CO_2-refrigeration in a historic perspective

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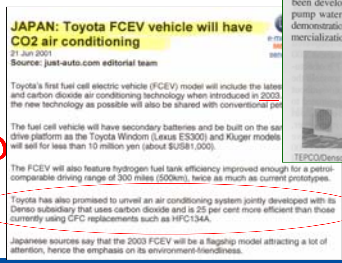
CO_2 is back!



JAPAN: Toyota FCEV vehicle will have CO2 air conditioning
21 Jun 2001
Source: just-auto.com editorial team

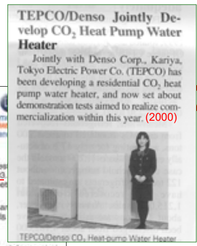
Toyota's first fuel cell electric vehicle (FCEV) model will include the lates[t] ... and carbon dioxide air conditioning technology when introduced in 2003. ... the new technology as possible will also be shared with conventional pe[trol] ...

The fuel cell vehicle will have secondary batteries and be built on the sa[me] ... drive platform as the Toyota Windom (Lexus ES300) and Kluger models ... will sell for less than 10 million yen (about $US81,000).

The FCEV will also feature hydrogen fuel tank efficiency improved enough for a petrol-comparable driving range of 300 miles (500km), twice as much as current prototypes.

Toyota has also promised to unveil an air conditioning system jointly developed with its Denso subsidiary that uses carbon dioxide and is 25 per cent more efficient than those currently using CFC replacements such as HFC134A.

Japanese sources say that the 2003 FCEV will be a flagship model attracting a lot of attention, hence the emphasis on its environment-friendliness.



TEPCO/Denso Jointly Develop CO_2 Heat Pump Water Heater

Jointly with Denso Corp., Kariya, Tokyo Electric Power Co. (TEPCO) has been developing a residential CO_2 heat pump water heater, and now set about demonstration tests aimed to realize commercialization within this year. (2000)

TEPCO/Denso CO_2 Heat-pump Water Heater

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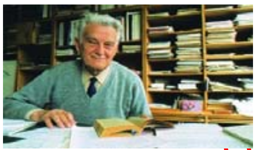
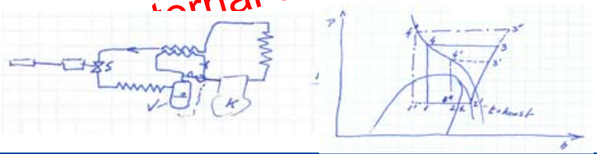


Professor Gustav Lorentzen 1915-1995

First draft made for a patent application on how to operate and control transcritical CO_2- vapour compression systems
November 1988



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CO_2-refrigeration technology prior 1988?

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Content

- How developed refrigeration technology?
- Factors which contributed to the development
- CO_2 i relation to other working fluids
- The people behind the innovations
- Synergies to todays situation
- **CO_2 processes / system configurations and modifications**
- Reasons why CO_2 refrigeration technology was absent between 1960 to 1990

MOTIVATION:
Can we learn something when studying the historic CO_2 refrigeration systems?

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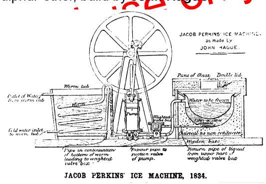
Inventors and pioneers of mechanical refrigeration

Vapour compression cycle:
- ***Oliver Evans*** (1755-1819), USA
  "*The Abortion of the Young Steam Engineer's Guide*", 1805
- ***Jacob Perkins*** (1766-1849), American living in London
  British Patent No 6662, 14. August 1834
  Machine applying sulphur-ether, build by ***John Hague***



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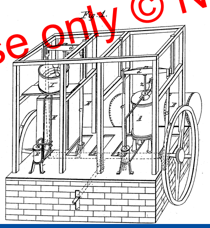
Inventors and pioneers of mechanical refrigeration

Air cycle:

- *John Gorrie* (1802-1855), Florida, USA
  "An engine for ventilation and cooling air in tropical climates by mechanical power" 1842-1844



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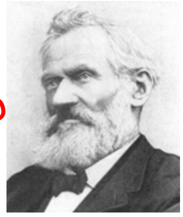
Inventors and pioneers of mechanical refrigeration

Absorption cycle:

- *Ferdinand Carré* (1824-1900), France
  Patent NH_3/H_2O absorption system in 1859



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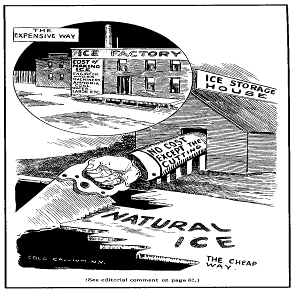
Three important 'drivers' in the late 19th century

Factors pushing the development of mechanical refrigeration technology from 1850 →

- "Artificial" ice production
- Brewing of beer (all year long)
- Transport of meat



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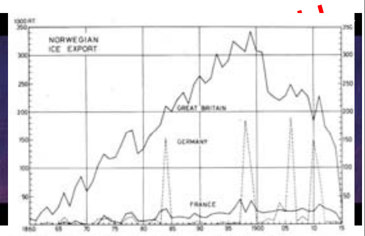
150 years ago: ICE = refrigeration



Norwegian Ice Export from 1860 to 1915

Natural working fluids also common in the US:

Advertisement in ICE and REFRIGERATION, 1922, vol. 63

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Three important 'drivers' in the late 19th century

Factors pushing the development of mechanical refrigeration technology from 1850 →

- "Artificial" ice production
- Brewing of beer (all year long)
- Transport of meat

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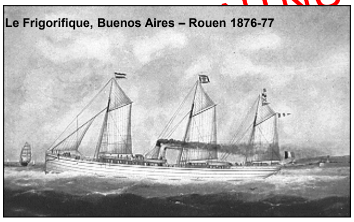
Three important ‘drivers’ in the late 19th century

Factors pushing the development of mechanical refrigeration technology from 1850 →

- “Artificial” ice production
- Brewing of beer (all year long)
- Transport of meat

Le Frigorifique, Buenos Aires – Rouen 1876-77



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Theory and Practice 1840-1870

- 2. law of thermodynamics: **Carnot**, 1824
- 1. law of thermodynamics: **Clausius, Helmholz, Joule, Mayer, Thomson** (Lord Kelvin), 1842-1852
- Joule-Thomson expansion, 1862

- **Perkins**, 1834 (inventor, designer)
- **Gorrie**, 1842 (medical doctor)
- **Harrison**, 1850-1860 (journalist, publisher)

”*Perkins had little, if any, real understanding of the fundamental nature of his cycle*” J. F. Sandfort, 1962

1870: **Carl Linde** established the fundamental thermodynamically base for mechanical refrigeration

End of 19th century: **Development moved from single pioneers/developers to companies with economic and technical resources**

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CO_2-refrigeration technology was born

- 1850: CO_2 mentioned (?) as potential working fluid in patent application of *Alexander C. Twining* (1801-1884), USA
  ”*...a volatile liquid, as alcohol, ether,* ***sulfuret of carbon****, &c.*”
- 1866: First machine build (?) by *Thaddeus Sobeski Carlincourt Lowe* (1832-1913), USA.
  - Applied compressed CO_2 to inflate military balloons 1865-1866
  - British Patent No 952 on CO_2 system in 1867
  - Build Ice machines in Dallas, Texas, and Jackson, Mississippi 1869
- 1882: *Ca*
- 1884: Bri ... CO_2 vapour compres
- 1886: Bri

This Invention consists, first, in compressing carbonic acid or other gas into a liquid state, then bringing such liquid into contact or vicinity with water or other material to be refrigerated, and then relieving the pressure, so that the liquid carbonic acid or other gas may return to its gaseous state. The material in its gaseous state is then collected and returned to the pump or compressing apparatus, and again compressed and used as before.

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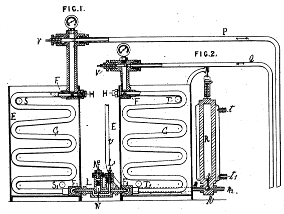
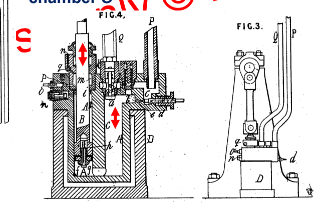
Franz Windhausen (1829-1904)

Britisk Patent No 2864, 1886



Mercury applied as ”pressure fluid” (fluid piston), to transfer the movement of the plunger (*B*) to the compression of CO_2 in chamber *C*



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Carl von Linde (part1)
(1842 – 1934)

Linde’s articles on refrigeration technology had aroused the interest of **brewers who had been looking for a reliable year-round method** of refrigeration for the fermentation and storage of their beer.

