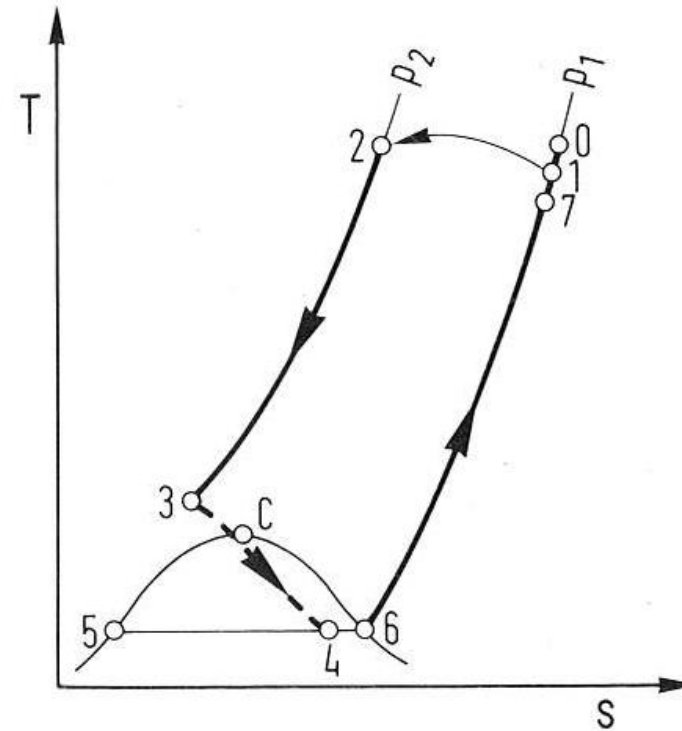
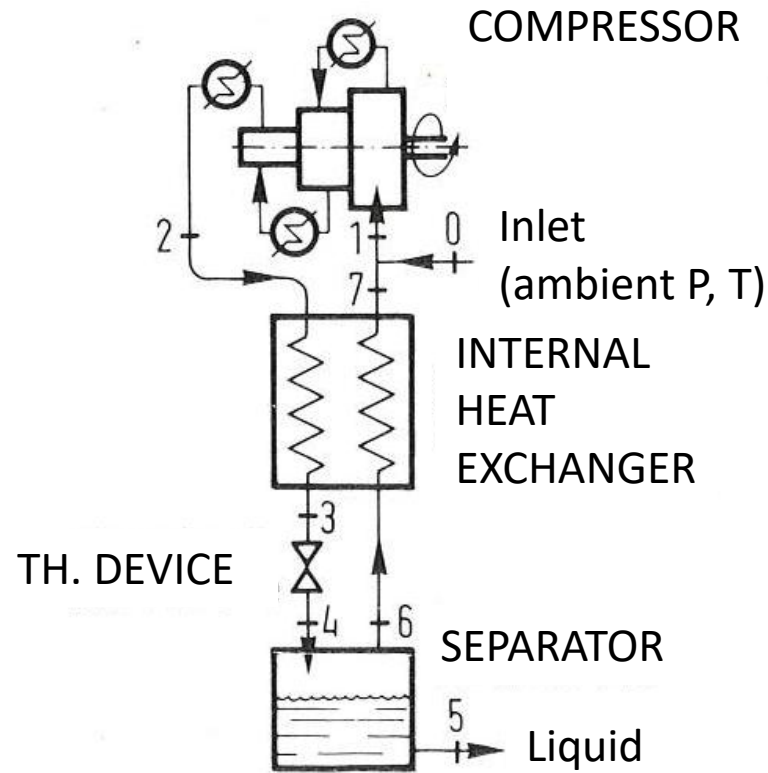


Cycle for liquefaction of gases

Linde Cycle for liquefaction of gases



NOTE: For the throttling process we need to have a Joule-Thomson coefficient > 0

Linde Cycle for liquefaction of gases

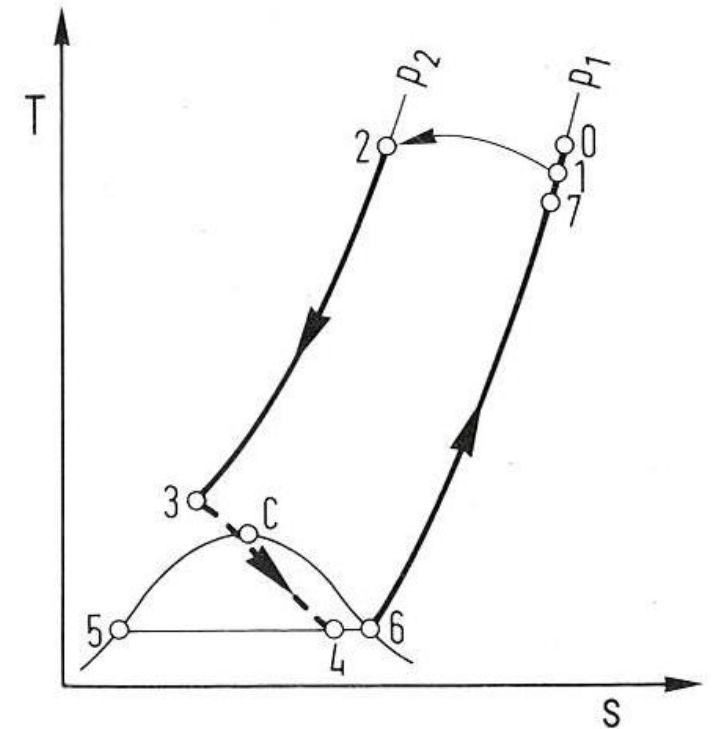
From 1 to 2 compression with intercooler system

At point 2 the temperature is almost equal to the ambient temperature but the pressure is much higher (for air liquefaction is between 50-200 bar)

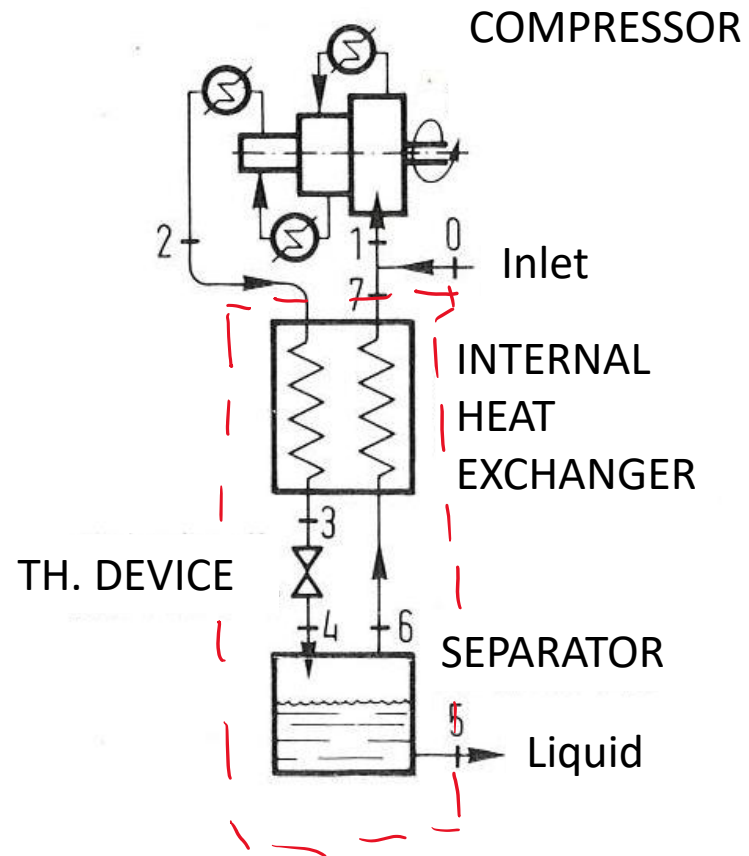
From point 3 to 4 the expansion process is down to the ambient pressure

