Geneva, December 1877

When Cryogenic Engineering was born

Raoul Pictet

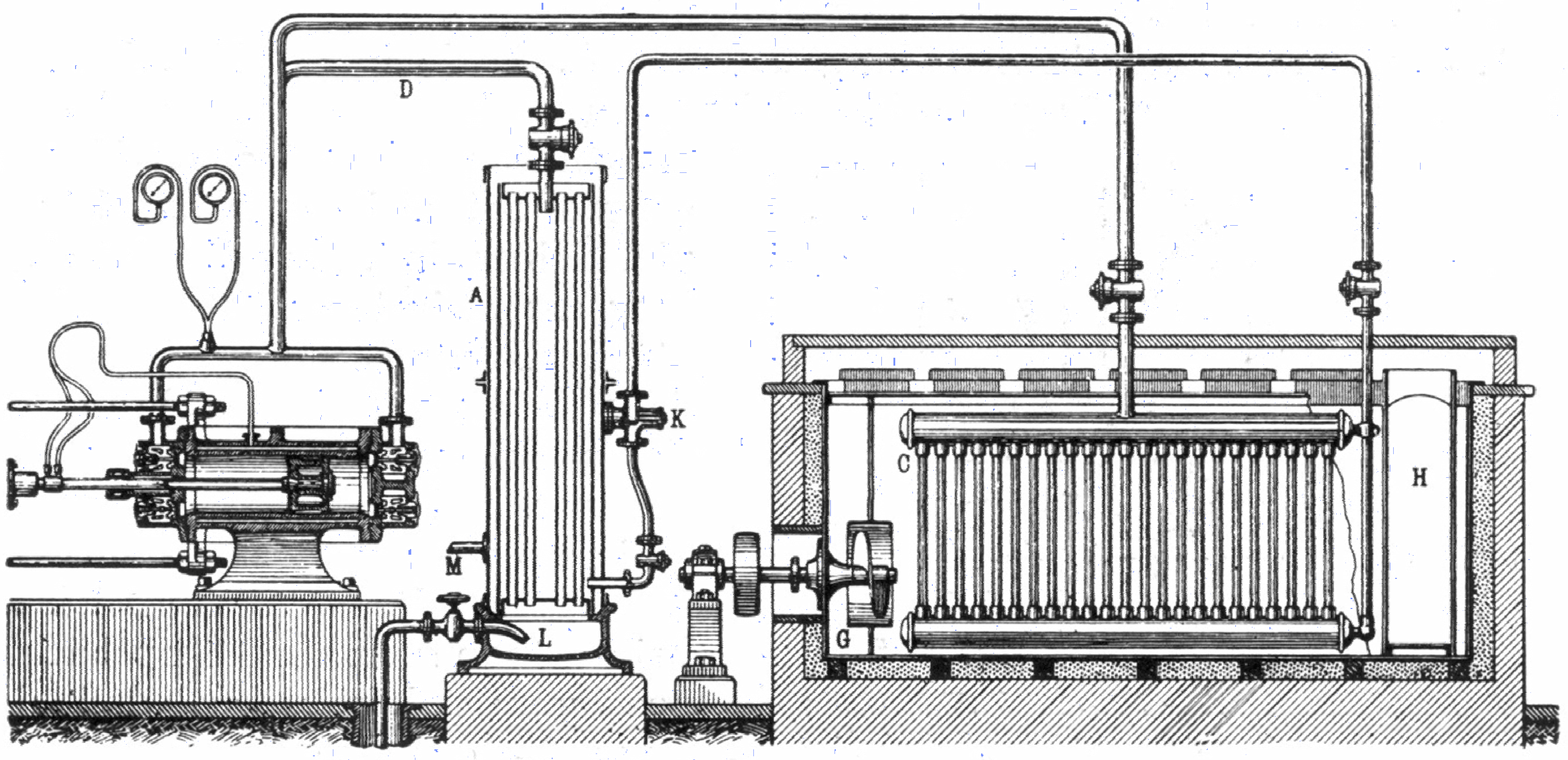
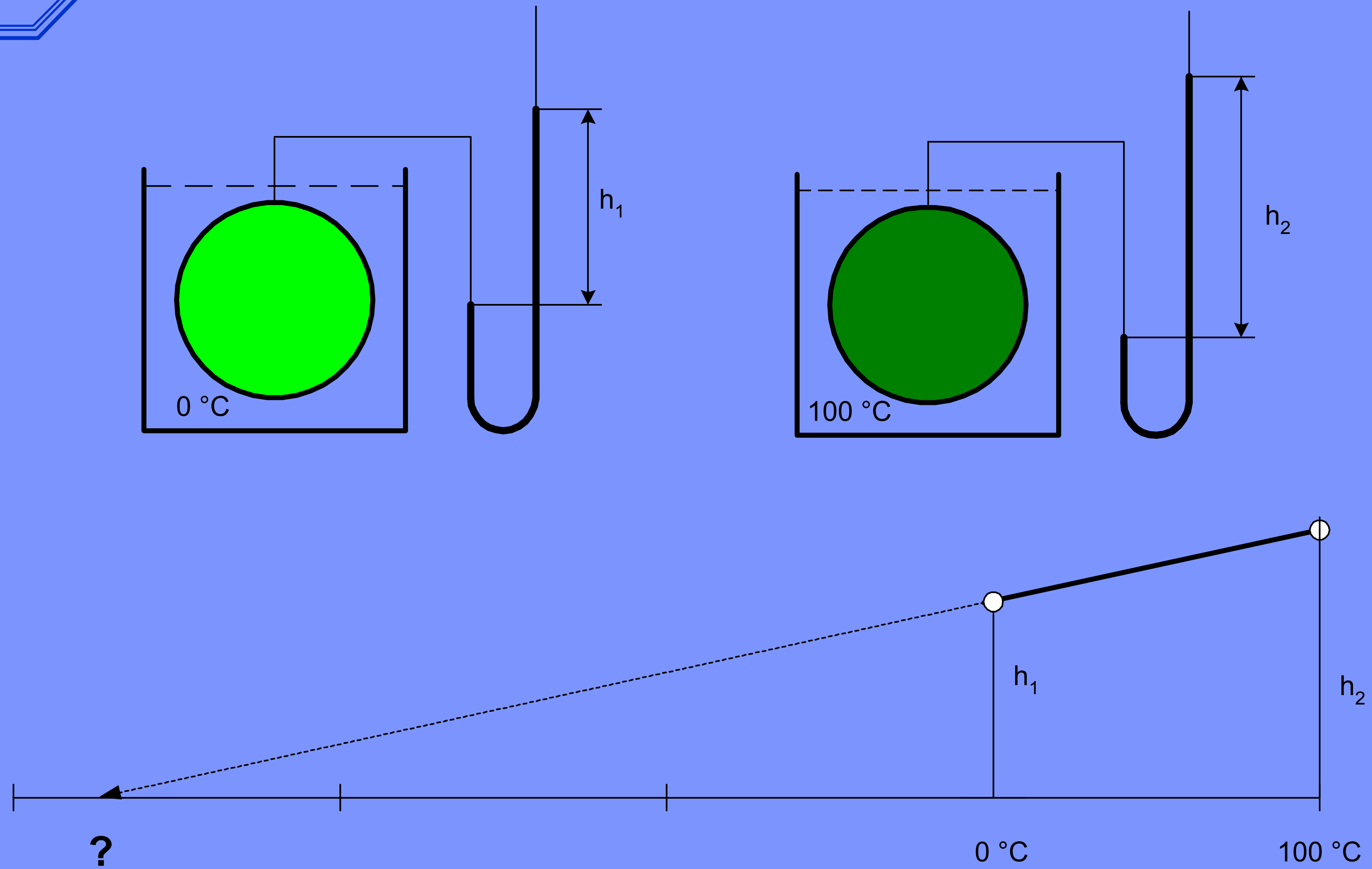


