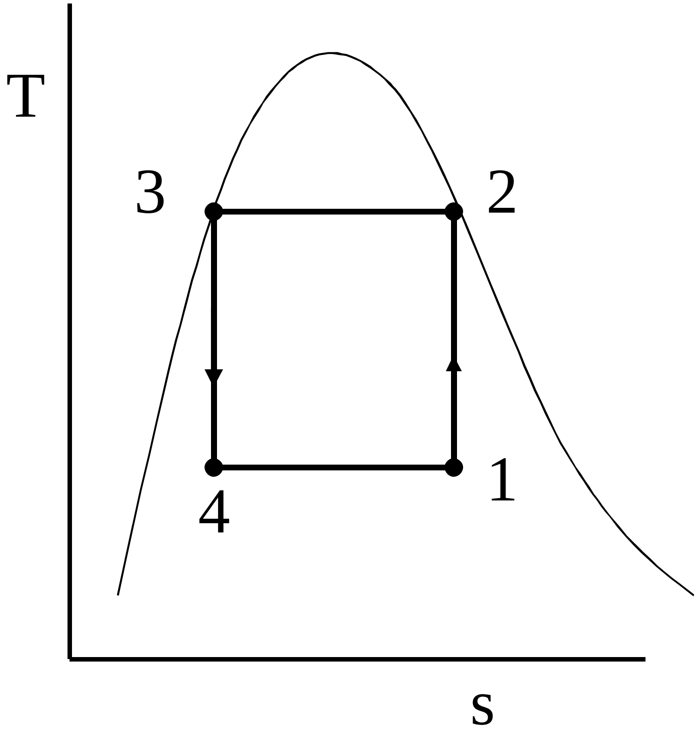
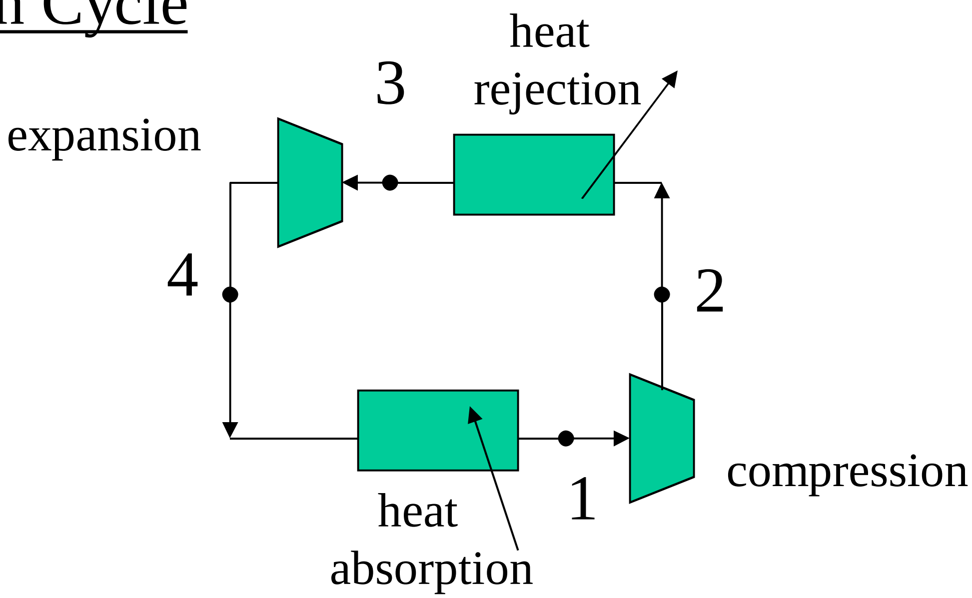
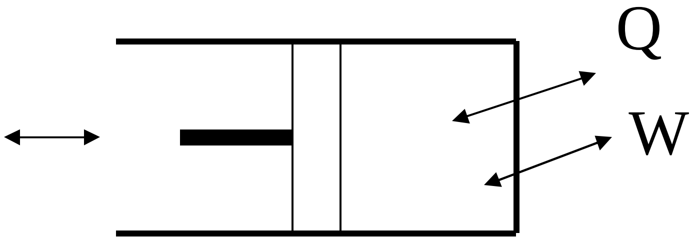
# Carnot Refrigeration Cycle



