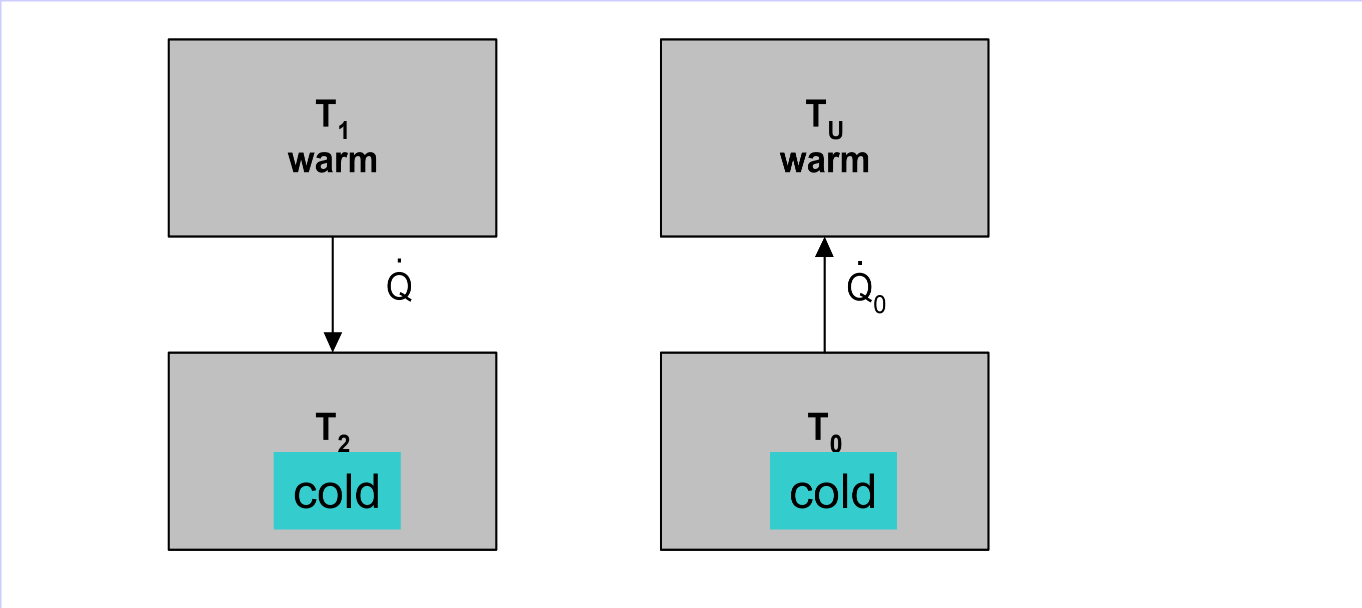
Cryogenic Engineering

CERN, March 8 - 12, 2004

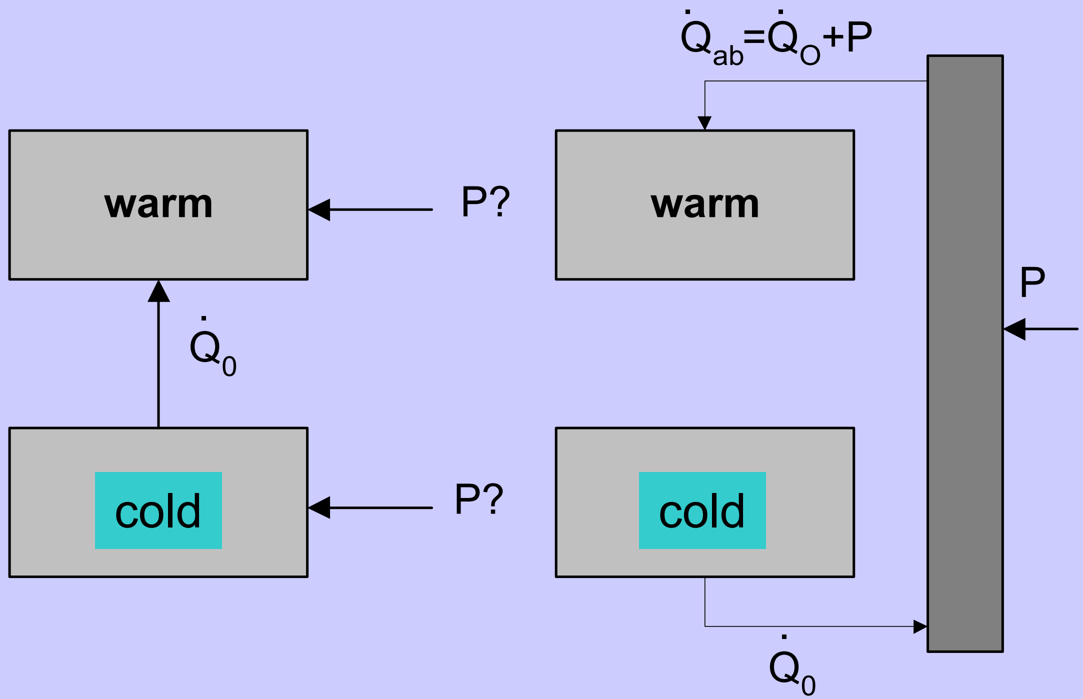
- Temperature reduction by throttling and mixing
- Temperature reduction by work extraction
- Refrigeration cycles: Efficiency, compressors, helium, hydrogen
- Cooling of devices



Process running by itself　　Process needing driving power

Mankind had an intellectual difficulty with the production of refrigeration: We could not learn it from nature.

The problem: One has to add energy to remove energy.



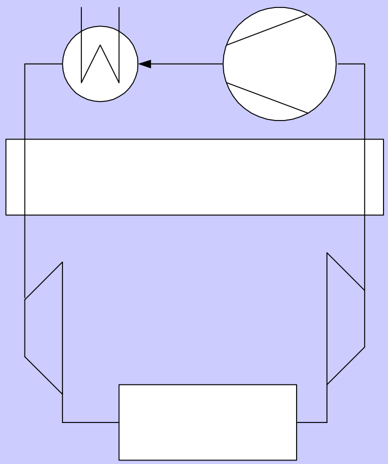
Where should the outside power be applied

Solution: One needs an additional sytem: The refrigerator

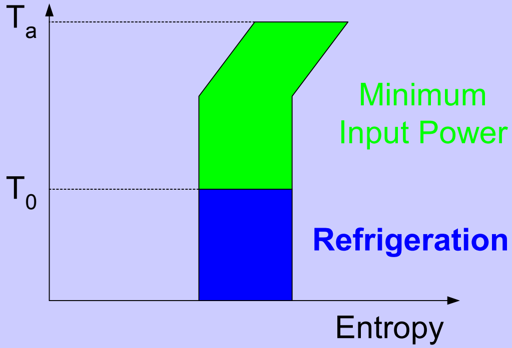
Refrigeration cyle

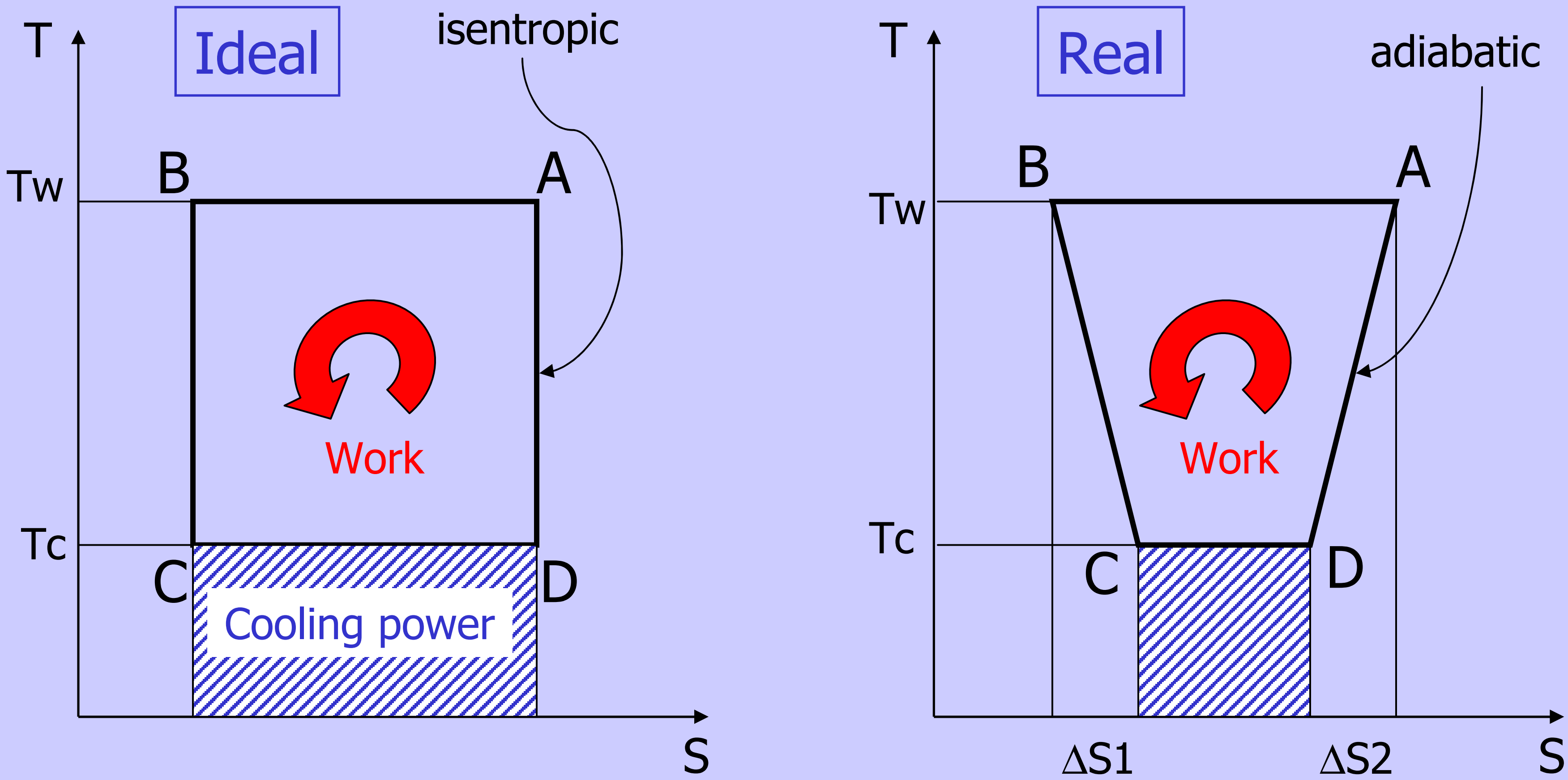
- Refrigerant
- Method to increase pressure
- Method to reduce entropy
- Method to reduce the temperature
- Method to transfer the refrigeration
- Recuperation