Abb. 44. SO_2-Eismaschine von RAOUL PICTET.
A Kondensator, *C* Verdampfer, *D* Druckrohr, *G* Rührwerk, *H* Eiszelle, *K* Drosselventil, *L* Wassereintritt in den Kondensator, *M* Wasseraustritt.



Vorhersage des absoluten Nullpunkts

Amontons (17. Jahrh.)

- Fliessbild von Pictets Anlage

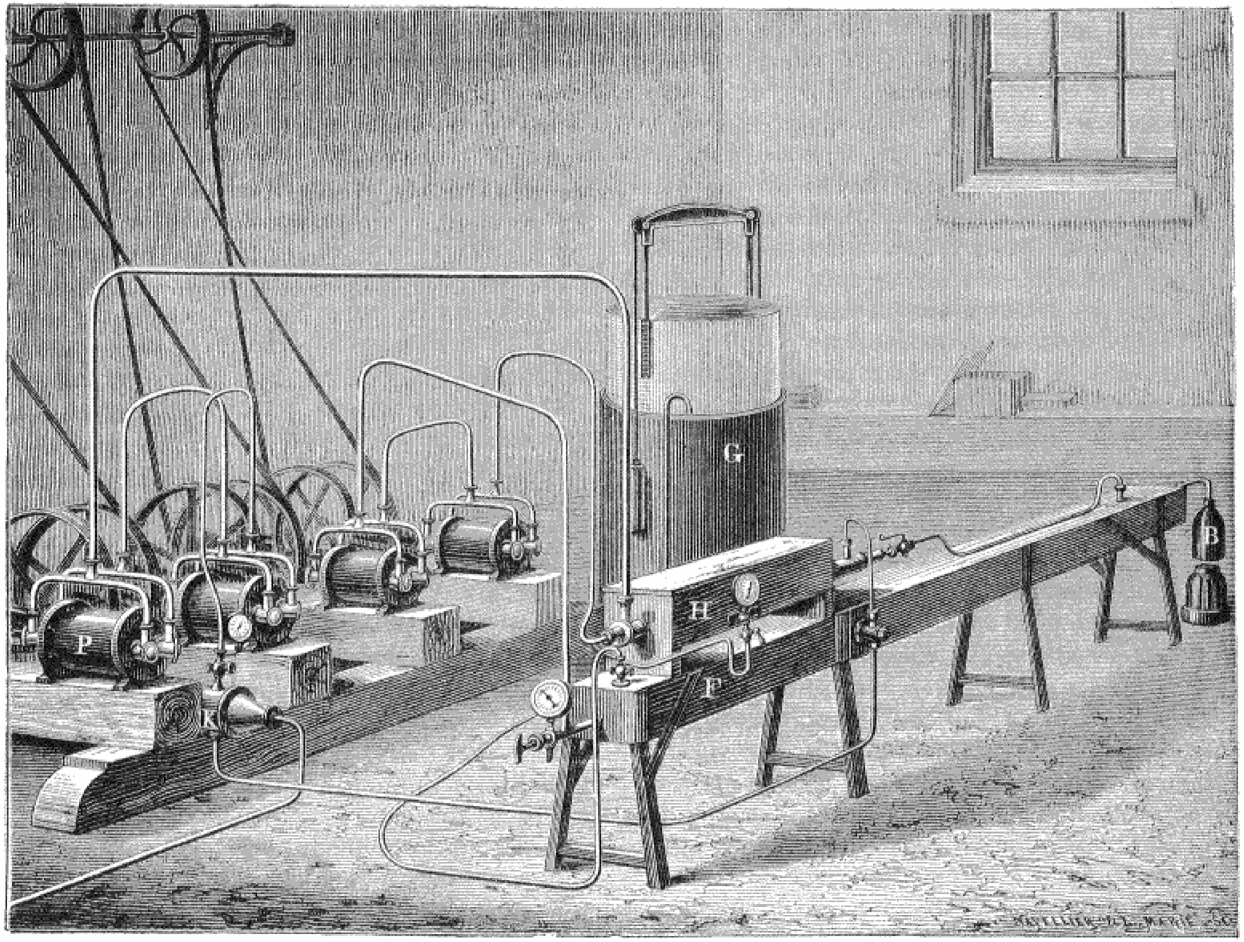