$$Z_L = \frac{\dot{m}_5}{\dot{m}_2} = 1 - x_4$$

Z_L is the liquefaction yields or liquefaction efficiency



Linde Cycle for liquefaction of gases



$$\dot{m}_2 h_2 = \dot{m}_5 h_5 + \underbrace{(\dot{m}_2 - \dot{m}_5)}_{\dot{m}_7} h_7$$

$$Z_L = \frac{\dot{m}_5}{\dot{m}_2} = \frac{h_7 - h_2}{h_7 - h_5}$$

Linde Cycle for liquefaction of gases

$$Z_L = \frac{\dot{m}_5}{\dot{m}_2} = \frac{h_7 - h_2}{h_7 - h_5}$$

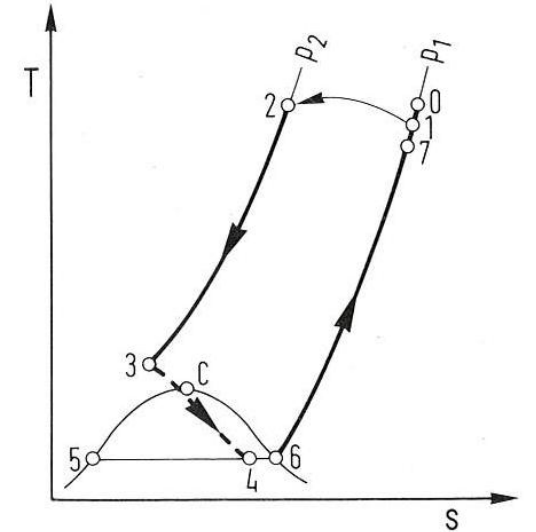
Z_L depends only on thermodynamic state at point 2, 5, 7

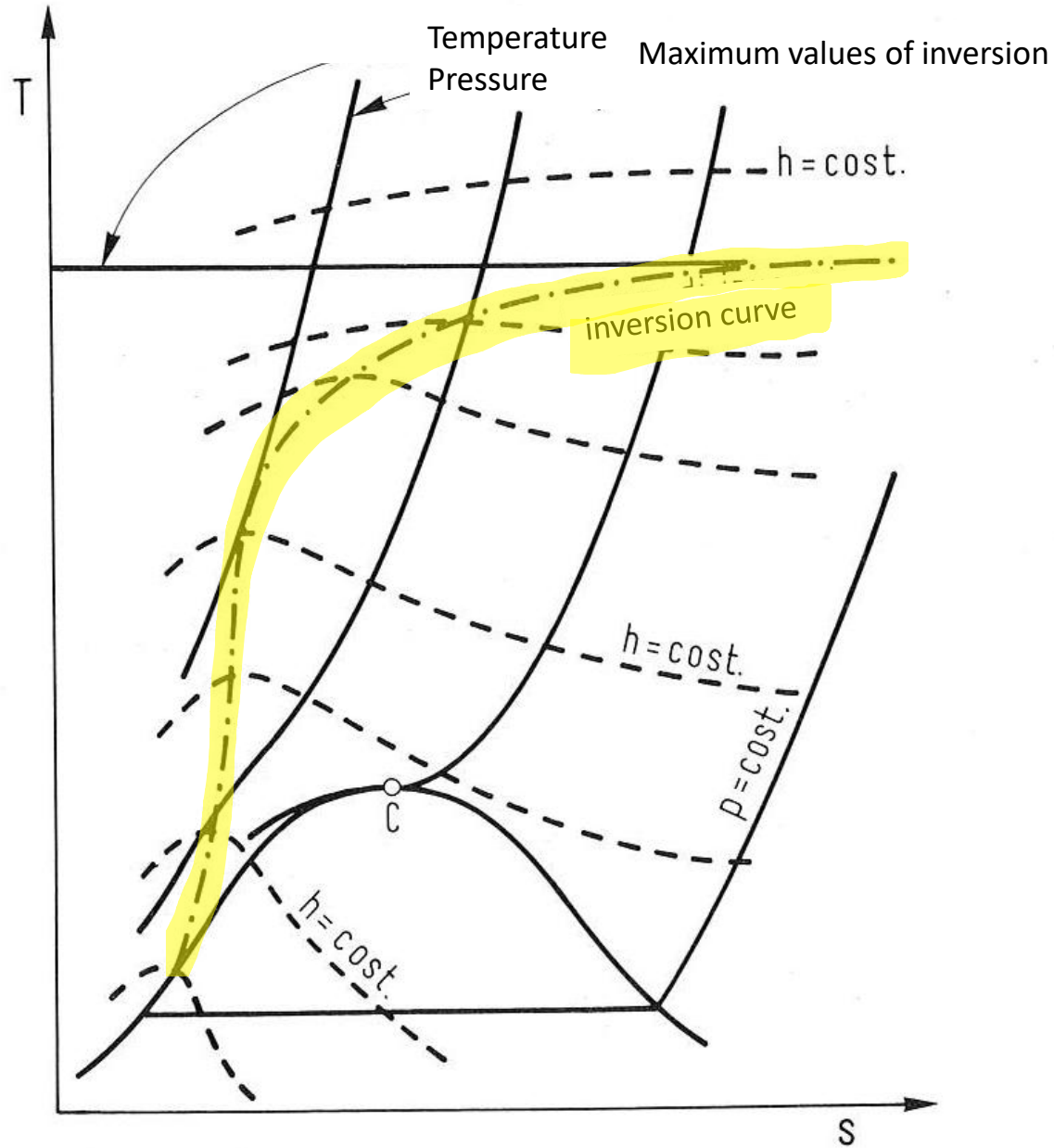
At point 2 the temperature can be 5-10 K higher than the ambient temperature and in general $T_2 > T_7$

The difference $h_7 - h_2$ should be higher positive

It is not possible to apply a Linde cycle for the liquefaction of gases if its maximum inversion temperature is lower than the ambient temperature (not applicable to hydrogen and helium)

Exergy efficiency of this process $\eta_{ex} = 0,07$





It is not possible to apply a Linde cycle for the liquefaction of gases if its maximum inversion temperature is lower than the ambient temperature (not applicable to hydrogen and helium)

For other fluids:

- High ($h_7 - h_2$) differences
- Discharge compression pressure close to the inversion curve at ambient temperature
- Small values of $(T_2 - T_7)$, which means heat exchangers with high efficiencies

The *Linde-cycle* solved the problem of liquefaction of gases like air.

It is based on the so-called Thomson-Joule effect as a consequence of which (under certain circumstances) the simple process of throttling a gas from a high pressure to a lower one will cause the temperature of the gas to drop.

An (irreversible) throttling process is, as we know from thermodynamics, characterized by the fact that the enthalpies, h , of the fluid before and after the process are the same.

For a perfect ideal gas the enthalpy is independent of the pressure and for such cases the Thomson-Joule effect is zero.

However, for *real* gases at high pressures the enthalpy is a function of pressure as can be seen from the diagram in *Figure 4.33* giving a h, T -diagram for air.