Flow Diagram



T-s Diagramm



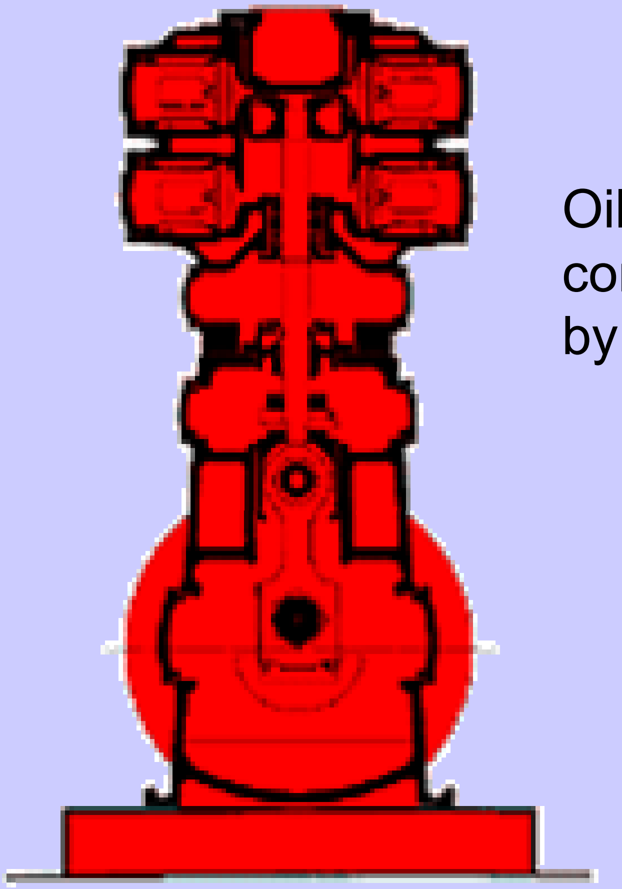


Widen the low-temperature end of the cycle as shown in the T-S diagram

Compressor and Aftercooler

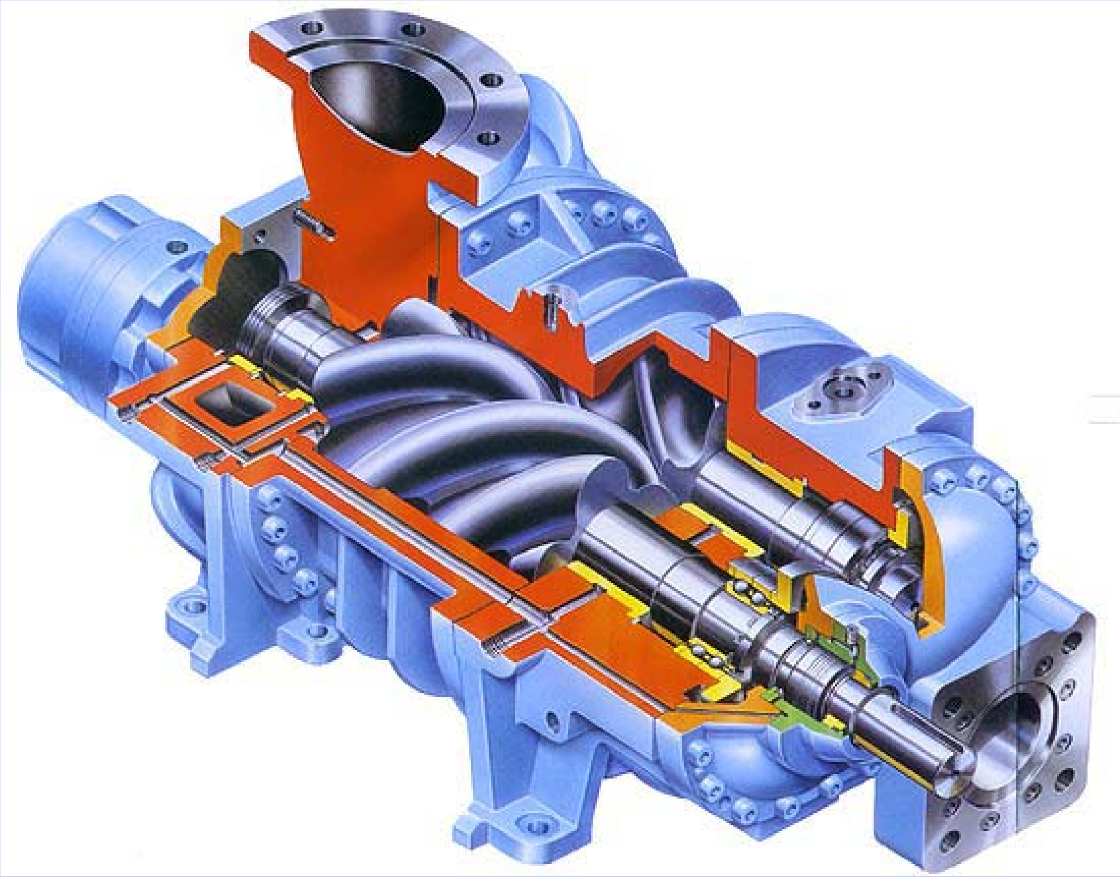
- Purpose: Increase the pressure and reduce entropy
- Types of compressors
  - Volumetric compressors: piston, screw
  - Turbocompressors

Piston compressor



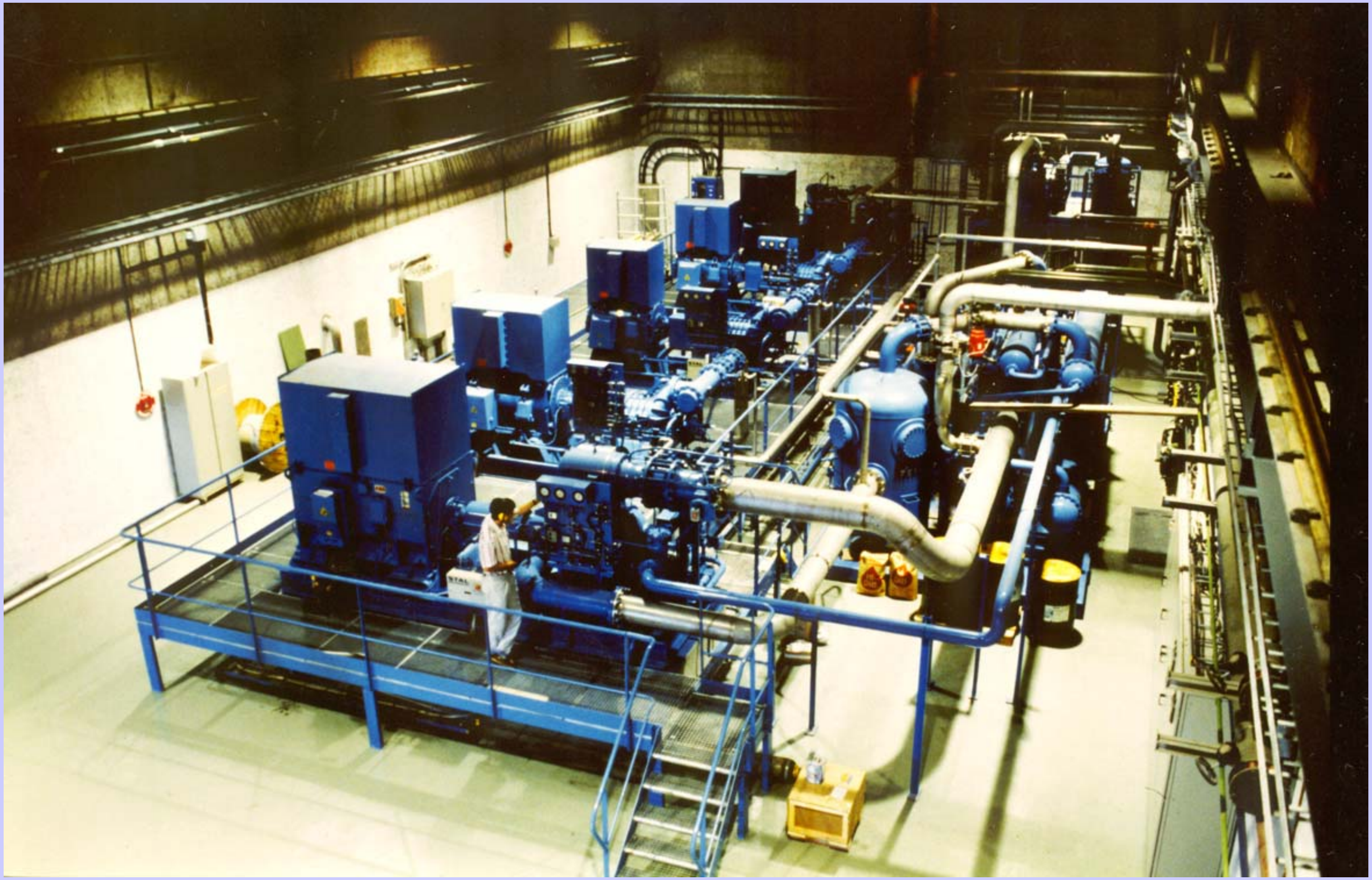
Oilfree labyrinth piston compressors. Preferred by CERN until about 1980.

Screw Compressor

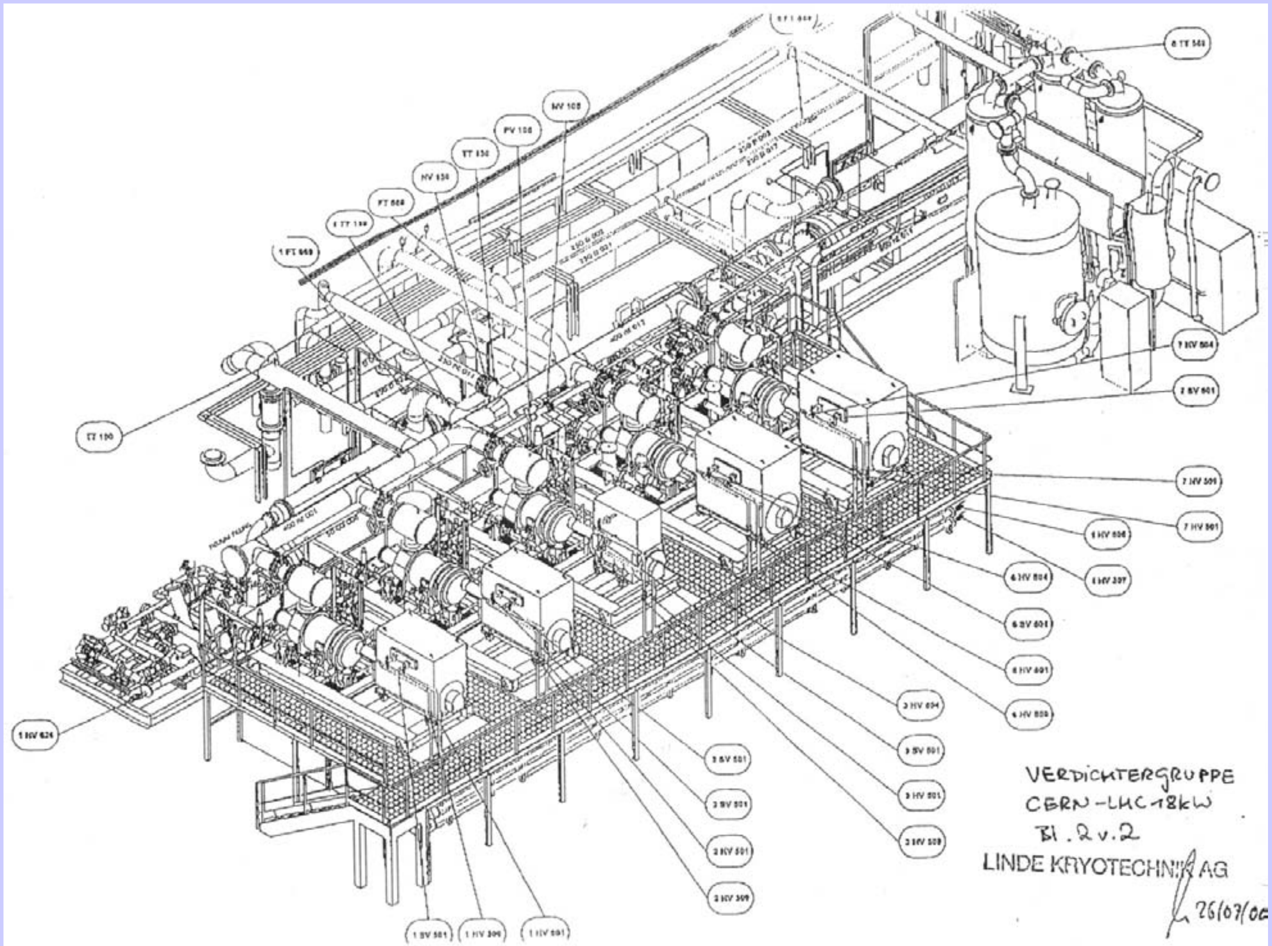


Oil flooded screw
compressor preferred
at CERN since about 1985.

Screw compressor principle



Screw Compressor Installation



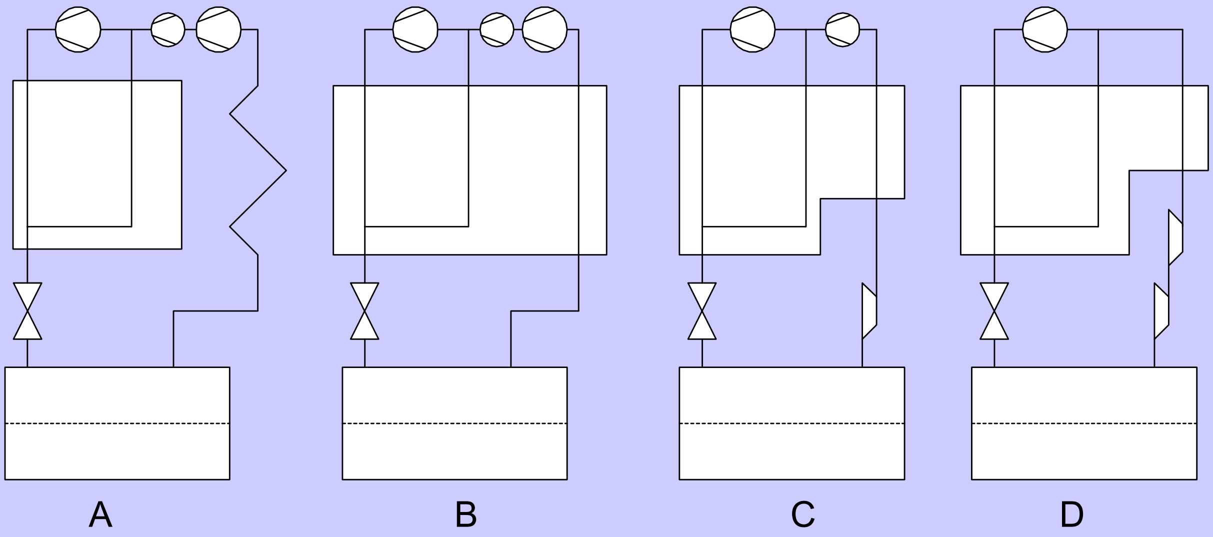
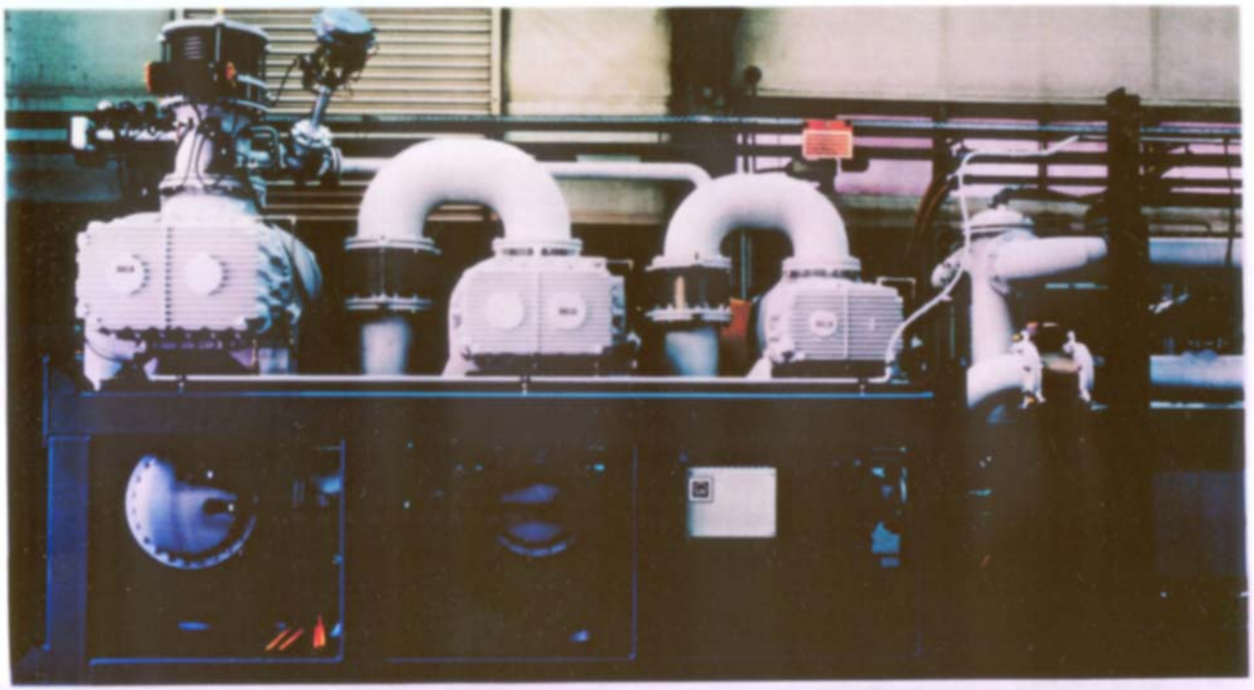