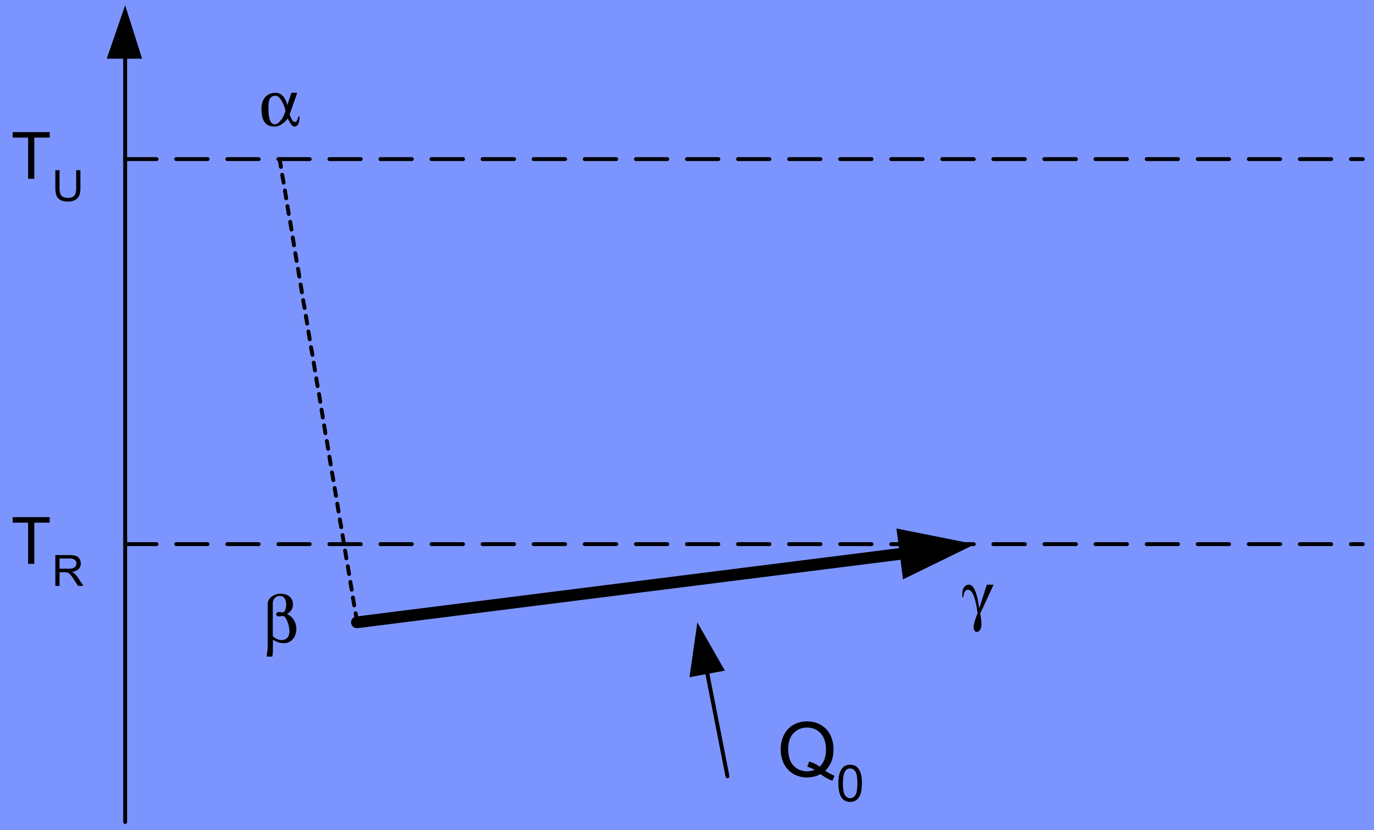


Fig. 1. — Grand appareil de M. Raoul Pictet pour la liquéfaction des gaz. (D'après une photographie.)

Lowering of Temperature and Production of Refrigeration



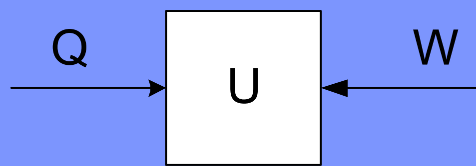
How can one reduce the temperature of a refrigerant below ambient temperature?