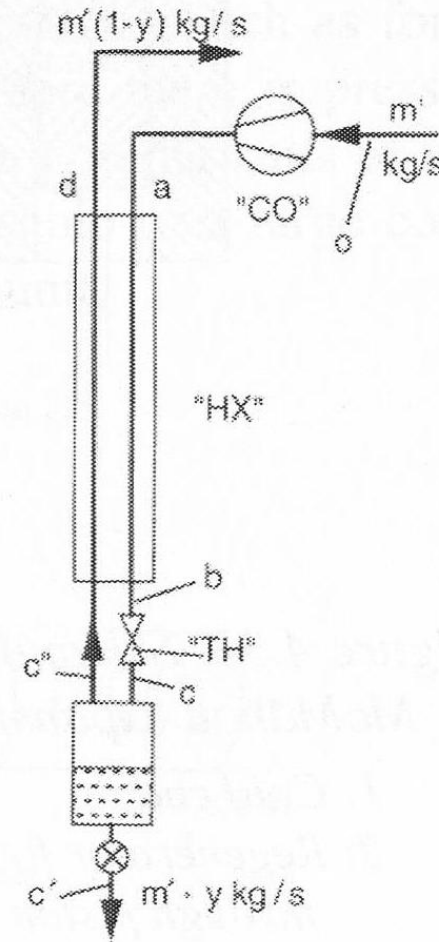
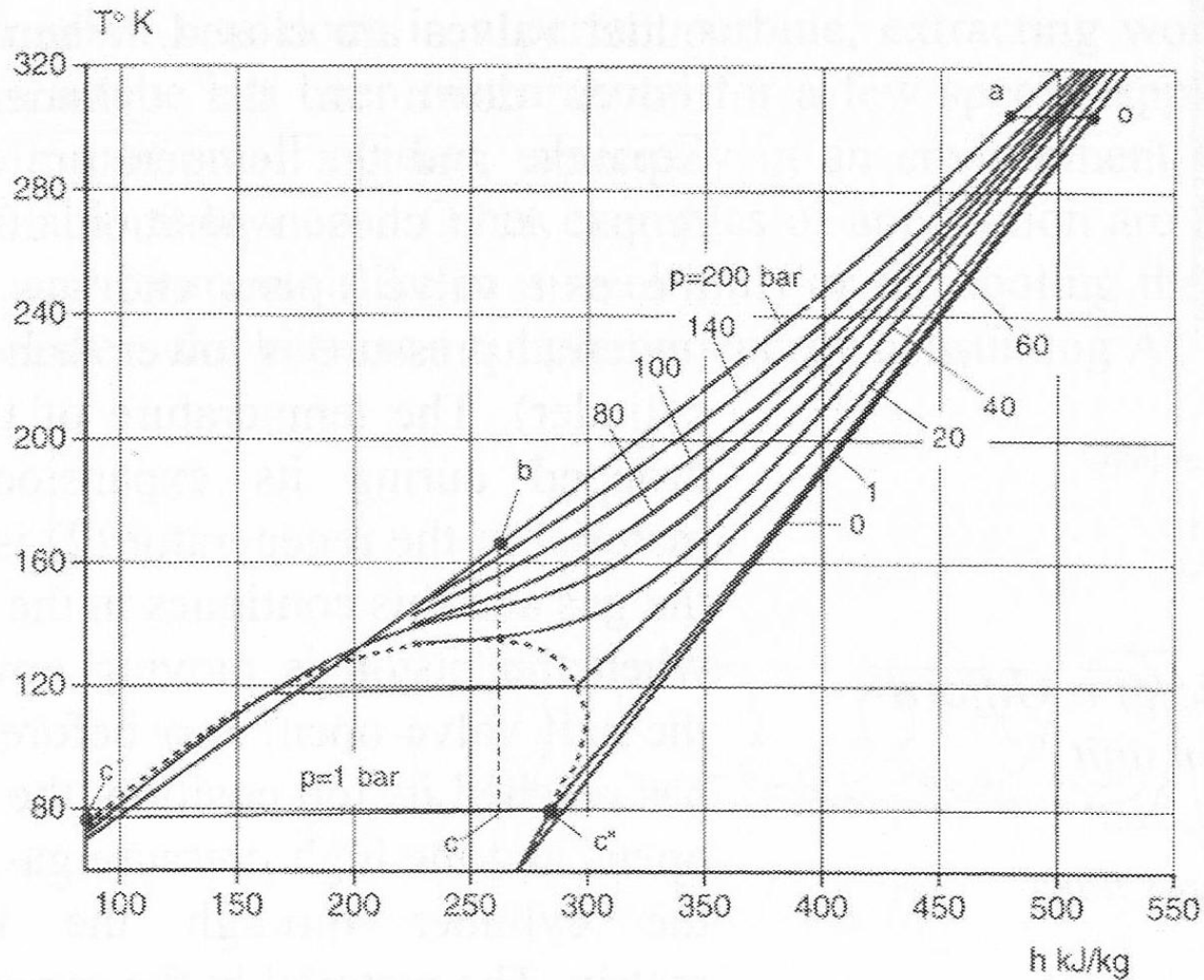
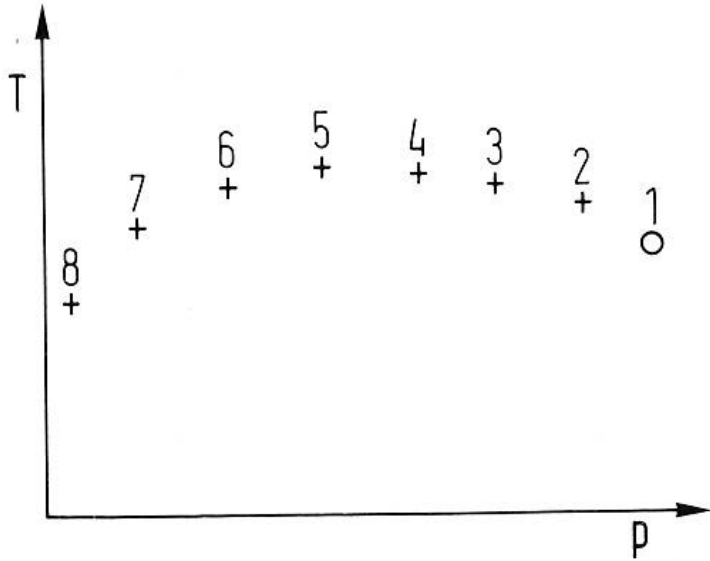


Figure 4.33. Enthalpy-Temperature diagram of air (from Pierre 1982)

Figure 4.34. Scheme of a simple Linde cycle.

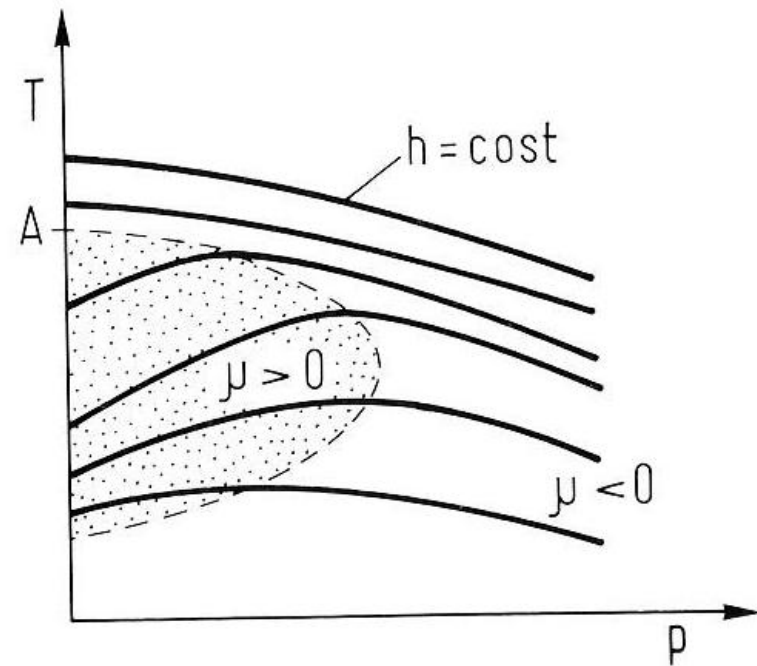
Example: consider throttling air from 200 bar and 30°C (point a) down to atmospheric pressures