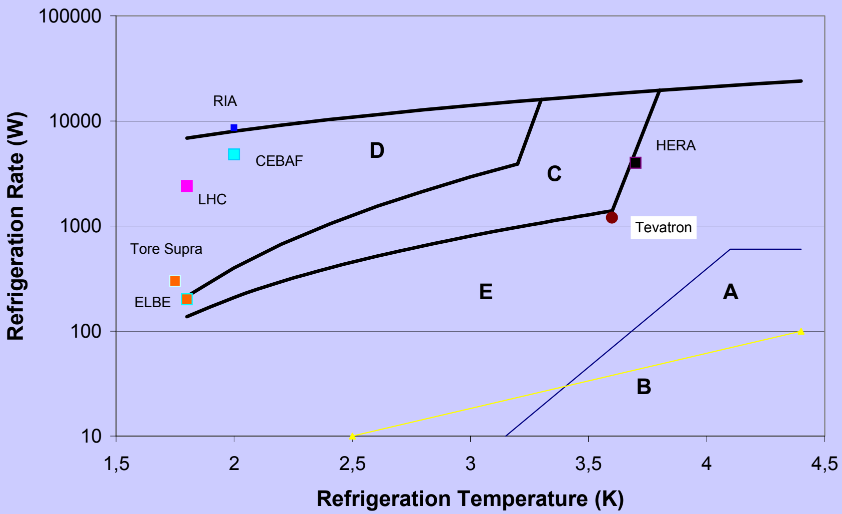
Fig. 2 Low Temperature Options

RUTA 16000/4/1
Helium-Pumpsystem
Roots-Gruppe: RA 16000/RA 13000/RA 7001



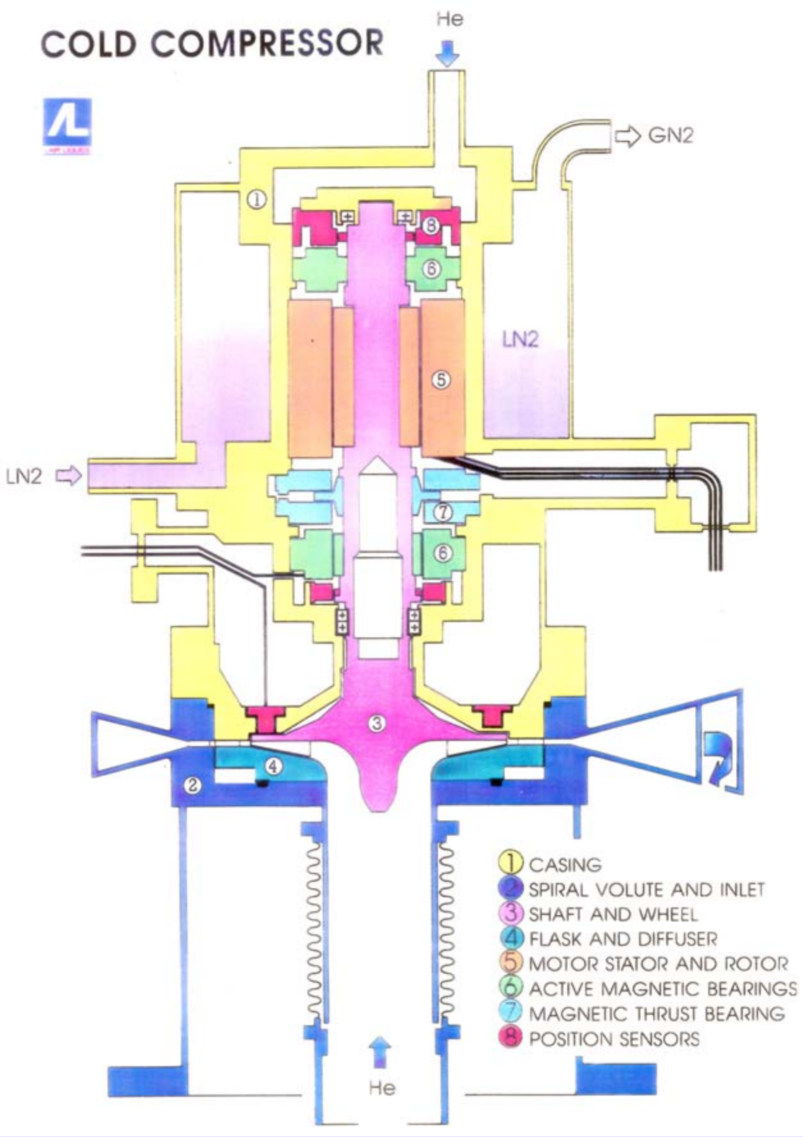
173.12.01

LEYBOLD



A Cold Ejector
B Cold Piston Compressor
C Cold Turbocompressor, One Stage
D Cold Turbocompressor Multi Stage
E Warm Vacuum Pump

Fig. 3 Cold Compressor diagram [3]

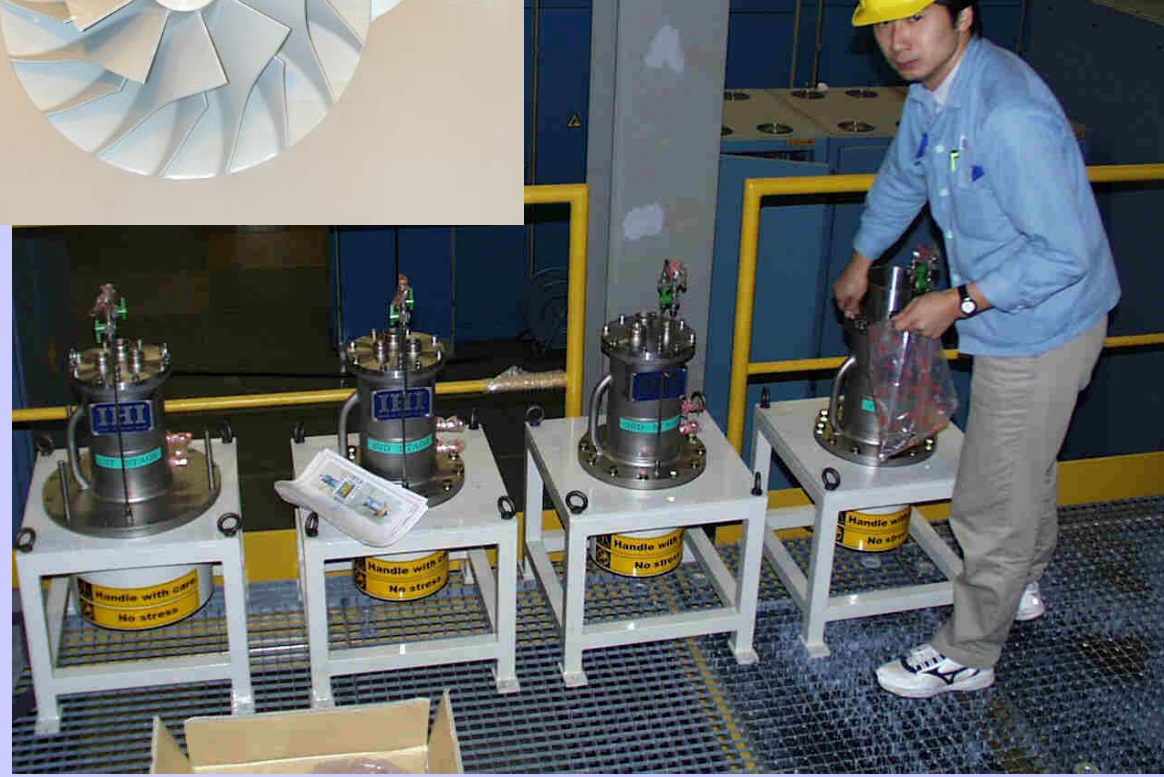

COLD COMPRESSOR
He
GN2
LN2
LN2
He
① CASING
② SPIRAL VOLUTE AND INLET
③ SHAFT AND WHEEL
④ FLASK AND DIFFUSER
⑤ MOTOR STATOR AND ROTOR
⑥ ACTIVE MAGNETIC BEARINGS
⑦ MAGNETIC THRUST BEARING
⑧ POSITION SENSORS

