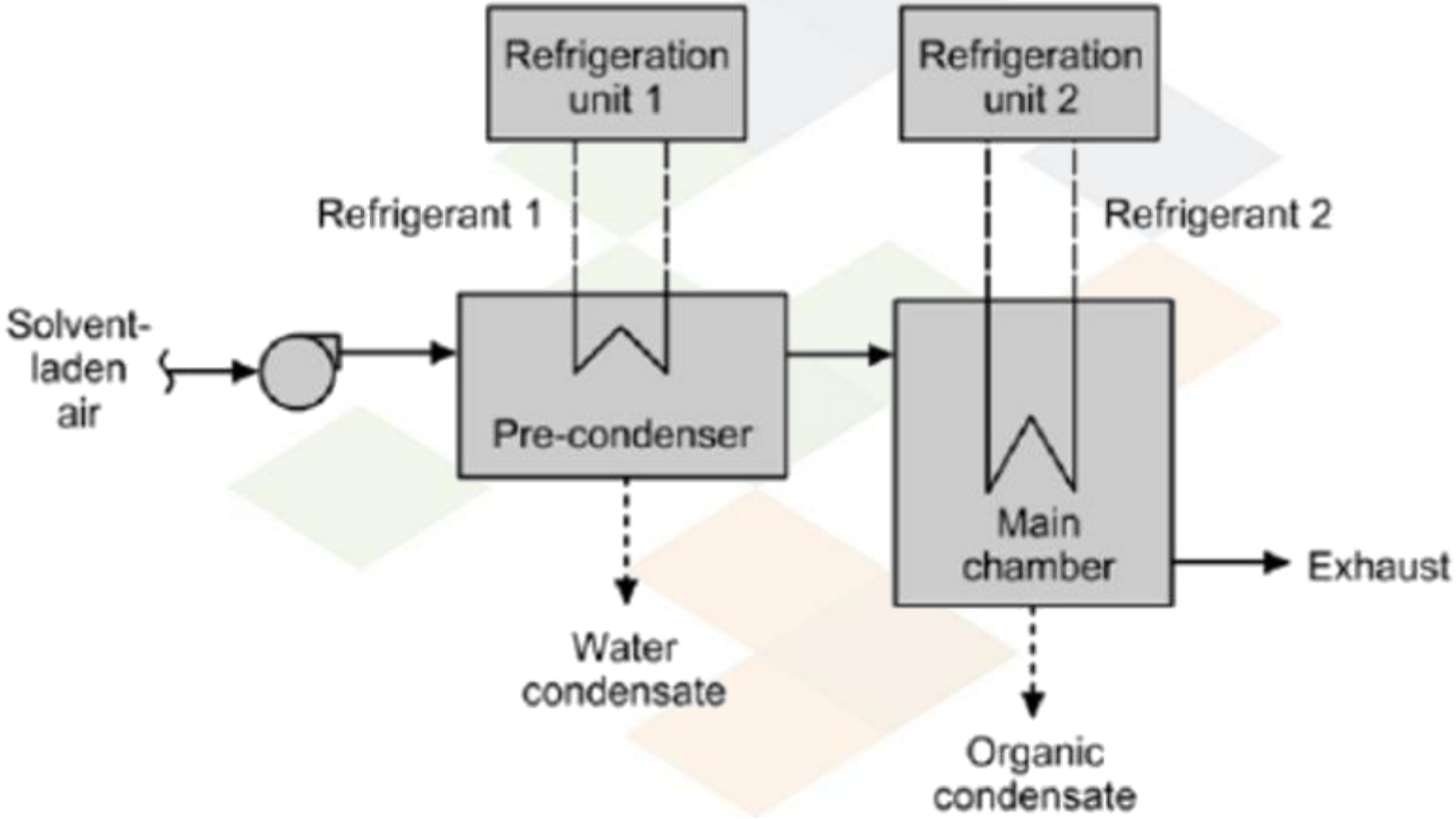
Refrigerated Condenser

- Operate -150ºF to -50ºF
- Multiple refrigerants:
  - Chlorofluorocarbons (CFCs) are ozone depleting substance (ODS)
  - Hydrofluorocrabons (HFCs) are greenhouse gases that replaced CFCs
  - Ammonia / Propane / simple hydrocarbons are also air pollutants
- Requires separate heat pumps:
  - One for refrigerated condenser, where refrigerant is chilled
  - One for contact chamber, where VOC are condensed
- May have multiple chambers (multiple heat exchangers)