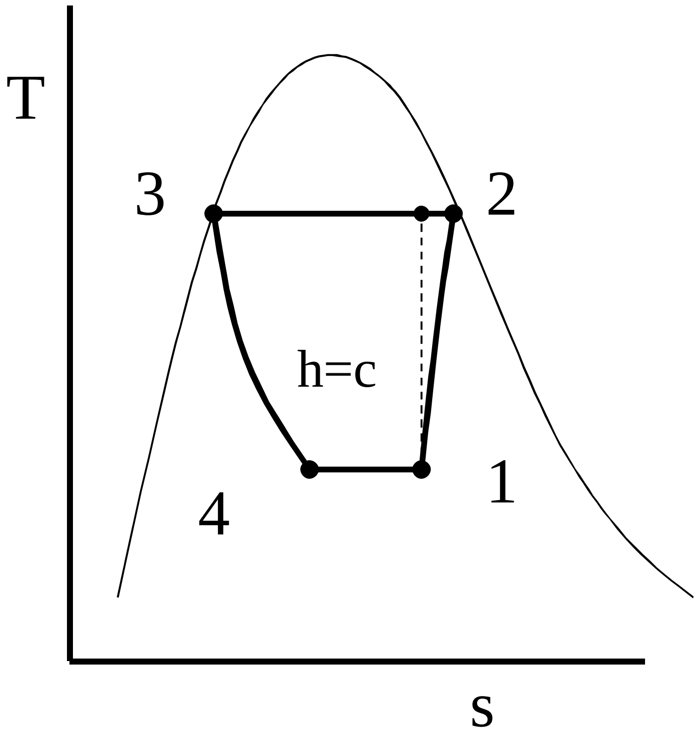


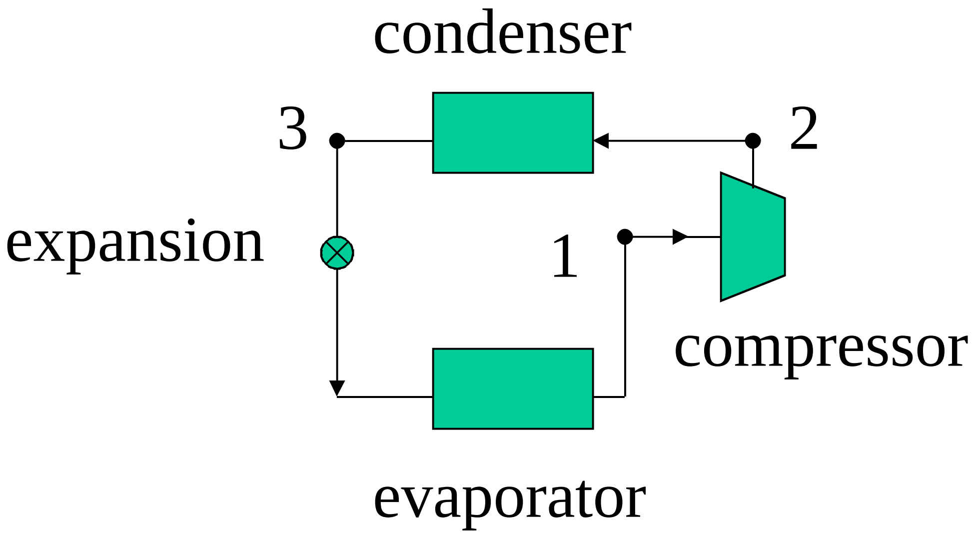
Open, steady flow systems



Closed non-flow system

# Modified Carnot Refrigeration Cycle

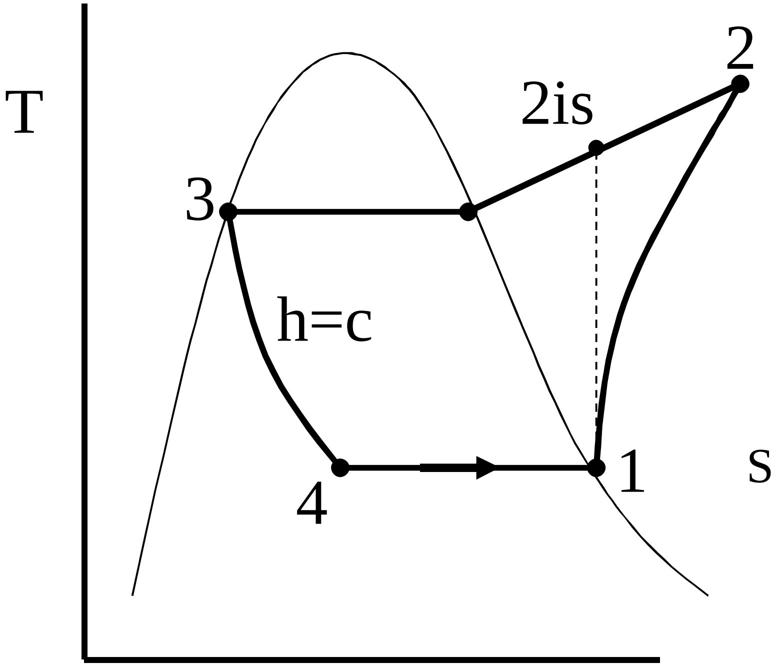


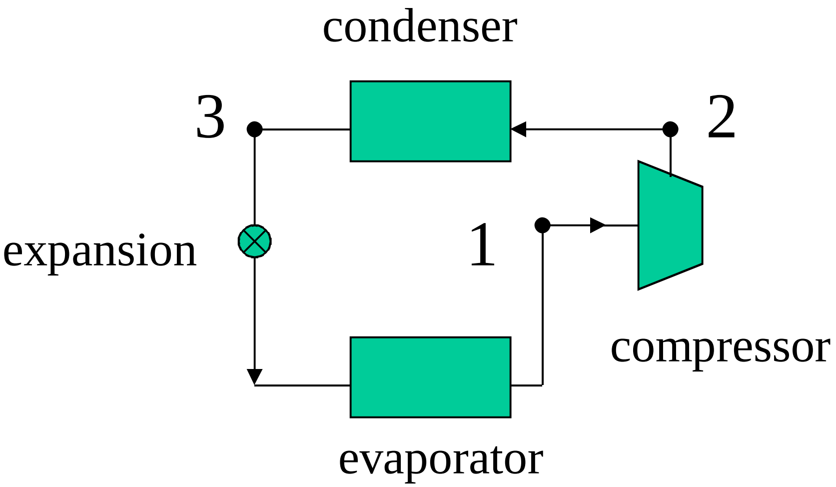


Open, steady flow systems

# Vapor Compression Refrigeration Cycle

## Open systems, Steady flow





Steady Flow, Open System - region in space

Steady Flow Energy Equation

$$Q = m \times \varphi(u + pv + \frac{V^2}{2} + \jmath gh) + W_{shaft}$$

$\text{Compression Process, } 1 \Rightarrow 2, \quad Q = 0, \quad W_{in} = m(h_2 - h_1)$

$\text{Condenser Process, } 2 \Rightarrow 3, \quad W = 0, \quad Q_{out} = m(h_2 - h_3)$

$\text{Expansion Process, } 3 \Rightarrow 4, Q = 0, \quad W = 0, \quad h_3 = h_4$

$\text{Evaporator Process, } 4 \Rightarrow 1, \quad W = 0, \quad Q_{in} = m(h_1 - h_4)$

