Introduction to Cryogenic Engineering

5. - 9.12.2005

G. Perinić, G. Vandoni, T. Niinikoski, CERN

Introduction to Cryogenic Engineering

MONDAY From History to Modern Refrigeration Cy

Introduction

From History to Modern Refrigeration Cycles

Refrigeration Cycle Examples

TUESDAY Standard Components, Cryogenic Design (G. Perinić)

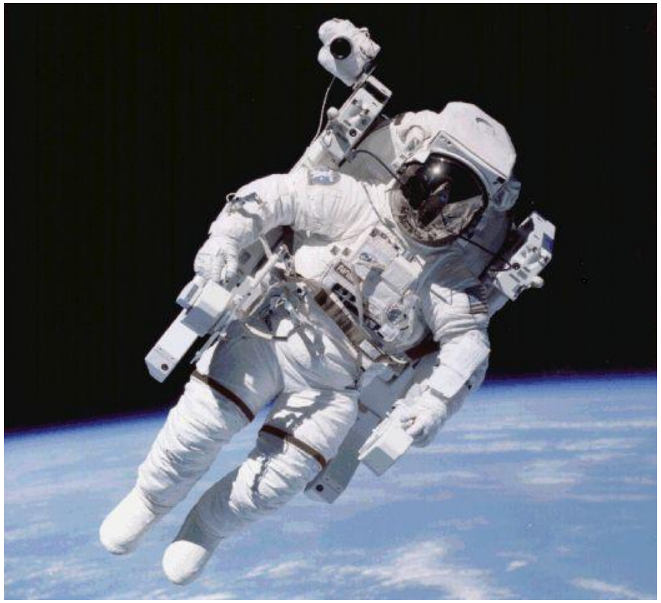
WEDNESDAY Heat Transfer and Insulation (G. Vandoni)

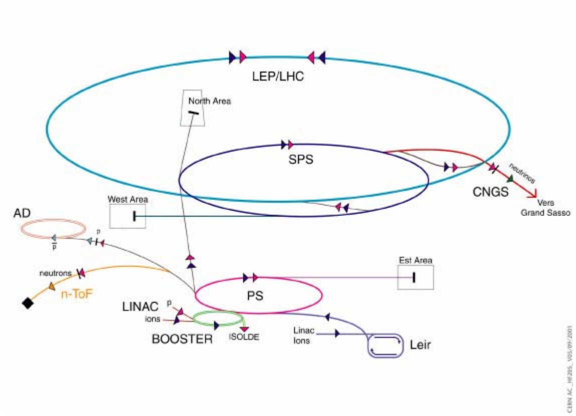
THURSDAY Safety, Information Resources (G. Perinić)

FRIDAY Applications of Cryogenic Engineering (T. Niinikoski)

Day 1

What is cryogenics?





History

Time of I. Newton

I. Newton
1642 - 1727

- F. Bacon (1561 - 1621)

Novum organum (1620)

The third of the seven modes […] relates to […] heat and cold. And herein man's power is clearly lame on one side. For we have the heat of fire which is infinitely more potent and intense than the heat of the sun as it reaches us, or the warmth of animals.

But we have no cold save such as is to be got in wintertime, or in caverns, or by application of snow and ice, […]

And so too all natural condensations caused by cold should be investigated, in order that, their causes being known, they may be imitated by art.

Time of I. Newton

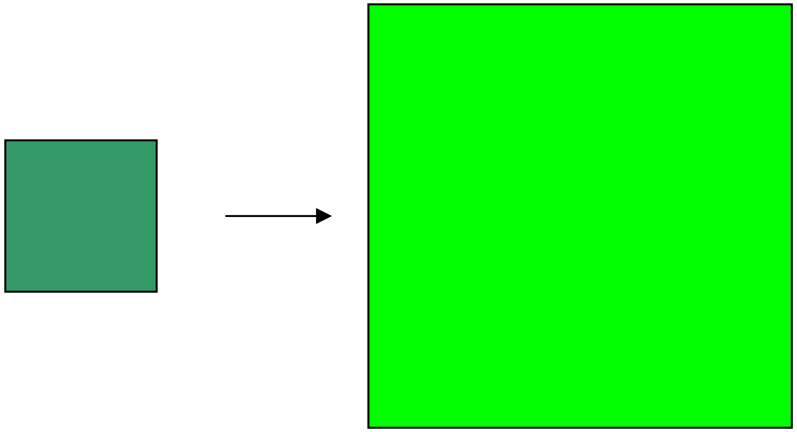
I. Newton
1642 - 1727

- Known refrigeration methods
  - refrigeration by a colder object
    e.g. ice or snow
  - refrigeration by evaporation
  - refrigeration by dissolving saltpeter in water
    (saltpeter = sodium nitrate $NaNO_3$ or potassium nitrate KNO_3)

Time of I. Newton

I. Newton
1642 - 1727

- R. Boyle (1627 - 1691); E. Mariotte (1620 - 1684)

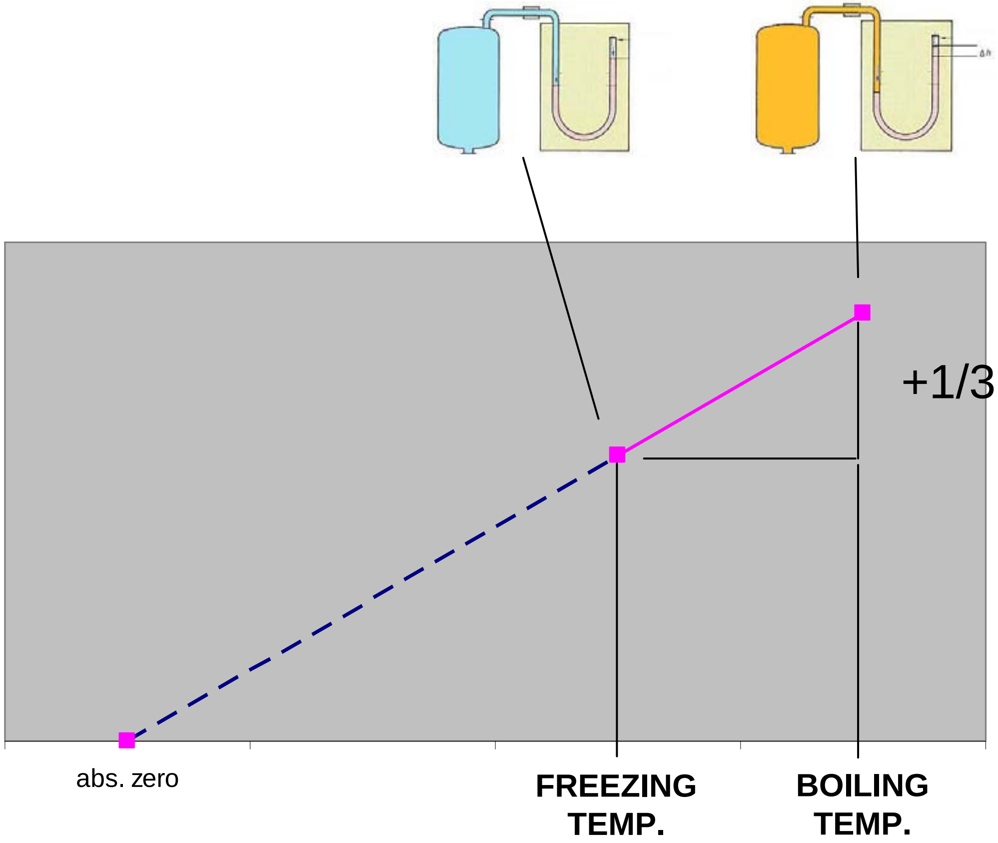


p V = constant

Time of I. Newton

I. Newton
1642 - 1727

- G. Amontons (1663 - 1705)



Further development of thermodynamics

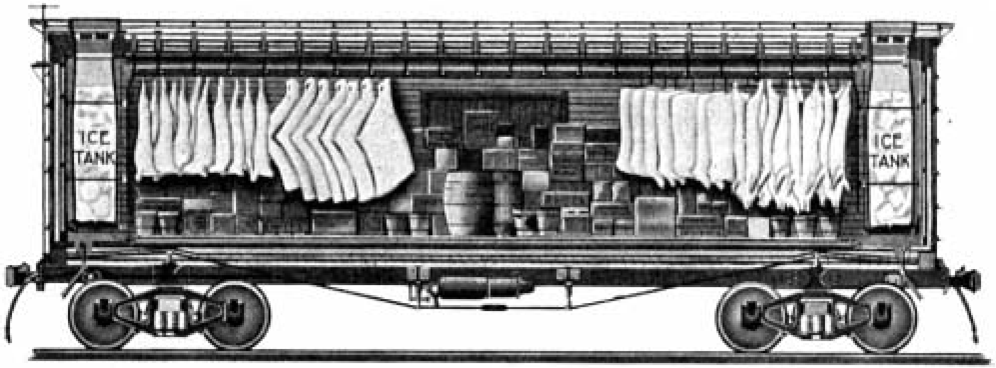
J. Black (1728 - 1799)	latent heat
A. Lavoisier (1743 - 1794)	caloric theory
S. Carnot (1824)	work
R. Clausius (1865)	entropy
W. Gibbs (1867); R. Mollier (1923)	enthalpy

Incentives for refrigeration and cryogenics

- Early 19th century
  - large scale refrigeration only by natural ice
  - increasing demand for artificial refrigeration by
    - the butchers,
    - the brewers and later on
    - the industrialists

ice harvesting

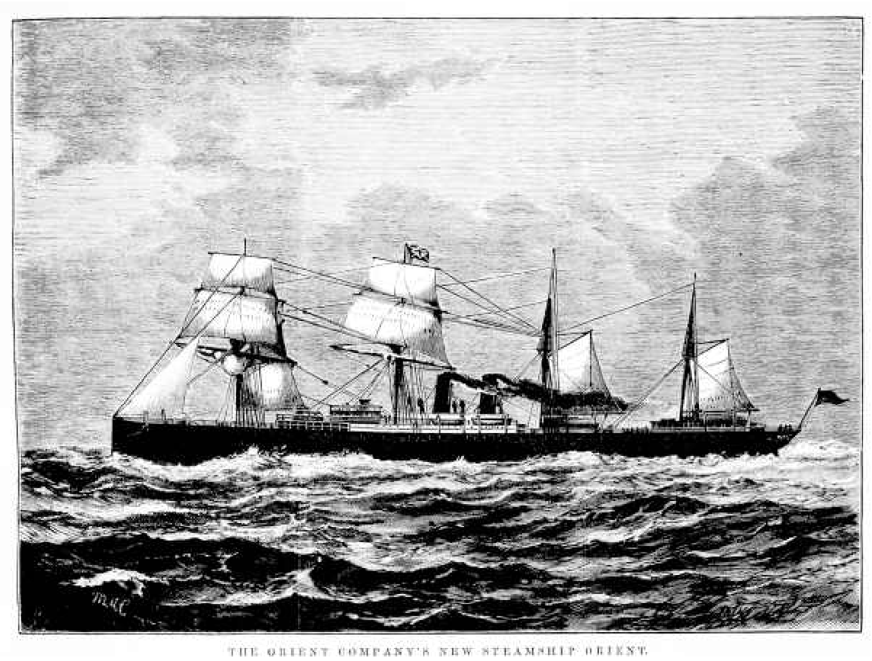
ice storage cave in Bliesdahlheim



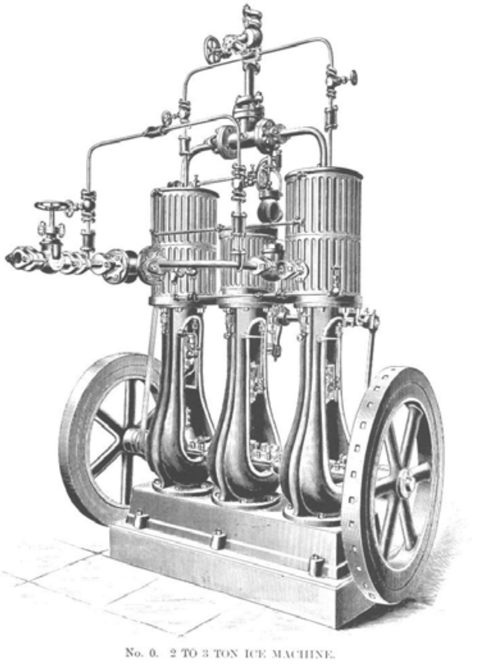
refrigerated railroad car

Incentives for refrigeration and cryogenics

- Examples of first commercial refrigeration applications



S.S. Strathleven, equipped with Bell&Coleman air-cycle refrigerator. First meat cargo transported from Australia to London 6.12.1879 - 2.2.1880.
By courtesy of "La Trobe Picture Collection", State Library of Victoria



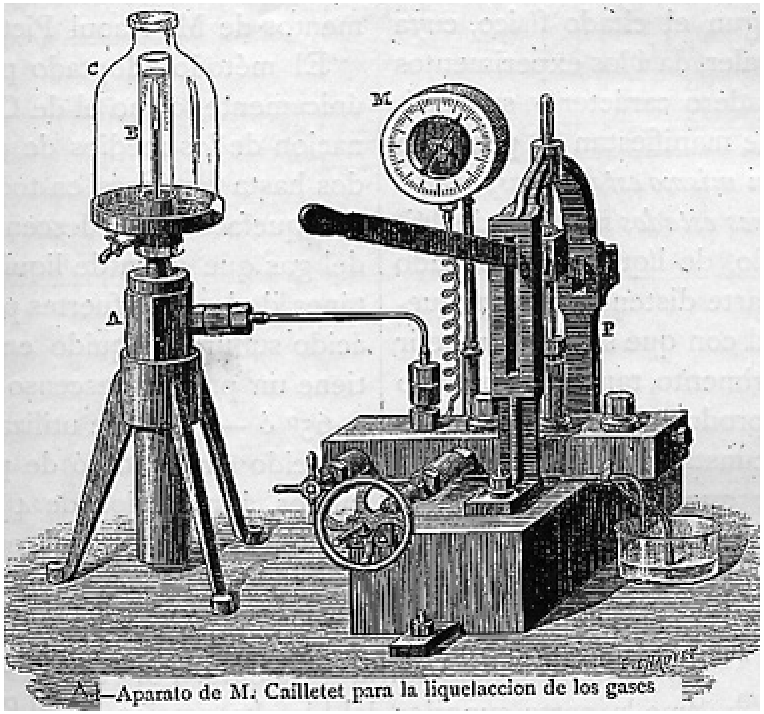
Standard ammonia cycle ice machine from York's 1892 catalogue.

Braking the cryo-barrier I

L.P. Cailletet
1832 - 1913

- The successful liquefaction of Oxygen was announced at the meeting of the Académie de Sciences in Paris on December 24th, 1877 independently by the physicist Louis Paul Cailletet from Paris and the professor Raoul Pictet from Geneva.