Our forefathers found three methods:

- Heat rejection to an even colder system
- Throttling (the method Pictet used)
- Performance of work by the refrigerant

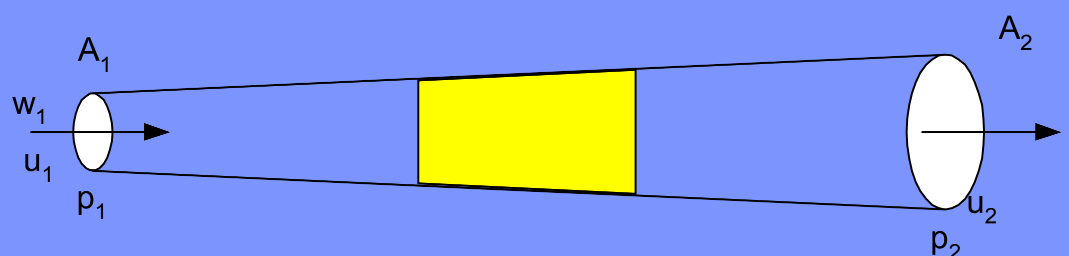
Energy Conservation

Energy conservation for a closed system



$\Delta U = \Delta Q + \Delta W$

Energy conservation for an open system



$m*u_1+p_1*A_1*w_1 = m\,(u_1+p_1v_1) = m*h_1$

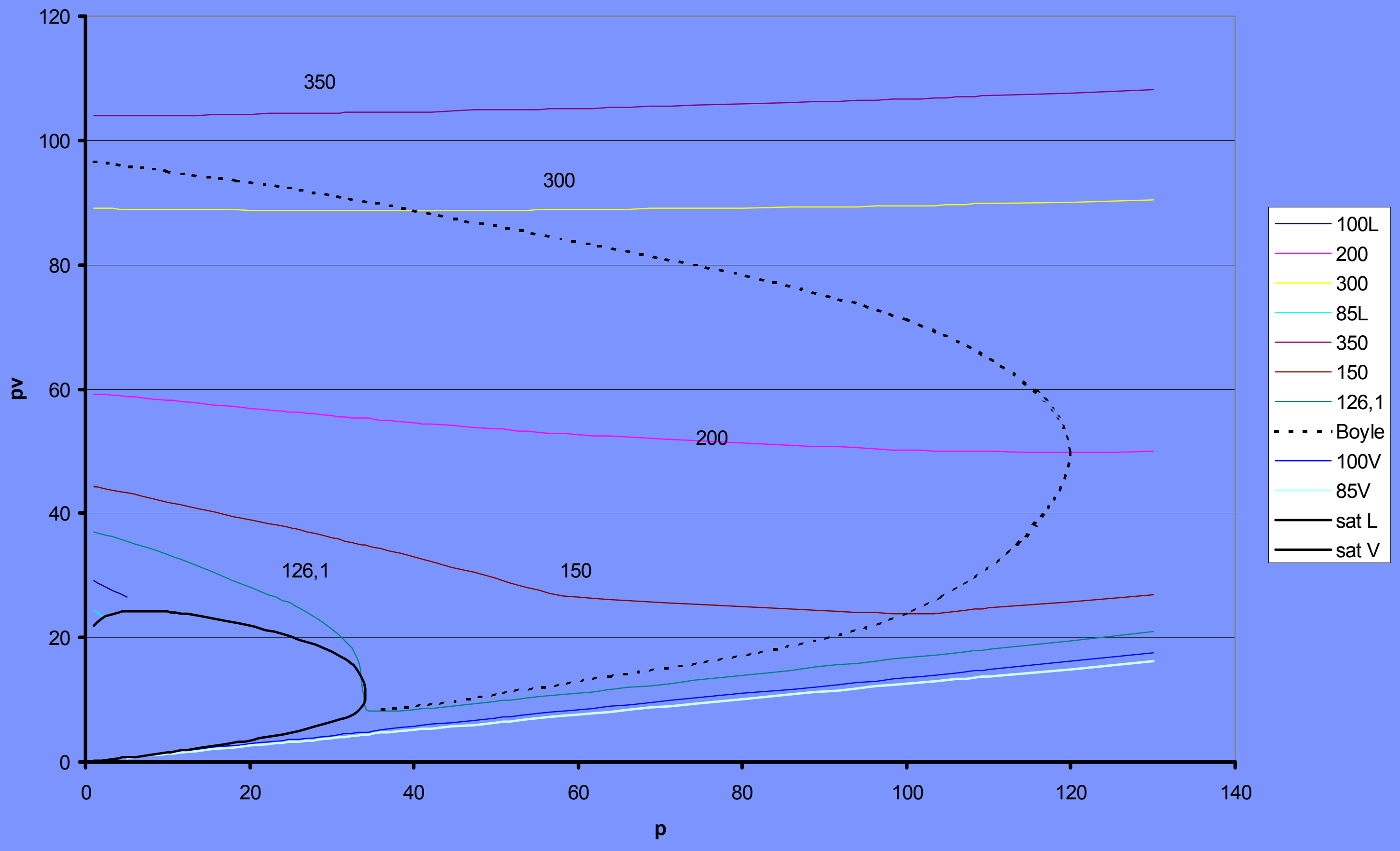
$m*u_2+p_2*A_2*w_2 = m\,(u_2+p_2v_2) = m*h_2$

$u_2-u_1 = p_1v_1-p_2v_2$

Temperature change of the fluid through throttling depends on the properties

if v increases slower than p decreasing	internal energy is increased
if p*v = constant	internal energy stays constant
if v increases faster than p decreases	internal energy is reduced