$Q_{in} = m(h_1 \overset{3}{-} h_3)$

$$COP = \frac{\text{Desired Effect}}{\text{Effort Required}}$$

$$COP_{ref} = \frac{Q_{in}}{W}$$

$$COP_{\substack{heat \\ pumo}} = \frac{Q_{out}}{W}$$

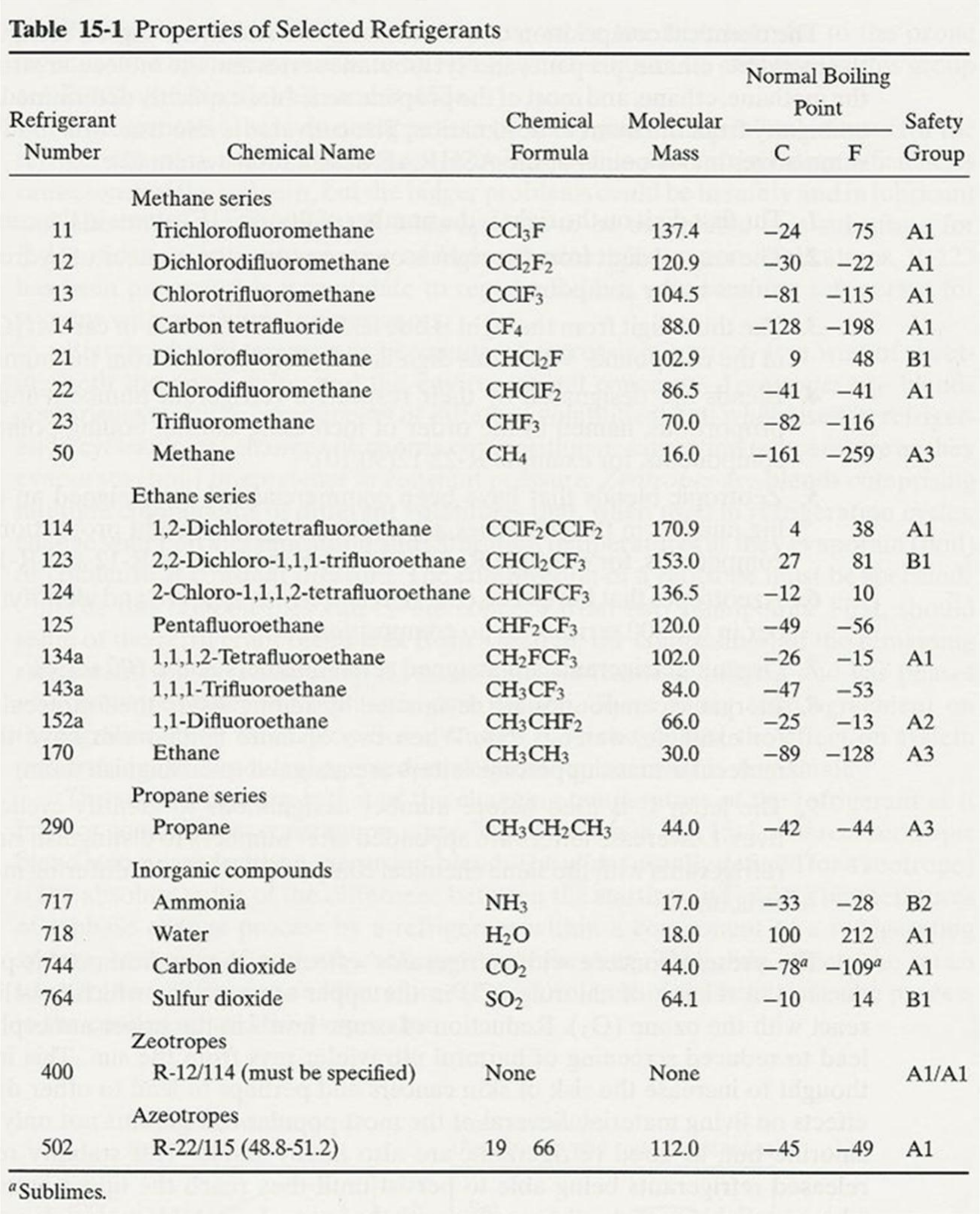


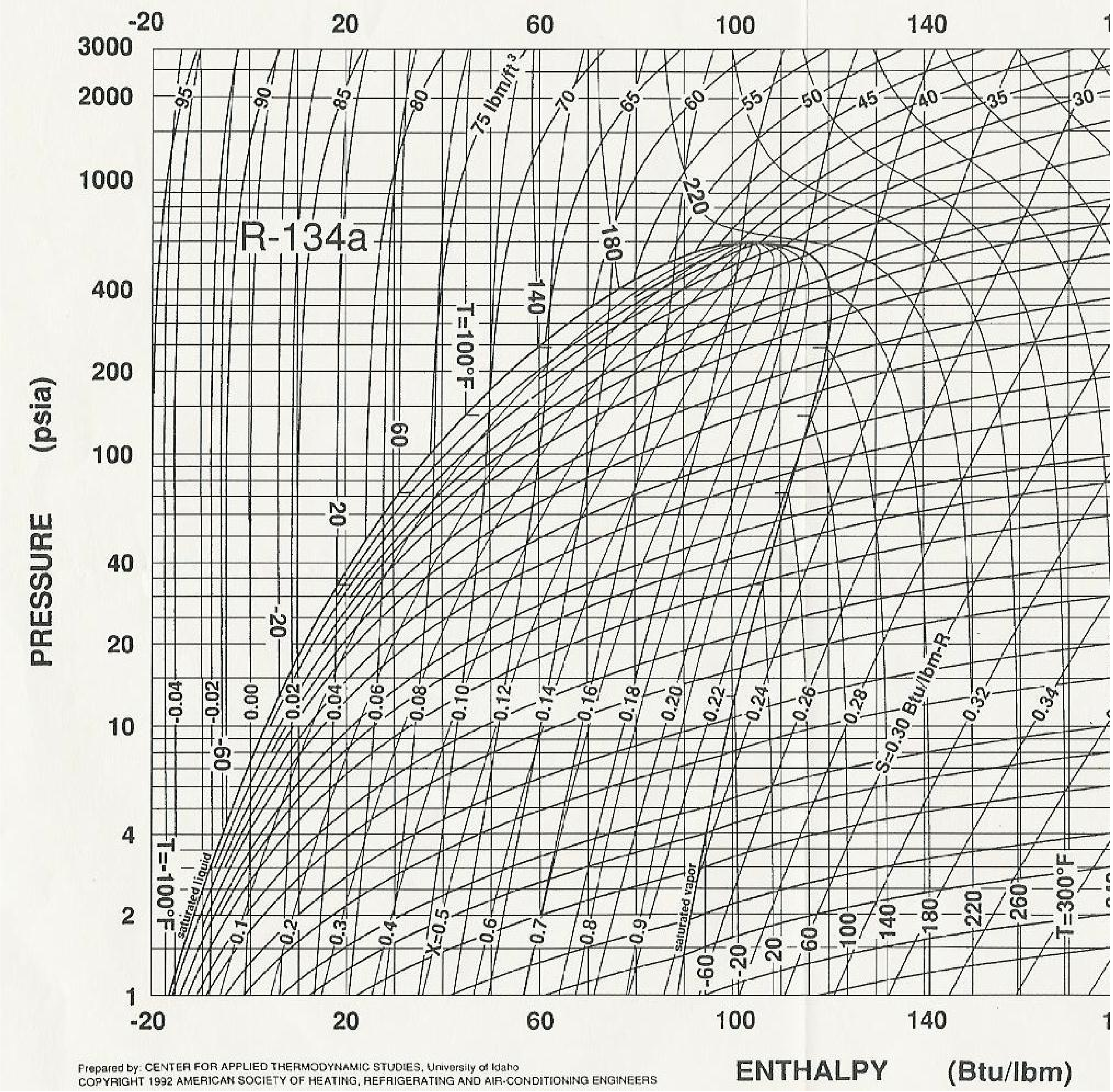
**Table 15-1** Properties of Selected Refrigerants

| Refrigerant Number | Chemical Name | Chemical Formula | Molecular Mass | Normal Boiling Point | | Safety Group |
|---|---|---|---|---|---|---|
| | | | | C | F | |
| | Methane series | | | | | |
| 11 | Trichlorofluoromethane | $CCl_3F$ | 137.4 | −24 | 75 | A1 |
| 12 | Dichlorodifluoromethane | $CCl_2F_2$ | 120.9 | −30 | −22 | A1 |
| 13 | Chlorotrifluoromethane | $CClF_3$ | 104.5 | −81 | −115 | A1 |
| 14 | Carbon tetrafluoride | $CF_4$ | 88.0 | −128 | −198 | A1 |
| 21 | Dichlorofluoromethane | $CHCl_2F$ | 102.9 | 9 | 48 | B1 |
| 22 | Chlorodifluoromethane | $CHClF_2$ | 86.5 | −41 | −41 | A1 |
| 23 | Trifluoromethane | $CHF_3$ | 70.0 | −82 | −116 | |
| 50 | Methane | $CH_4$ | 16.0 | −161 | −259 | A3 |
| | Ethane series | | | | | |
| 114 | 1,2-Dichlorotetrafluoroethane | $CClF_2CClF_2$ | 170.9 | 4 | 38 | A1 |
| 123 | 2,2-Dichloro-1,1,1-trifluoroethane | $CHCl_2CF_3$ | 153.0 | 27 | 81 | B1 |
| 124 | 2-Chloro-1,1,1,2-tetrafluoroethane | $CHClFCF_3$ | 136.5 | −12 | 10 | |
| 125 | Pentafluoroethane | $CHF_2CF_3$ | 120.0 | −49 | −56 | |
| 134a | 1,1,1,2-Tetrafluoroethane | $CH_2FCF_3$ | 102.0 | −26 | −15 | A1 |
| 143a | 1,1,1-Trifluoroethane | $CH_3CF_3$ | 84.0 | −47 | −53 | |
| 152a | 1,1-Difluoroethane | $CH_3CHF_2$ | 66.0 | −25 | −13 | A2 |
| 170 | Ethane | $CH_3CH_3$ | 30.0 | −89 | −128 | A3 |
| | Propane series | | | | | |
| 290 | Propane | $CH_3CH_2CH_3$ | 44.0 | −42 | −44 | A3 |
| | Inorganic compounds | | | | | |
| 717 | Ammonia | $NH_3$ | 17.0 | −33 | −28 | B2 |
| 718 | Water | $H_2O$ | 18.0 | 100 | 212 | A1 |
| 744 | Carbon dioxide | $CO_2$ | 44.0 | −78[a] | −109[a] | A1 |
| 764 | Sulfur dioxide | $SO_2$ | 64.1 | −10 | 14 | B1 |
| | Zeotropes | | | | | |
| 400 | R-12/114 (must be specified) | None | None | | | A1/A1 |
| | Azeotropes | | | | | |
| 502 | R-22/115 (48.8-51.2) | 19 66 | 112.0 | −45 | −49 | A1 |

[a] Sublimes.