- Cailletet's apparatus
  - compression to 200 bar in a glass tube with a hand-operated jack, using water and mercury for pressure transmission
  - pre-cooling of the glass tube with liquid ethylene to -103°C
  - expansion to atmosphere via a valve



Braking the cryo-barrier II

R. Pictet
1832 - 1913

- Pictet’s apparatus
  - production of oxygen under pressure in a retort
  - two pre-cooling refrigeration cycles:

    first stage SO_2 (-10°C)
    second stage CO_2 (-78°C)
  - oxygen flow is pre-cooled by the means of heat exchangers and expands to atmosphere via a hand valve

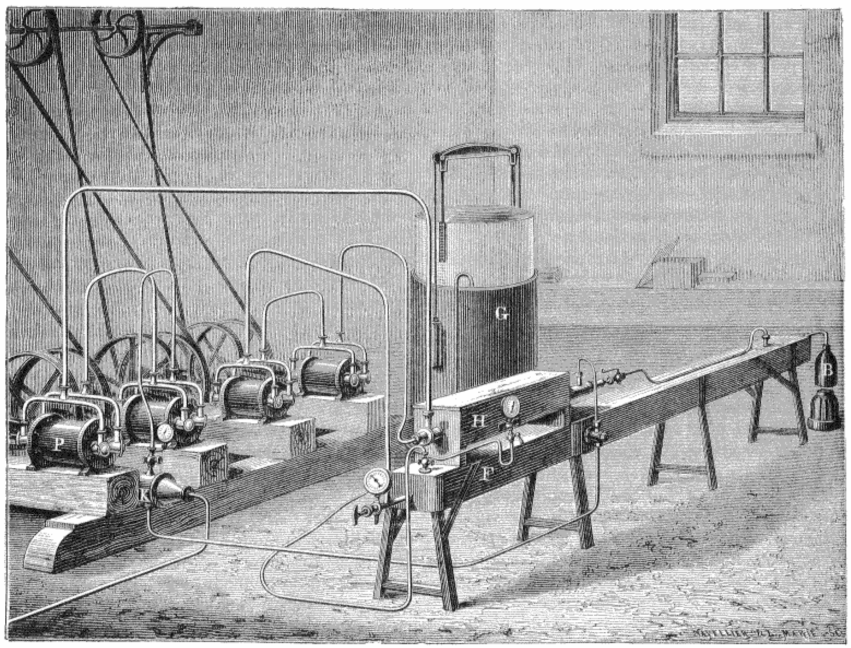


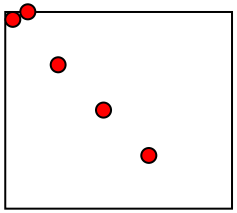
Fig. 1. — Grand appareil de M. Raoul Pictet pour la liquéfaction des gaz. (D'après une photographie.)

Milestones in the history of cryogenic technology

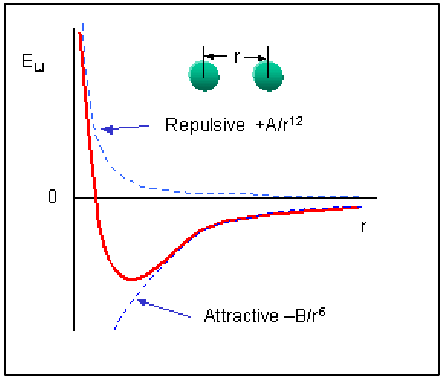
1892	Dewar - use of silvering and vacuum in double walled glass vessel
1895	Linde and Hampson build air liquefiers with recuperative heat exchangers
1898	Dewar - liquefies hydrogen
1902	Claude - use of piston expander
1908	Kamerlingh Onnes - liquefies helium
1908	Becquerel - freezes seeds and single cells
1910	use of LOx in the production of steel
1911	discovery of superconductivity

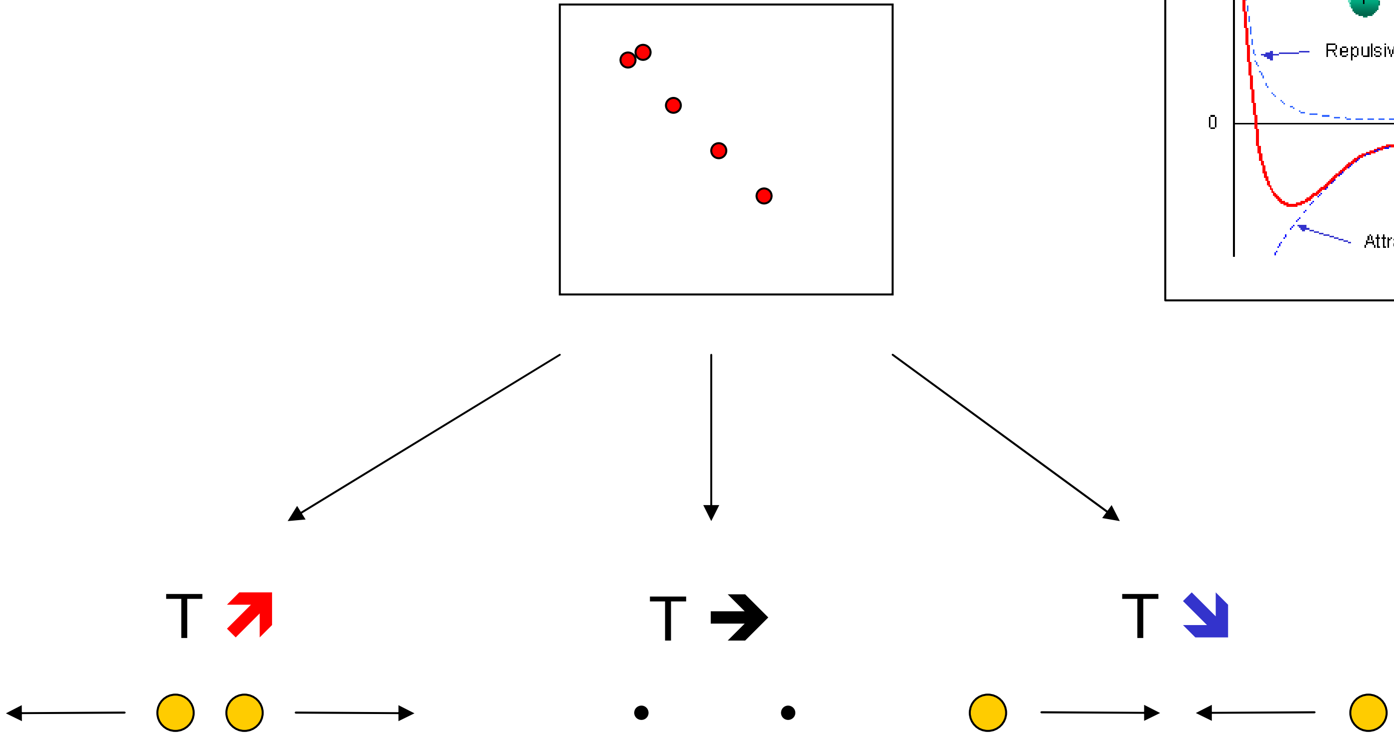
Thermo-dynamics

The magic of throttling - physicist's explanation



The magic of throttling - physicist’s explanation





repulsion
dominates
(Coulomb)
→

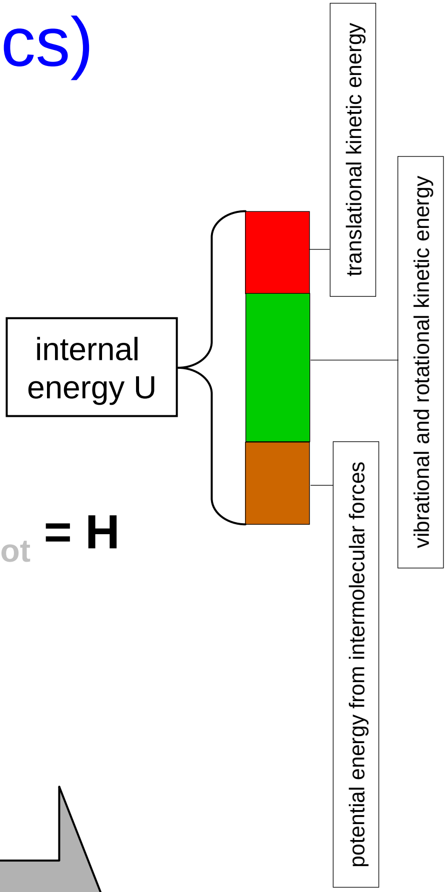
ideal gas

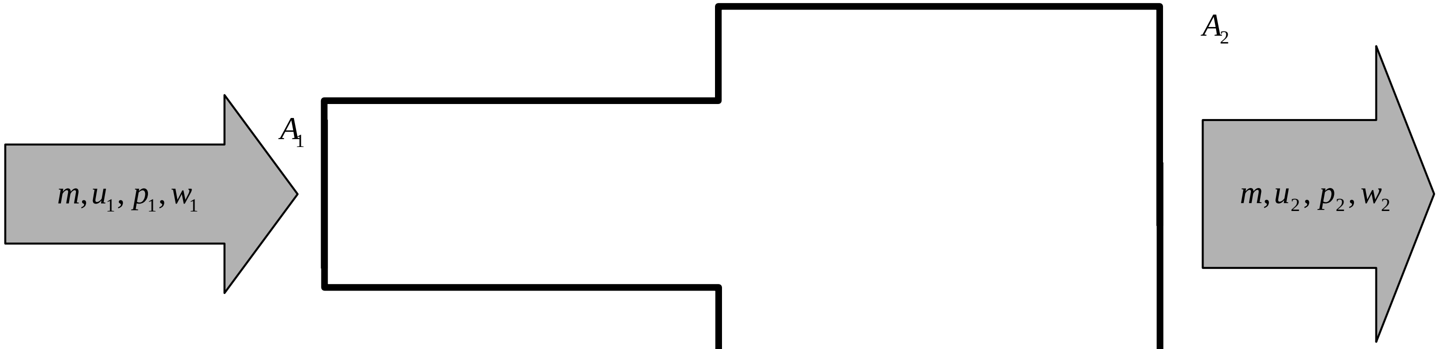
Gay-Lussac

attraction
dominates
(gravity)
Joule-Thompson

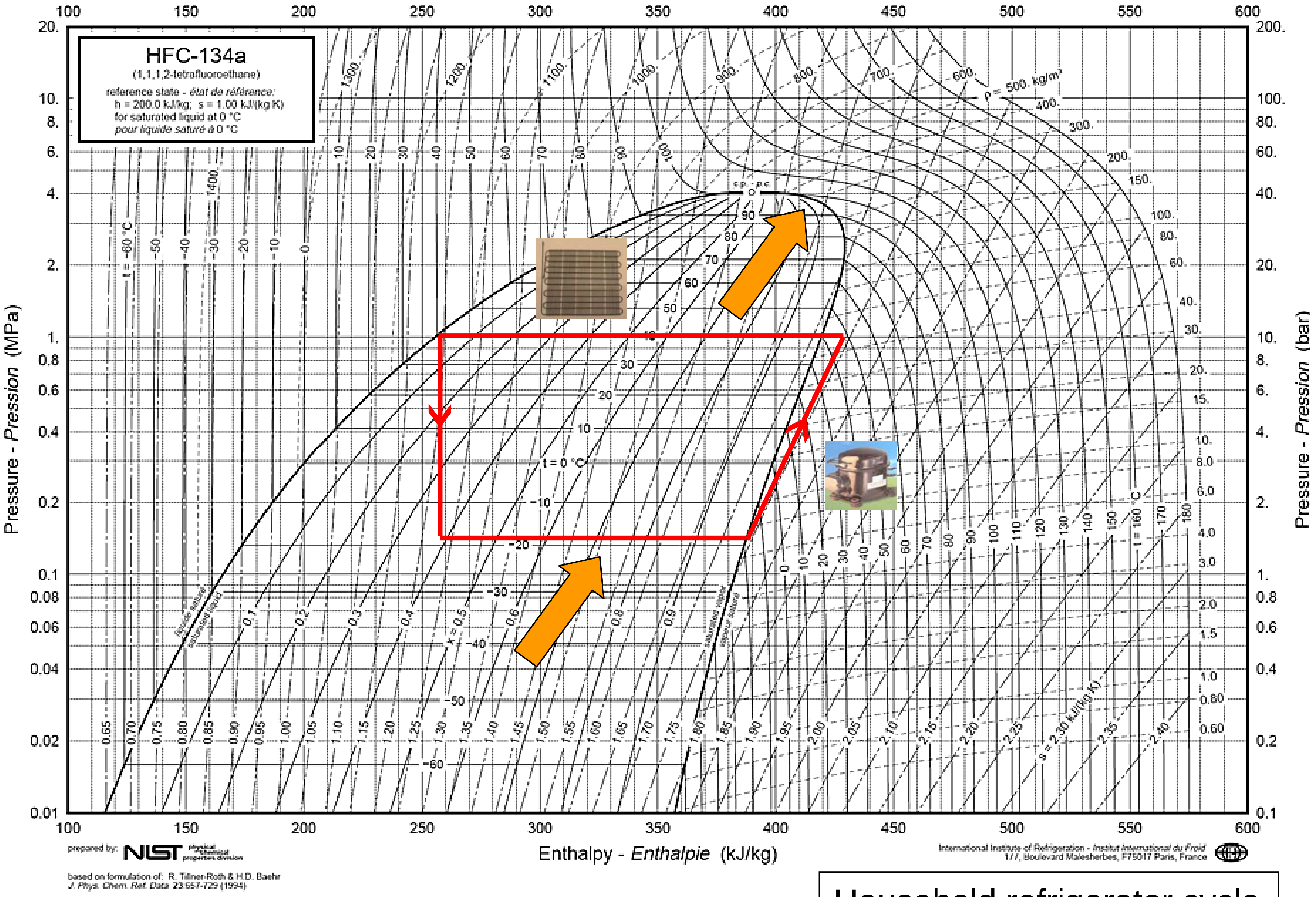
Throttling - thermodynamist’s explantion (and first law of thermodynamics)

- energy conservation $\quad \mathbf{dQ + dW = dE = 0}$
- internal energy closed system $\quad \mathbf{E = U} + E_{kin} + E_{pot}$
- energy content open system $\quad \mathbf{E = U + pV} + E_{kin} + E_{pot}\ \mathbf{= H}$