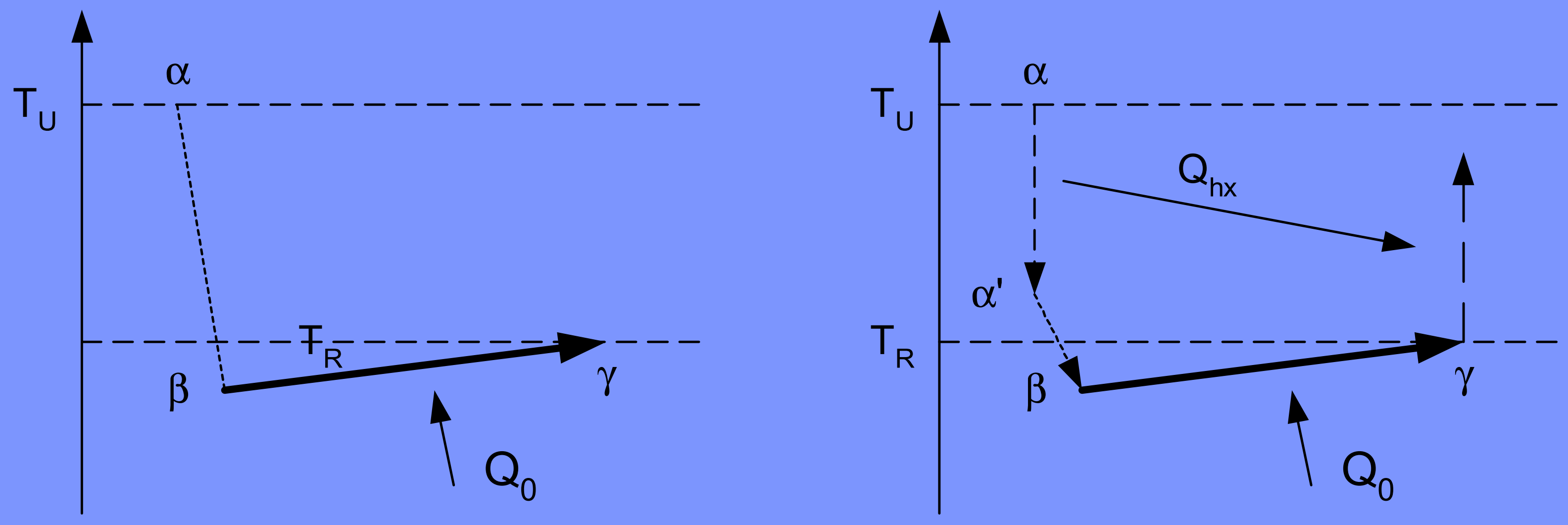
pv - p Diagram of Nitrogen



Temperature change due to throttling

- Temperature reduction due to throttling of a saturated liquid is a large effect
- Temperature change of a gas can be positive or negative, depending on the region in the phase diagram
- In any case it is a small effect, initially considered not to be technically usable.
- But: Remember our assistant!

Internal heat exchange makes the production of refrigeration much easier



Recover unused Refrigeration by counter-current heat exchange

- Often not all produced refrigeration is used
- Idea: Recover the not-used refrigeration and use it for precooling of the inlet stream before the throttling
- Wilhelm Siemens (later Sir William Siemens) 1858 (long before Pictet!)

Combination of throttle refrigeration with counter-current heat exchange (Linde 1895)