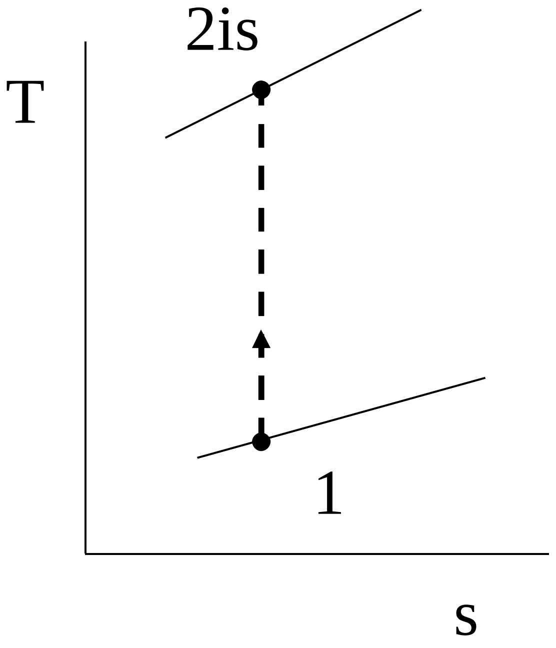
# REFRIGERANTS

| Temperature | Refrigerant Pressures, psia | | |
|---|---|---|---|
| | water | R −134a | R22 |
| 35 F | .1 | 22.21 | 76.25 |
| 95 F | .82 | 76. | 183.17 |
| Pressure Ratio | 8.31 | 3.42 | 2.40 |



Prepared by: CENTER FOR APPLIED THERMODYNAMIC STUDIES, University of Idaho

# Isentropic Process



1) **Table Fluid Properties** – steam, refrigerants

$$s_{2is} = s_1$$

interpolate at $(s_{2is}, p_{2is})$ for $h_{2is}$ and $T_{2is}$

2) **Ideal Gas** - constant specific heats

$$T_{2is} = T_1 \times \left( \frac{p_{2is}}{p_1} \right)$$

$$h_{21s} = h_1 + c_p \times \left( T_{2is} - T \right)$$

3) **"Real Gas"** - variable specific heats

$$(p_{r1}) = (p_r) @ T_1$$

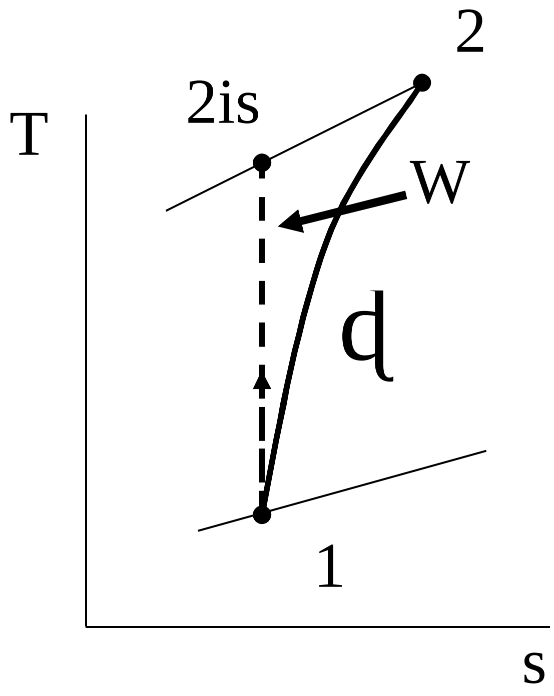
$$(p_{r2is}) = (p_{r1}) \times \left( \frac{p_{2is}}{p_1} \right)$$

$$T_{2is} = T@(p_{r2is})$$

$$h_{2is} = h@(p_{r2is})$$

# Compressor Efficiency

All possibilities - 7 variables (3 Temperatures, 2 pressures, W and $\eta$) known 4 at a time. Find the other 3.



$$\eta_{comp} = \frac{h_{2is} - h_1}{h_2 - h_1}$$

$$W = m \times \left(h_2 - h_1\right)$$

**1) Known : $T_1, p_1, p_2, \eta$**

Machine Specification

Find : $h_1$ and $s_1$ @ $T_1, p_1$

$T_{2is}$ and $h_{2is}$ @ $p_2, s_1$

$$\eta = \frac{h_{2is} - h_1}{h_2 - h_1}$$

$$h_2 = h_1 + \frac{h_{2is} - h_1}{\eta}$$

$$W = m \times \left(h_2 - h_1\right)$$

**3) Known : $T_1, p_1, p_2, W$**

Find : $h_1$ and $s_1$ @ $T_1, p_1$

$T_{2is}$ and $h_{2is}$ @ $p_2, s_1$

$$h_2 = h_1 + \frac{W}{m}$$

$$\eta = \frac{h_{2is} - h_1}{h_2 - h_1}$$

**2) Known : $T_1, p_1, T_2, p_2$**

TestData

Find : $h_1$ and $s_1$ @ $T_1, p_1$

$h_2$ @ $T_2, p_2$

$h_{2is}$ @ $p_2, s_1$

$$W = m \times \left(h_2 - h_1\right)$$

$$\eta = \frac{h_{2is} - h_1}{h_2 - h_1}$$

**4) Known : $T_2, p_2, p_1, W$**

Find : $h_2 = h$ @ $T_2, p_2$

$T_1 = T$ @ $p_1, h_1$

$s_1 = s$ @ $p_1, h_1$ or @ $p_1, T_1$

$s_1 = s_{2is}$

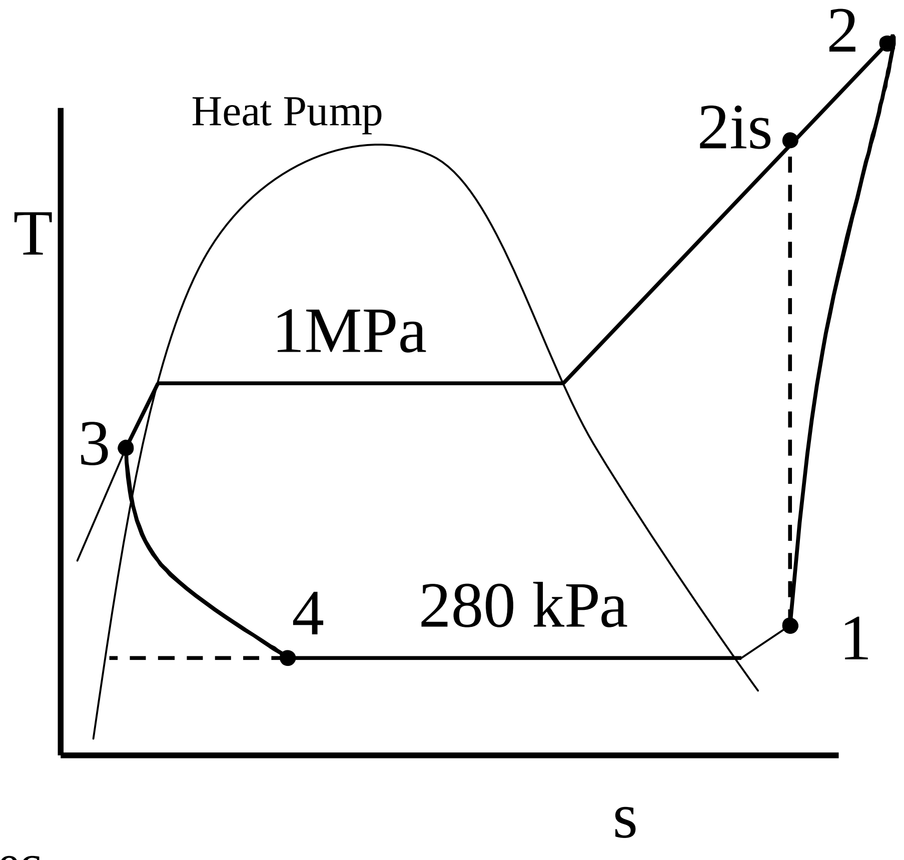
$h_{2is} = h$ @ $s_{2is}, p_2$

$$\eta = \frac{h_{2is} - h_1}{h_2 - h_1}$$

$$W = m \times \left(h_2 - h_1\right)$$

**An R-134a heat pump uses 8 C ground water as a heat source to supply 60,000 kJ/hr. Refrigerant enters the compressor at 280 kPa, 0 C and leaves at 60 C. The condenser exit temperature is 30 C. Determine :**