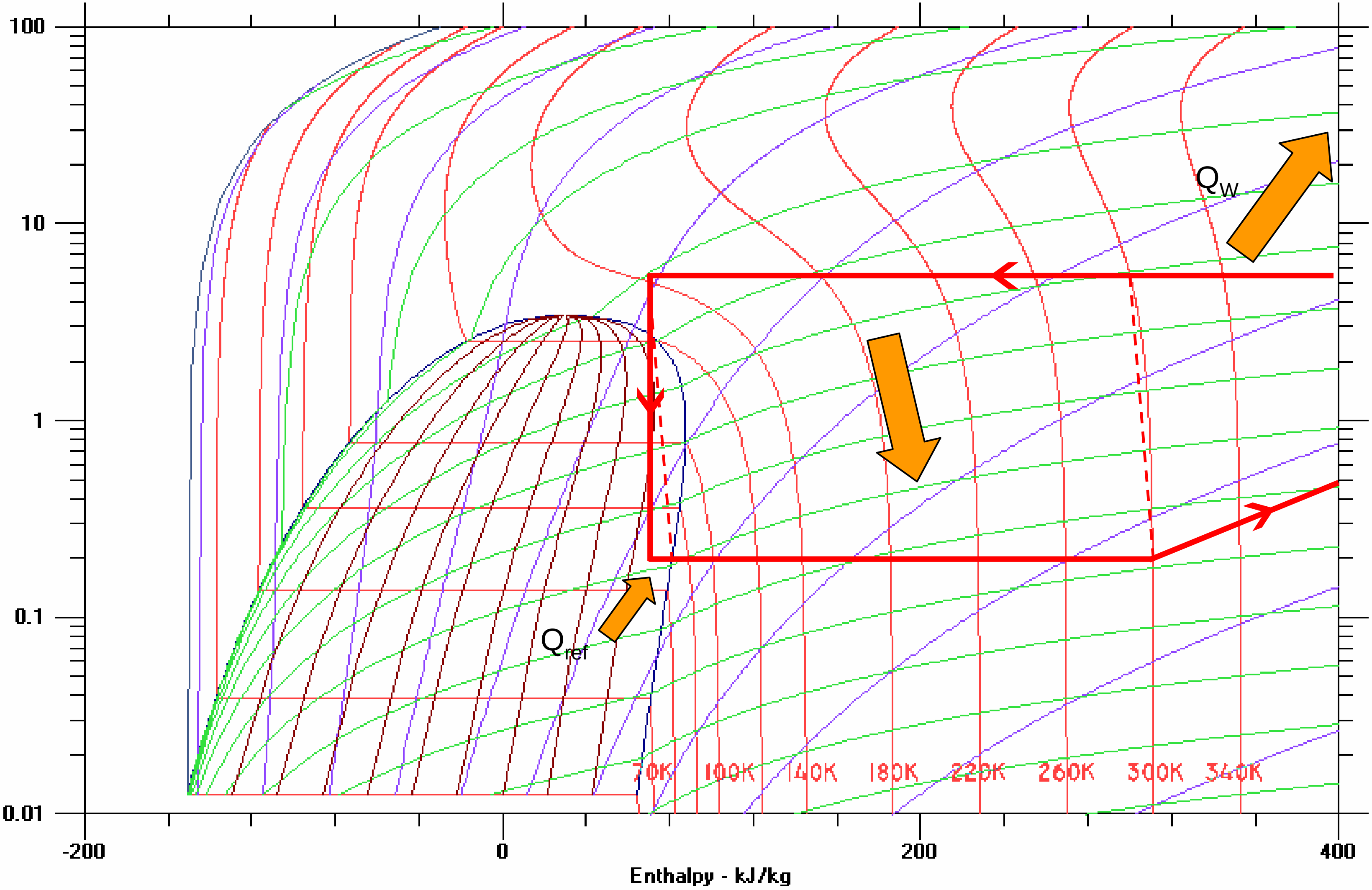
$\mathbf{H_1} \quad = \quad \mathbf{H_2}$



Household refrigerator cycle

Nitrogen

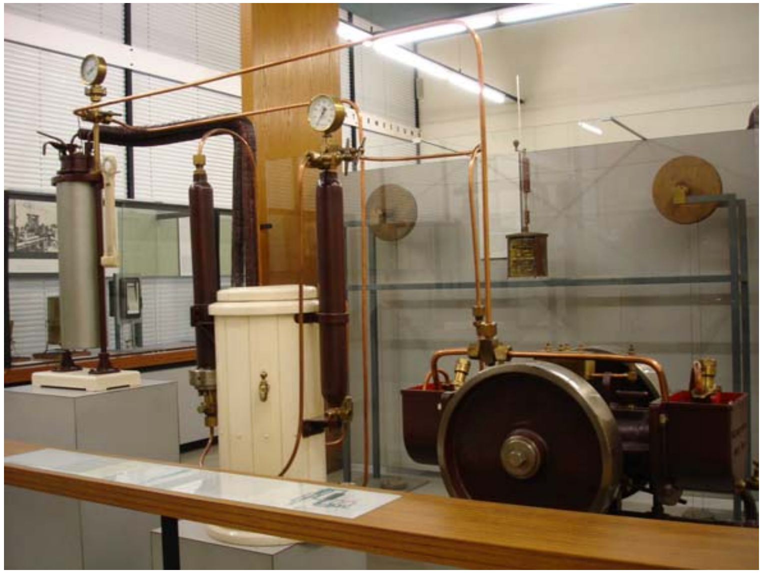
Linde/Hampson refrigeration cycle



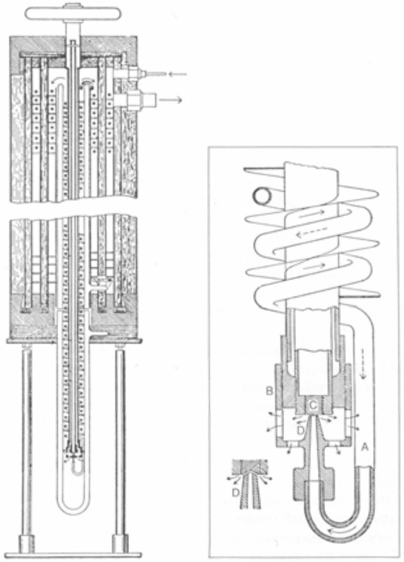
Linde and Hampson

C. von Linde
1842-1934

Linde liquefier



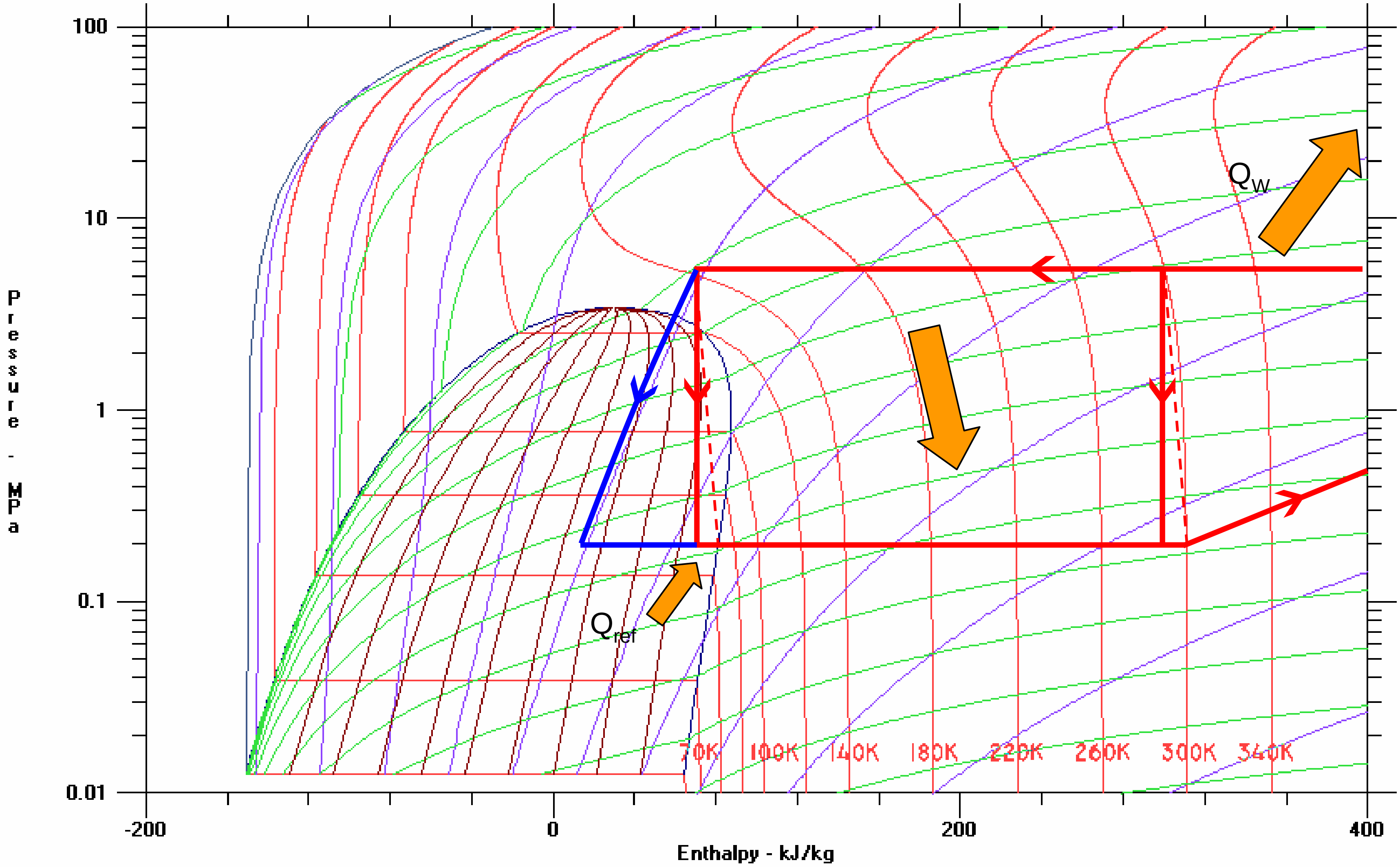
Hampson liquefier



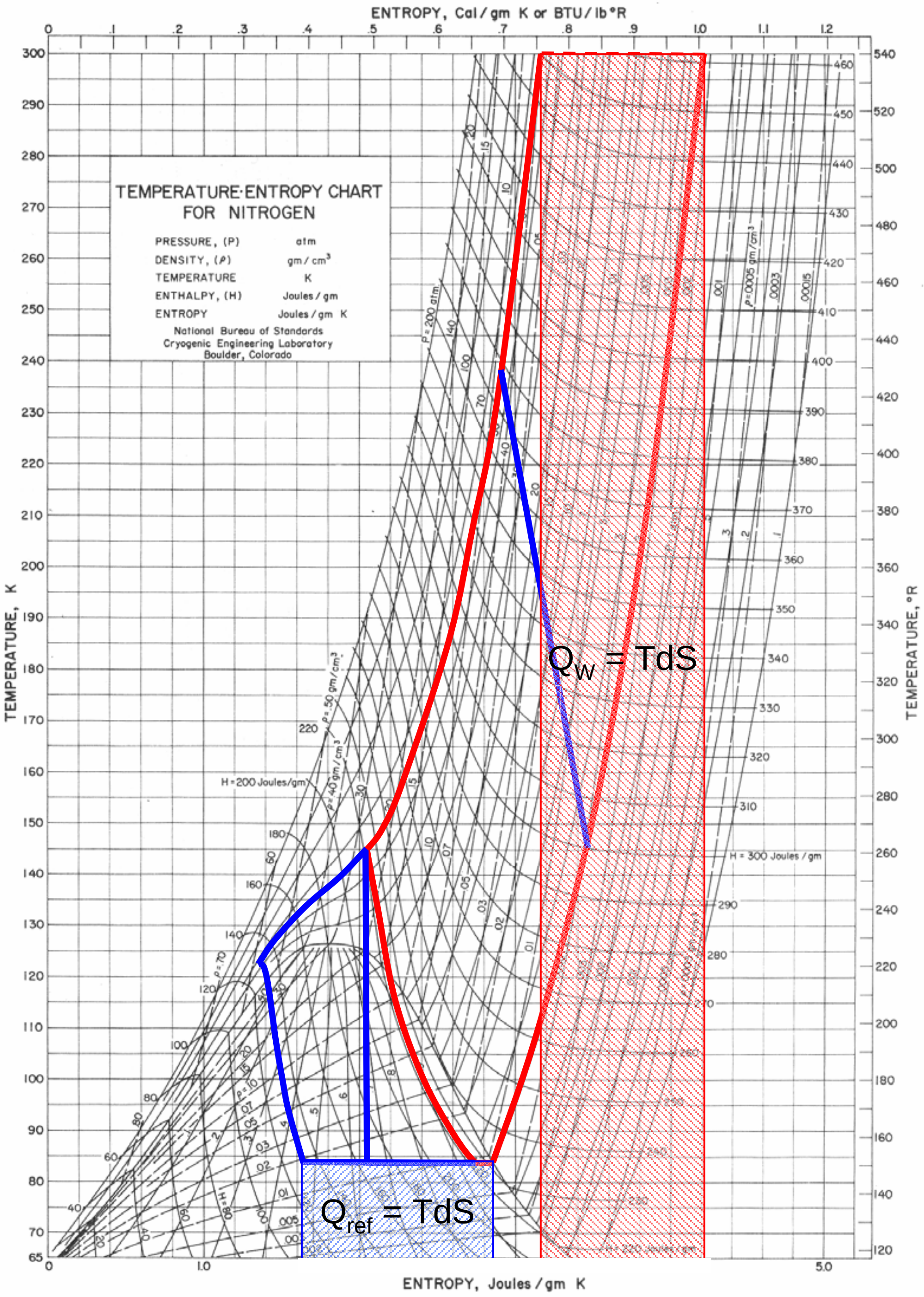
Hampson's air liquefier 1895. The inset shows the coil (A) terminating in the jet piece (D) which delivers cold gas against a flat plug on the valve screw (C).