Cycles for liquefaction of gases / Joule Thomson expansion



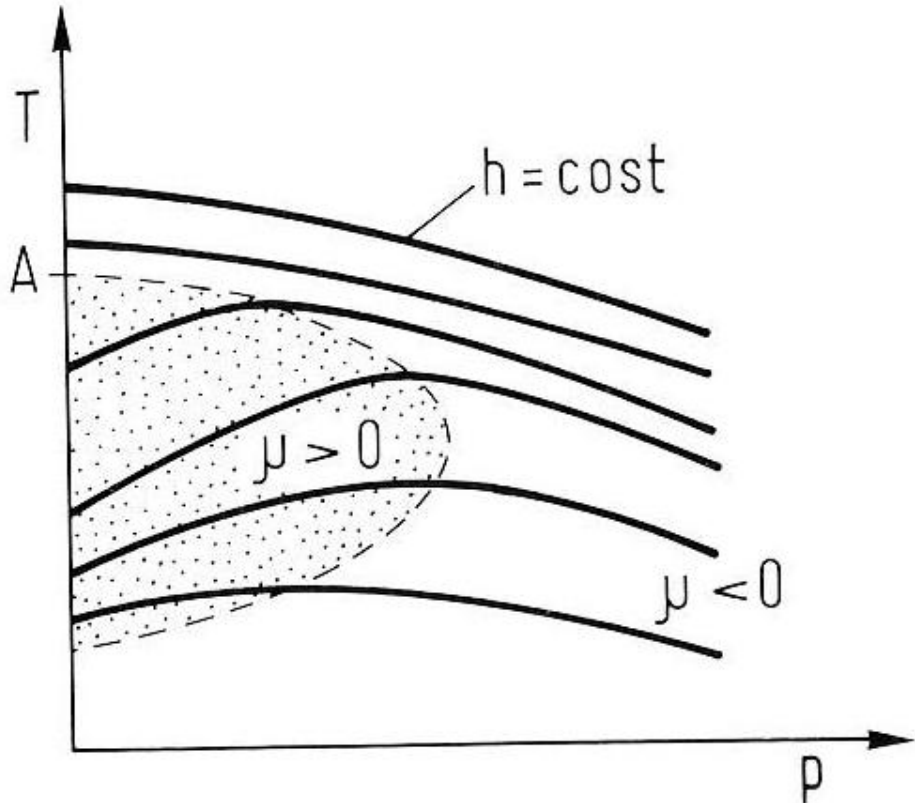
$$\mu = \left(\frac{\partial T}{\partial p} \right)_h$$

Joule-Thomson coefficient



Isoenthalpic lines for the J-T expansion

Cycles for liquefaction of gases



Gas	Max inversion temperature [K]
CO_2	1500
Ar	723
N_2	621
Aria	603
H_2	204,6
He	40

In other words:

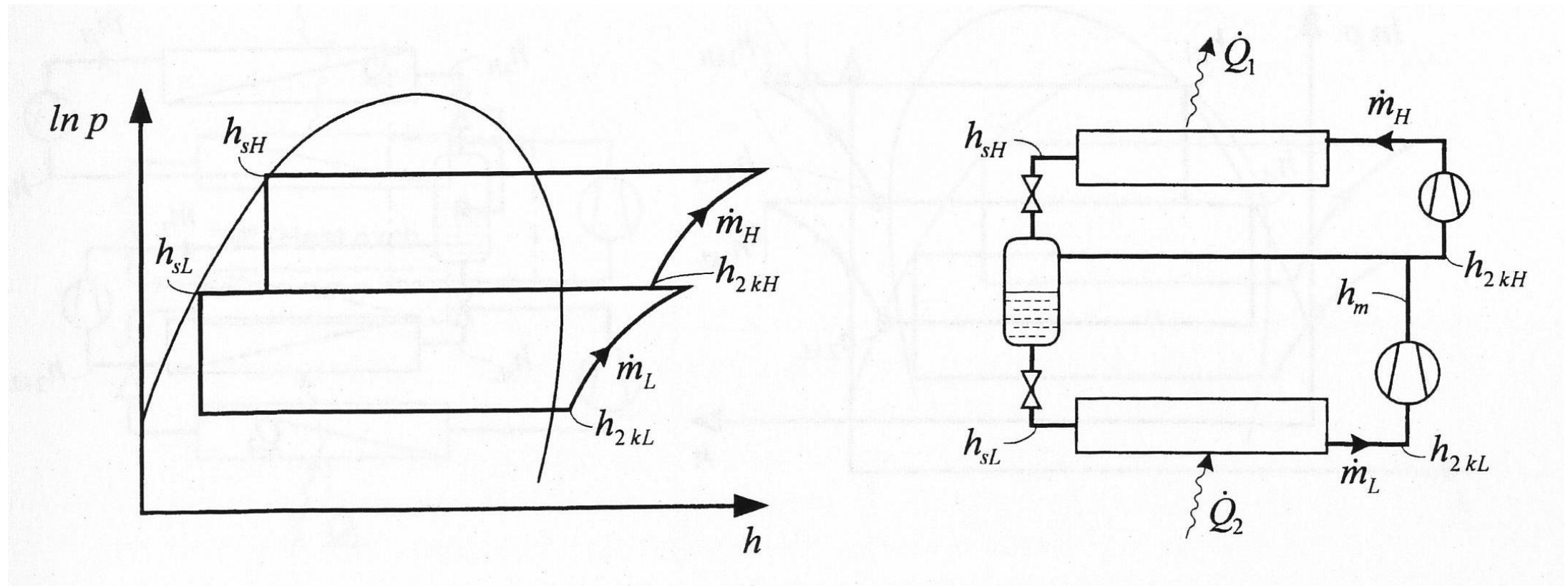
To have a positive J-T coefficient, hydrogen should be cooled down to 204.6 K else the J-T is negative and if the pressure is decrease, the temperature increases