Cold Compressor Cartridges of 2.4 kW @ 1.8 K Refrigeration Units

IHI-Linde

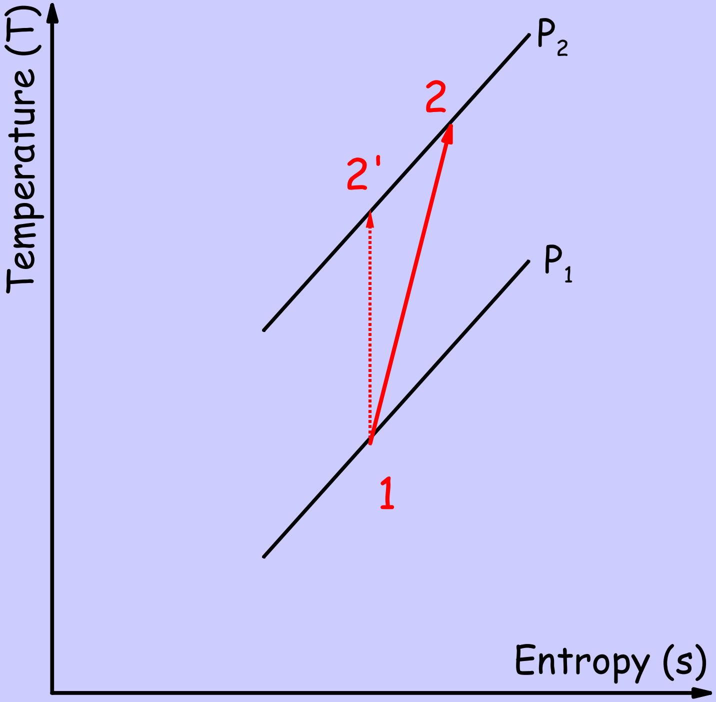
Cold compressor impeller

1st stage

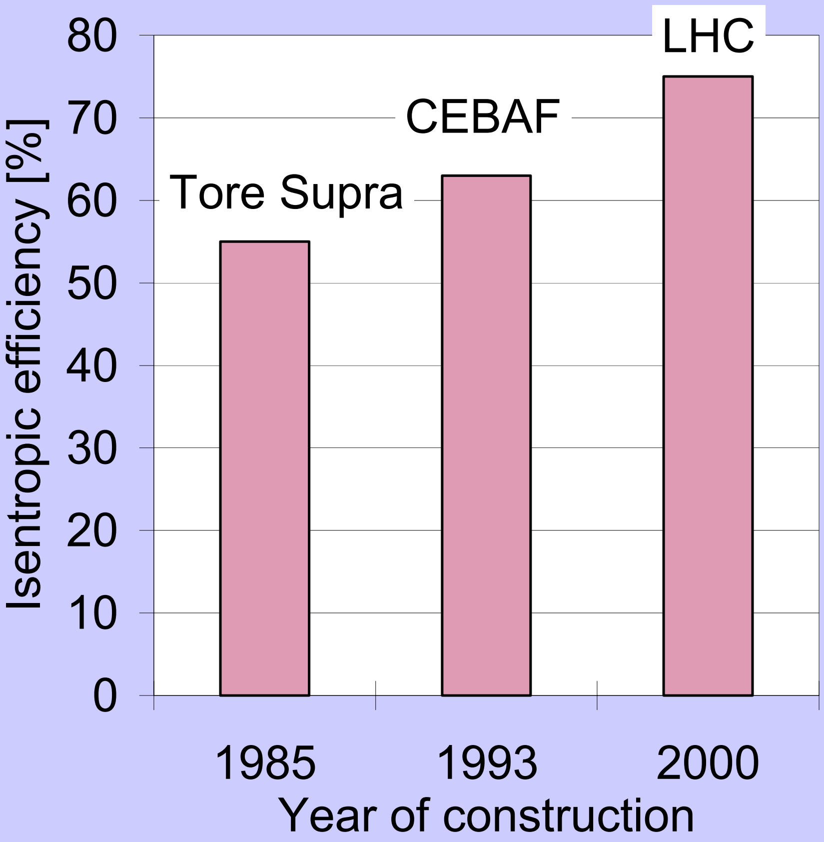


The four-stage LHC cold compressors

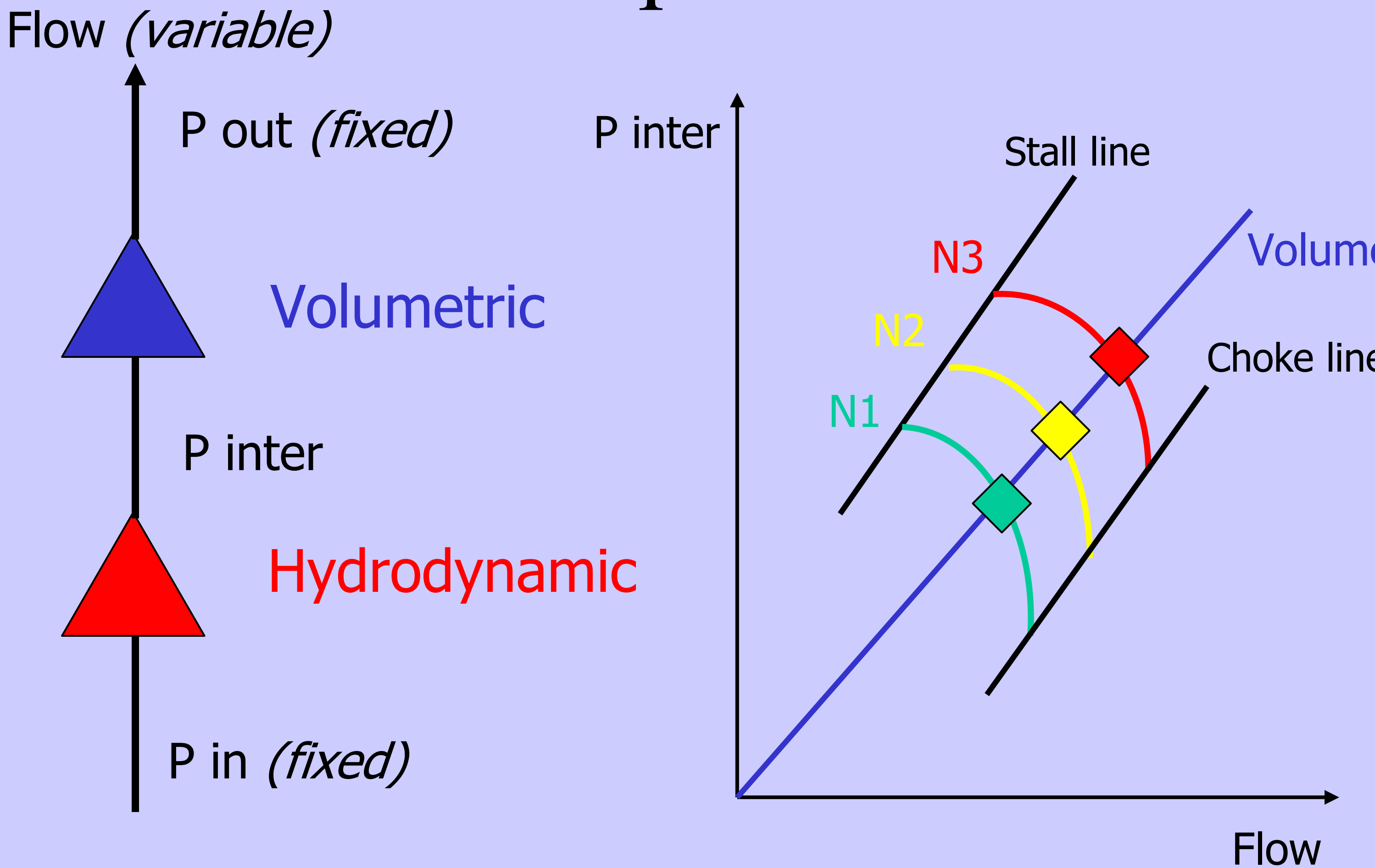
Isentropic Efficiency of Cold Compressors



$$\eta_{is} = \frac{H_{2'} - H_1}{H_2 - H_1}$$



Flow Compliance of "Mixed" Compression



For fixed overall inlet & outlet conditions, coupling of the two machines *via* P inter maintains the operating point in the allowed range

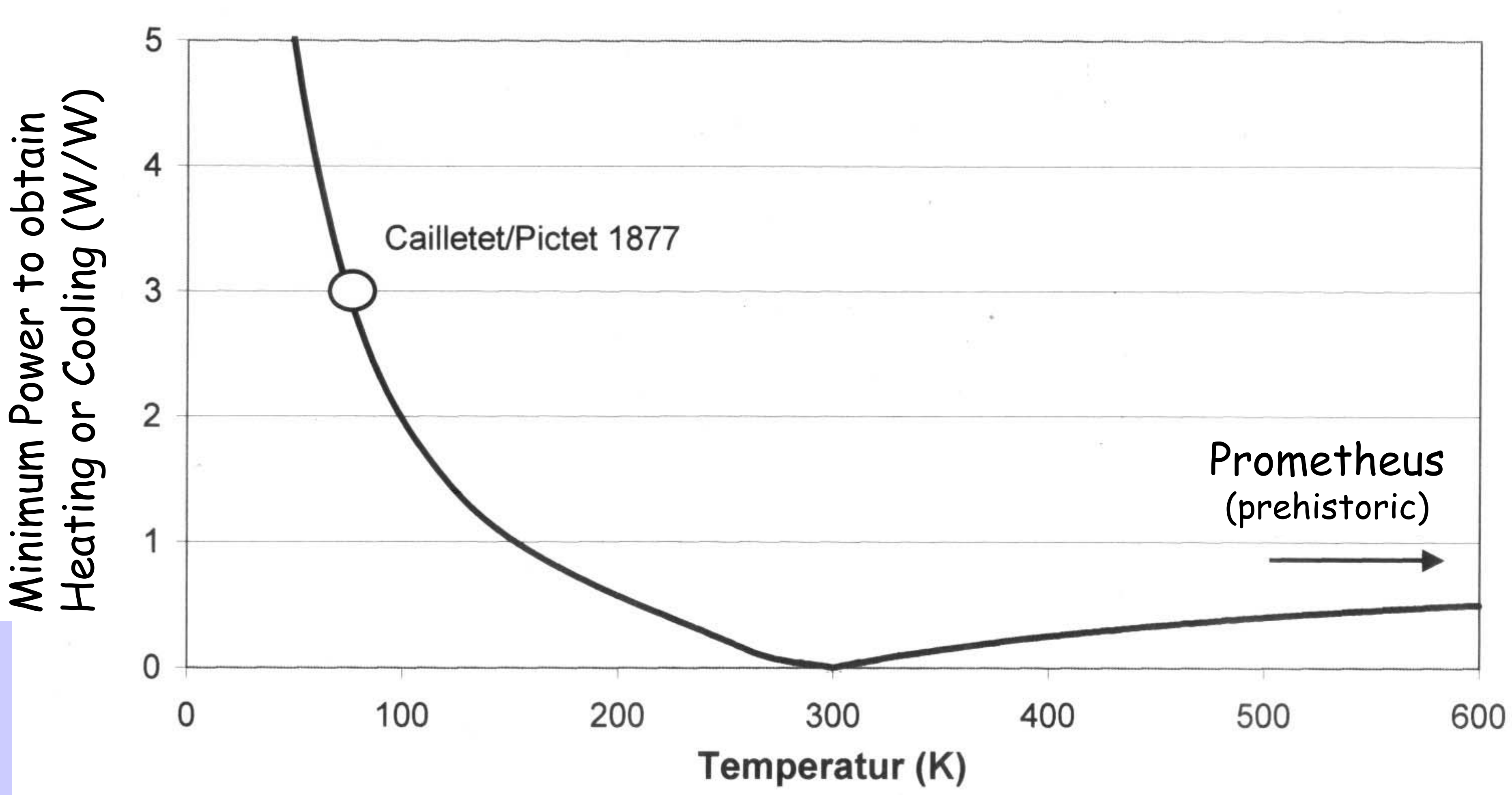
How to evaluate efficiency and to identify losses

- When discussing expanders, we shortly talked about reversibility
- In power engineering there is always a best method to do something, i. e. no unnecessary losses = reversibility
- Losses can be idebtified by the deviation from reversibility
- Comparison is the input power
- We have to give refrigeration a value in the scale of the input power
- Carnot ratio

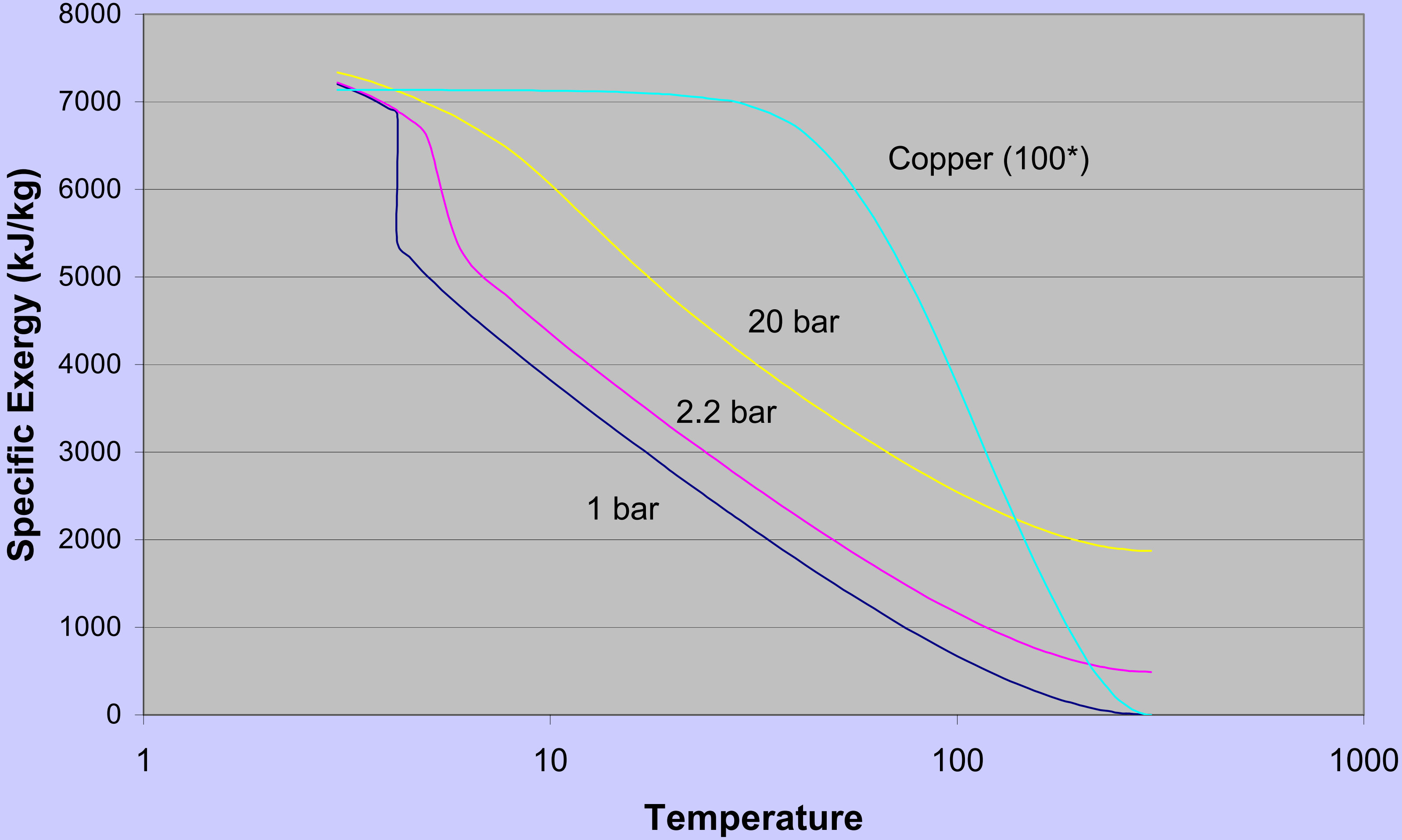
The definition of exergy

- Minimum amount of work to produce refrigeration
- Exergy= Mimimum Power= $Q^*(T_a-T_0)/T_0$
- Minimum amount of power to change the state of a fluid from an initial state 1 to a final state 2:
- $e_2-e_1 = h_2-h_1 + T_a^*(s_2-s_1)$