**a) power input.**
**b) heat input.**
**c) the power saving over electrical resistance heating**



$$Q_{reject} = m \times (h_2 - h_3)$$

$$m = \frac{Q_{reject}}{(h_2 - h_3)} = \frac{60{,}000\ \text{kJ/sec}/3600}{(291.36 - 91.49)} = .0834\ \text{kg/sec}$$

a) $W = m(h_2 - h_1) = .0834 \times (291.36 - 247.74)$

$W = 3.65\ \text{KW}$

b) $Q_{water} = Q_{in} = m(h_1 - h_3) = .0834 \times (247.74 - 91.49)$

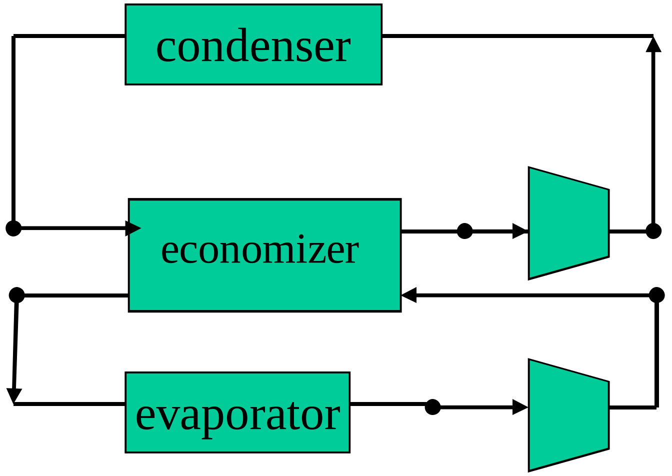
$Q_{water} = 13.02\text{kJ/sec}$

c) $Q_{electrical} = 60{,}000/3600 = 16.67\ \text{KW}$

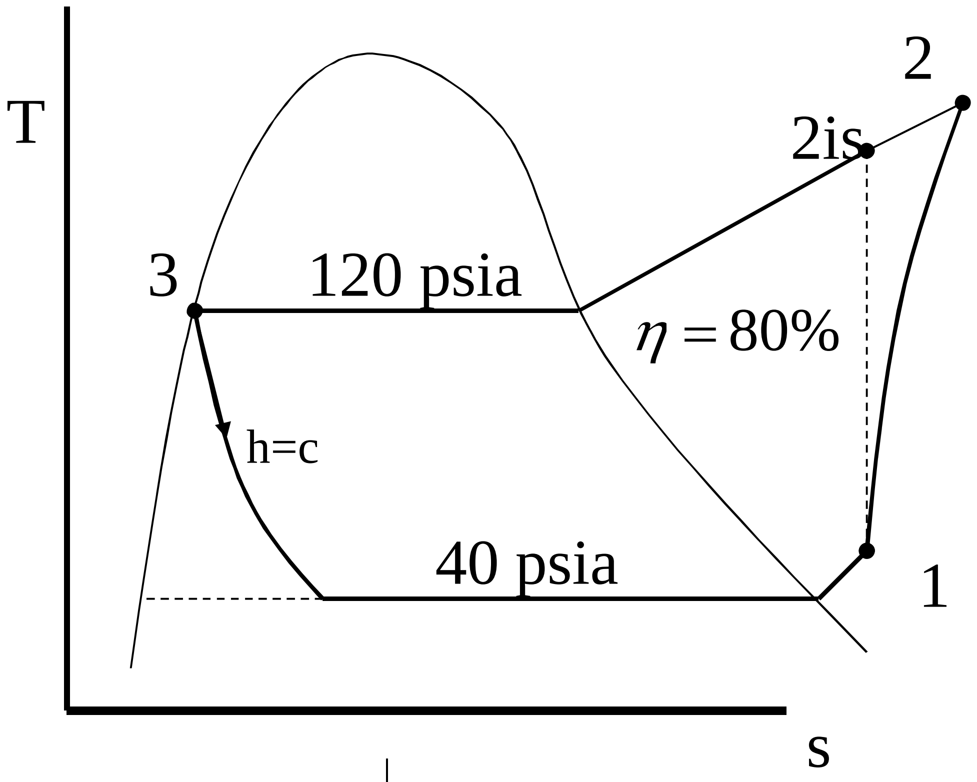
φ Electrical Power $= 16.67 - 3.65 = 13.02$ KW

| Pt | T | p | h |
|---|---|---|---|
| 1 | 0 | 280 kPa | 247.64 |
| 2 | 60 | 1 MPa | 291.36 |
| 3 | 30 | 1 MPa | 91.49 |
| 4 | | 280 kPa | 91.49 |

A refrigeration cycle operating with R-134a and uses two stages of compression with an economizer flash chamber between stages. The high pressure cycle flow is 2 lb/sec. The high pressure compressor inlet conditions are 70 psia and 60 F. The low pressure compressor inlet conditions are 40 psia, 40 F. The R-134a is a saturated liquid leaving the condenser and the economizer. Determine, a) the bottom cycle mass flow, b) the cycle efficiency and c) compare the two stage cycle to a single stage cycle.



**A vapor compression refrigeration cycle operates between 120 psia and 40 psia with 2 lb/sec R-134a. The compressor efficiency is 80%. The compressor inlet condition is 40 psia , 40 F. Find the Coefficient of Performance for the Cycle.**



$@\,120\text{ psia},\quad s_{2is} = s_1$

| T | h | s |
|---|---|---|
| 120 | 122.54 | .23232 |
| | | .22738 |
| 100 | 117.59 | .22362 |

$h_{2is} = 119.72\text{ BTU/lb}$

$$h_2 = h_1 + \frac{h_{2is} - h_1}{.8} = 122.26\text{ Btu/lb}$$

$$Q_{in} = 2\times(h_1 - h_3) = 2\times(109.58 - 41.787) = 135.59\text{ Btu/sec}$$

$$Q_{out} = 2\times(122.26 - 41.787) = 160.95\text{ Btu/sec}$$

$$W = Q_{out} - Q_{in} = 160.95 - 135.59 = 25.36\text{Btu/sec}$$

$$COP_{ref} = \frac{Q_{in}}{W} = \frac{135.59}{25.36} = 5.35$$

$$COP_{\substack{heat\\pump}} = \frac{Q_{out}}{W} = \frac{160.95}{25.36} = 6.35$$

| Pt | T | p | h | s |
|---|---|---|---|---|
| 1 | 40 | 40 | 109.58 | .22738 |
| 2 is | | 120 | | .22738 |
| 2 | | 120 | | |
| 3 | | 120 | 41.787 | |