Carl Linde (1868)

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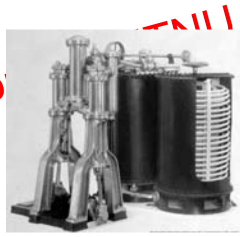
First industrial refrigeration machine: developed for a brewery

- Linde's first refrigeration system used *Dimethyl ether* as the refrigerant and was built by *Maschinenfabrik Augsburg* (now MAN AG) **for the Spaten Brewery in 1873**.
- He quickly moved on to develop more reliable ammonia (R717)-based cycles. These were early examples of vapor-compression refrigeration machines, and ammonia is still in wide use as a refrigerant in industrial applications.



The first Linde refrigeration machine. (1873)

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Spaten → Heineken → Carlsberg →

Rotterdam based Heineken Brewery ordered an ice machine in 1877 for ice production. In his collaboration with the Heineken Brewery, Linde developed "natural convection cooling" with a system of cooling pipes under the ceiling of the cellar.

Fermentation cellar of a brewery with natural convection cooling

Linde came in contact with J.C. Jacobsen, head of the Carlsberg Brewery in Copenhagen, who ordered a large refrigeration unit in 1878.

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Linde: *godfather* of industrial refrigeration

- Linde's **efficient new refrigeration technology offered big benefits to the breweries**, and by 1890 Linde had sold **747** ammonia refrigeration machines. In addition to the breweries, other uses for the new technology were found in slaughter-houses and cold storage facilities all over Europe.

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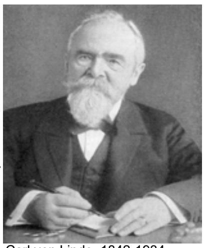
Carl von Linde and "Refrigeration as a Science " (part 2)

- Developed the fundamental thermodynamics for mechanical refrigeration in 1870-71 (Amanuensis, *TH München*)
- Experimental investigation funded by *Spatenbrauerei* 1872-73 ; (ether), NH_3
- Consortium with *Maschinenfabrik Augsburg-Nürnberg* (MAN) 1873-79
- *Established 'Gesellschaft für Linde's Eismaschinen'*, 1879-
- *Test facility for refrigeration machines*, Munich 1888-?



Carl von Linde, 1842-1934

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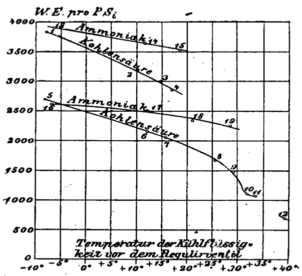
Linde's comparison of NH_3 and CO_2 systems

- Theory, 1894: "..*[CO_2] can never reach the efficient performance ratio of ammonia [NH_3] ...*"
- Had to correct the existing thermodynamic (Zeuner) due to operation at supercritical high side pressure
- Results from experimental investigations performed at test facility in Munich published in *Zeitschrift des VDI*, 1895
- Published later "*Ungleichwertigkeit von Ammoniak, Kohlensäure und schwefliger Säure in Kompressions-Kaltdampfmaschinen*" → *non – equivalence of NH_3, CO_2, and sulphurous acid in vapour compression machines*



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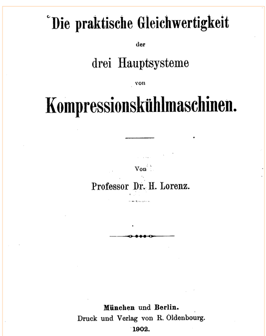
Hans Lorenz (1865-?)



Die praktische Gleichwertigkeit

der

drei Hauptsysteme

von

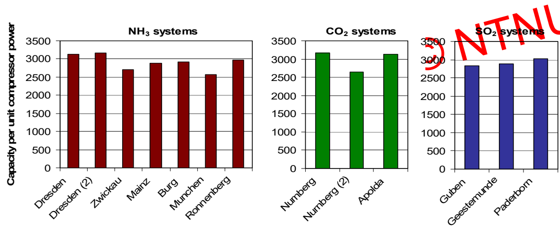
Kompressionskühlmaschinen.