The Exergy Mountains



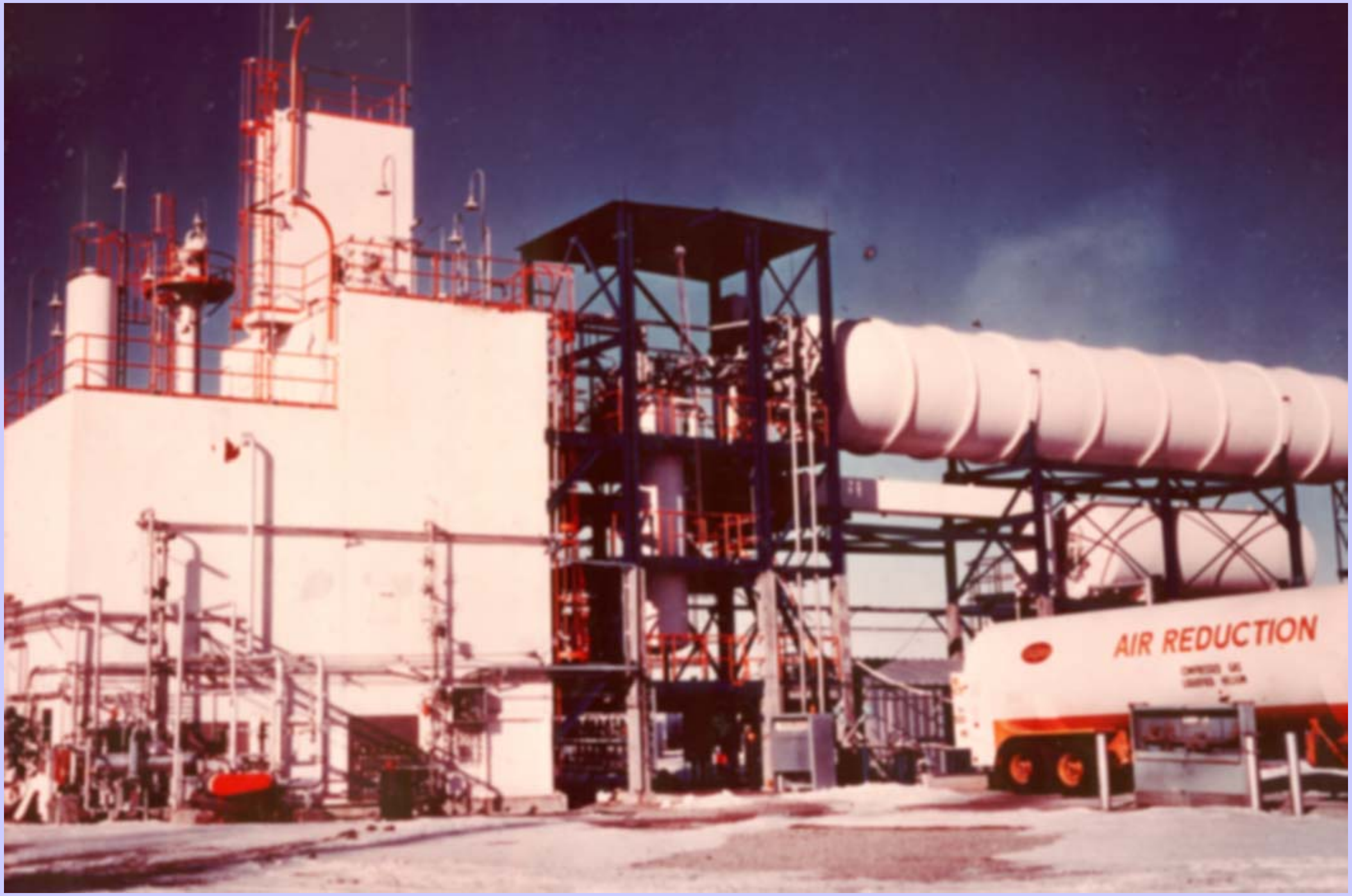
Specific exergy of cold copper and helium



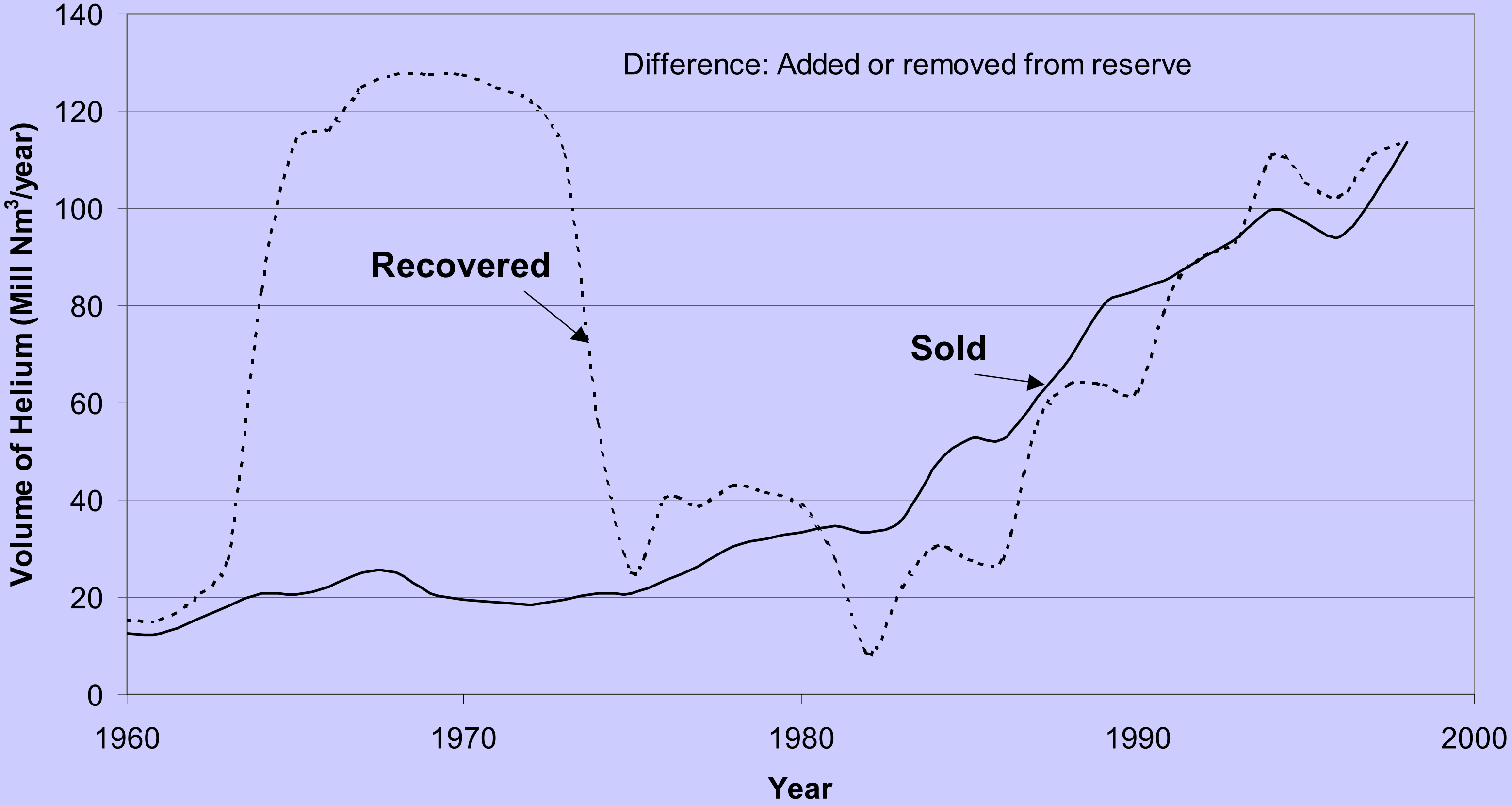
Stored exergy in the cooled-down LHC

	Mass (tons)	Specific Exergy (MJ/kg)	Stored Exergy (GJ)
Helium	96	6.8	660
Metal	36.000	0.065	2.340
Total			3.000
Magnetic energy			10

- Helium is recovered from natural gas



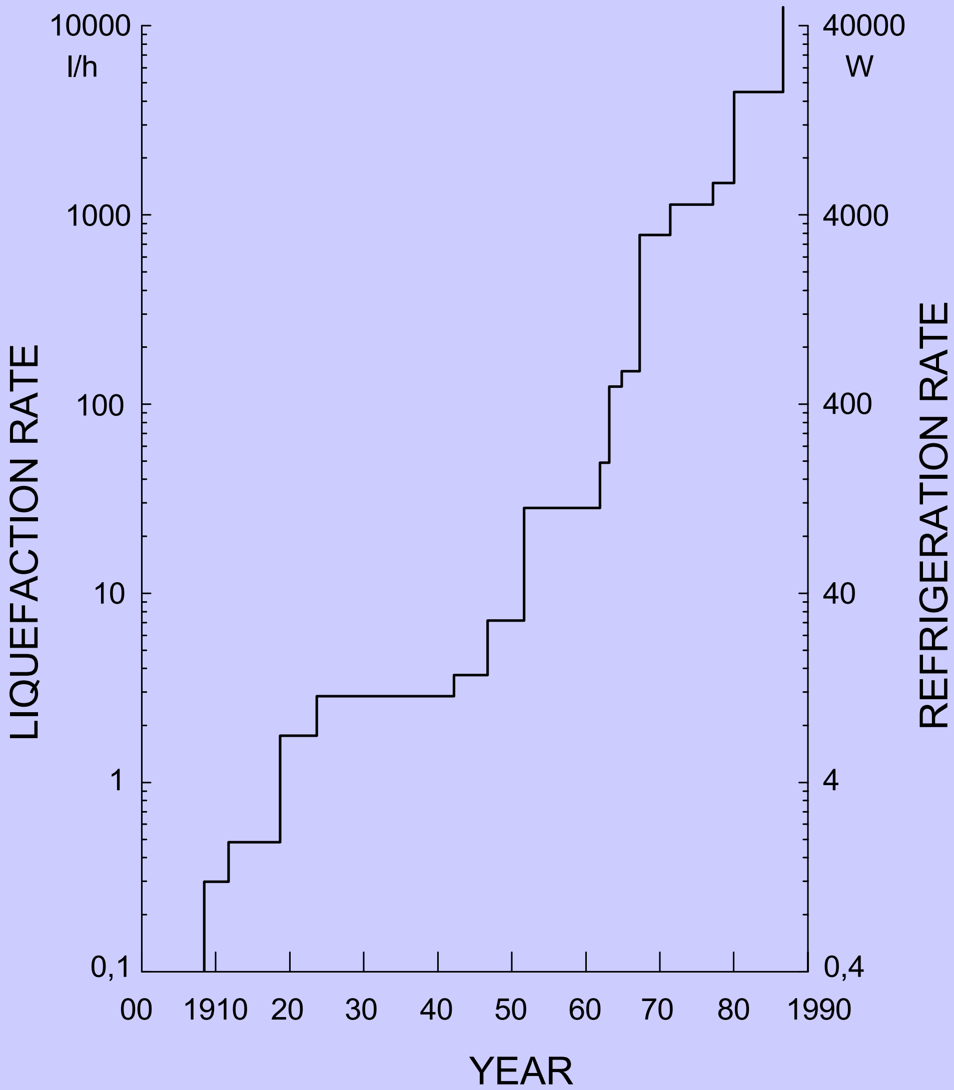
Annual Helium Recovery and Sales (USA)



1999 Helium World Production

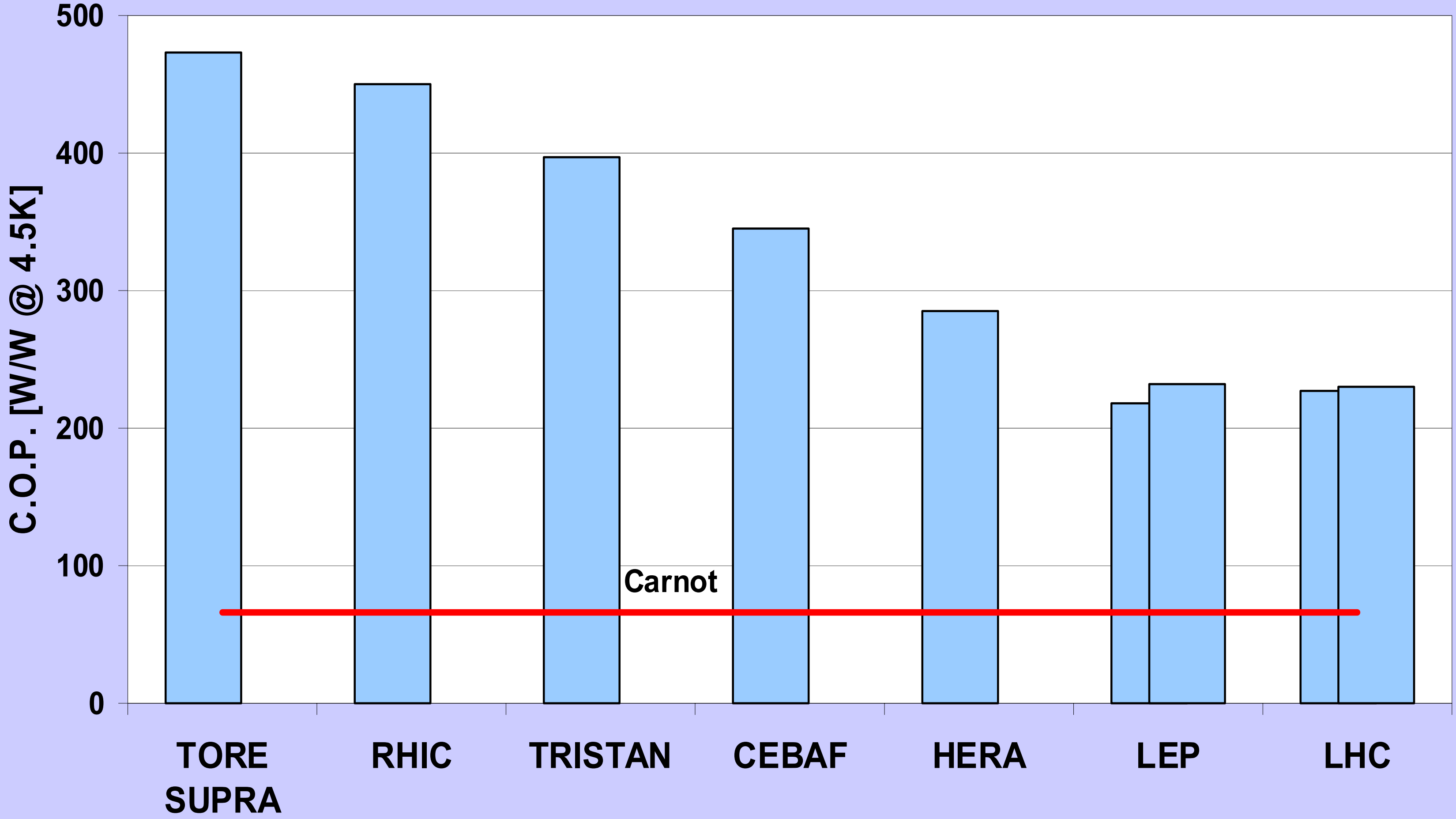
(Estimated by U.S. Geological Survey)