Refrigerated Condenser



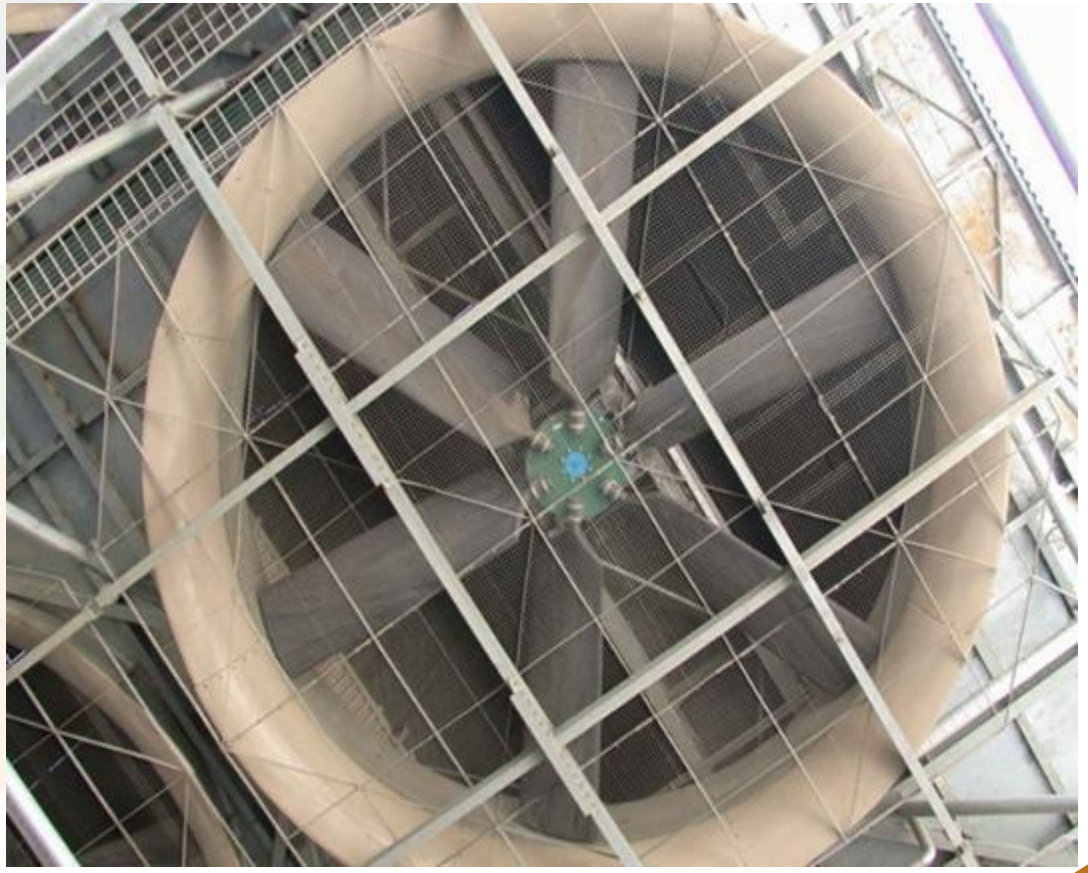
Multi-Stage Refrigerated Condenser



Air-Cooled Heat Exchanger Steam Condenser



Air-Cooled Heat Exchanger Condenser Fans



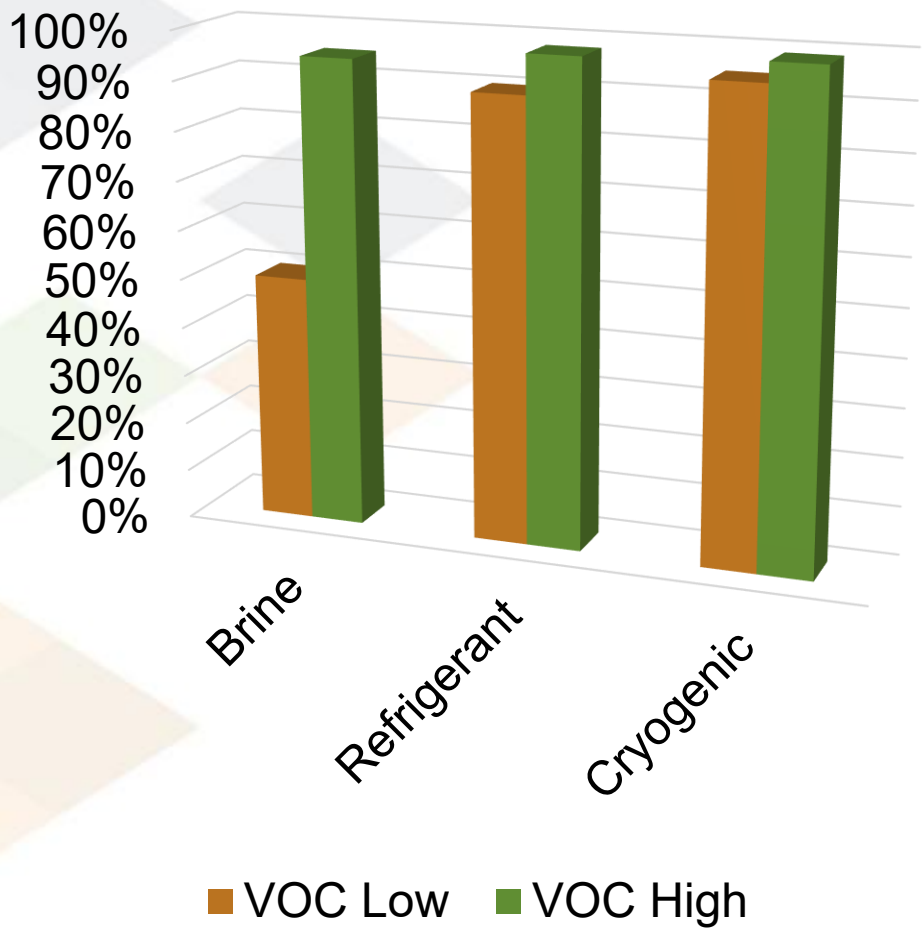
Cryogenic Condenser

- Operate -320ºF to -100ºF
- Uses cryogenic liquid
  - Liquid Nitrogen – LIN (can be used in direct condenser, as N_2 is inert)
  - Liquid Oxygen – LOX (not suitable for VOC)