Von

Professor Dr. H. Lorenz.

München und Berlin.
Druck und Verlag von R. Oldenbourg.
1902.

Results from field tests, Lorenz 1892-1901



Similar results are shown by *Stetefeld, 1904*

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Applications and systems

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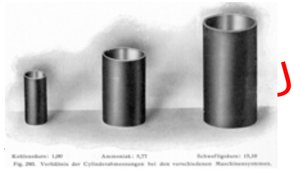
CO_2 as a working fluid

- High working pressures
- Small compressor displacements
- Low critical temperature

CO_2: 31.1ºC
NH_3: 132.4ºC
SO_2: 157.5ºC



Vergleich der Spannungen der Kaltdämpfe.					
Temperatur ⁰ Cels.	Spannung in absoluten Atmosphären = kg pro qcm				
	Ammoniak NH_3	Schweflig-säure SO_2	Kohlensäure CO_2	Chlormethyl C_2H_3Cl	Äthylchlorid C_2H_5Cl
− 30	1,192	0,39	14,66	0,76	0,150
− 20	1,900	0,65	20,03	1,15	0,255
− 10	2,923	1,04	27,10	1,72	0,410
− 5	3,579	1,29	31,00	2,07	0,522
0	4,347	1,58	35,40	2,48	0,633
+ 5	5,242	1,93	40,30	2,96	0,787
+ 10	6,271	2,34	45,70	3,51	0,94
+ 15	7,451	2,81	51,60	4,25	1,148
+ 20	8,792	3,35	58,10	4,82	1,355
+ 30	12,009	4,67	73,01	6,50	1,90
+ 40	16,01	6,35	100,03	8,50	2,61

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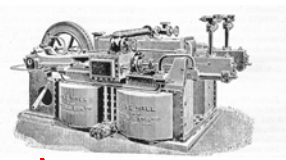
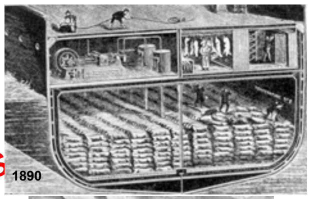
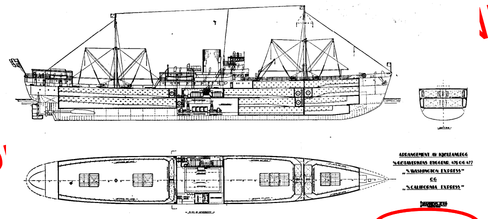
Marine Refrigeration





Reefer, ca 1930



Skibskjøleanlegg for tropefart. 175 000 cbf. netto ruminnhold for fruktlast ÷ 0,5° C., utstyrt med 2 kullsyrekompressorer for en samlet ydelse av 320 000 kal. time ved + 30° kjølevann og ÷ 10° fordampertemperatur.

Freezing of fish

(Ottesen, Nekolai Dahls method), 1915

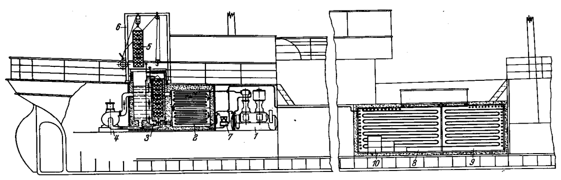
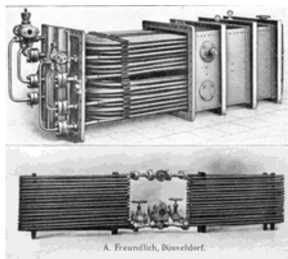


Abb. 102. Einbau einer OTTESEN-Fischgefrieranlage in den Dampfer „Karmøy" (Thomas Th. Sabroe, Aarhus, Dänemark).
1 Dampfmaschine und CO_2-Kompressor mit Kondensator, 2 Verdampfer, 3 Gefrierbehälter, 4 Solezirkulationspumpe, 5 galvanisierte Fischbehälter, 6 Hebevorrichtung für die Fischbehälter, 7 Solepumpe, 8, 9 Lagerräume, 10 gefrorene Fische versandfertig verpackt.