Liquefaction of gases

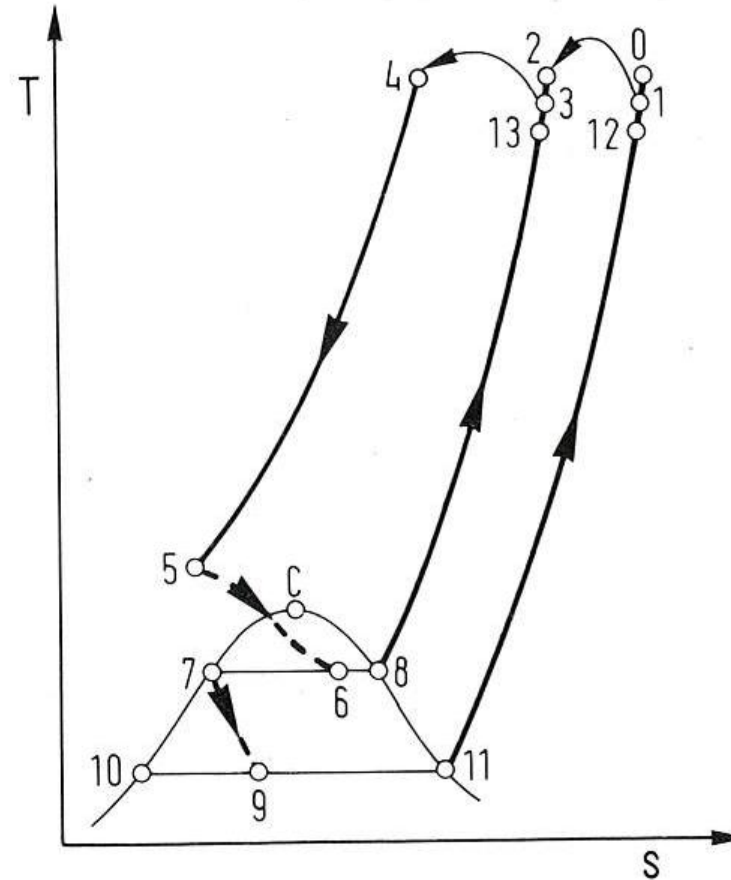
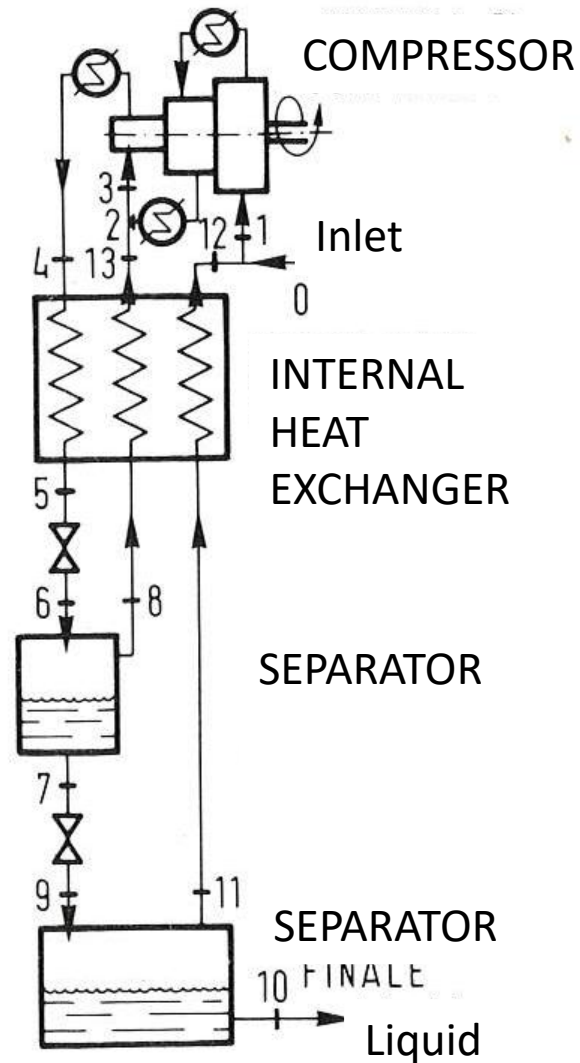
Property	Methane CH ₄	Oxygen O ₂	Air –	Nitrogen N ₂	n-Hydrogen H ₂	Helium-4 ⁴ He
Normal boiling point* [K]	111.42	90.19	78.8 (a) / 81.8 (b)	77.35	20.39	4.21
Normal freezing point* [K]	90.66	54.35	56.9 (c) / 60.3 (d)	63.15	13.95	–
Critical temperature [K]	190.55	154.77	132.6	126.20	33.23	5.19
Critical pressure [bar]	46.41	50.80	37.69	33.94	12.97	2.29
Normal saturated liquid density* [kg/m ³]	424.3	1135.7	876	807.1	71.1	125
Normal heat of vaporization* [kJ/kg]	511.8	212.3	201.5	197.6	456	20.9
Maximum inversion temperature [K]	–	893	603	621	204.6	40

*at normal atmospheric pressure $p_0 = 1.01325$ bar. (a) bubble point; (b) dew point; (c) onset of solid melting; (d) onset of liquid solidification.

How to increase the efficiency?

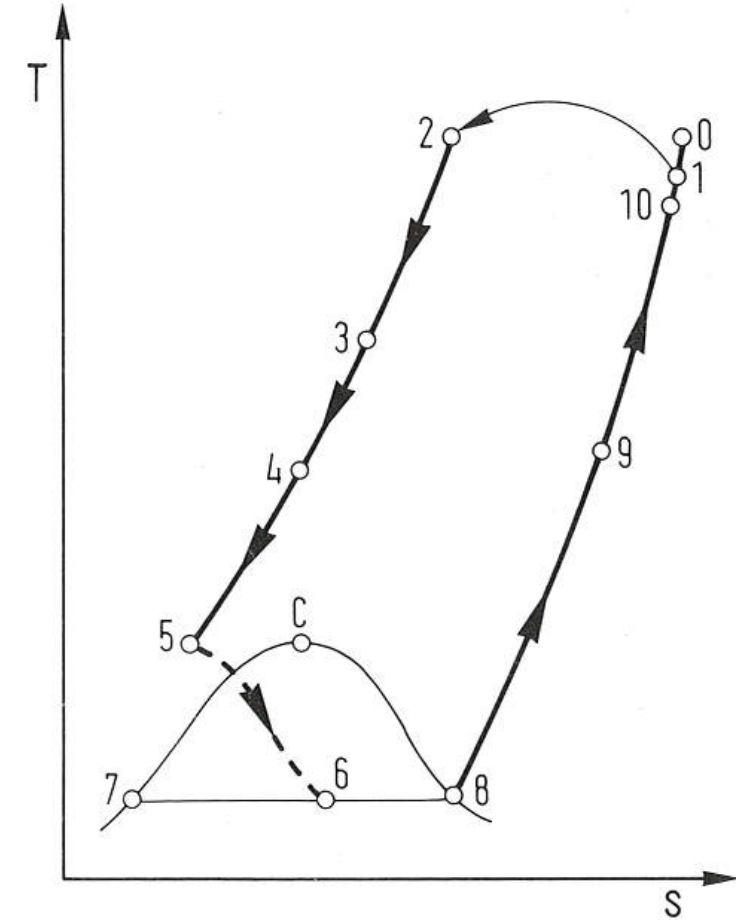
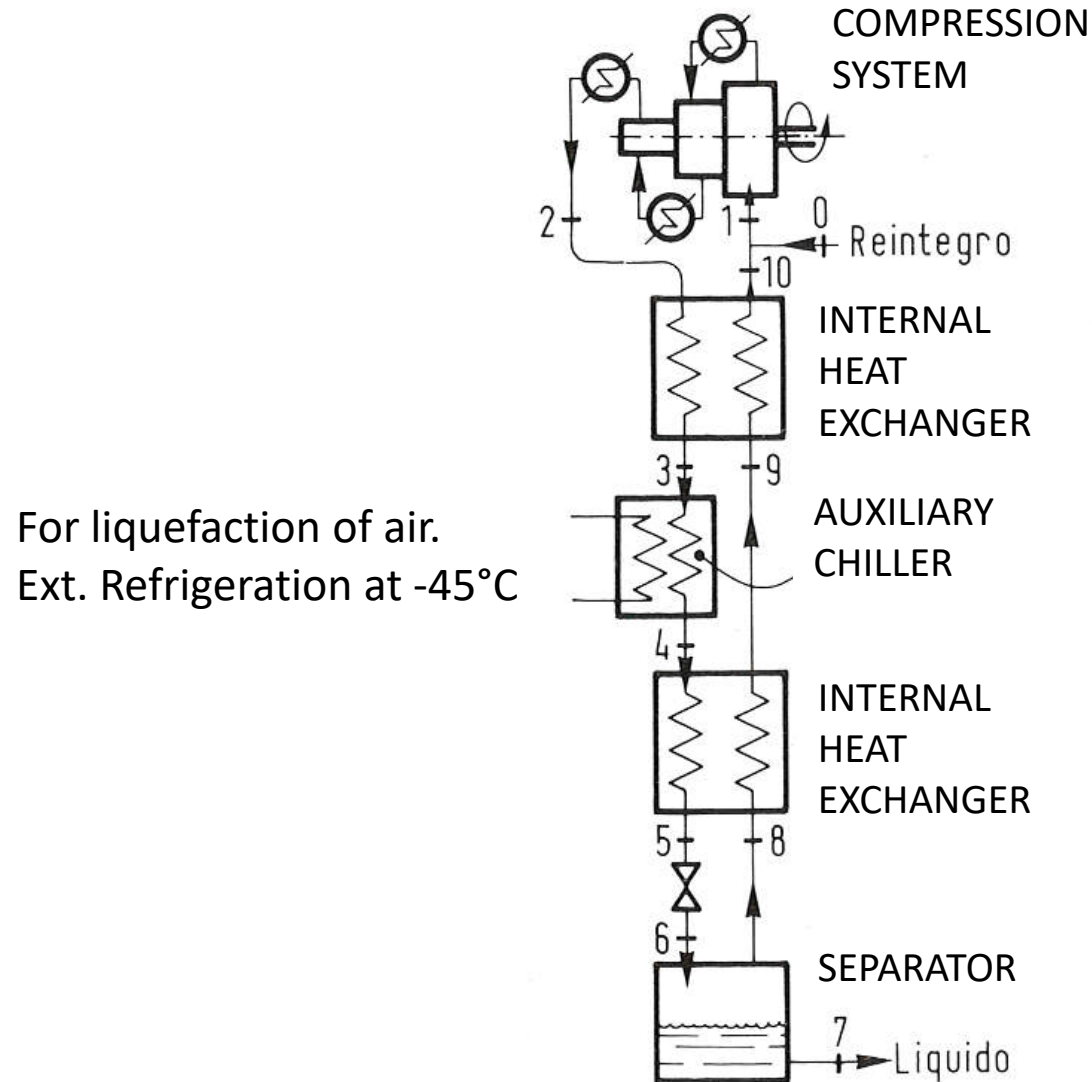