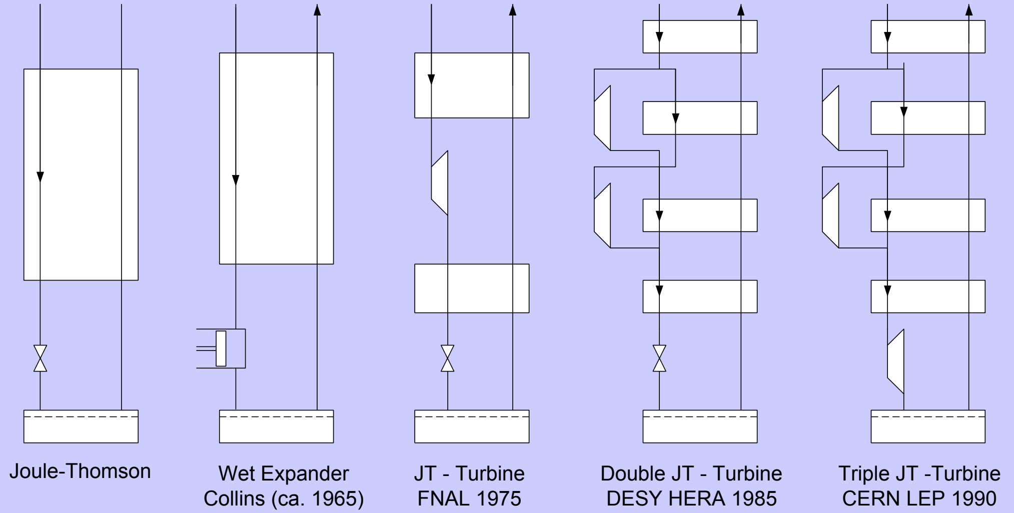
	Produced 10^6 Nm^3/year	Liquefied 10^6 Nm^3/year	Shipments per year	Shipments per week
United States	118,0	69,0 (export 29,3)	2450	49
Algeria	16,0	16,0	550	11
Russia	4,2	4,2	150	3
Poland	1,4	1,4	50	1
Total	139,6	90,6	3200	64
		(15.000 l/h)		



Development of the size of helium refrige-rators and liquefiers in the last century.

C.O.P. of Large Cryogenic Helium Refrigerators





	Joule-Thomson	Wet Expander	JT - Turbine	Double JT - Turbine	Triple JT -Turbine
Efficiency (%)	18	23	23	28	30
COP (W_{el}/W_{refr})	370	290	290	240	224

Fig. 4 Development of the Joule-Thomson Stage of Large Helium Refrigerators

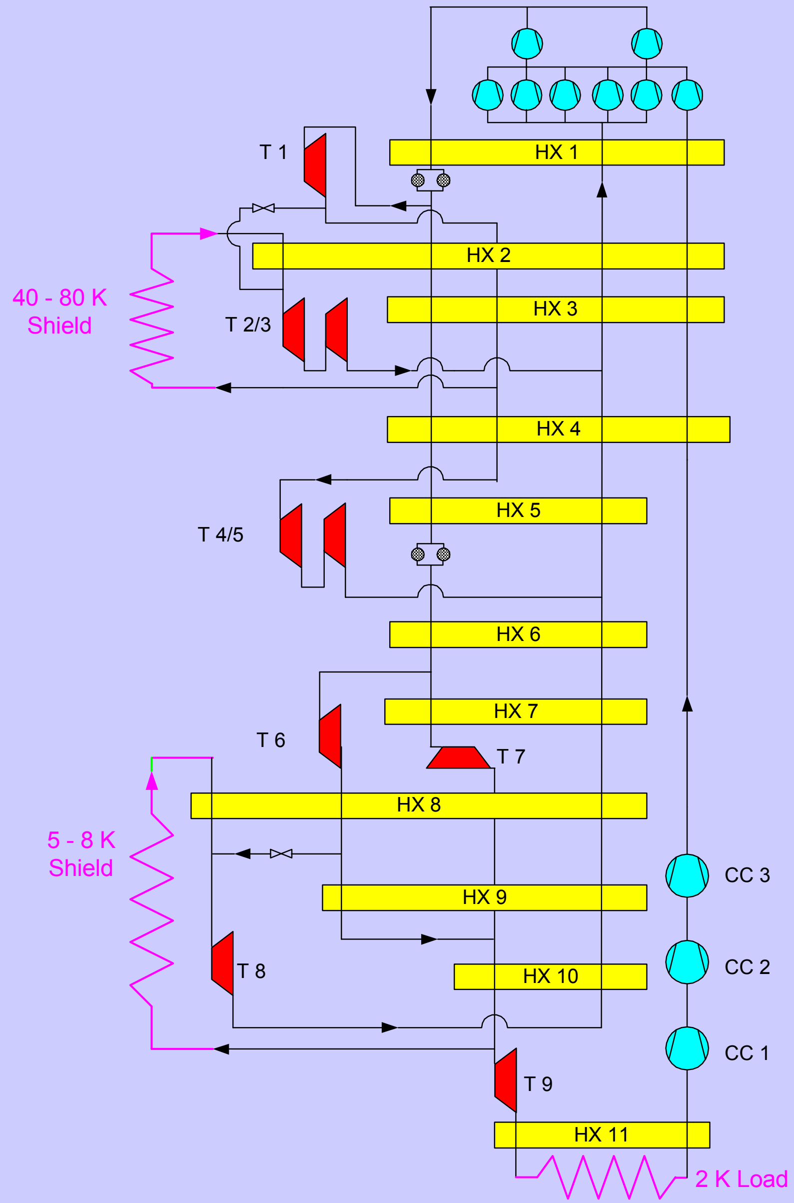
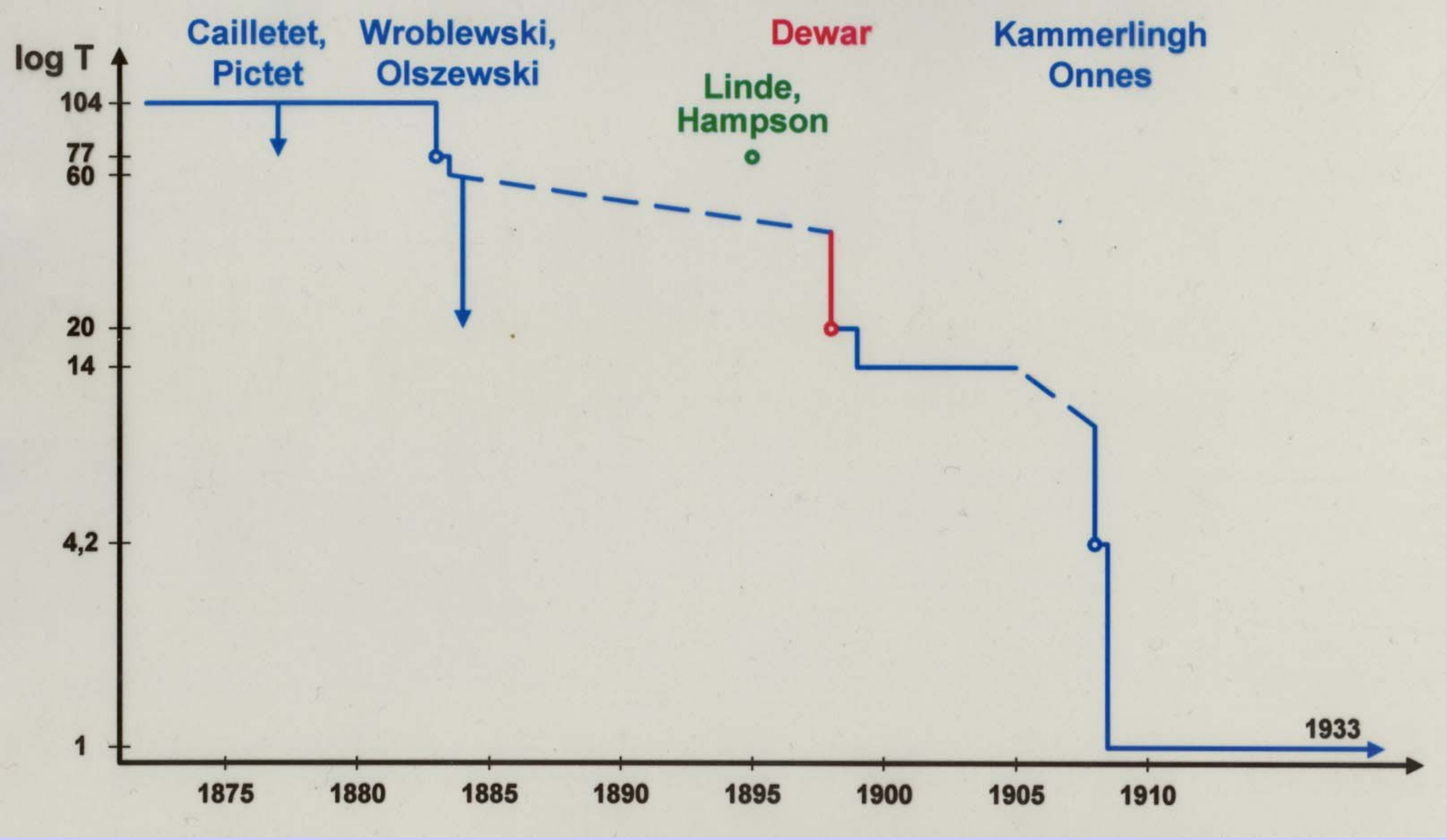

T 1
HX 1
HX 2
40 - 80 K
Shield
T 2/3
HX 3
HX 4
T 4/5
HX 5
HX 6
HX 7
T 6
T 7
HX 8
5 - 8 K
Shield
HX 9
T 8
HX 10
CC 3
CC 2
CC 1
T 9
HX 11
2 K Load

Table 1 Cryogenic Accelerator and Fusion Projects

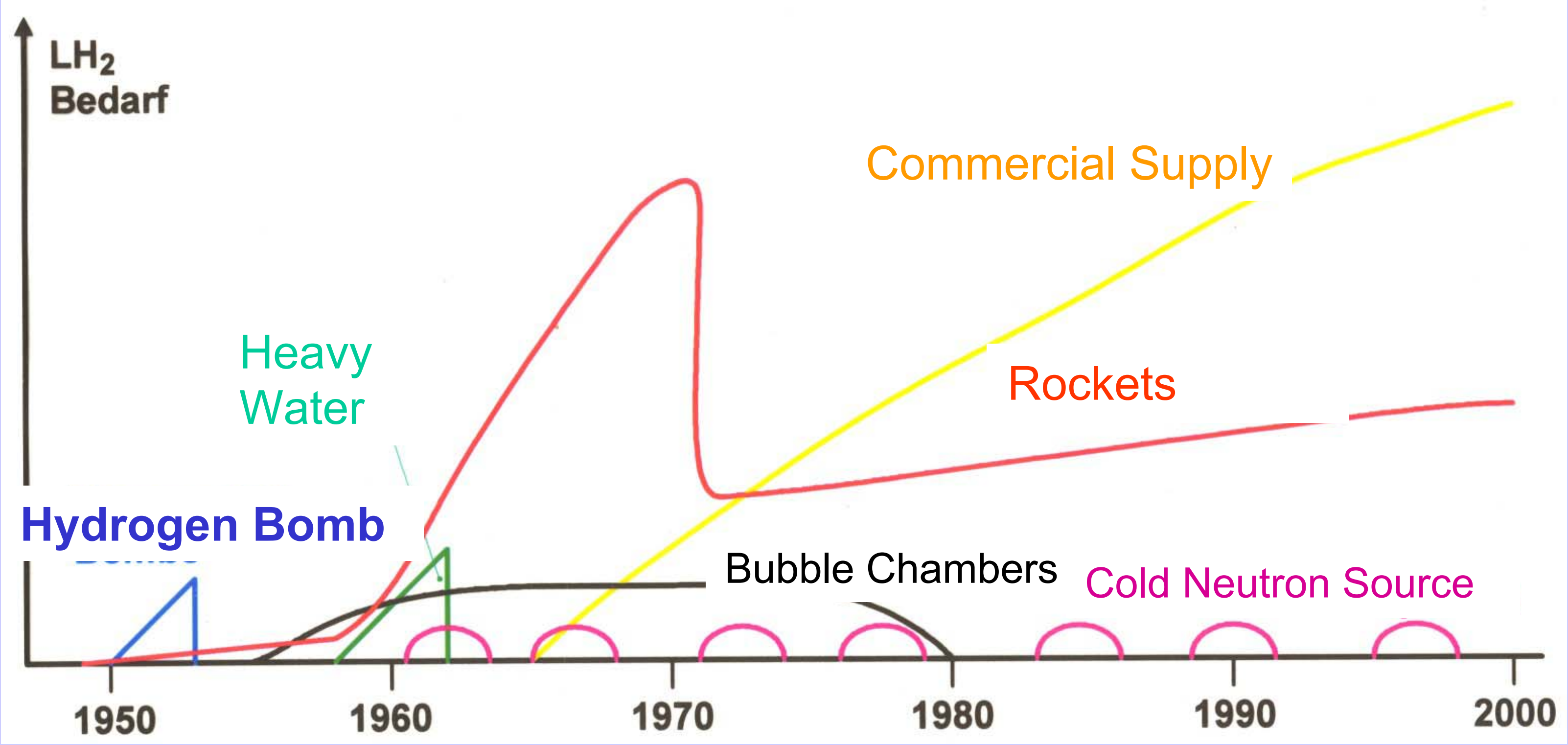
Project	Location	Capacity (kW at 4.4 K)	No. Refr	Refr. below 4.4 K	Status
Accelerators					
Tevatron	Fermilab	30	2+12	1.2 kW at 3.6 K	operation
RHIC	Brookhaven	25			operation
HERA	DESY	30	3	4 kW at 3.7 K	operation
CEBAF	TJNAF	12		5 kW at 2.0 K	operation
LEP	CERN	72	4		stopped
S-DALINAC	Darmstadt	0.4		0.1 kW at 2.0 K	operation
ELBE	Rossendorf	0.6		0.2 kW at 1.8 K	operation
LHC	CERN	144	8	2.4 kW at 1.8 K	construction
	Oak Ridge	12		5 kW at 2.0 K	construction
TESLA	DESY	140	7	5 kW at 2.0 K	adv. planning
RIA [1]	Argonne	30		8.6 kW at 2.0 K	early planning
SIS 100+200	GSI Darmstadt	20		?	early planning
SASE-FEL	BESSY	12		3.6 kW at 1.8 K	early planning