Marine Refrigeration

Göttsche, 1915)



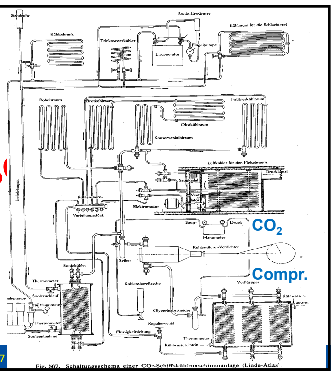


Fig. 567. Schaltungsschema einer CO_2-Schiffskühlmaschinenanlage (Linde-Atlas).

Small capacity units
(Göttsche, 1915) (Hubendick, 1921)

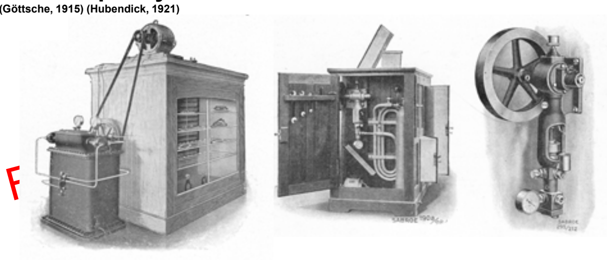


Fig. 455. Kleinkältemaschine „Augusta" mit Kühlschrank (Riedinger).

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AC system (USA)

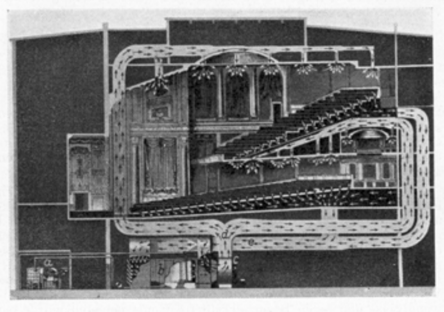
Abb. 114. Theater-Kühlanlage (nach L. L. Lewis).

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Components

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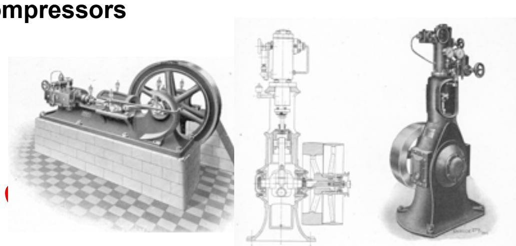
Compressors



Slow rpm cross head compressors
Stuffing box and piston rings i leather
Lubricant: glycerine

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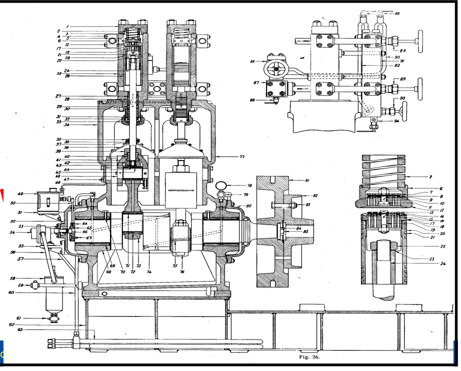
Compressor ca. 1930



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Condenser concepts (1)

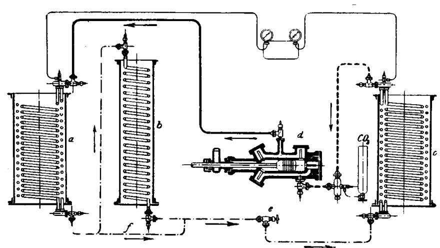


Fig. 448. CO_2-Maschinenanlage mit Nachkühler.

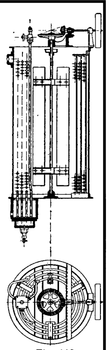
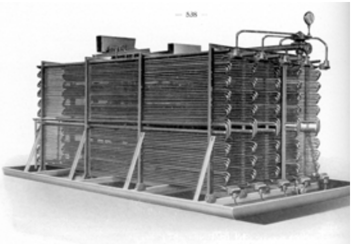


Fig. 446.

Condenser concepts (2)



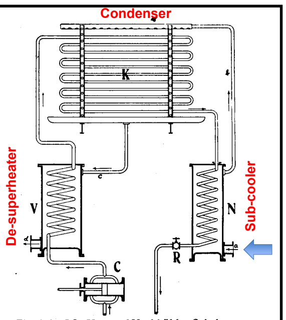


Fig. 450. CO_2-Vor- und Nachkühler-Schaltung.