Nitrogen

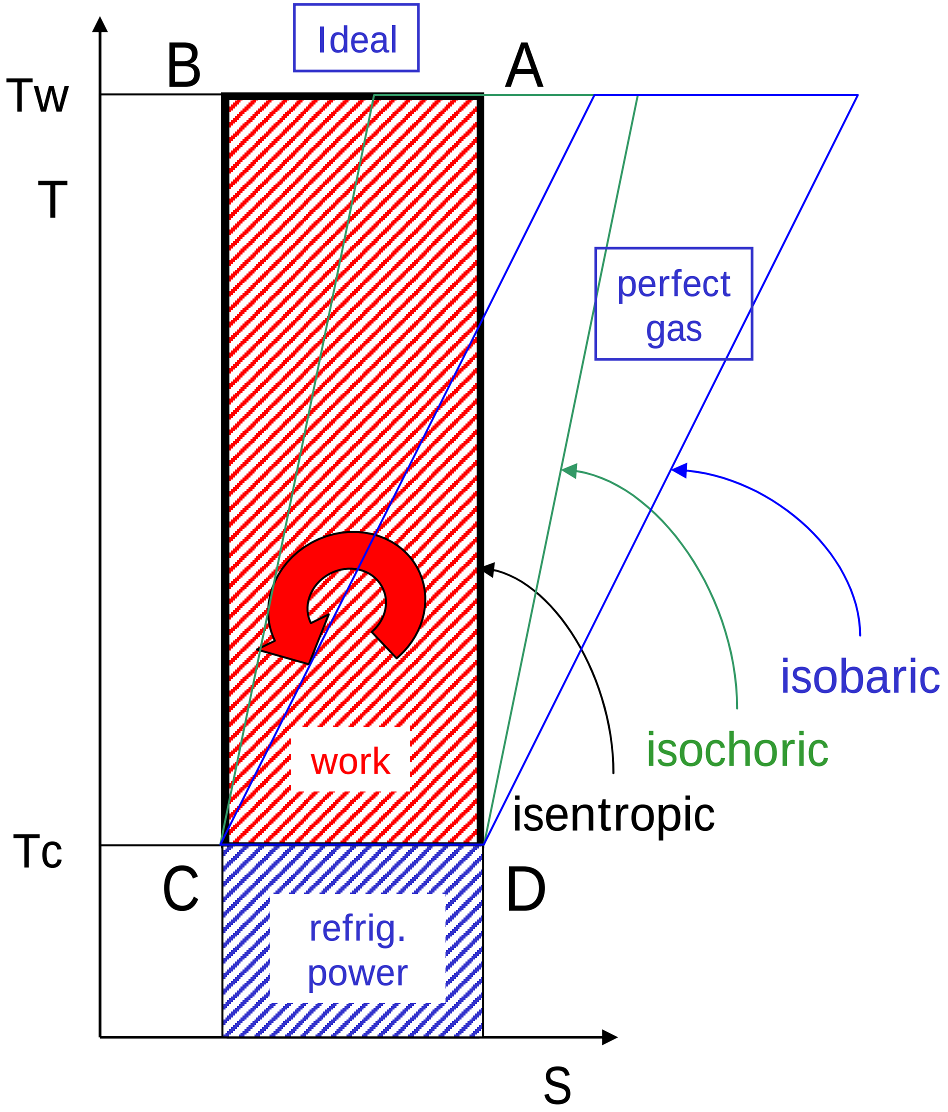
Linde/Hampson refrigeration cycle



Claude refrigeration cycle



Carnot cycle



- heat removed / heat introduced

  $Q_W = (S_A - S_B) * T_W \quad Q_{ref} = (S_D - S_C) * T_C$

- energy conservation

  $Q_W = Q_{ref} + W \quad$ and $(S_A - S_B) = (S_D - S_C)$

  $\Rightarrow \; W = (S_A - S_B) * (T_W - T_C)$

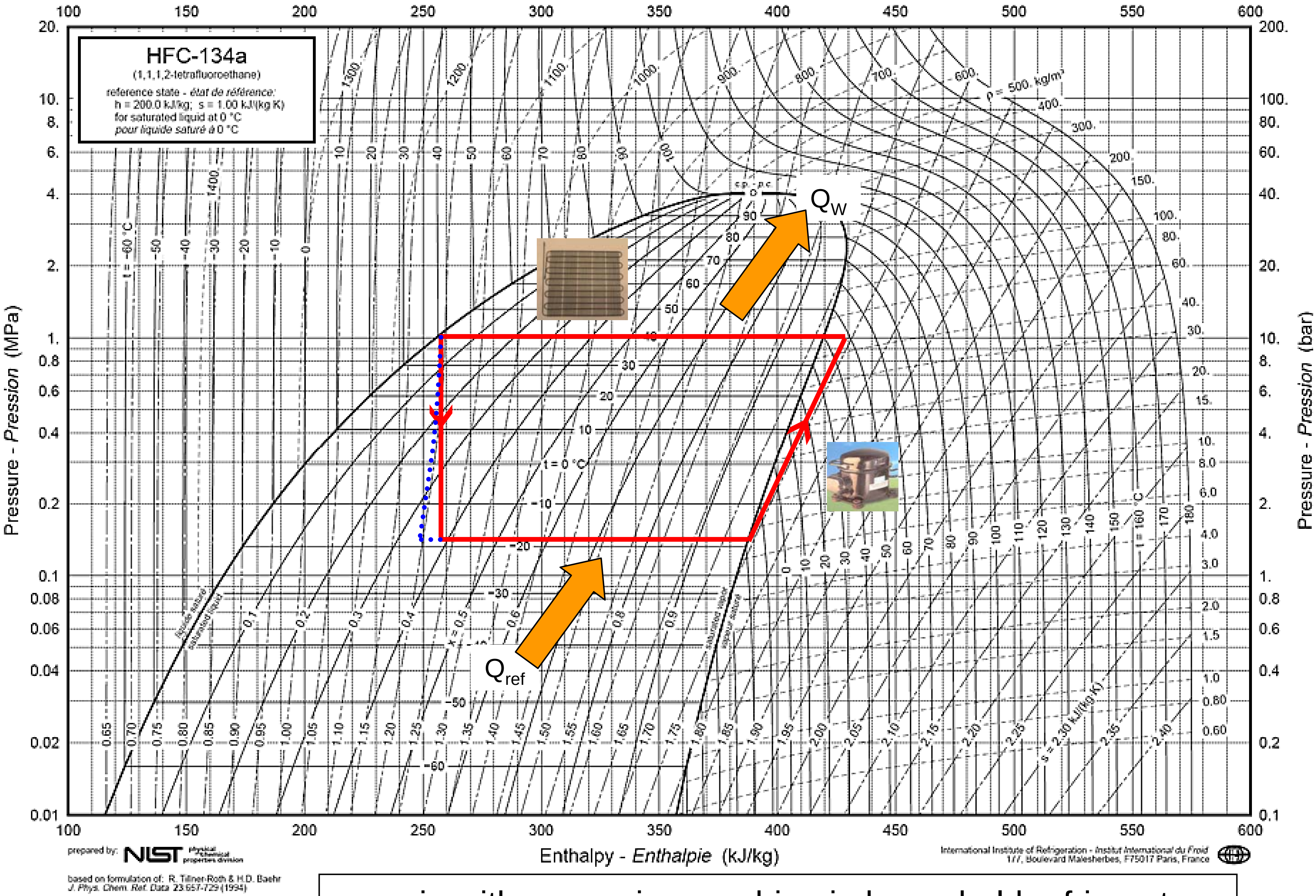
- coefficient of performance or efficiency
  (index i = ideal)

  $COP_i = \eta_i = Q_{ref} / W = T_C / (T_W - T_C)$

T_C	80 K	20K	4K
COP_i, η_i	0.364	0.071	0.014

- figure of merit or
  thermodynamic (Carnot) efficiency

  $FOM = COP_{real} / COP_i = \eta_{th} = \eta_{real} / \eta_i$



no gain with expansion machine in household refrigerator

Summary - refrigeration

refrigeration can be achieved by

- **contact with a colder surface**
- **throttling**
- **work extraction**

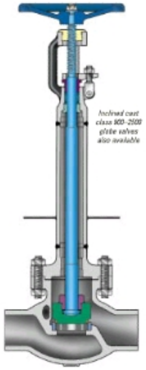
refrigeration can reach lower temperatures by

- **heat recovery**

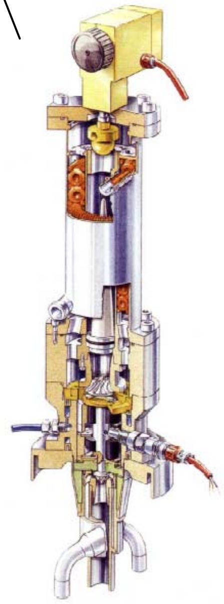
Cycles

Bricks to build a refrigerator

A - expansion device

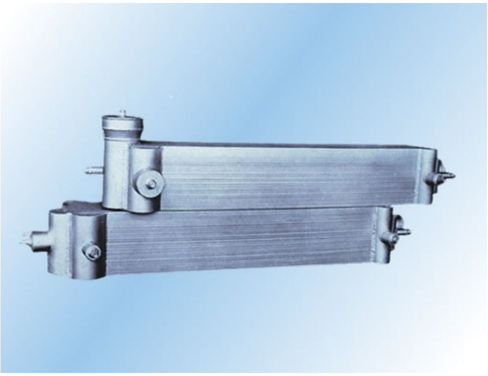


J-T valve

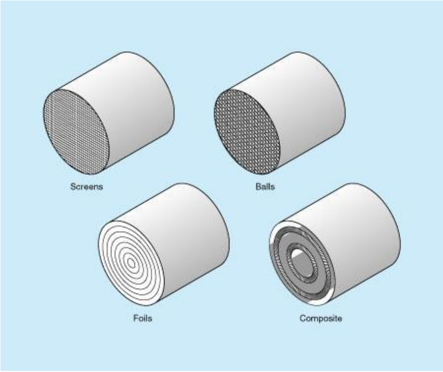


expansion
machine

B - heat regeneration/recuperation



heat exchanger



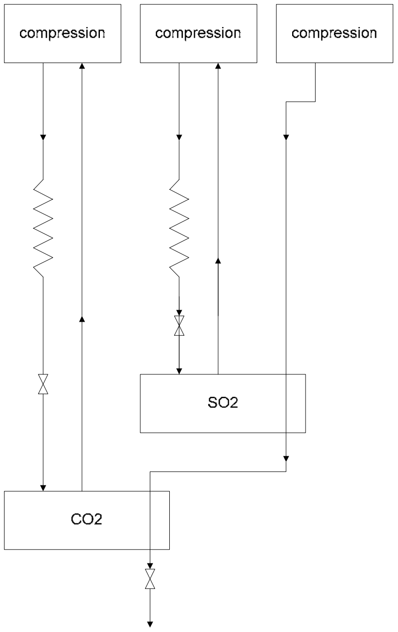
regenerator

Refrigeration cycles/principles

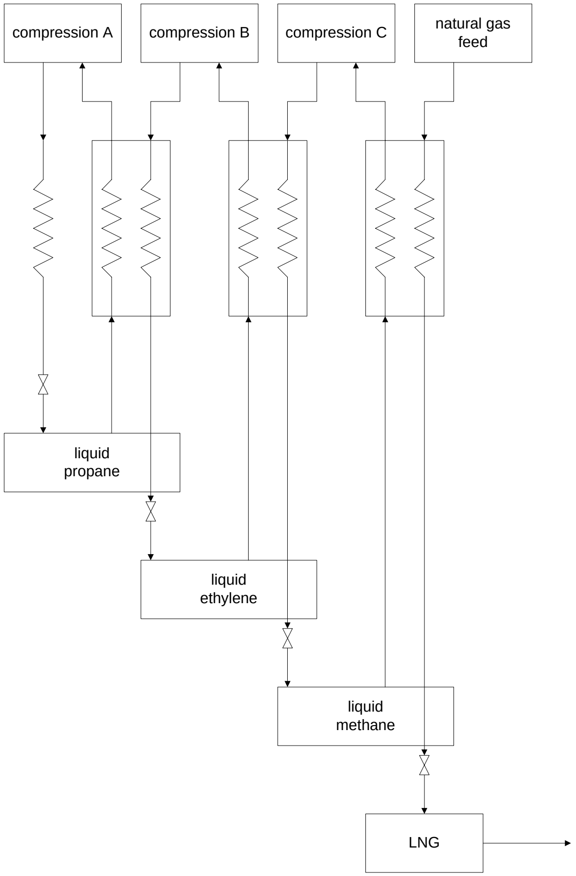
	without heat recovery	with recuperator	with regenerator
throttling	cascade sorption	Joule – Thomson Linde – Hampson dilution	
expansion	Ranque Hilsch	Claude Brayton Collins	Stirling Solvay Vuilleumier Gifford – McMahon pulse tube
other principles	thermoelectric (cascade)	magnetic	

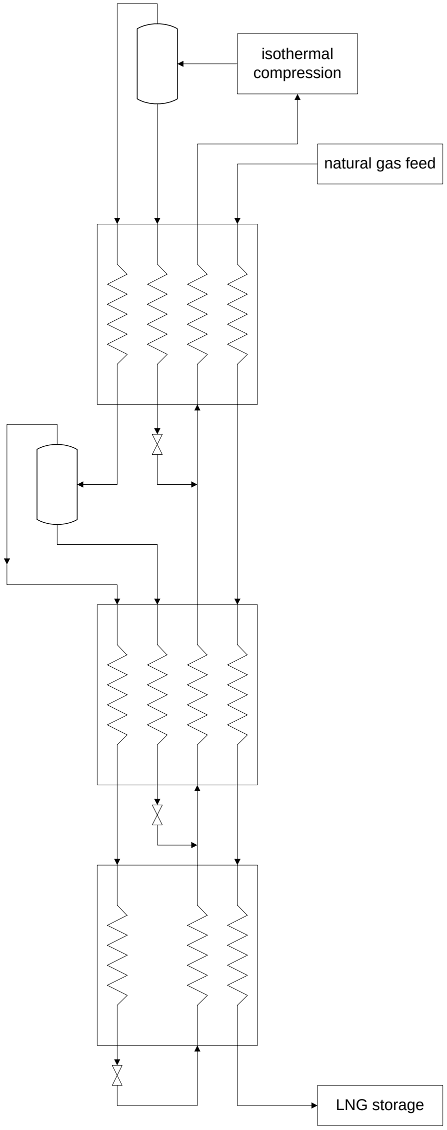
Mixed refrigerant cascade (MRC) refrigerator (Klimenko)

Pictet's cascade



Cascade refrigerator

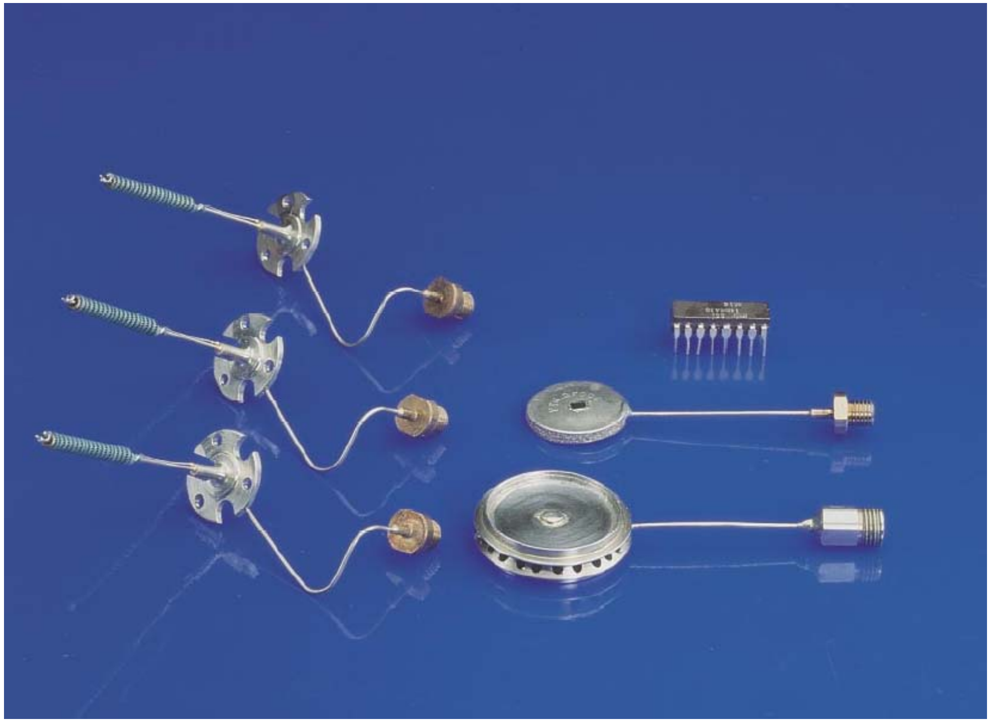


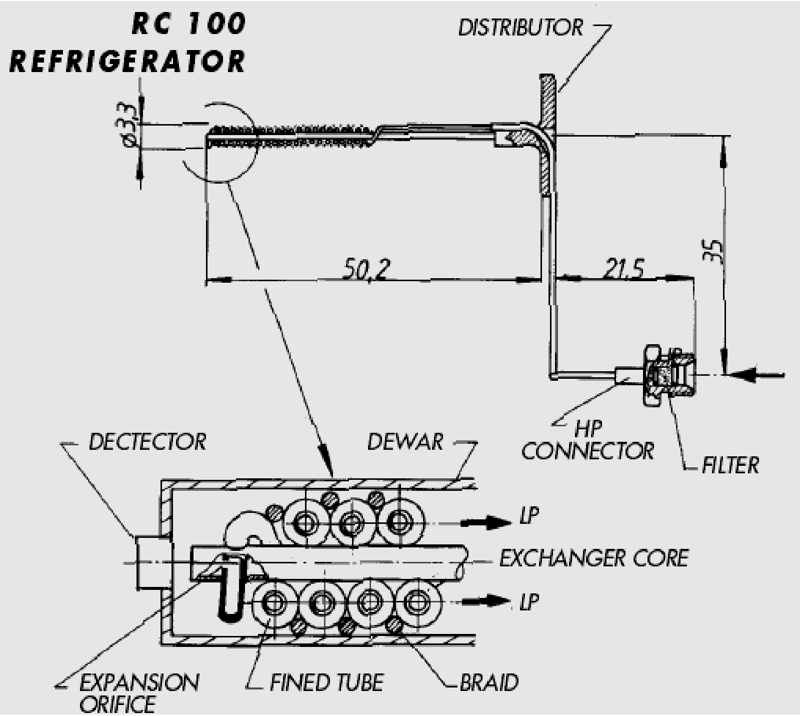


Refrigeration cycles/principles

	without heat recovery	with recuperator	with regenerator
throttling	cascade sorption	Joule – Thomson Linde – Hampson dilution	
expansion	Ranque Hilsch	Claude Brayton Collins	Stirling Solvay Vuilleumier Gifford – McMahon pulse tube
other principles	thermoelectric (cascade)	magnetic	