Linde Cycle for liquefaction of gases (two-stage throttling)

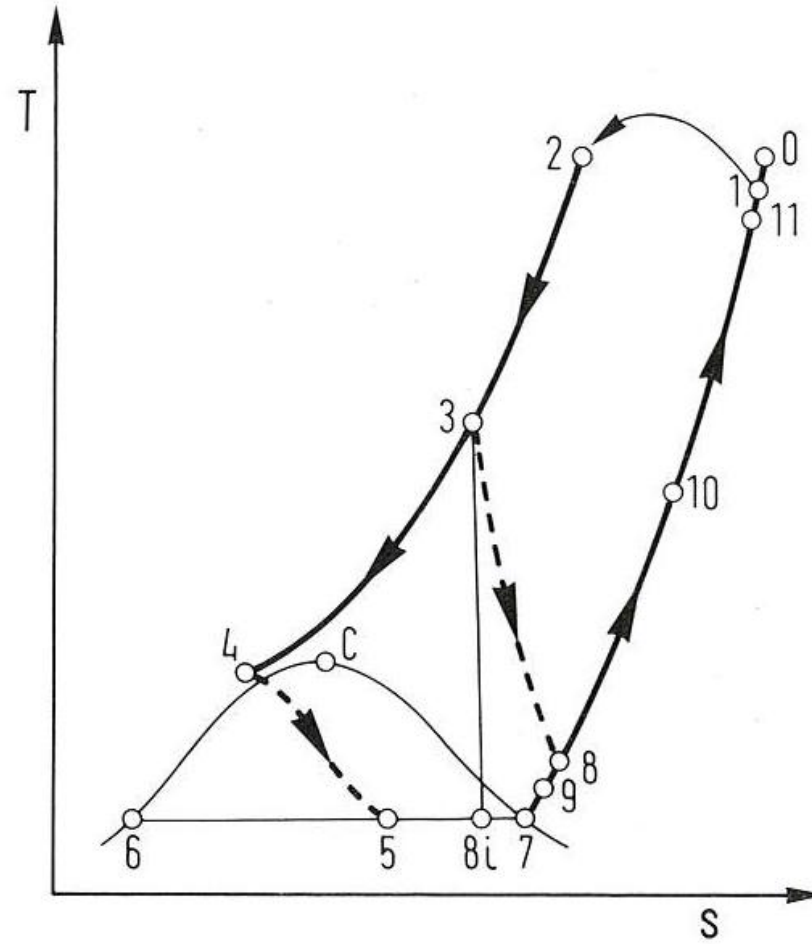
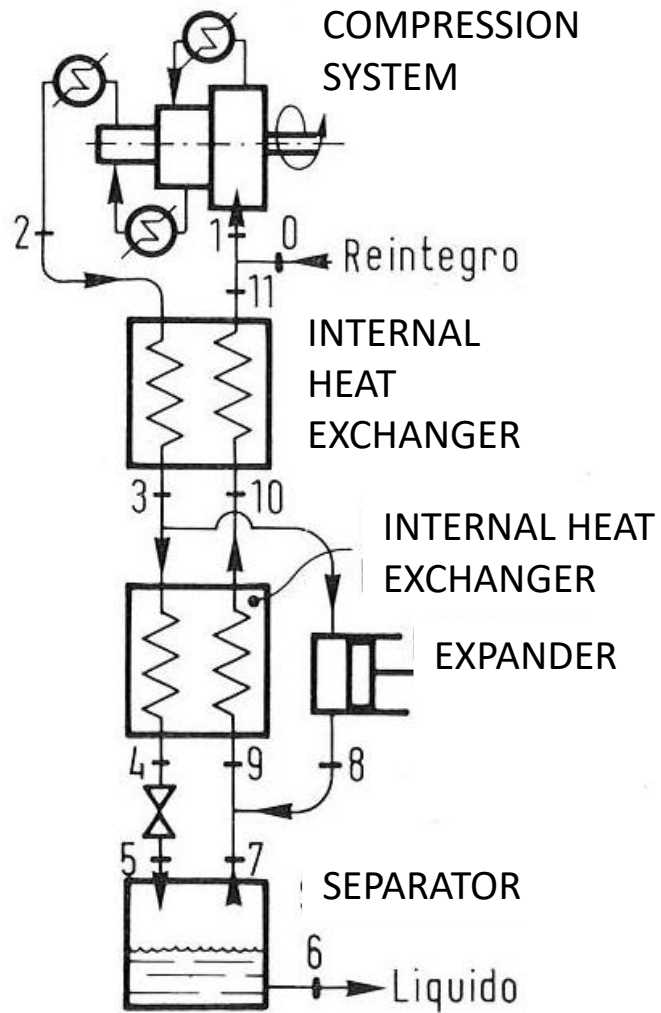