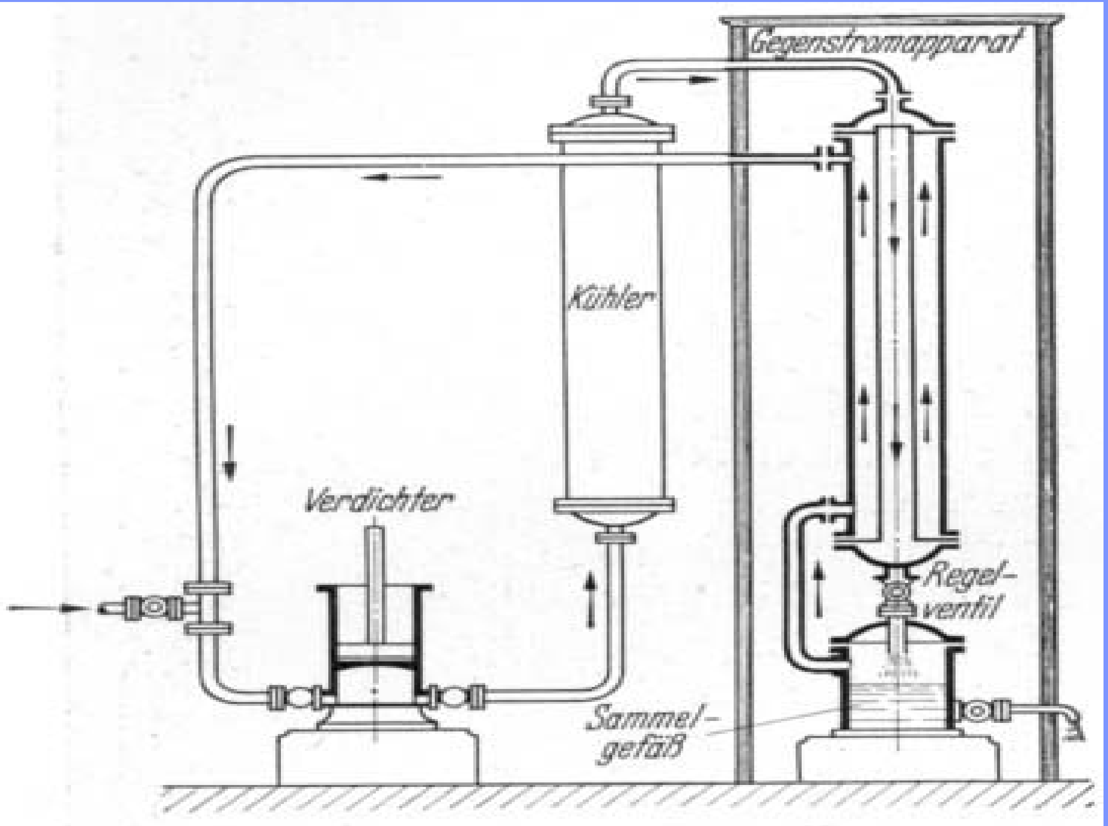
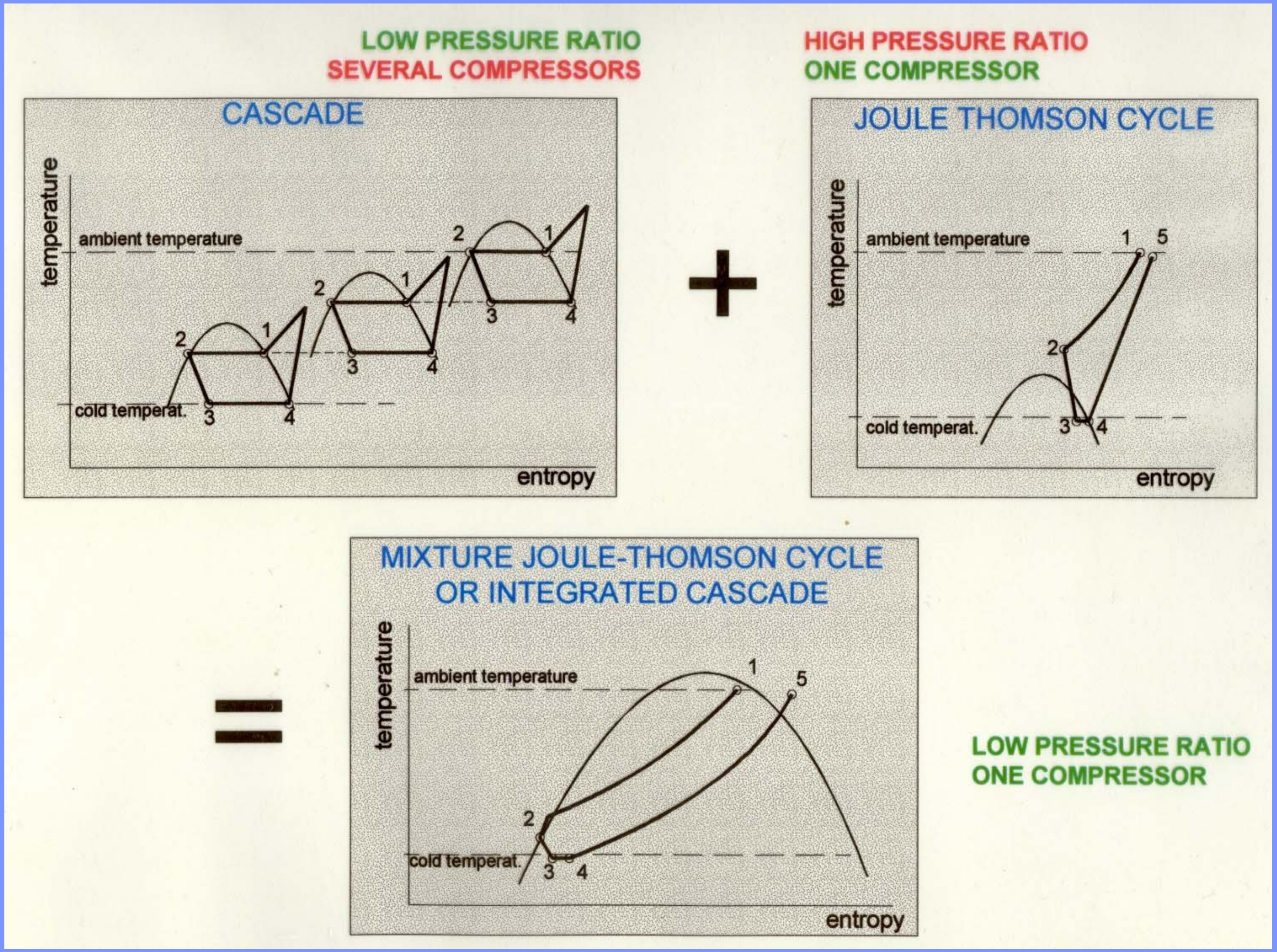


Abb. 70. Schema der ersten Luftverflüssigungsmaschine von LINDE.

The death and resurrection of throttle refrigeration in cryogenics

- Linde knew that throttling was simple, but not effective
- Eventually work extracting expansion was to replace the throttling
- But recently throttle refrigeration has made a surprise comeback:
- Mixed Refrigerant JT-systems