J-T cooler

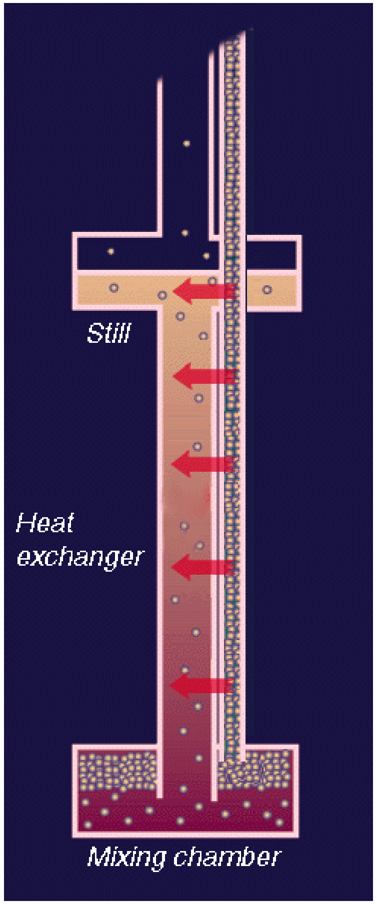




By courtesy of Air Liquide

Dilution refrigerator

- principle
  - temperature reduction by dilution of He3 in a He4 bath
  - combined with a heat exchanger
- range
  - e.g. 15mK - 2K



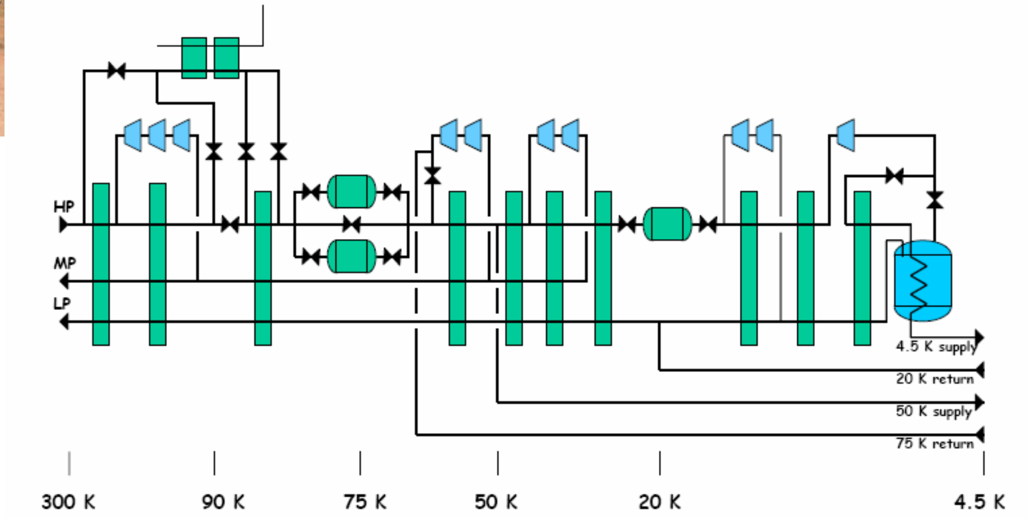
By courtesy of Lot Oriel Group Europe

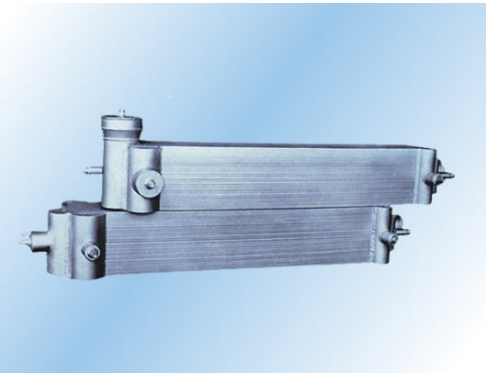
Refrigeration cycles/principles

	without heat recovery	with recuperator	with regenerator
throttling	cascade sorption	Joule – Thomson Linde – Hampson dilution	
expansion	Ranque Hilsch	Claude Brayton Collins	Stirling Solvay Vuilleumier Gifford – McMahon pulse tube
other principles	thermoelectric (cascade)	magnetic	

Modified Claude cycle refrigerator

Linde refrigerator as used for the LHC

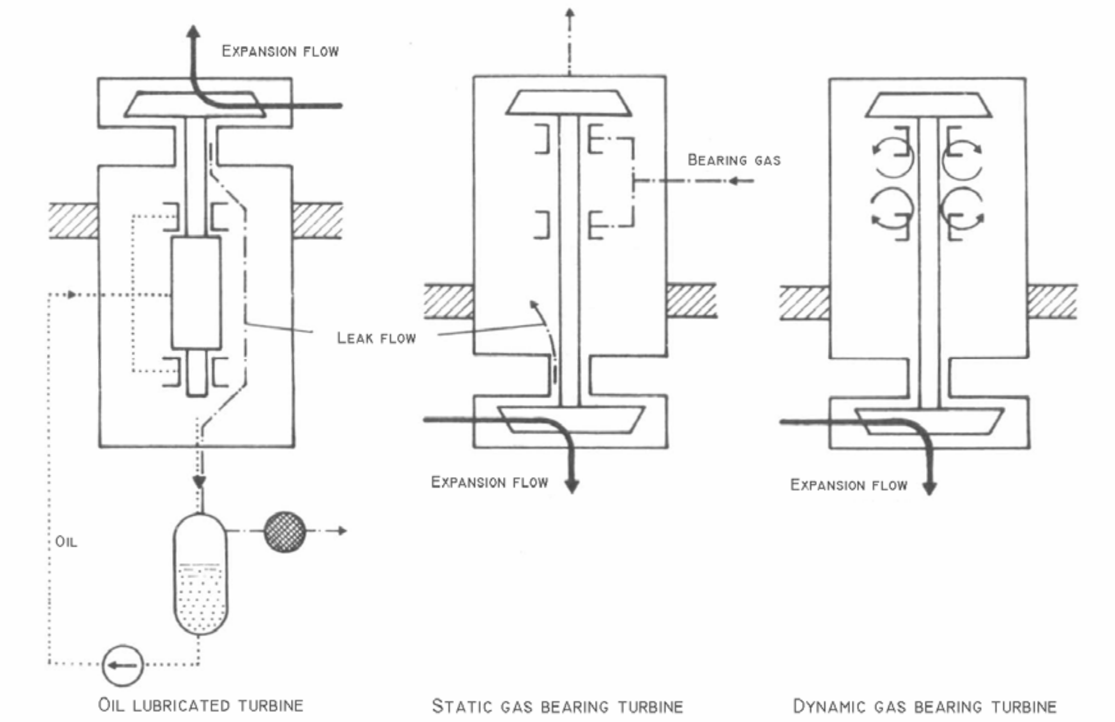




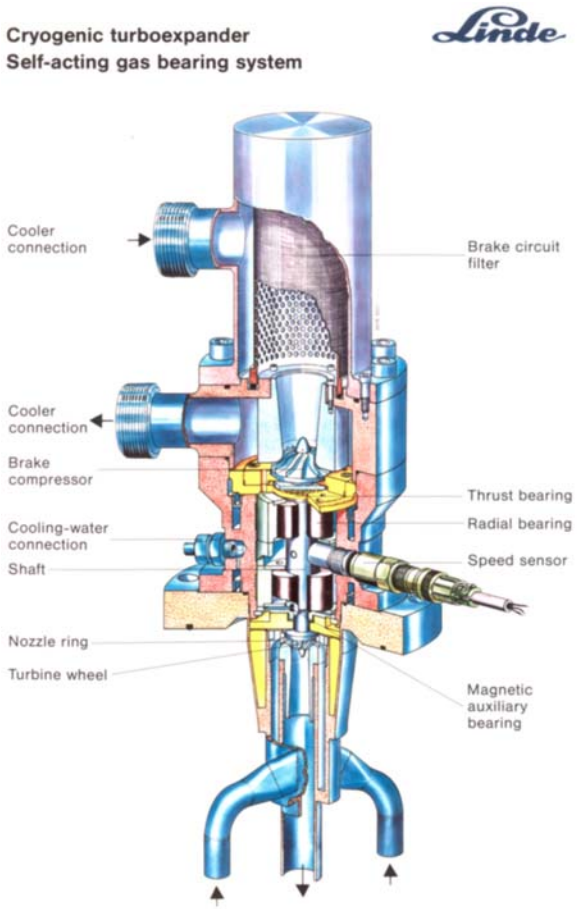
Aluminium fin plate heat exchanger

18kW at 4.4K

Expansion machines



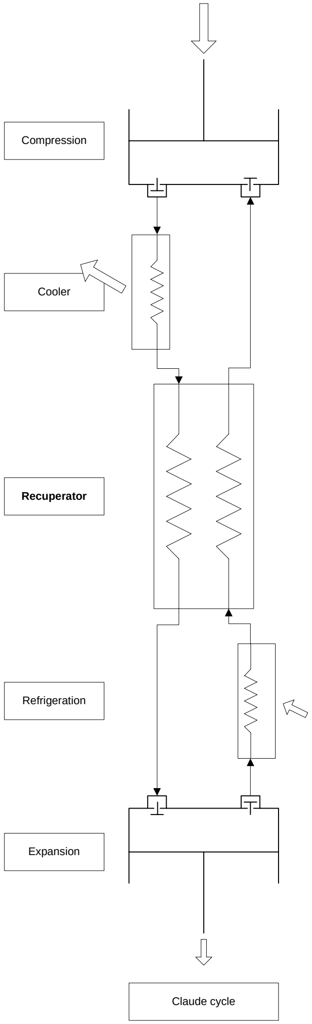
Expansion machines

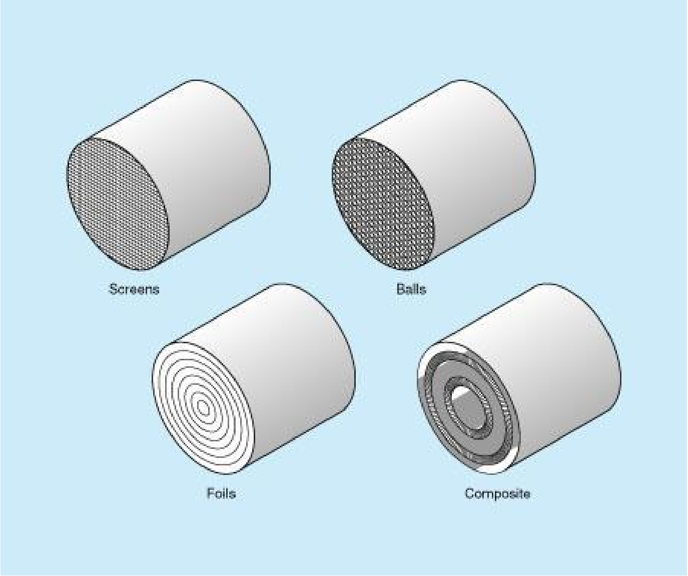


Refrigeration cycles/principles

	without heat recovery	with recuperator	with regenerator
throttling	cascade sorption	Joule – Thomson Linde – Hampson dilution	
expansion	Ranque Hilsch	Claude Brayton Collins	Stirling Solvay Vuilleumier Gifford – McMahon pulse tube
other principles	thermoelectric (cascade)	magnetic	