**R - 134a**

**$T_1 = 40$ F, $T_4 = 60$ F**

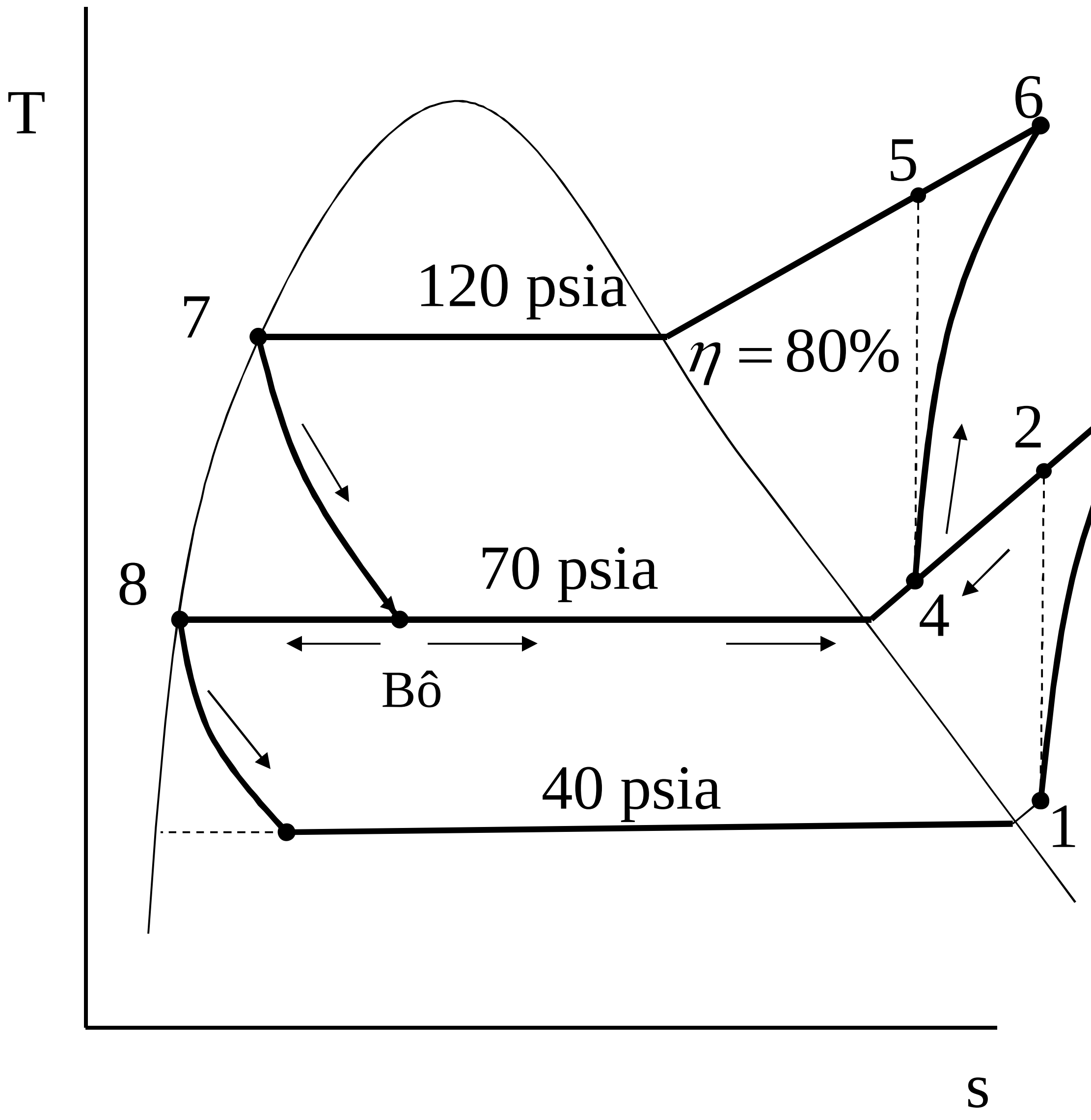
**2lb/sec top cycle**

**bottom cycle mass flow?**

**cycle efficiency?**

**compare to single stage**

| Pt | T | p | h | s |
|---|---|---|---|---|
| 1 | 40 | 40 | 109.58 | .22738 |
| 2 |  | 70 |  | .22738 |
| 3 |  | 70 |  |  |
| 4 | 60 | 70 | 111.62 | .22155 |
| 5 |  | 120 |  | .22155 |
| 6 |  | 120 |  |  |
| 7 |  | 120 | 41.787 |  |
| 8 |  | 70 | 30.867 |  |



At point Bôthe liquid and vapor divide in an adiabatic separation with no external heat input.

$@\,70\text{ psia},\ s_1 = .22738$

| T | h | s |
|---|---|---|
| 80 | 116.18 | .23016 |
|  |  | .22738 |
| 60 | 111.62 | .22155 |

$h_2 = 114.11\text{ BTU/lb}$

$$h_3 = 109.58 + \frac{(114.11 - 109.58)}{.8}$$

$h_3 = 115.24\text{ BTU/lb}$

$$x_5 = \frac{s_4 - s_f}{s_{fg}} = \frac{.2155 - .08589}{.1335} = .972$$

$h_5 = h_f + x \times h_{fg} = 41.787.972 \times 73.377 = 113.109$

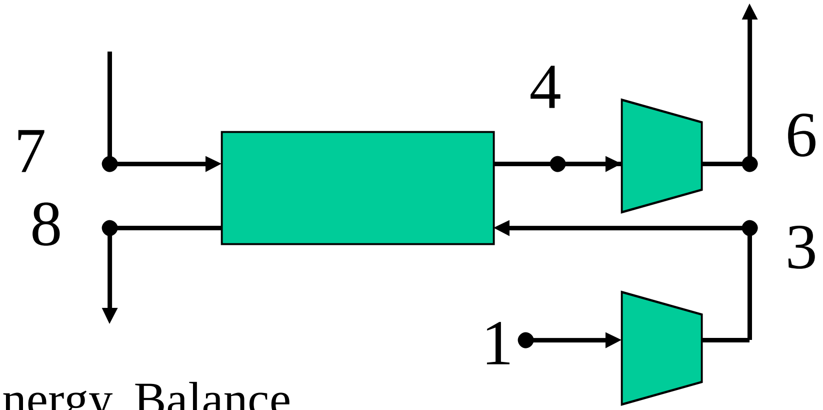
$@\,120\text{ psia}, s_4 = .22155$

| T | h | s |
|---|---|---|
| 100 | 117.59 | .22362 |
|  |  | .2155 |
| 90.49 | 115.16 | .21 |