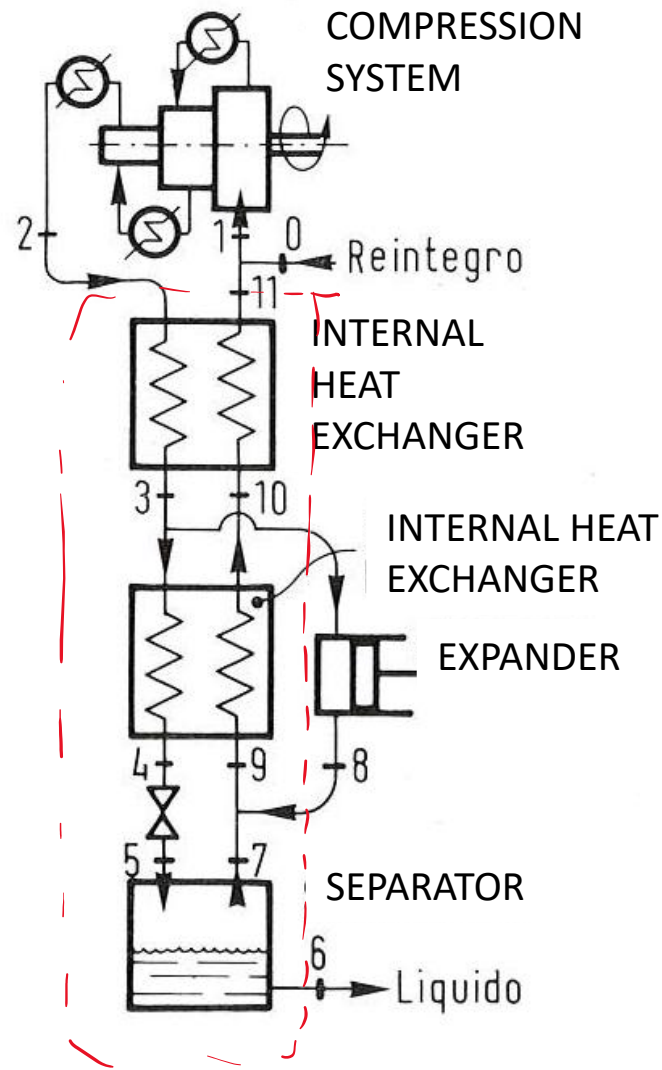
Exergy efficiency of this process $\eta_{ex} = 0,14$

Linde Cycle for liquefaction of gases (with external refrigerator)



Claude Cycle for liquefaction of gases





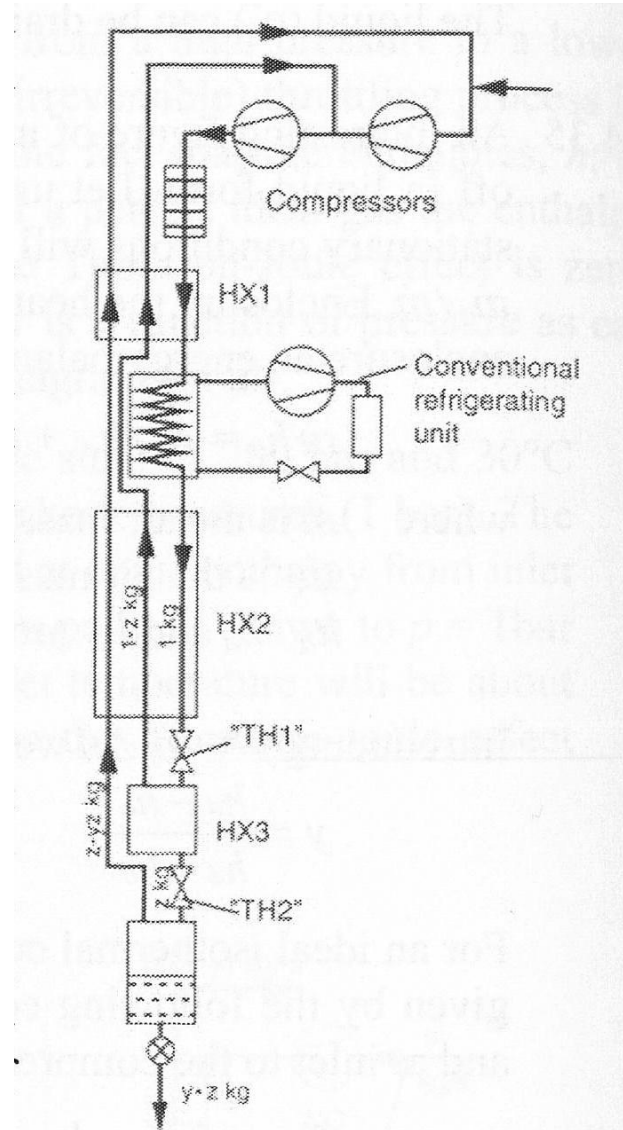
$$\dot{m}_2 h_2 + \dot{m}_g h_g = \dot{m}_{11} h_{11} + \dot{m}_g h_3 + \dot{m}_6 h_6$$

$$\dot{m}_2 = \dot{m}_6 + \dot{m}_{11}$$

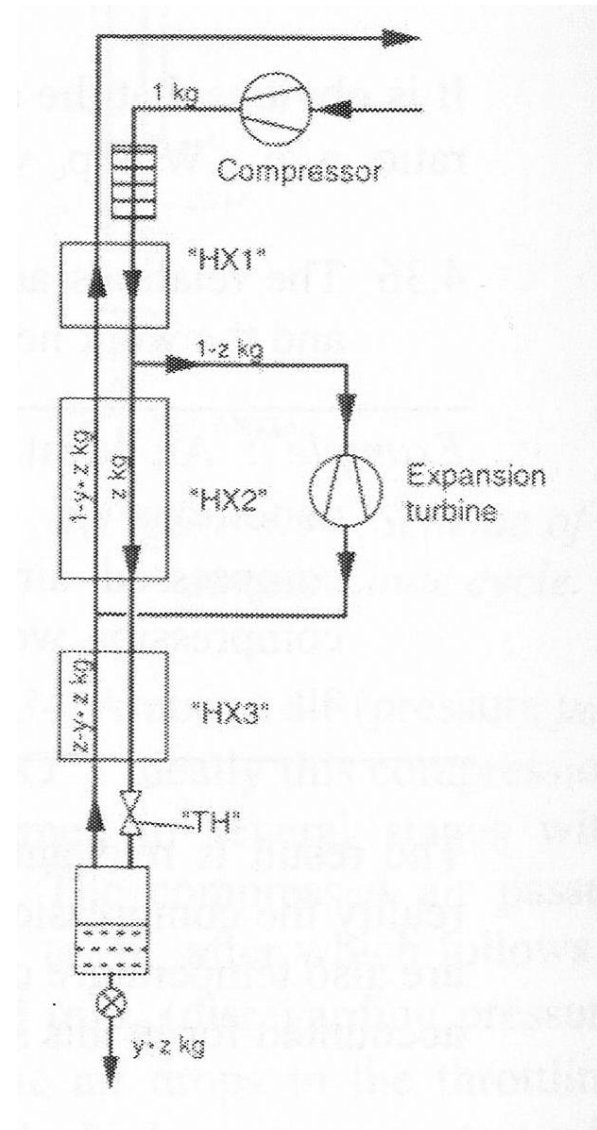
$$z_c = \frac{\dot{m}_6}{\dot{m}_2} = \frac{h_{11} - h_2}{h_{11} - h_6} + \frac{\dot{m}_g}{\dot{m}_2} \frac{h_3 - h_g}{h_{11} - h_6}$$