LOW PRESSURE RATIO
SEVERAL COMPRESSORS
HIGH PRESSURE RATIO
ONE COMPRESSOR
CASCADE
temperature
ambient temperature
cold temperat.
entropy
1
2
3
4
+
JOULE THOMSON CYCLE
temperature
ambient temperature
cold temperat.
entropy
1
5
2
3
4
=
MIXTURE JOULE-THOMSON CYCLE
OR INTEGRATED CASCADE
temperature
ambient temperature
cold temperat.
entropy
1
5
2
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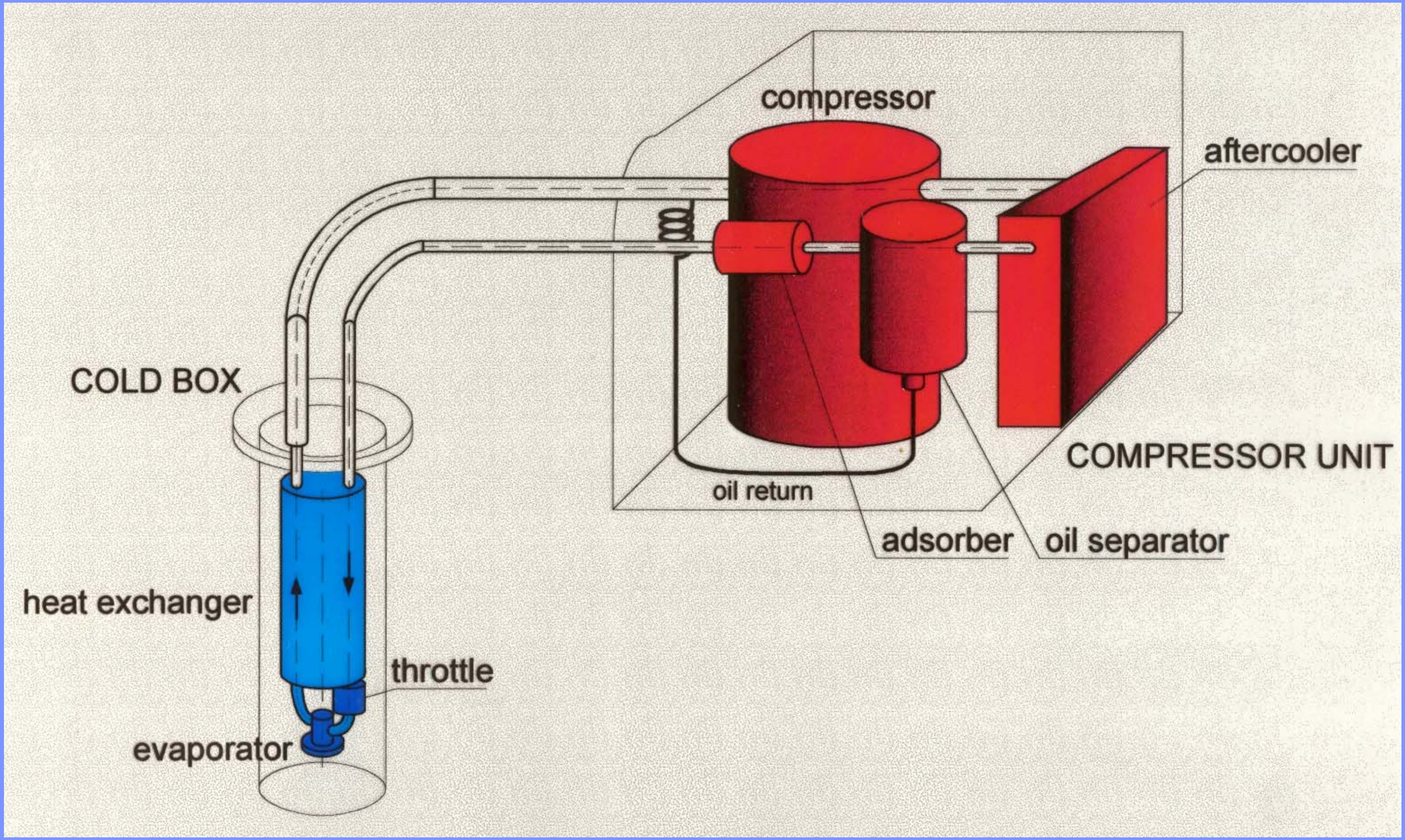
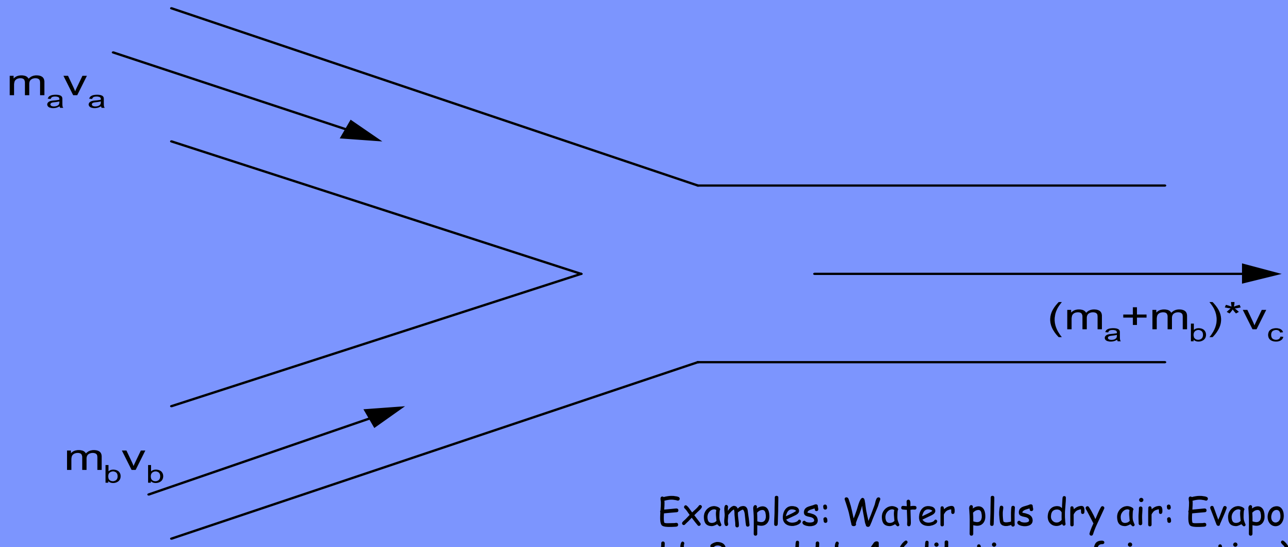
LOW PRESSURE RATIO
ONE COMPRESSOR


compressor
aftercooler
COLD BOX
COMPRESSOR UNIT
oil return
adsorber
oil separator
heat exchanger
throttle
evaporator