Principle of regenerator cycles





various types of regenerators

Stirling cycle refrigerator

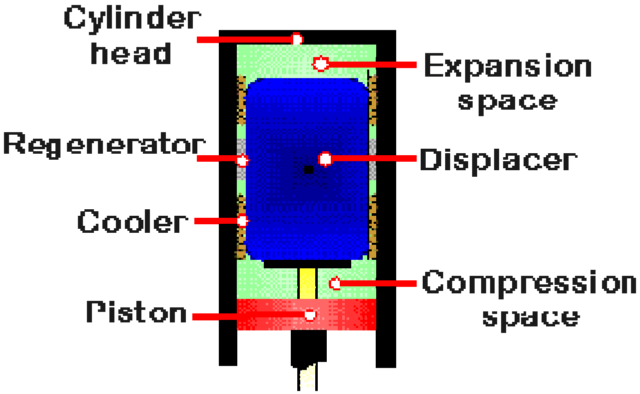
Cycle

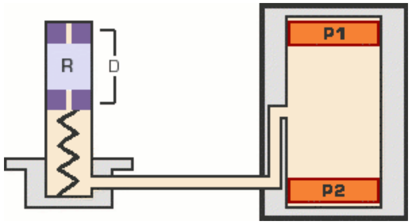
1 - Compression
in warm end

2 - Displacement
warm ➔ cold

3 - Expansion
in cold end

4 - Displacement
cold ➔ warm

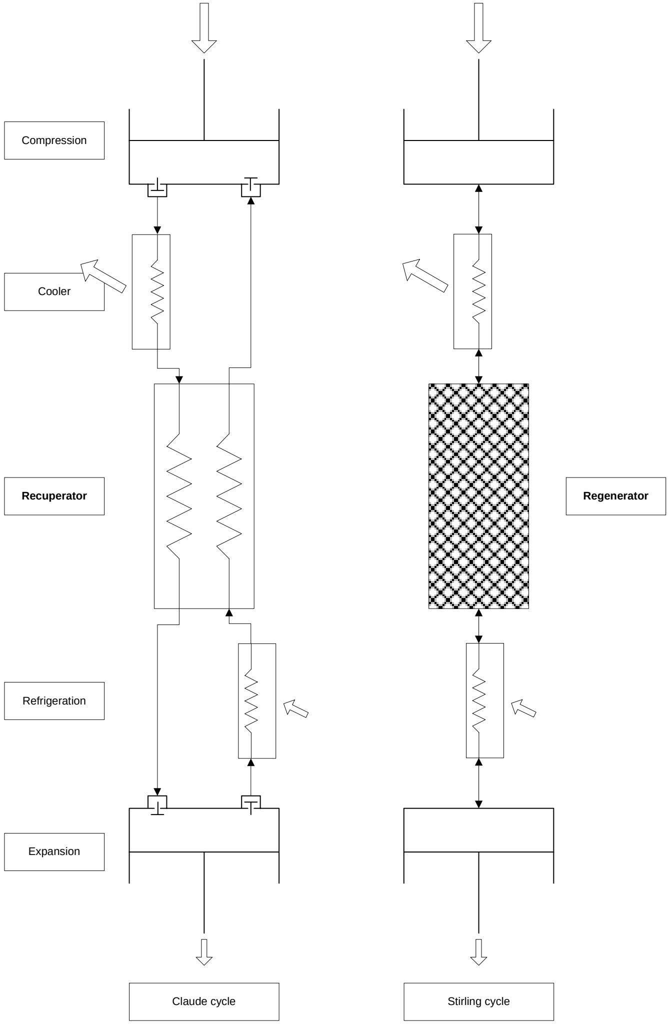




By courtesy of Thales Cryogenics

By courtesy of Stirling Cryogenics and Refrigeration BV

Principle of regenerator cycles



Compression

Cooler

Recuperator

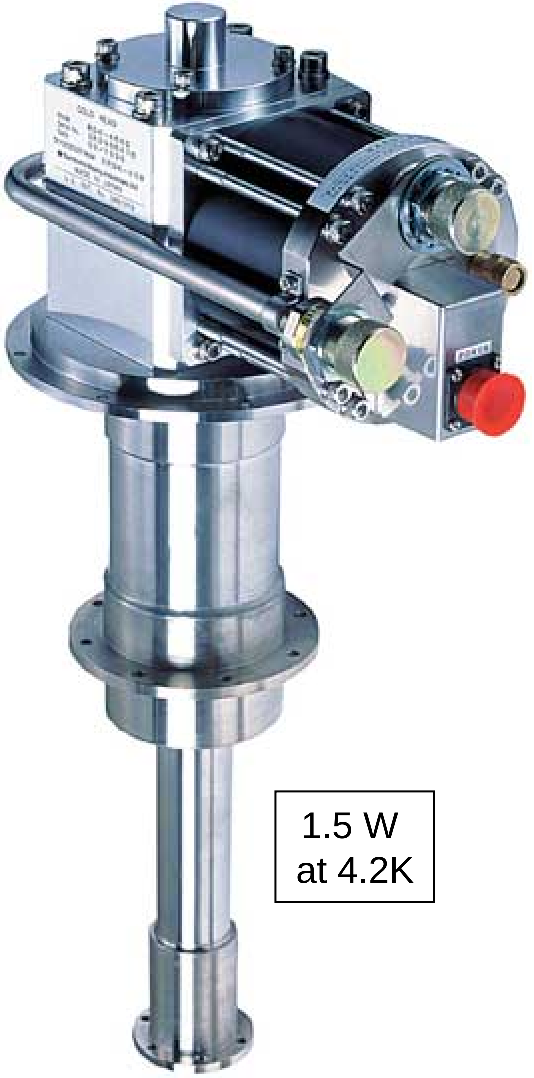
Regenerator

Refrigeration

Expansion

Claude cycle

Stirling cycle



1.5 W
at 4.2K

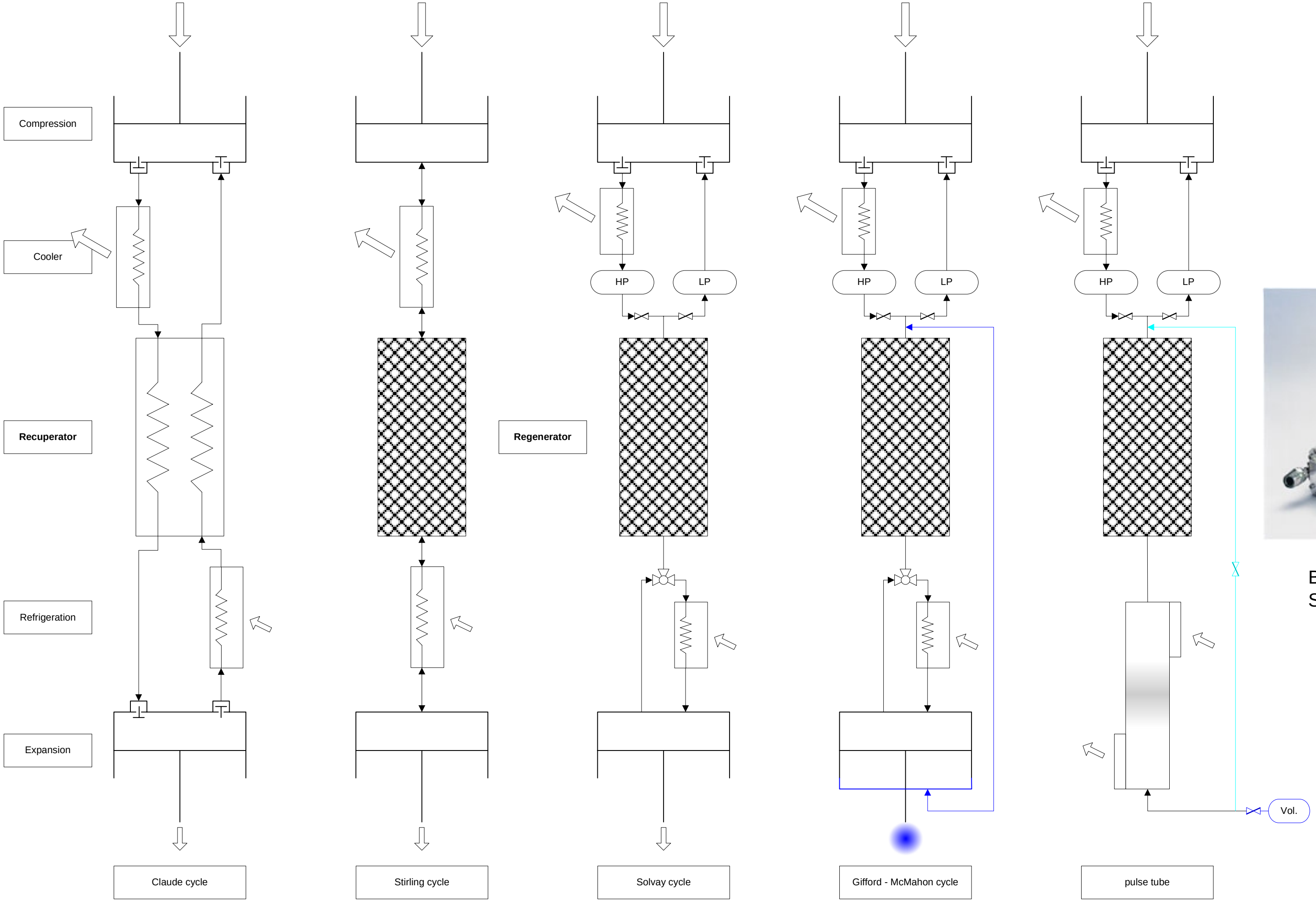
By courtesy of Sumitomo Heavy Industries

Gifford - McMahon cycle refrigerator

1.5 W at 4.2K

By courtesy of Sumitomo Heavy Industries

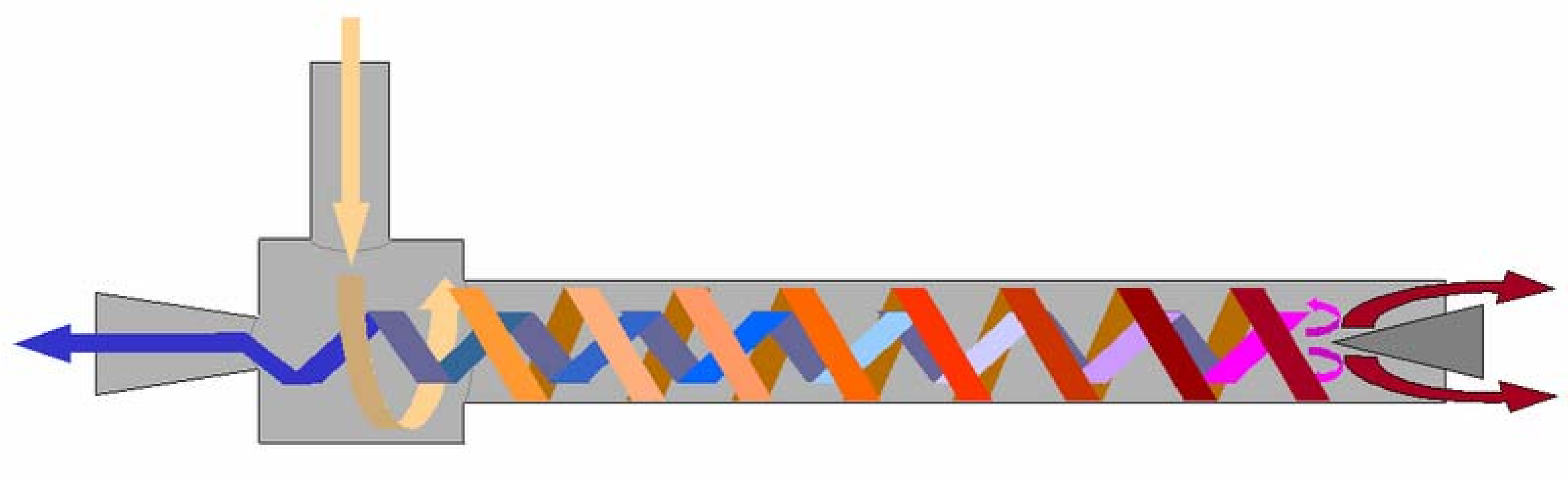
Principle of regenerator cycles



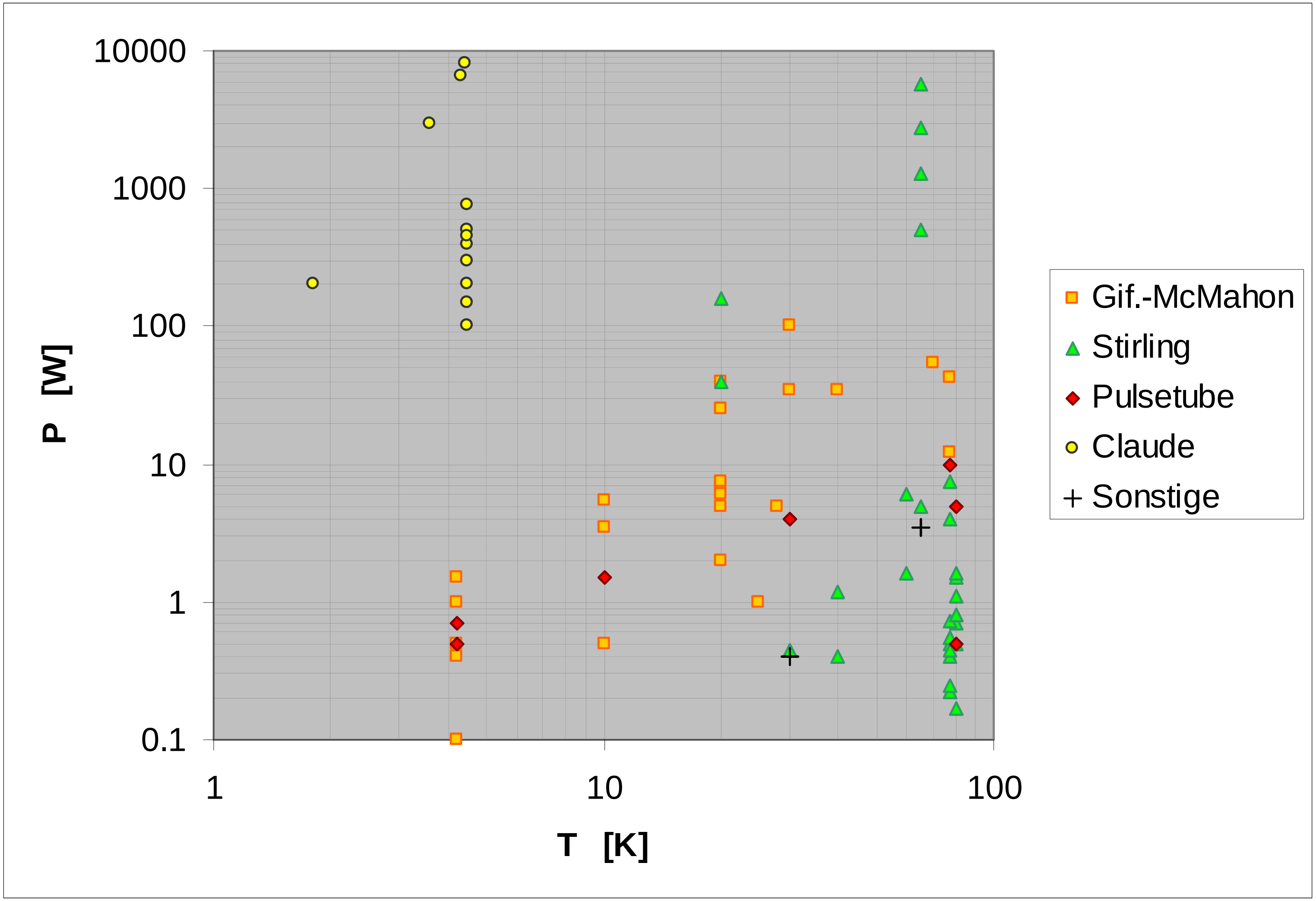
By courtesy of
Sumitomo Heavy Industries

Ranque Hilsch

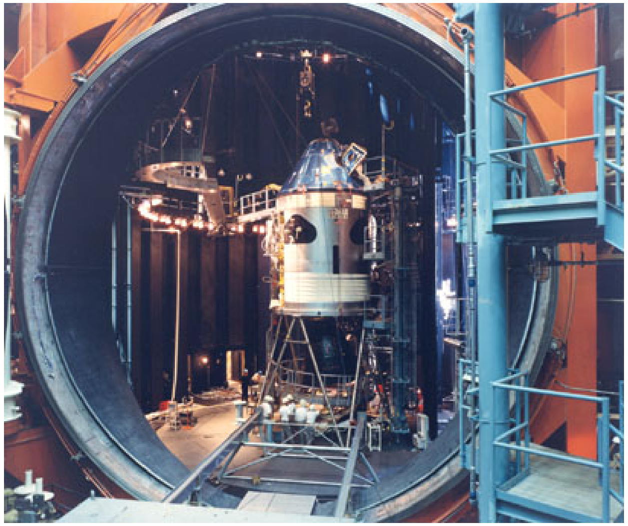
- Vortex tube
  - a vortex is created by tangential injection
  - accelleration of molecules from external to internal vortex
  - friction between vortices ➔ faster molecules of internal vortex work on slower molecules of external vortex



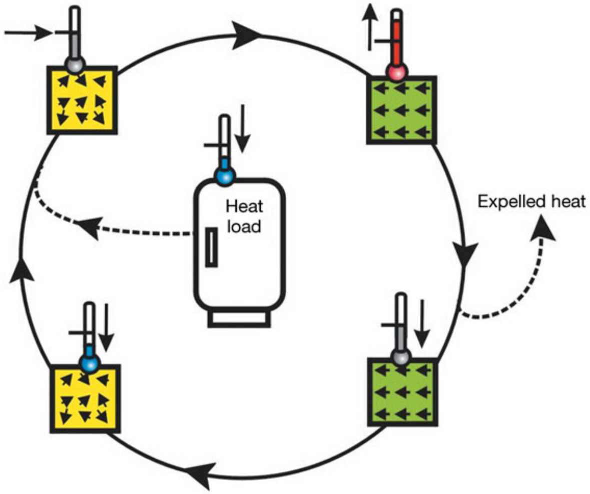
Commercial refrigerators and cryocoolers