$$z_c = z_c + \frac{\dot{m}_g}{\dot{m}_2} \frac{h_3 - h_g}{h_{11} - h_6}$$

Linde and Claude cycles for liquefaction of gases

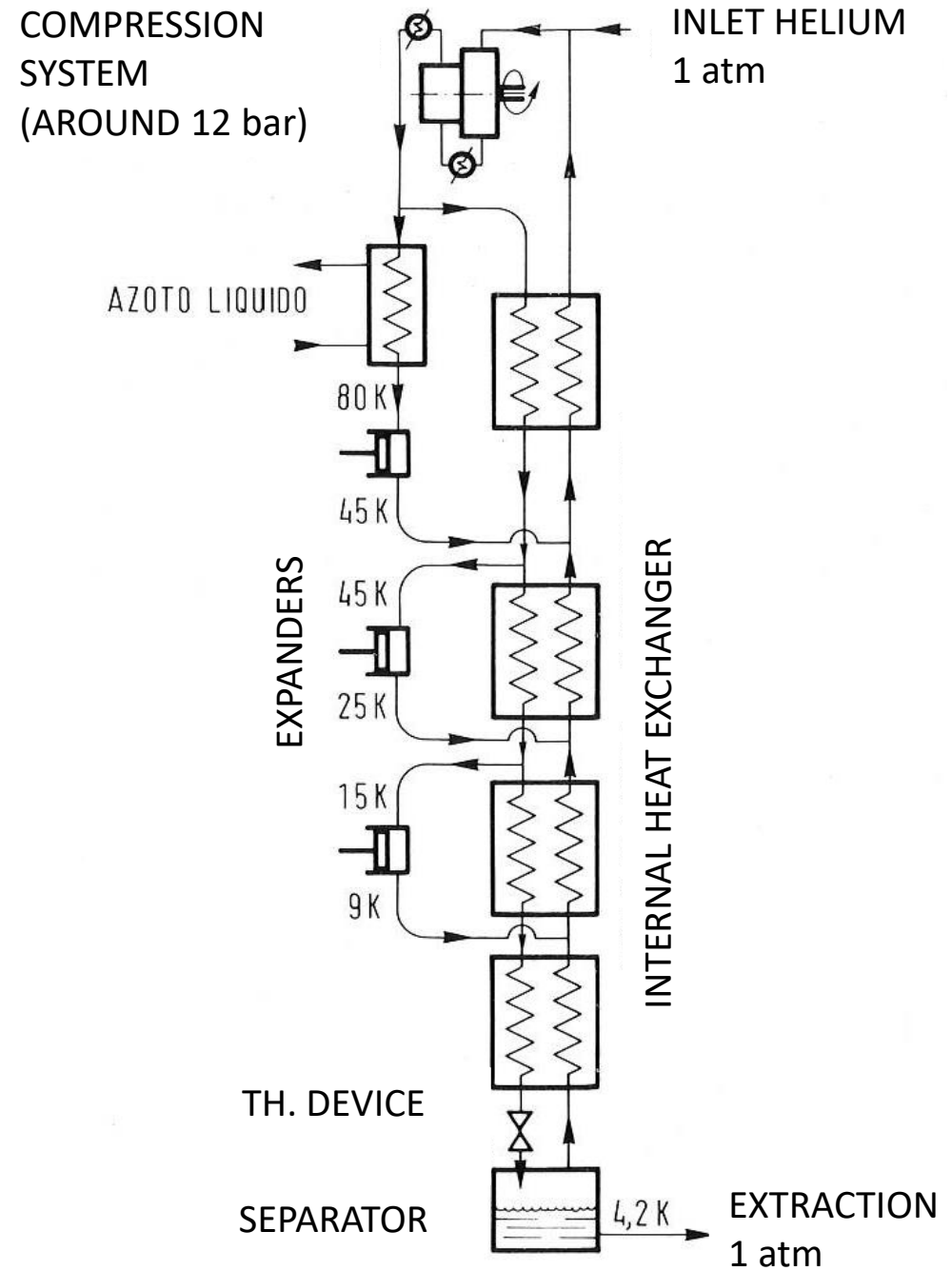


Improved Linde cycle with two stage throttling and pre-cooling.

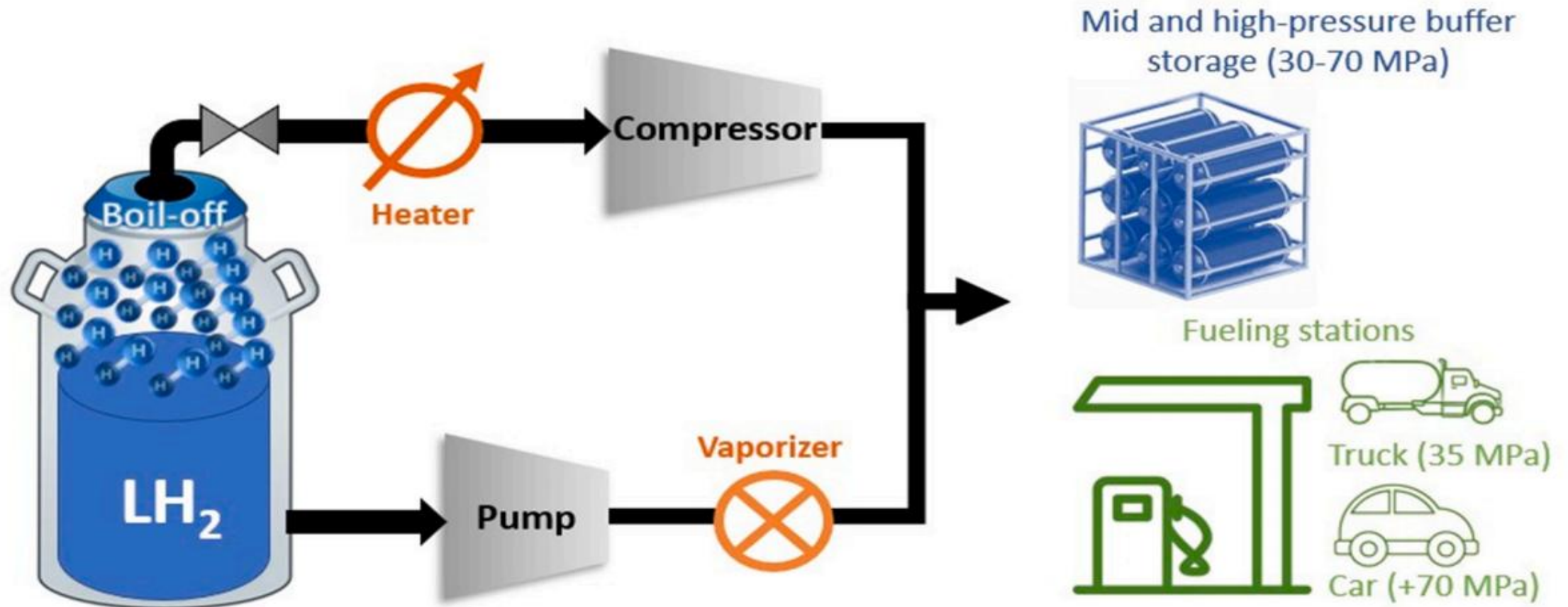


Scheme of the Claude process.

Liquefaction of Helium Collins cycle



Use of liquid and gas from the storage



Large-Scale Liquefaction Plants Worldwide

Company	Location	Capacity	SEC
Praxair (Linde)	California, Alabama, Indiana, New York, USA	6–30 ton/day	~12.5–15 kWh/kg
Praxair La Porte	Texas, USA	30 ton/day	—
Linde Ingolstadt	Germany	4.4 ton/day	13.58 kWh/kg
Linde Leuna	Germany	~3,200 ton/year	—
Air Liquide	North Las Vegas, USA	30 ton/day	—
Air Liquide (planned)	South Korea (SK E&S)	90 ton/day	—

Most large-scale H₂ liquefaction plants use the Claude process with LN₂ pre-cooling due to lower specific energy consumption (SEC) and simplicity. Maximum LH₂ production of existing plants worldwide: ~32 ton/day per liquefaction train.