Fusion					
MFTF	Livermore	12	2		stopped
JET	Culham	1.5	2	0.6 kW at 3.8 K	operation
Tore Supra	Cadarache	2		0.3 kW at 1.75 K	operation
TOSKA	Karlsruhe	3		2 kW at 3.7 K	operation
LHD	Toki	8			operation
Wendelstein	Greifswald	4		3 kW at 3.5 K	construction
SST-1	India	1			construction
KSTAR	Korea	10			construction
ITER	?	120			planning

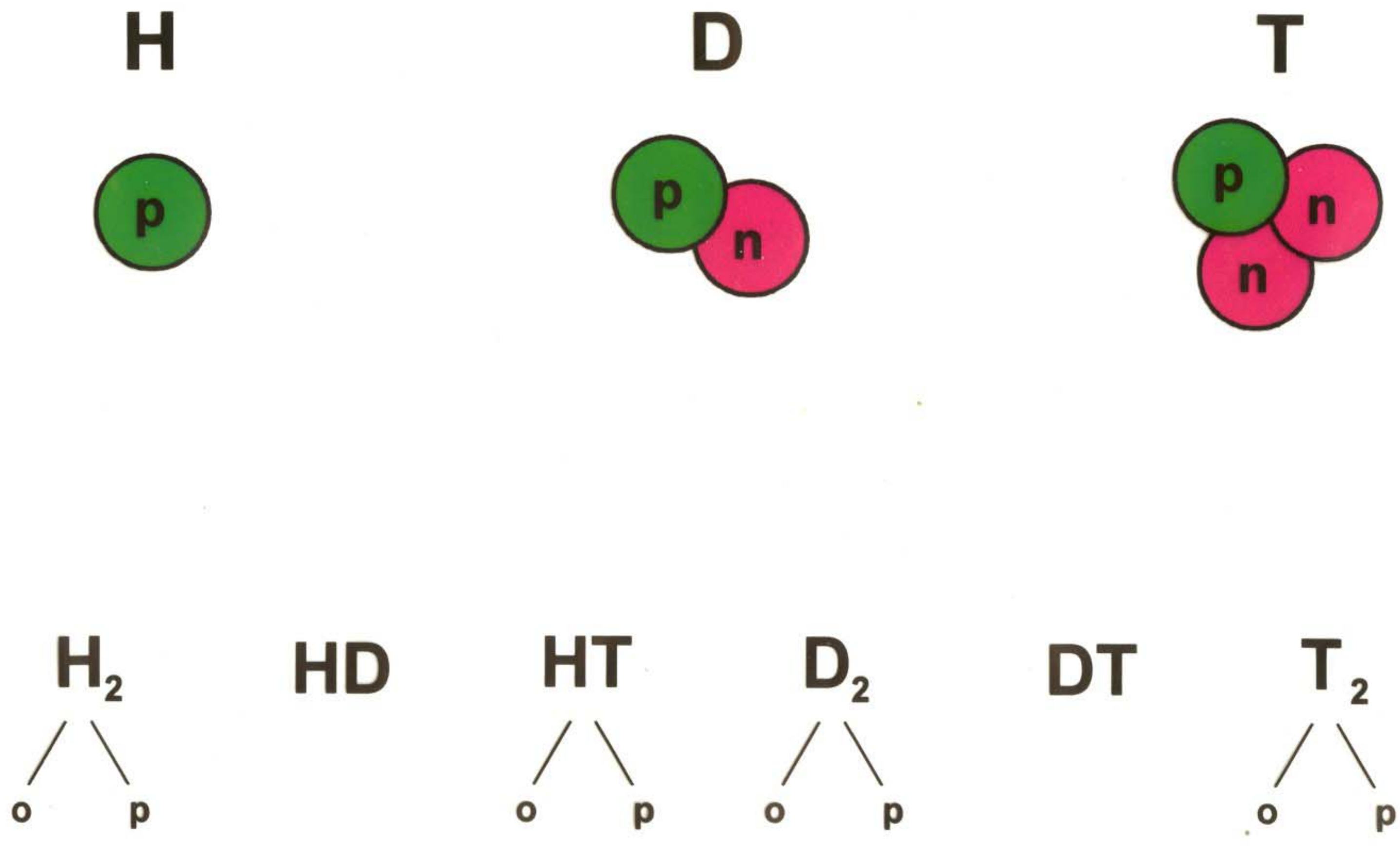
History of gas liquefaction

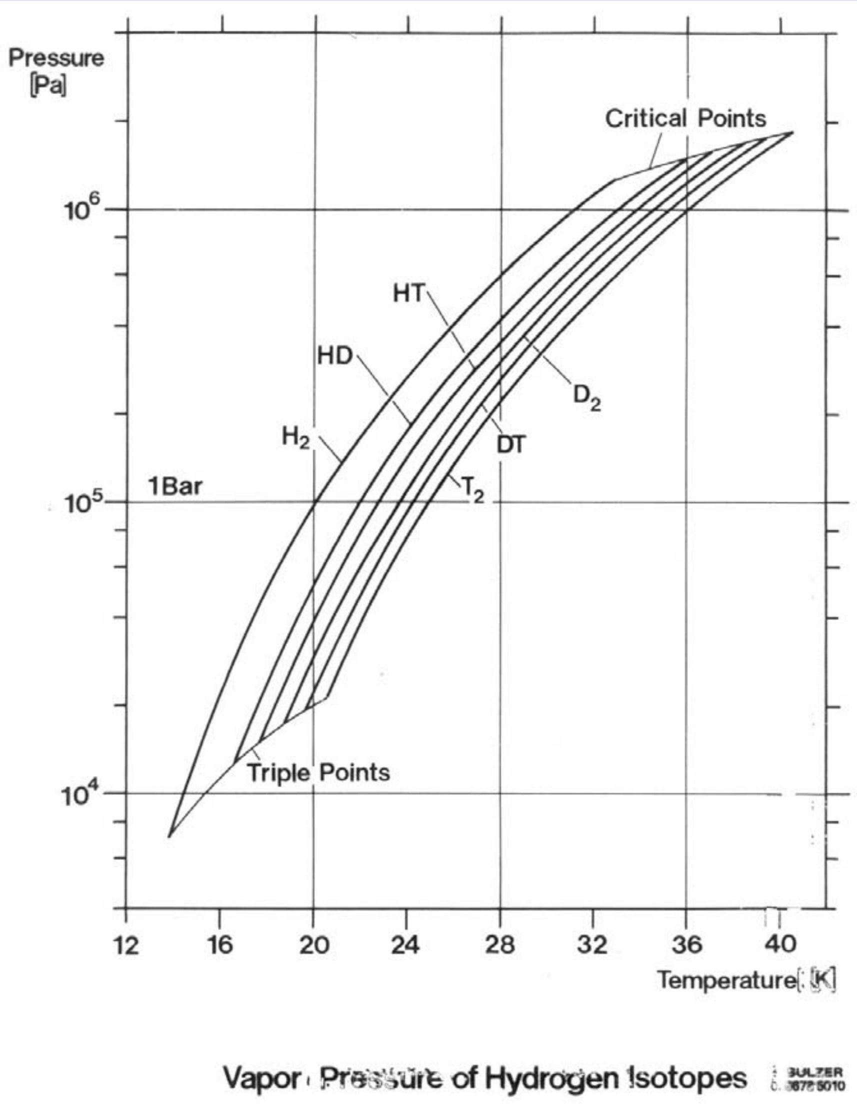


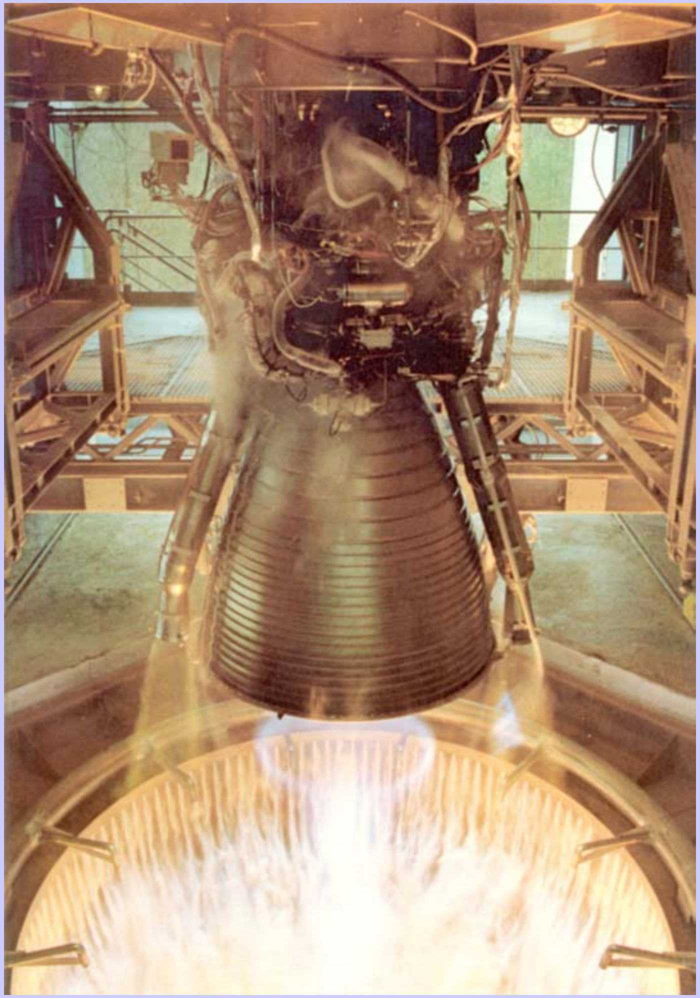
History of use of liquid hydrogen



Wasserstoff - Isotope




Pressure [Pa]
Critical Points
10^6
HT
HD
D_2
H_2
DT
1Bar
T_2
10^5
Triple Points
10^4
12
16
20
24
28
32
36
40
Temperature [K]
Vapor Pressure of Hydrogen Isotopes
SULZER



Liquid Hydrogen Fuelled Rocket

BEBC (Big European Bubble Chamber at CERN)

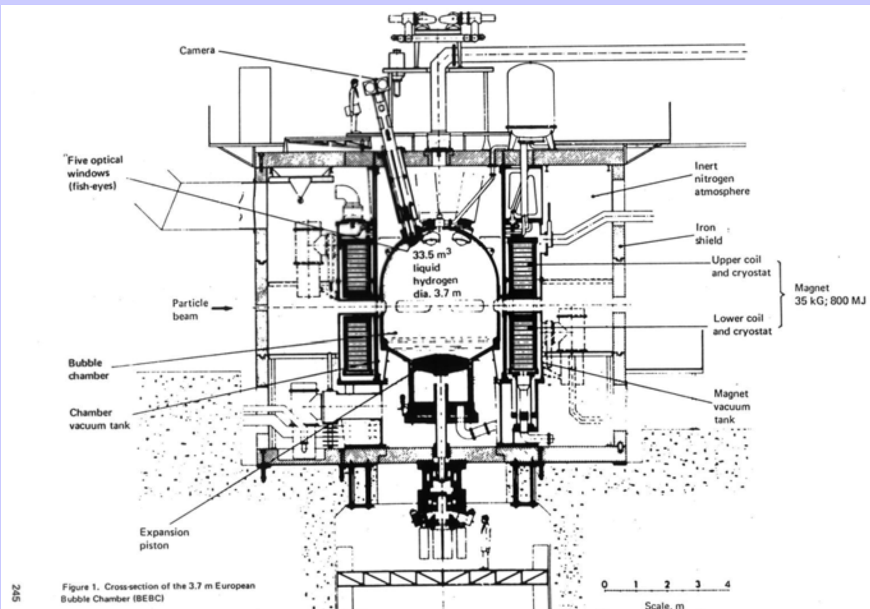
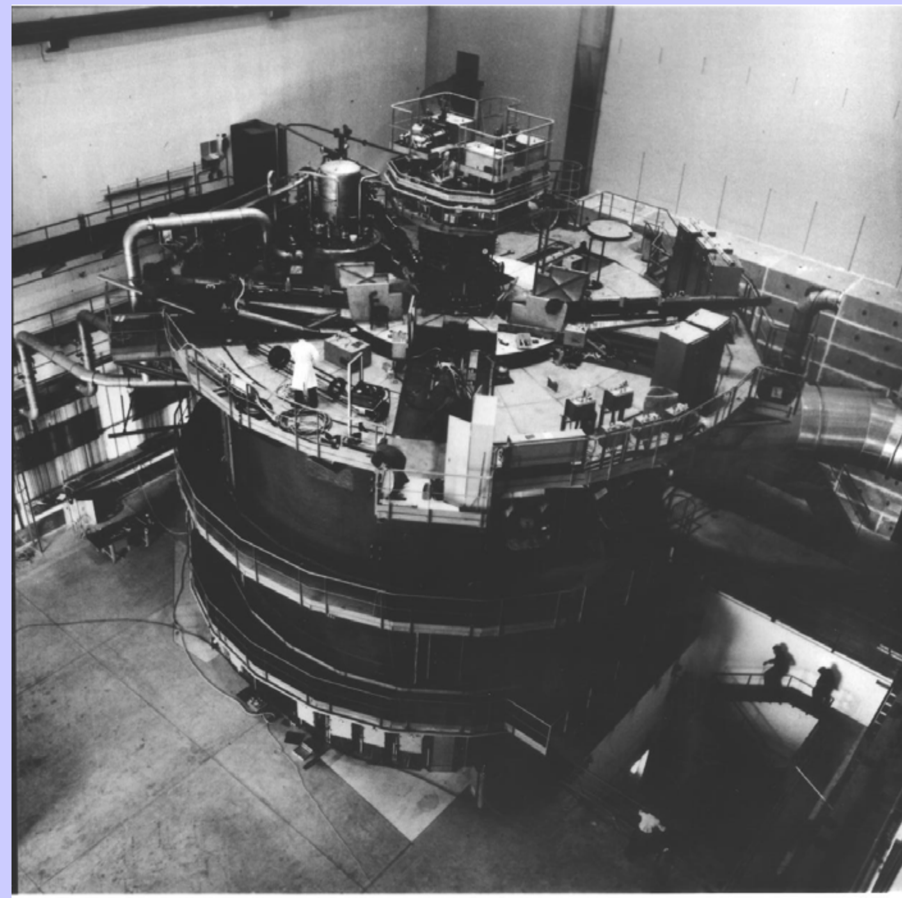