$h_5 = 114.60\text{ Btu/lb}$

$$h_6 = 111.62 + \frac{(114.6 - 111.62)}{.8}$$

$h_6 = 115.345\text{ Btu/lb}$



Energy Balance

$$m_{top}(h_4 - h_7) = m_{bottom}(h_3 - h_8)$$

$$2\text{ lb/sec}\,(111.62 - 41.787) = m_{bottom}(115.24 - 30.867)$$

$$m_{bottom} = 1.655\text{ lb/sec}$$

$$Q_{in} = m(h_1 - h_8) = 1.655 \times (109.58 - 30.867)$$

$$Q_{in} = 130.27\text{ Btu/sec}$$

$$Q_{out} = m(h_6 - h_7) = 2 \times (115.345 - 41.867)$$

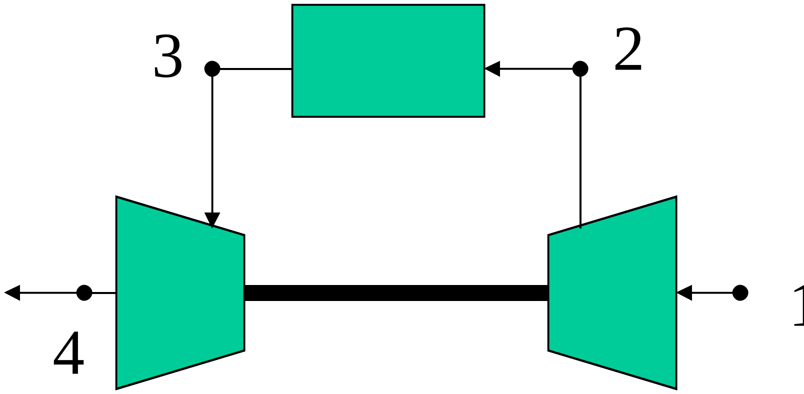
$$Q_{out} = 146.96\text{ Btu/sec}$$

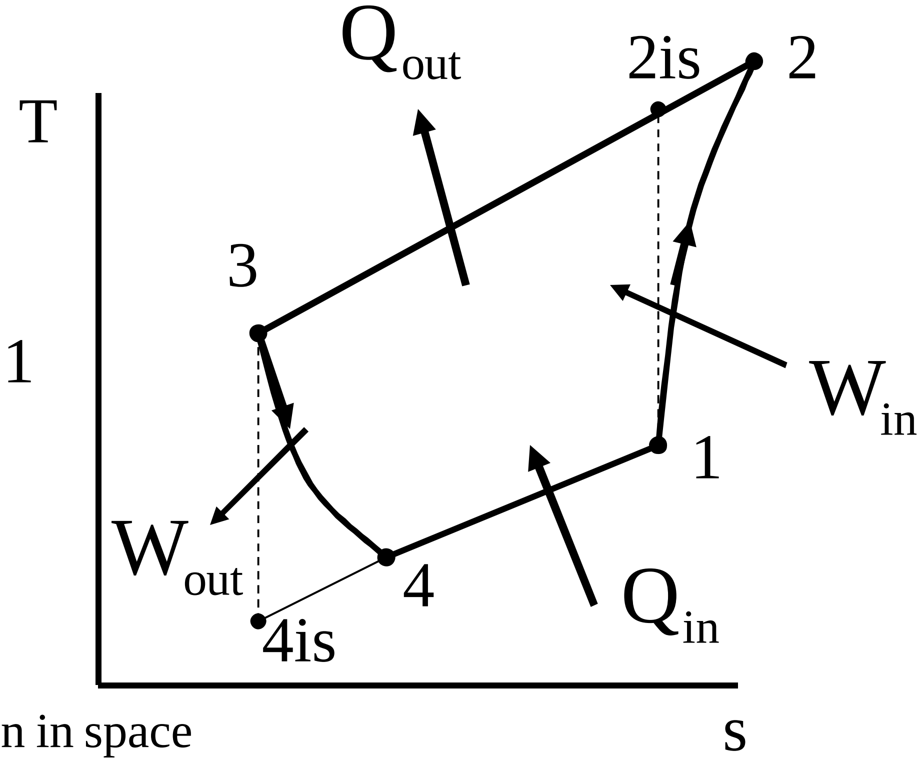
$$W = Q_{out} - Q_{in} = 16.686\text{ Btu/sec}$$

$$COP = \frac{Q_{in}}{W} = \frac{130.27}{16.86} = 7.72$$

$$\frac{COP_{\text{single stage}}}{COP_{\text{two stage}}}\ \frac{5.35}{7.72} = 69.3\%\text{ of Sinlge Stage Work}$$

# Reverse Brayton Refrigeration Cycle





Steady Flow, Open System - region in space

Steady Flow Energy Equation

$$Q = m \times \varphi(u + pv + \frac{V^2}{2} + \jmath\, gh) + W_{shaft}$$

Compression Process, $1 \Rightarrow 2$, $Q = 0$, $W_{in} = m(h_2 - h_1)$

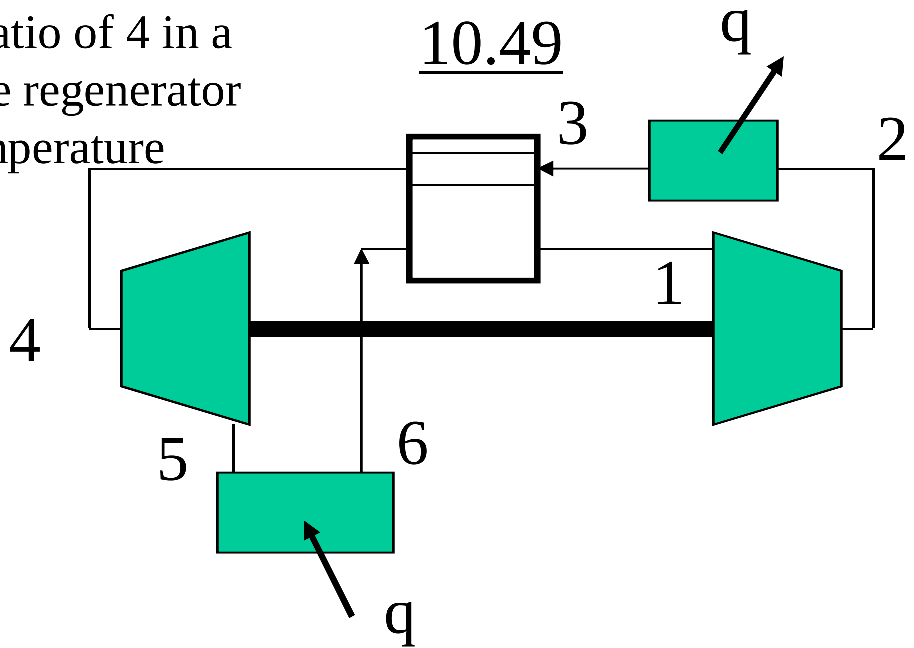
Heat Rejection Process, $2 \Rightarrow 3$, $W = 0$, $Q_{out} = m(h_2 - h_3)$

Expansion Process, $3 \Rightarrow 4$, $Q = 0$, $W_{out} = m(h_3 - h_4)$

Heat Absorption Process, $4 \Rightarrow 1$, $W = 0$, $Q_{in} = m(h_1 - h_4)$

100 kPa,270 K air is compressed with a pressure ratio of 4 in a regenerated reversed Brayton Cycle. Air enters the regenerator at 300 K and leaves at 280 K. Find: a) the low temperature b) work/kg, c) capacity/kg, and d) COP.

10.49



$$T_3 = T_1\left(\frac{p_2}{p_1}\right) = 270(4)^{.2857} = 369.55\ \text{K}$$

$$\text{a)}\ \ T_5 = T_4\left(\frac{p_5}{p_4}\right) = 280\left(\frac{1}{4}\right)^{.2857} = 204.57\ \text{K}$$

Regenerator Heat Balance

$$h_3 - h_4 = h_1 - h_6$$

$$c_p(T_3 - T_4) = c_p(T_1 - T_6)$$

$$T_6 = 270 - 310 + 280 = 240\ \text{K}$$

$$\text{b)}\ \ Q_{out} = c_p(T_2 - T_3)$$

$$Q_{out} = 1.005 \times (369.55 - 310) = 59.85\ \text{kJ/kg}$$

$$\text{c)}\ \ Q_{in} = c_p(T_6 - T_5)$$

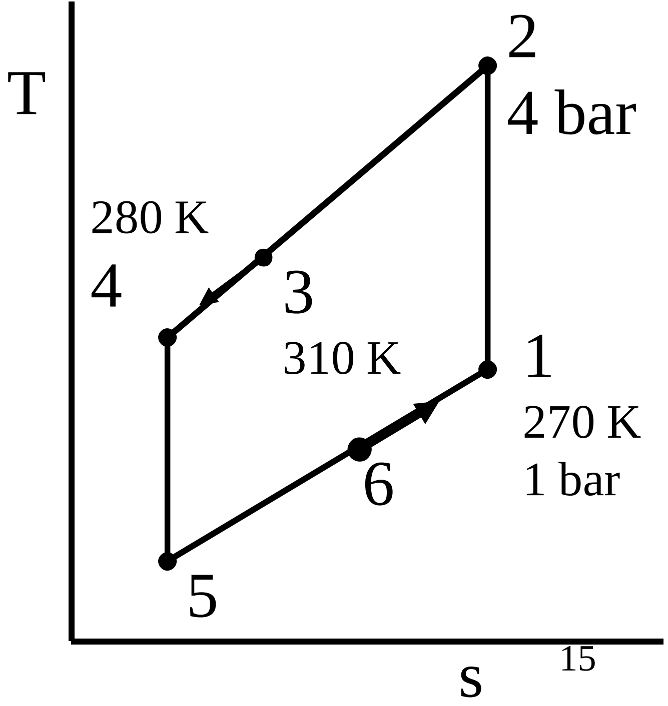
$$Q_{in} == 1.005 \times (240 - 204.57) = 35.61\text{kJ/kg}$$