- May require dual stage heat exchangers to prevent frosting and clogging
  - First stage removes most heat and water
  - Second stage cools below dew point and recovers VOC (solvent)



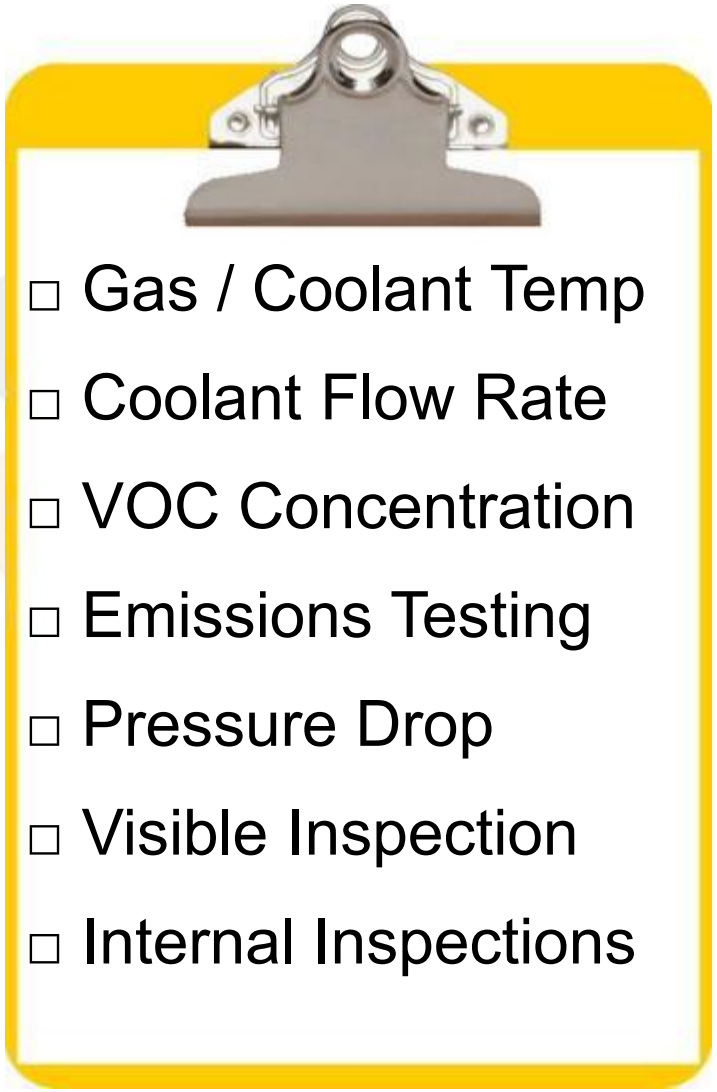
Control Efficiency

- 50-95% Brine
- 90% Refrigerant
- 95-99% Cryogenic
- Highly dependent on VOC concentration (>5,000 ppm VOC) and temperature of process gas