Figure 1. Cross-section of the 3.7 m European Bubble Chamber (BEBC)

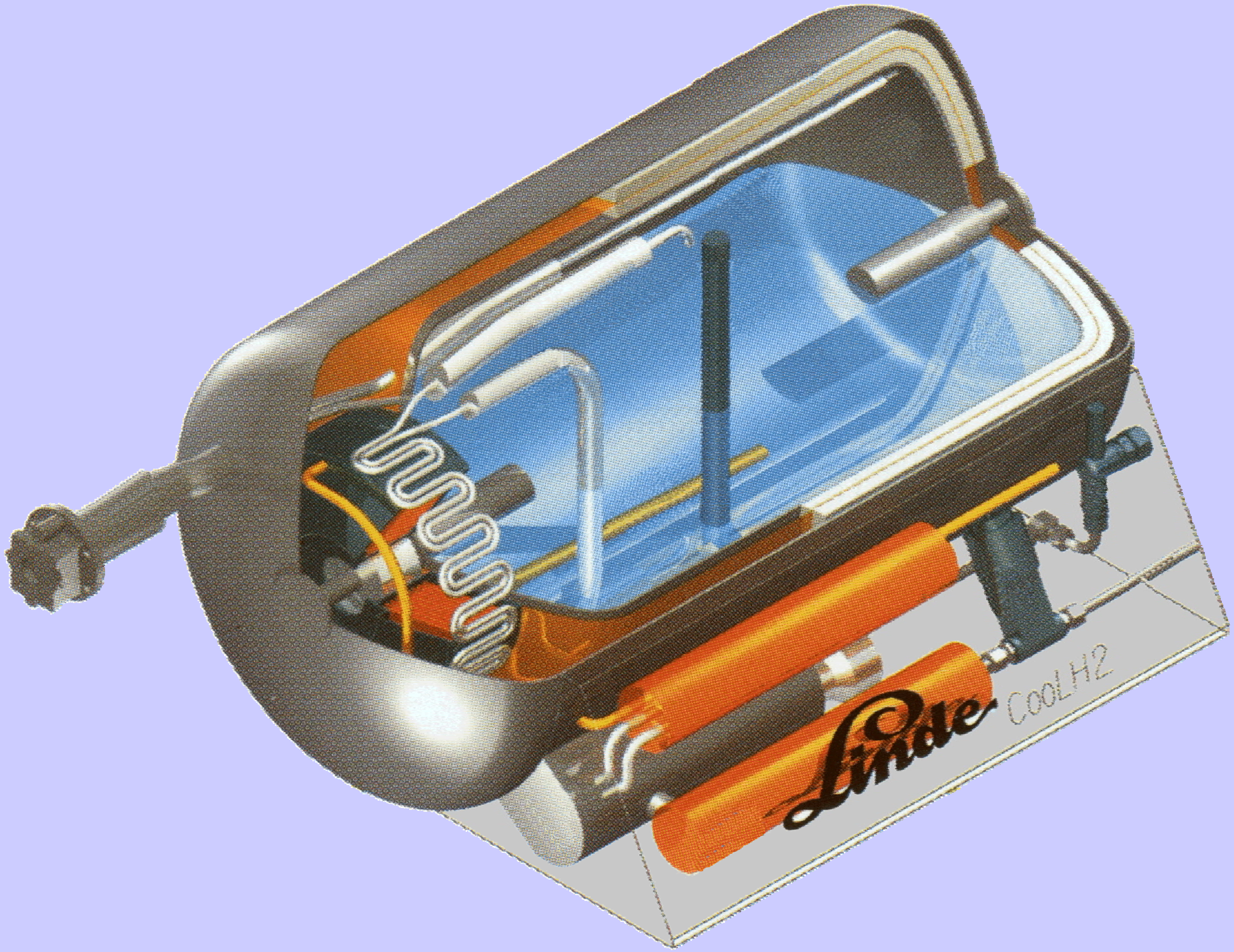
F. Birchler, J.P. Dauvergne, W. Erdt, D. Güsewell, F. Schmeissner & J. Schmid, "Cryogenic Aspects of the 3.7 m European Bubble Chamber", Proc. ICEC3, 244-250 (1970)



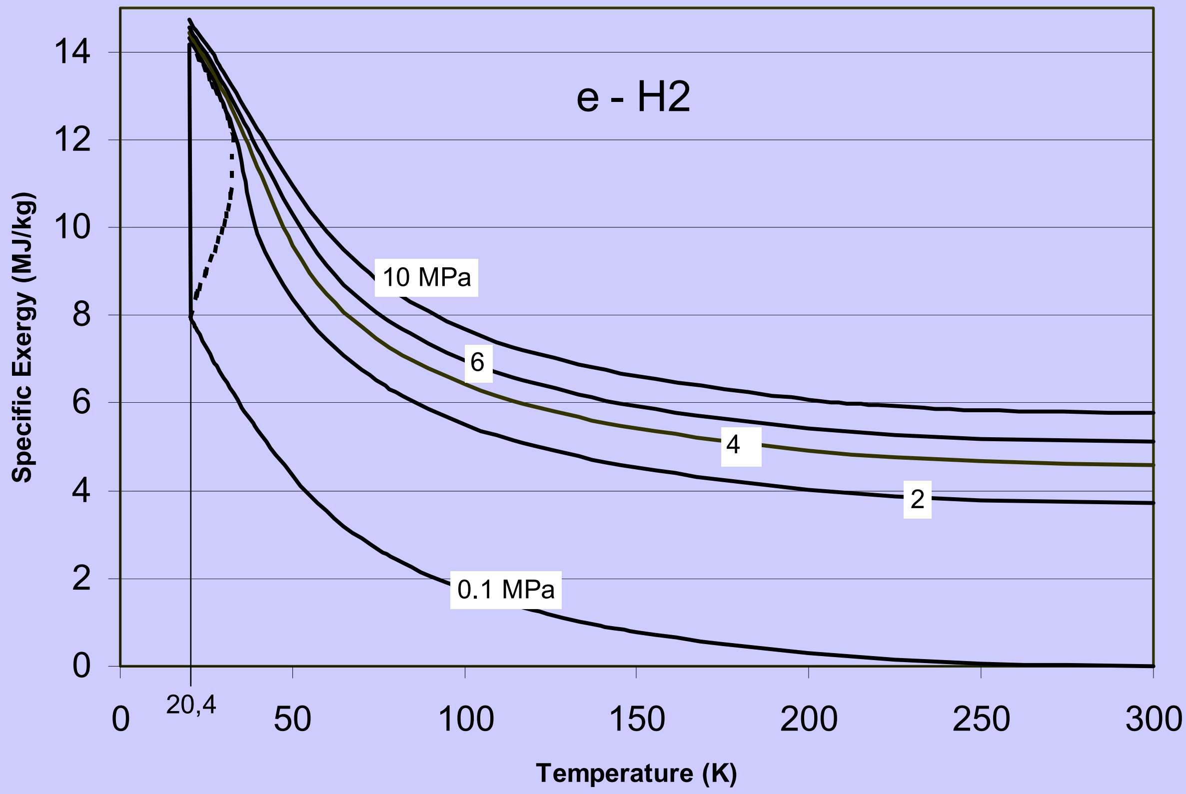
Liquid Hydrogen Fuelled Car


TOTAL
LH2
Wasserstoff-Kompetenz-
Zentrum Berlin
BVG
TOTAL
Linde

Liquid hydrogen tank in car

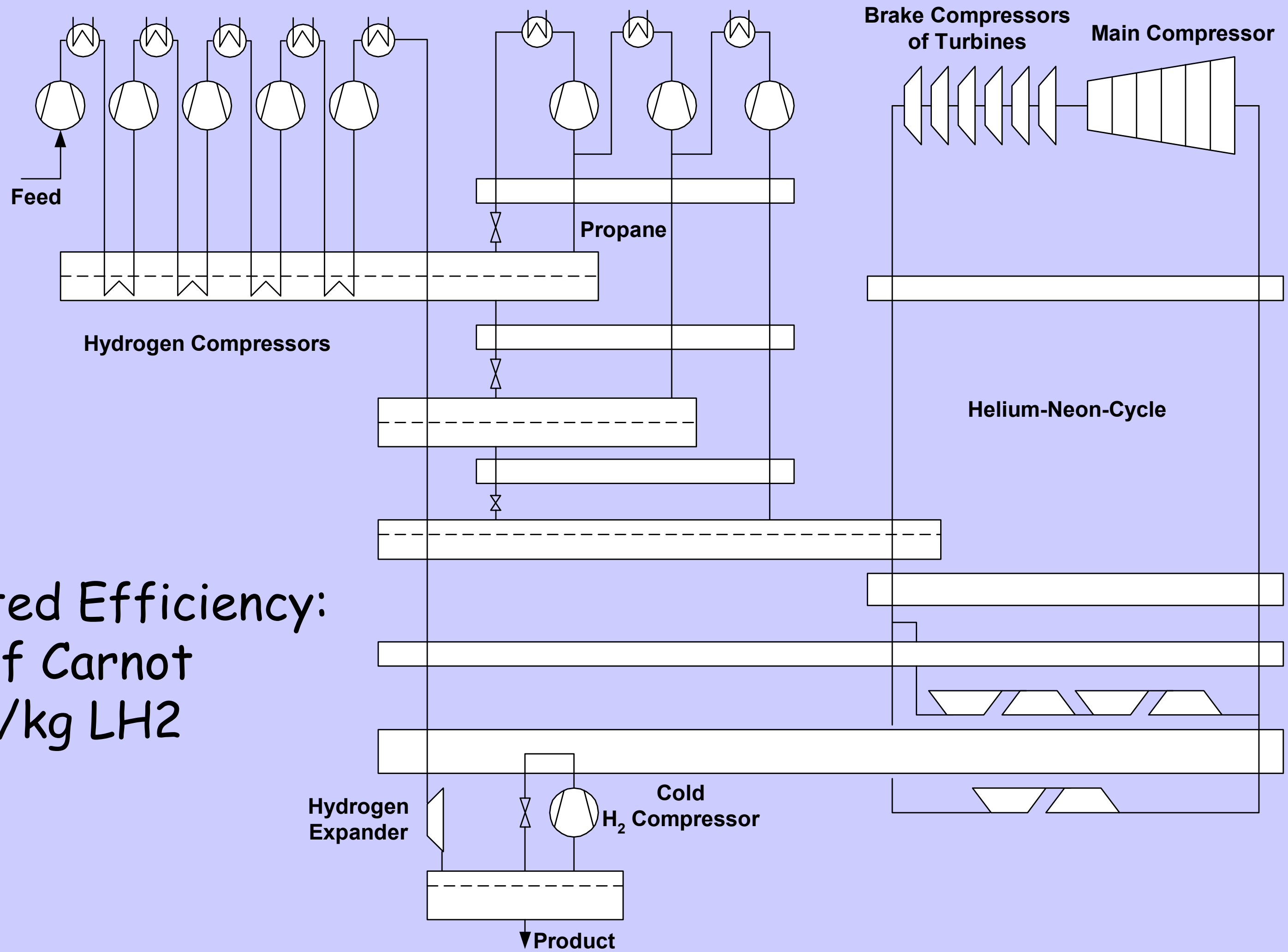


Hydrogen



e - H2
10 MPa
6
4
2
0.1 MPa
Specific Exergy (MJ/kg)
Temperature (K)
0
2
4
6
8
10
12
14
0
20,4
50
100
150
200
250
300

Future Large Scale Hydrogen Liquefier



Expected Efficiency:
60 % of Carnot
7 kWh/kg LH2