$$\text{b)}\qquad w_{net} = w_c - w_t = c_p(T_2 - T_1) - c_p(T_4 - T_5)$$

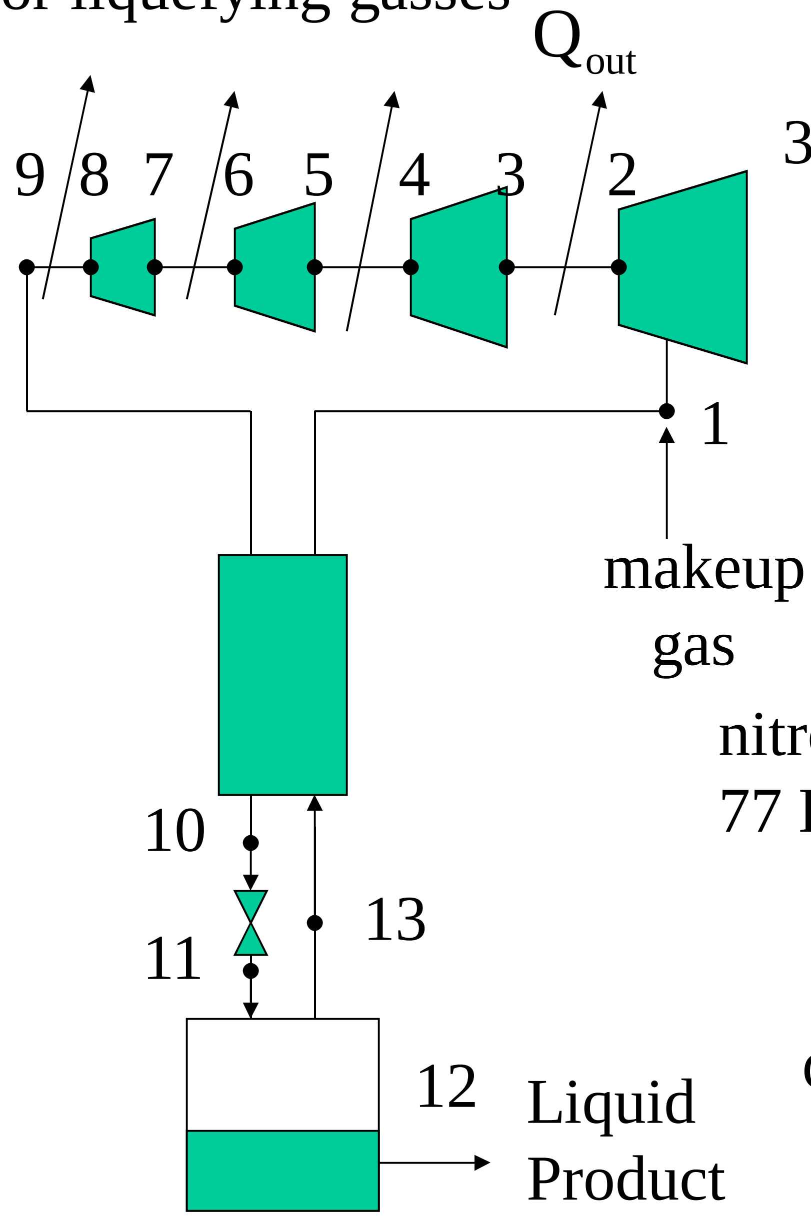
$$w_{net} = 1.005 \times (369.55 - 270) - 1.005 \times (280. - 204.57)$$

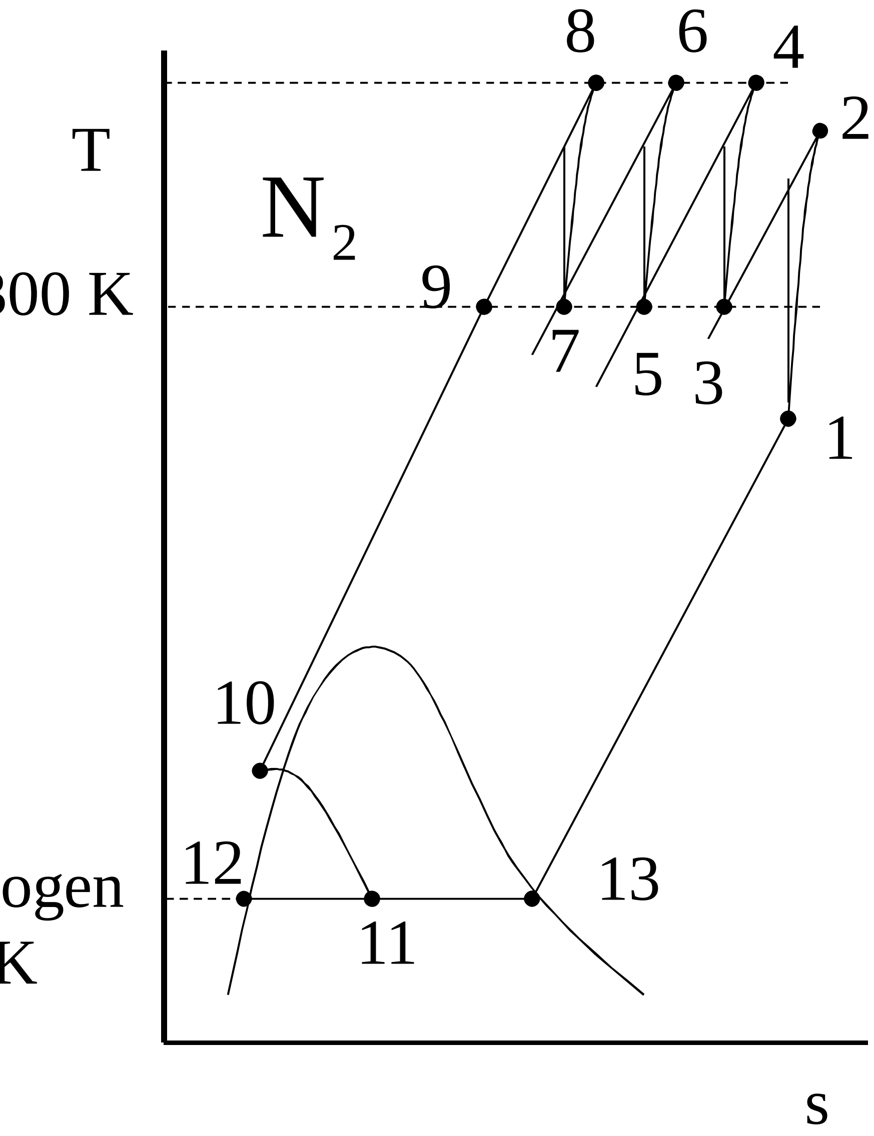
$$w_{net} = 24.12\text{kJ/kg}$$

$$\text{d)}\qquad COP_{eef} = \frac{q_{in}}{w_{net}} = \frac{35.61}{24.12} = 1.48$$



# Linde Hampson Cycle
for liquefying gasses





$$COP_{\substack{ref \\ Carnot}} = \frac{T_L}{T_H - T_L} = \frac{77}{350 - 77} = .28$$