"Tube and Shell heat exchangers"

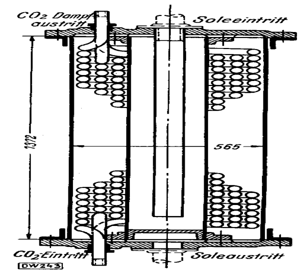
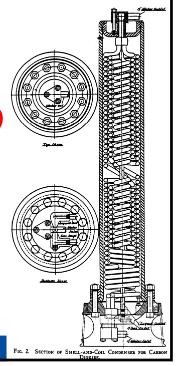


Abb. 63. Mantel- und Schlangen-Verdampfer (Shell and Coil) für Kohlensäure.



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Prosess- and system-modifications

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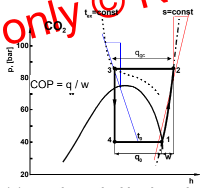
R-744 (carbon dioxide) as Working Fluid

- specific refrigerant capacity and COP is reduced at high cooling water/ambient temperatures compared to other refrigerants.
- COP optimization in transcritical operation by operating the system at the optimum high side pressure:

$$\left(\frac{\partial h_3}{\partial p}\right)_T = -COP\left(\frac{\partial h_2}{\partial p}\right)_s$$

$$COP_{AC} = (h_1-h_3) / (h_2-h_1)$$

$$COP_{HP} = (h_2-h_3) / (h_2-h_1)$$



1928 *H. Inokuty, (Mitsubishi Laboratory, Japan)* developed the **mathematical basis and a graphical method** to find the optimum high side pressure, which maximizes the COP.

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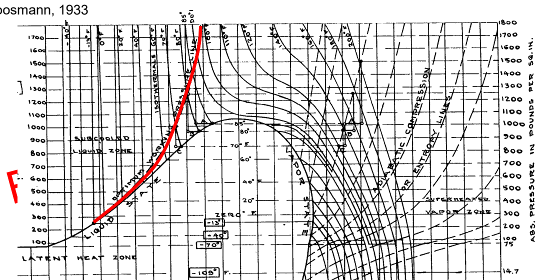
Opt. high side pressure versus gascooler temperature

Goosmann, 1933



Expansion losses

(Göttsche, 1915)

Das Regulierventil mit seiner drosselnden Wirkung bedeutet bei allen Kompressionsmaschinen einen Effektverlust, der aber bei den CO_2-Maschinen besonders gross ist, zumal bei warmen Kühlwasserverhältnissen. Dieser Verlust beträgt theoretisch beispielsweise bei

+ 20 ° und — 10 ° Cels.		+ 30 ° und — 10 ° Cels.	
bei CO_2	47,8 %	bei CO_2	85,5 %
„ NH_3	9,8 %	„ NH_3	13,6 %
„ SO_2	13,0 %	„ SO_2	18,7 %

Modified processes can reduce these losses →

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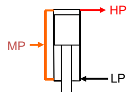
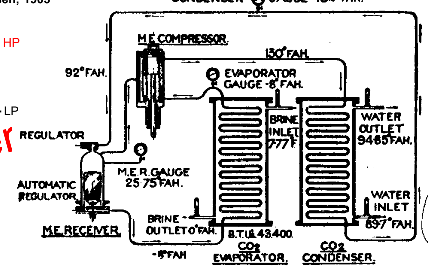
Two-stage compression in one cylinder

Lightfoot, 1893, Windhausen, 1903





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"Multiple effect compression"

G.T. Voorhees Patent 1905

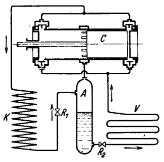


Abb. 27. Verfahren von Vorhees.

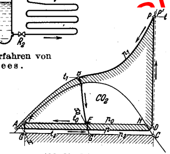
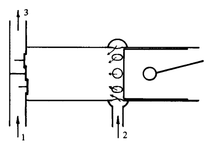
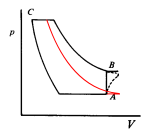


Abb. 29. TS-Diagramm.