Inspection Parameters

- Gas temperature (Inlet and Outlet)
- Coolant temperature (Inlet and Outlet)
- Coolant flow rate
- Outlet VOC concentration
  - CEMS
- Static pressure drop
- Corrosion, rust, and leaking coolant
- Internal inspection report

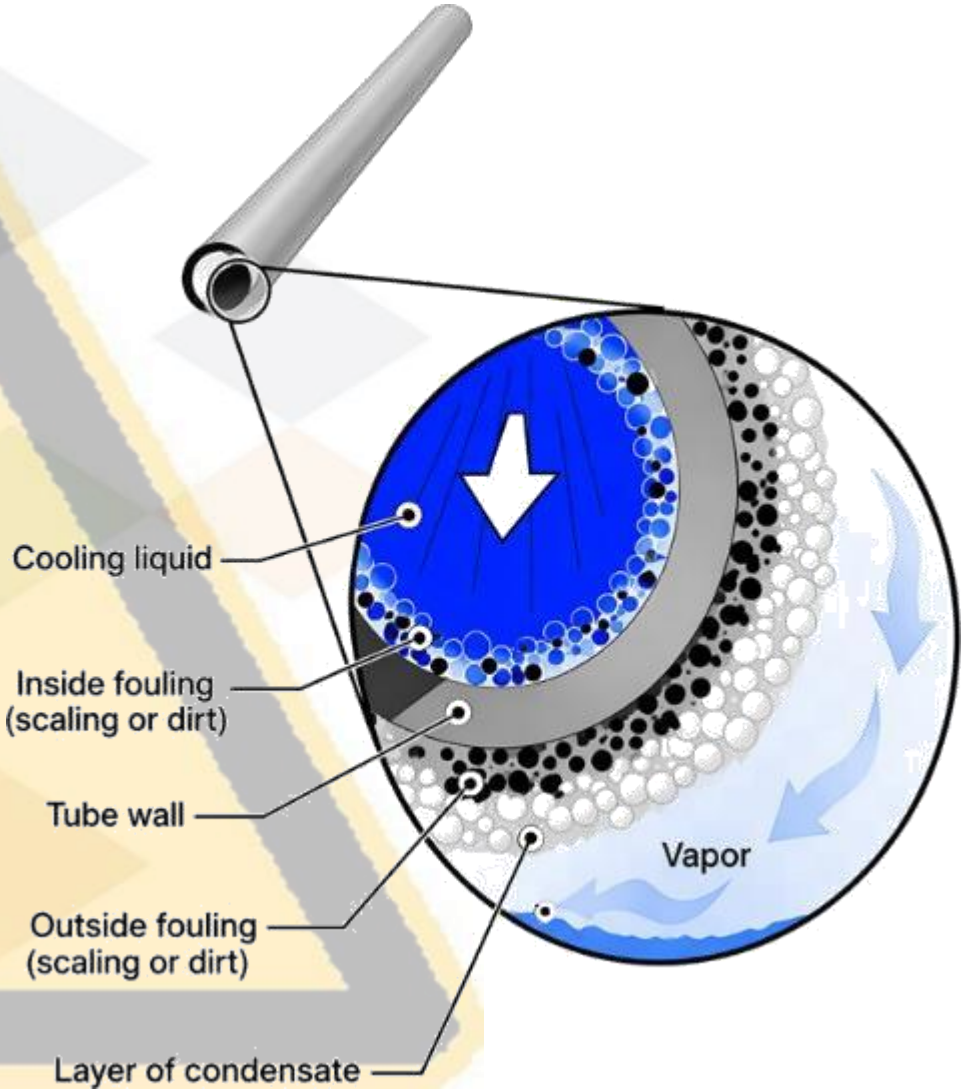


Decreased Control Efficiency:

- Increase in process gas temperature or flowrate
- Decrease in VOC concentration
  - VOC concentration in exhaust is not high enough
- Change in VOC type (different dew points)
- Tube plugging or fouling and erosion
- Freezing (water in process gas / ambient air)
- Refrigerant leaks
  - CFC / HFC are regulated refrigerants requiring leak detection and repair