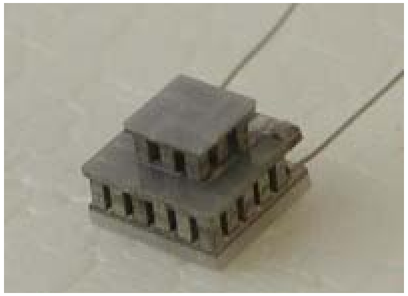
Other refrigeration principles



radiation cooling
space simulation chamber



magnetic refrigeration



thermoelectric cooling - Peltier cooler

Bath cryostat

Day 2

Introduction to Cryogenic Engineering

MONDAY   From History to Modern Refrigeration Cy

TUESDAY   Standard Components, Cryogenic Des

WEDNESDAY   Heat Transfer and Insulation   (

THURSDAY   Safety, Information Resources   (G. Perinić)

FRIDAY   Applications of Cryogenic Engineering   (T. Niinikoski)

Refrigerants

Standard Cryostats

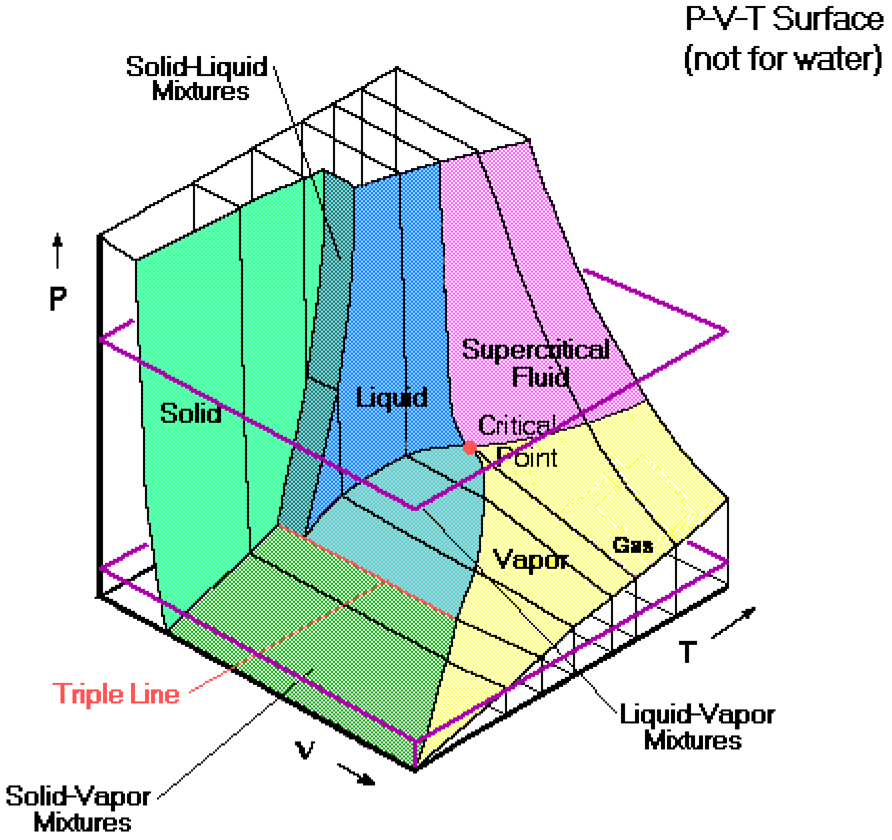
Material properties

Specifying a refrigeration task

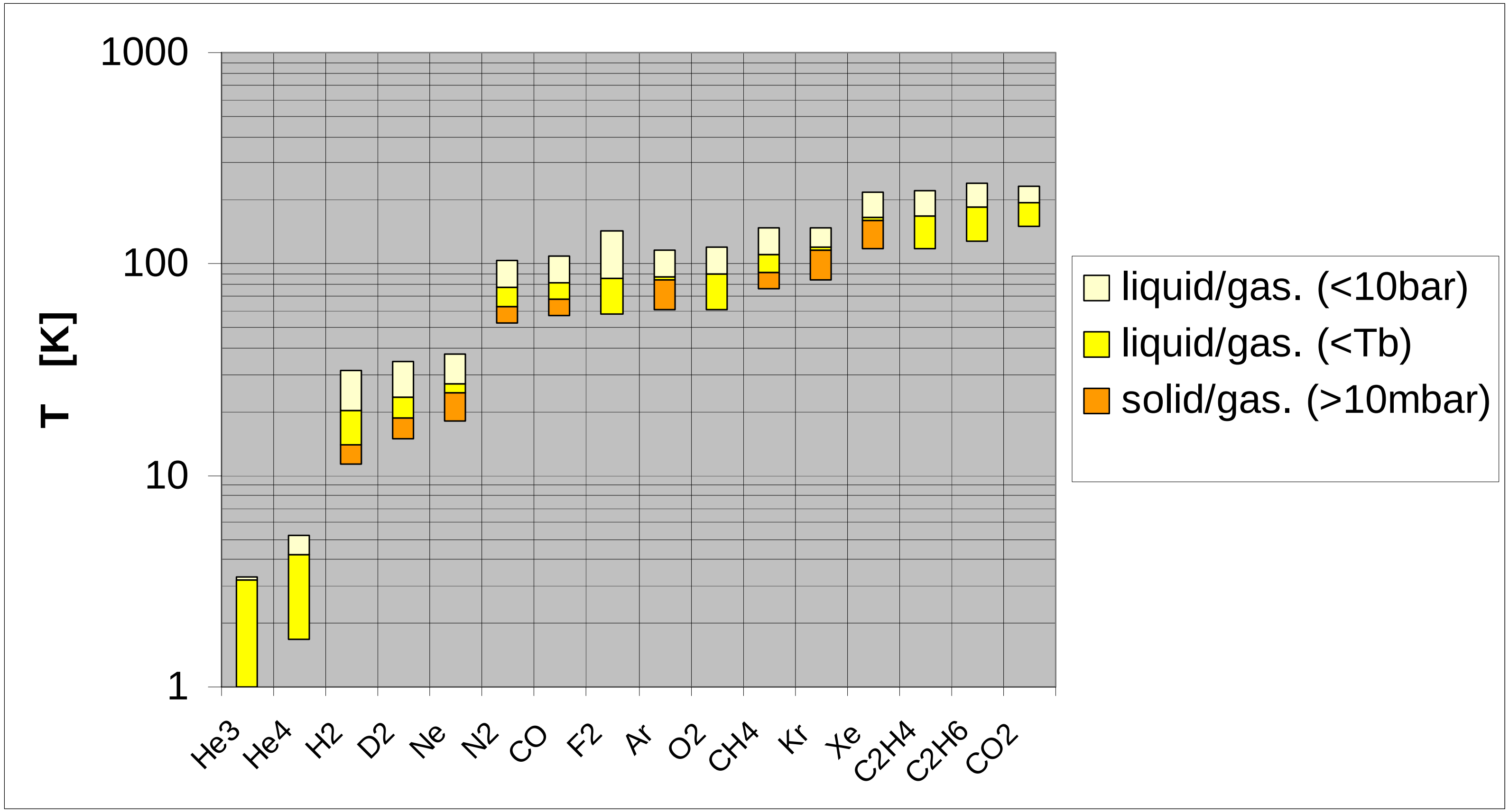
Manufacturing techniques and selected hardware components

Refrigerants

Refrigerants - states



Refrigerants - ranges

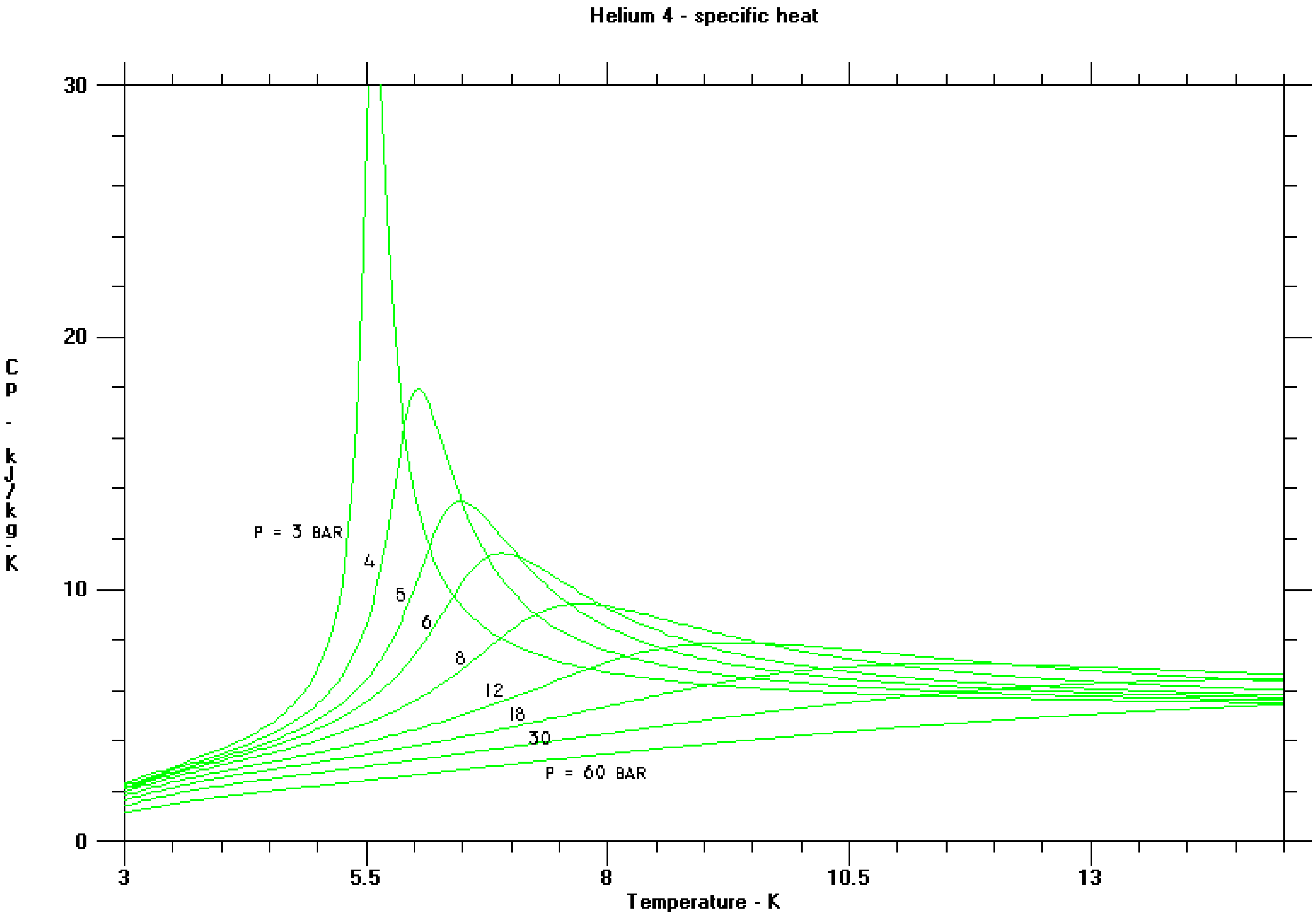


Refrigerants - data

Refrigerant	He^3 Helium	He^4 Helium	H_2 Hydrogen	D_2 Deuterium	Ne Neon	N_2 Nitrogen	CO Carbon Monoxide	F_2 Fluorine
Temperatures [K]		liq						liq
2-phase equilibrium at 10 mbar	0.97	1.67	11.4	15	18.1	53	57	58
triple point			13.9	18.7	24.559	63.148	68.09	53.6
boiling point at 1.01325bar	3.19	4.22	20.3	23.6	27.097	77.313	81.624	85.24
2-phase equilibrium at 10 bar			31.36	34.7	37.531	103.641	108.959	
critical point	3.33	5.2	33.19	38.3	44.49	126.19	132.8	144.41

Refrigerant	Ar Argon	O_2 Oxygen	CH_4 Methane	Kr Krypton	Xe Xenon	C_2H_4 Ethylene	C_2H_6 Ethane	CO_2 Carbon
Temperatures [K]		liq				liq	liq	
2-phase equilibrium at 10 mbar	60.7	61.3	76.1	84.3	117.3	117.6	127.8	151.2
triple point	83.82	54.361	90.67	115.94	161.36			
boiling point at 1.01325bar	87.281	90.191	111.685	119.765	165.038	169.242	184.548	194.65
2-phase equilibrium at 10 bar	116.55	119.623	149.198	149.198	218.612	221.25	241.9	233.038
critical point	150.66	154.58	190.56	109.43	289.73	282.35	305.33	

Specific heat



Particularities of Hydrogen

- exists in two molecular spin states:

  orthohydrogen and parahydrogen

- equilibrium depends on temperature

  300K 75% ortho 25% para
  20.4K 0.2% ortho 99.8% para

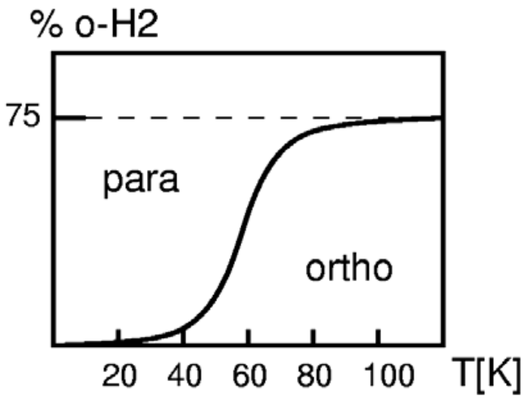
- conversion is slow (days) and exotherm

  $Q_{conv} = -703\ kJ/kg_{ortho}$

  or $527\ kJ/kg_{n\text{-}H2}$ > evaporation enthalpy of 447kJ/kg

- specific heat and thermal conductivity of ortho- and parahydrogen are significantly different

- forms slush



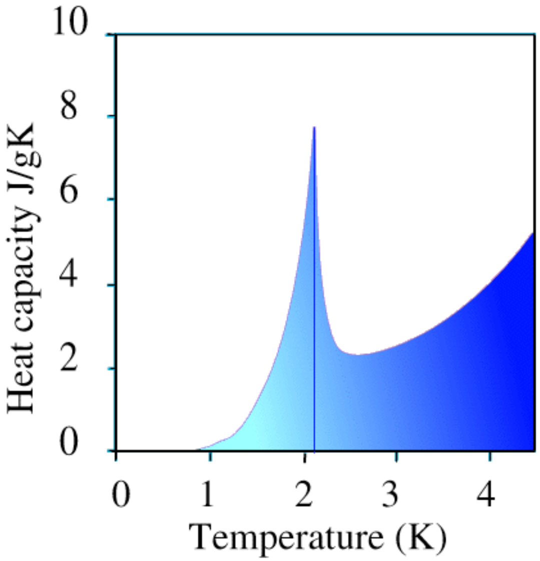
Particularities of Helium

- transition to a superfluid phase below the λ-point (2.17K)