„Mixing“ is Throttling at constant pressure:

If the mixing of two fluids leads to an increase in specific volume, a cooling effect will be observed

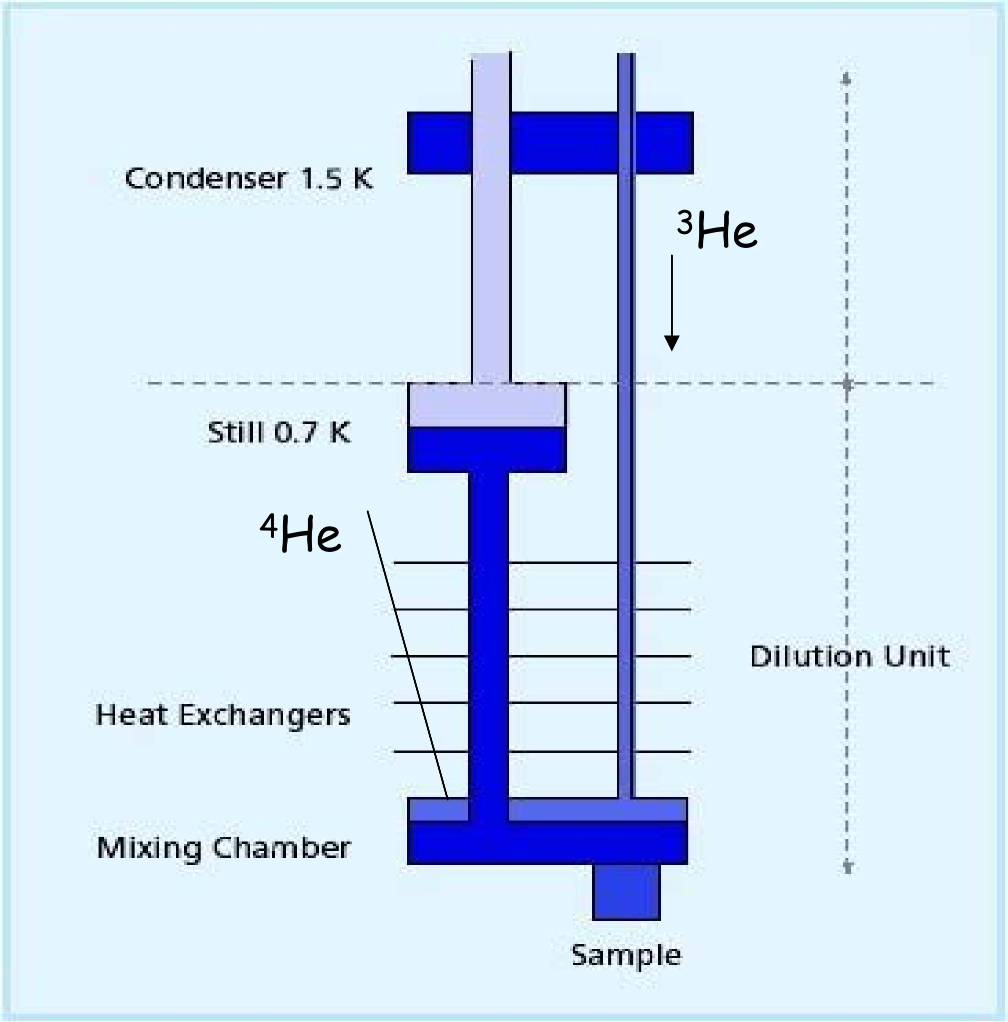
Energy conservation during mixing at constant pressure



Examples: Water plus dry air: Evaporative cooling
He3 and He4 (dilution refrigeration)

Temperature reduction by mixing at constant pressure and increase in specific volume: Cooling Tower

Mixing at constant pressure with increase in specific volume: Dilution Refrigerator



Summary of „Throttle Refrigeration“

- Throttling is a process at constant enthalpy
- Cooling effect depends on on the properties of refrigerant (the volume has to increase faster than the pressure decreases)
- Widely used in near ambient refrigeration
- Outside the two-phase region it is called the Joule-Thomson effect
- Effect can be extended to lower temperatures by recuperator
- Simple device without moving parts in cold section
- But: We can do better: Replace the throttling by a work extracting expander (tomorrow!)

Applications

Physics

Material Properties at low temperature

Side Effects

Engineering Thermodynamics

Refrigeration processes

Mechines, apparatures

Bis 1900 - Epoche der Pioniere

1700	Amonton	Tiefste Temperatur: -240 °C
1800	Charles, Gay-Lussac	Tiefste Temperatur: -273 °C
1842	R. Mayer	Äquivalenz von Wärme und Arbeit
1857	W. Siemens	Gegenstrom-Wärmeübertrager in Energie-Kreisläufen
1863	Andrews	Kritischer Punkt
1872		Kühleffekt beim Drosseln von realem Gas (Joule-Thomson-Effekt)
1873	Van der Waals	Prinzip der Korrespondierenden Zustände
1877	Cailletet, Pictet	Flüssige Luft als Nebel
1883	Wróblenski, Olszewski	Ruhig siedende flüssige Luft
1884	Wroblenski	Flüssiger Wasserstoff als Nebel
1892	Dewar	Verspiegelte Vakuumisolation
1895	Linde, Hampson	Kontinuierliche Luftverflüssigung mit Joule-Thomson Kreislauf
1898	Dewar	Wasserstoff Verflüssigung mit Joule-Thomson Kreislauf
1908	Kammerlingh Onnes	Helium Verflüssigung mit Joule-Thomson Kreislauf