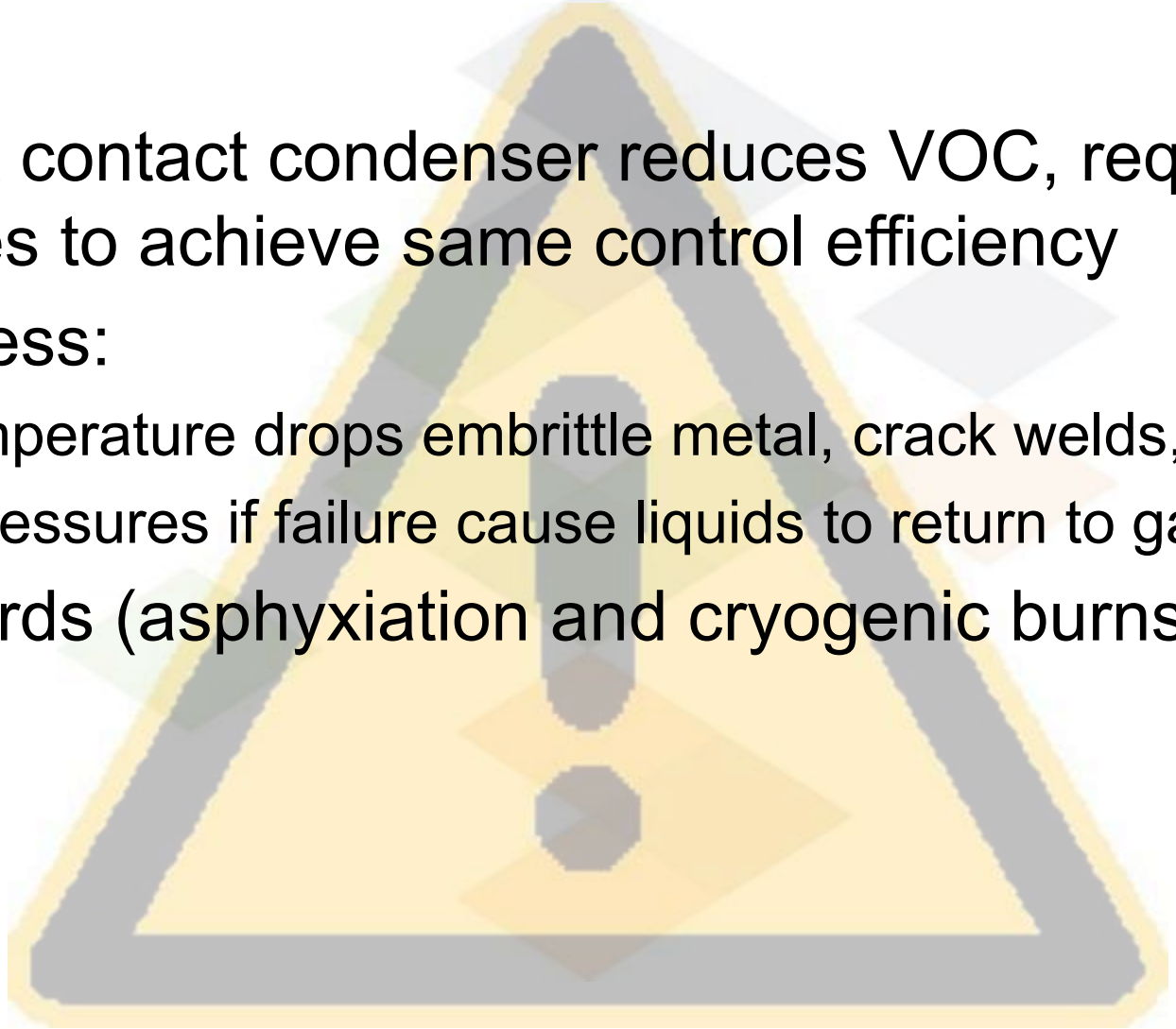
Surface Condenser Fouling:

- Water / brine can build up scale on interior of tubes / pipelines, reducing chilling capacity
- Scale or PM can build up on exterior of tubes / pipelines, reducing chilling capacity
- Water, brine, or water in process gas can build up as frost on exterior of tubes / pipelines, reducing chilling capacity



Cryogenic:

- LIN in direct contact condenser reduces VOC, requiring lower temperatures to achieve same control efficiency
- Thermal stress:
  - Extreme temperature drops embrittle metal, crack welds, & warp seals
  - Explosive pressures if failure cause liquids to return to gases
- Safety hazards (asphyxiation and cryogenic burns)



Chapter 4: Condensation
Recap

In this chapter, we discussed:

- How condensation control technologies operate
- Common types of condensation control technologies
- Key design considerations for condensation control technologies
- Typical achievable control efficiencies
- Monitoring methods for condensation control technologies
- Common problems with condensation control technologies
- Ensuring compliance