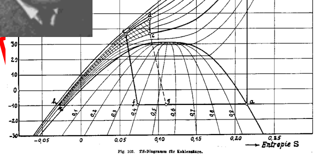


"Dual-effect" compression

"Zusatzkompression"

(Plank, 1912b and 1913) (additional compression)

Rudolf Plank
1886 -1973



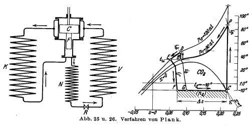
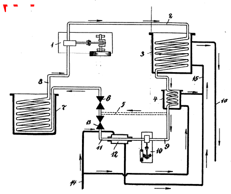


Abb. 25 u. 26. Verfahren von Plank.



Experimental investigation of add.-compression

(Plank, 1921)

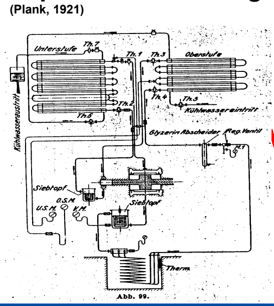
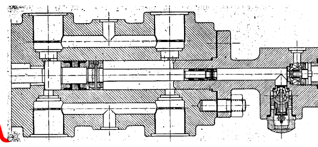


Abb. 99.



- Volume of high pressure "pump" ca. 10-15% of compressor displacement
- Measurement: 18% more capacity & 10% higher COP, at 30°C CO_2- gascooler exit temperature
- Potential for even larger improvements with higher gascooler exit temperature and at higher pressure ratio in the second stage

Other process modifications

Fra Ostertag, 1933

Use of suction line heat exchanger

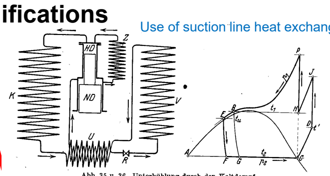


Abb. 35 u. 36. Unterkühlung durch den Kaltdampf.

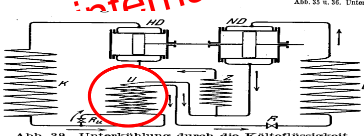


Abb. 39. Unterkühlung durch die Kältflüssigkeit.

Use of high pressure fluid to be evaporated in a sub-cooler to reduce CO_2 inlet temperature upstream of expansion device.

Expander (piston) and "flash gas bypass" (Goosmann, 1936)

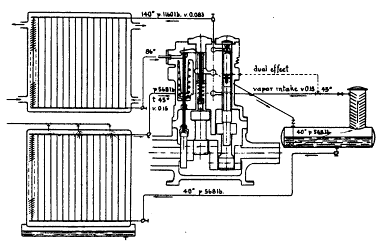


Fig. 6.
Refrigerating Cycle with Expansion Cylinder.

- Expander (piston type) with mechanical controlled inlet valve
- Maybe only a paper study?
- Plank (1912a) was very skeptical:
  - **Not enough time to develop vapour**
  - **Low pressure in the chamber and risk for dry ice**
  - **Requirement for variable volume**

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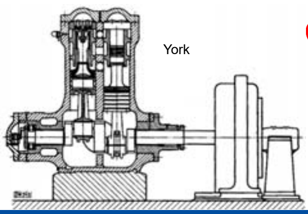
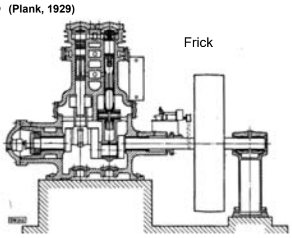
Later compressor versions (Plank, 1929)

- Pressurized- crank case and -lubrication
- Still slow rpm machines with cross head, i.e. heavy and large footprint machines

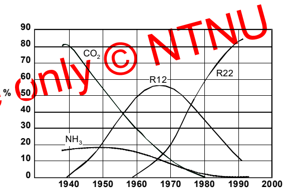




e

Why CO_2 disappeared in the early/midt 20th century?

- Problems with leaks
- Reduced cooling capacity at elevated heat rejection temperatures
- Cold cooling water not available everywhere (especially USA)
- Design of compressors with pressurized crank case[a] and high rpm (50/60Hz) not adapted for CO_2
- Development and offensive marketing of CFC's ("Freon")
- Opinion that high working pressures are a problem
- Missing production- and material-technology
- The safety standards and laws reduced the motivation to apply CO2 in the US more than in Europe.
- 1. world war in Europe



Prosentvis andel av kuldemedier i eksisterende lastkuldeanlegg på skip klasset av Lloyd's Register
Fra Stera (1992)

a: (Ballantine, 1877)

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Thank you for your attention

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