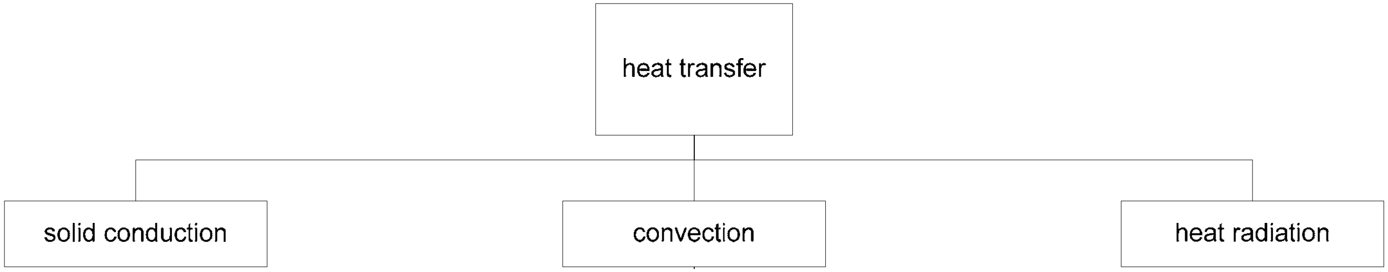
  effects:

  – viscosity decreases by several orders of magnitude
  – creeps up the wall
  – thermomechanic (fountain) effect
  – heat conductivity increases by several orders of magnitude
  – second sound

  due to the two-fluid character



heat transfer principle


heat transfer

solid conduction

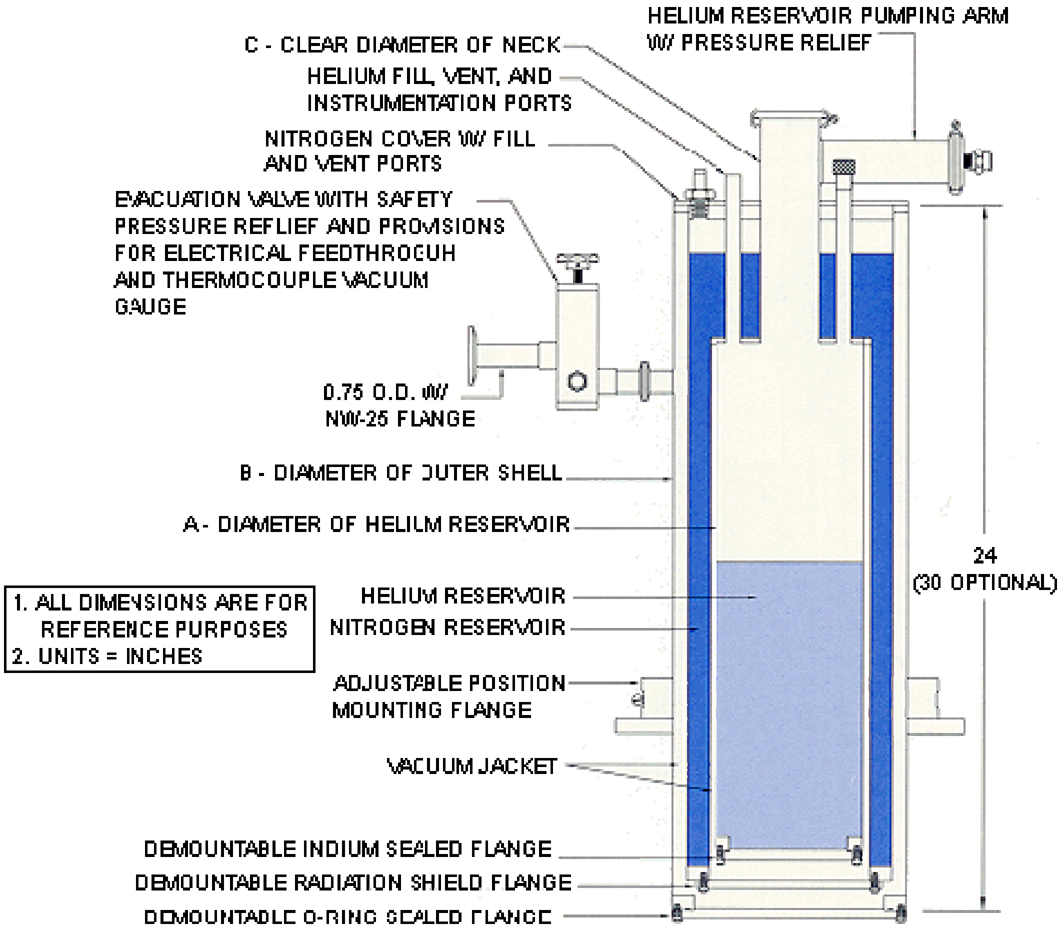
convection

heat radiation

Standard Cryostats

Cryostats - bath cryostats 1

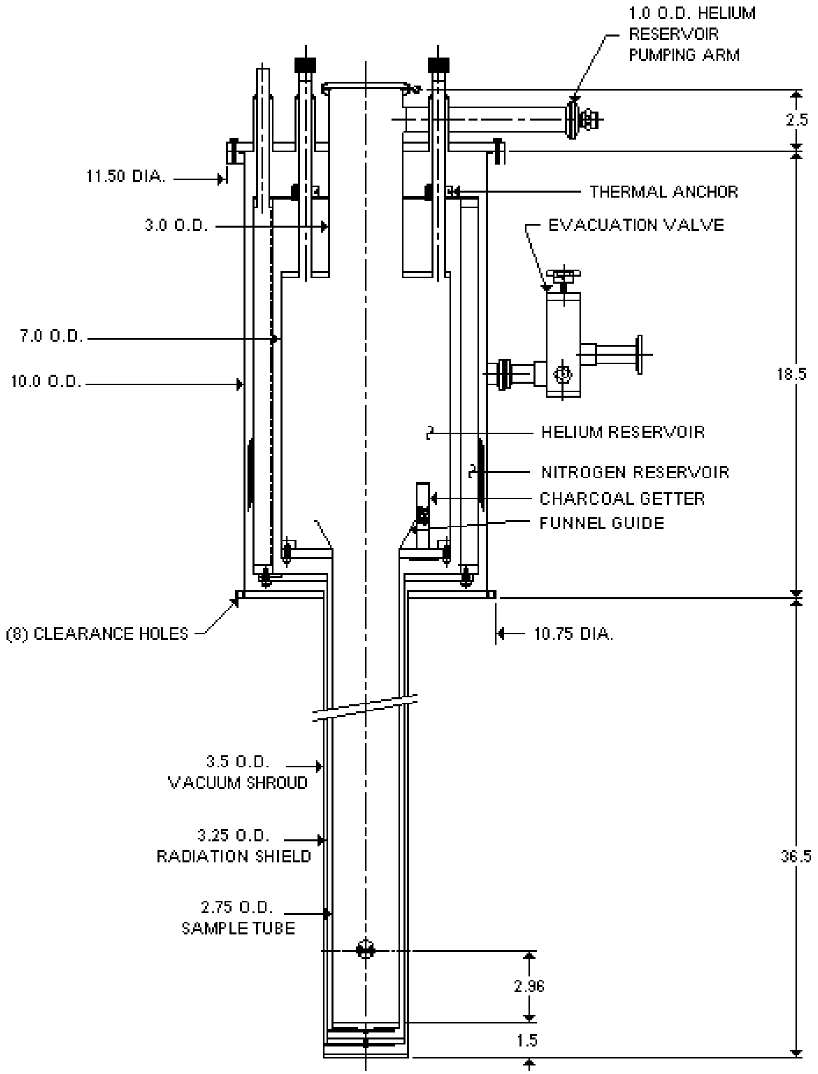
- principle
  - direct cooling of probe in cryogenic liquid bath
  - operation range: 1 - 4,2 K (63 - 78 K with LN2)
- advantages
  - no vibrations
  - stable temperatures
  - up-time (LHe-bath) several days (consumption 0,5-1% per hour)
- disadvantages
  - long cool-down time (in the order of 1 hour)



Courtesy of Janis Research Company, Inc.

Cryostats - bath cryostats 2

- tails
  - cryostat add-on for different applications: e.g. NMR-magnets or optical systems



Courtesy of Janis Research Company, Inc.

Cryostats - bath cryostats 3

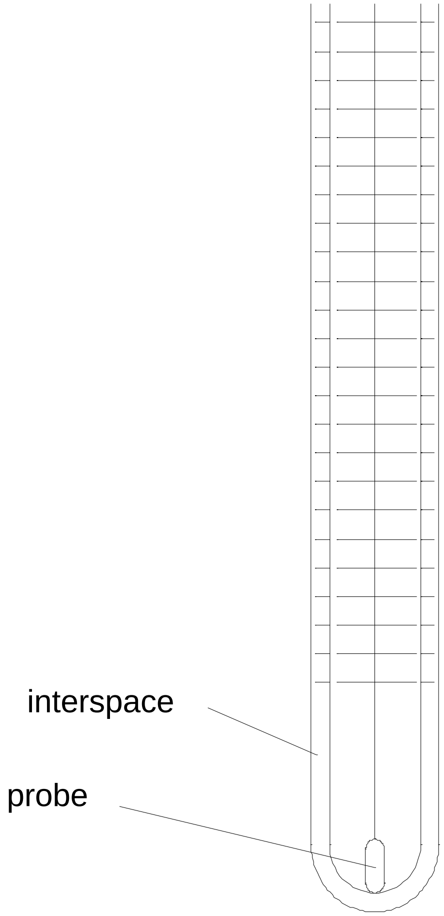
- anticryostat

  a) evacuated interspace

  probes can be exchanged while cryostat remains cold

  b) interspace flooded with contact gas

  operation - the temperature control is achieved with a heater in the probe support



Cryostats - evaporation cryostats 1

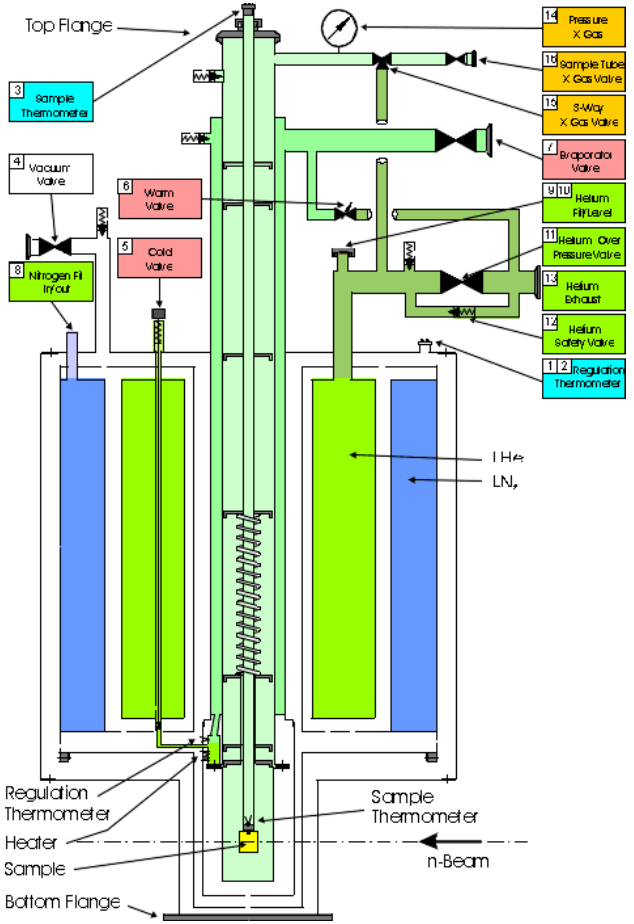
- principle
  - A small flow of cryogen is evaporated and cools the probe
  - operation range 1.5-300K
  - indirect cooling of probe i.e. probe in contact gas shown)

    or

    probe in vacuum

    or

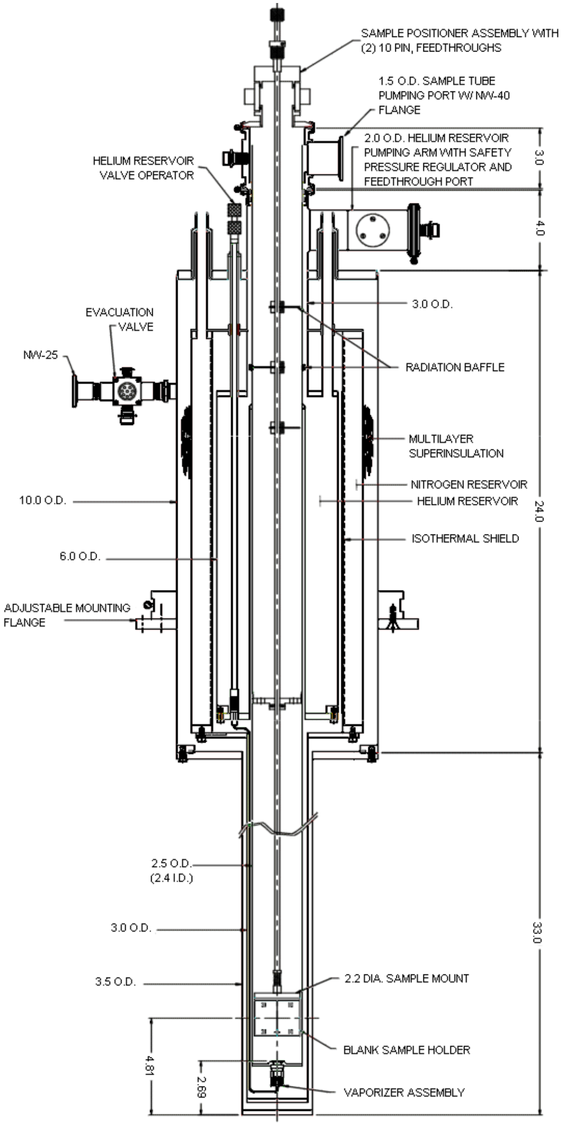
    …



Courtesy of AS Scientific Products Ltd.

Cryostats - evaporation cryostats 2

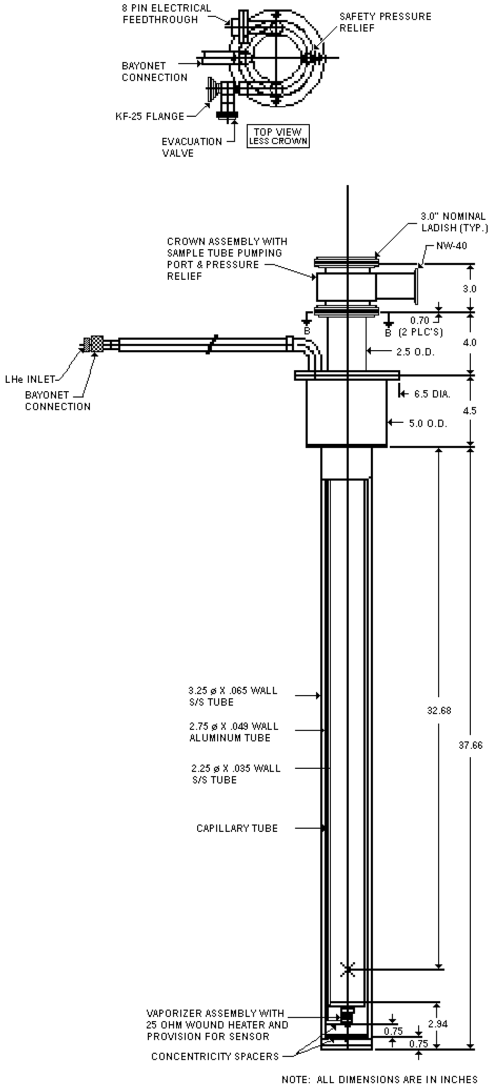
- principle …
  - direct cooling
    i.e.
    probe submerged in the evaporated helium/nitrogen



Courtesy of Janis Research Company, Inc.

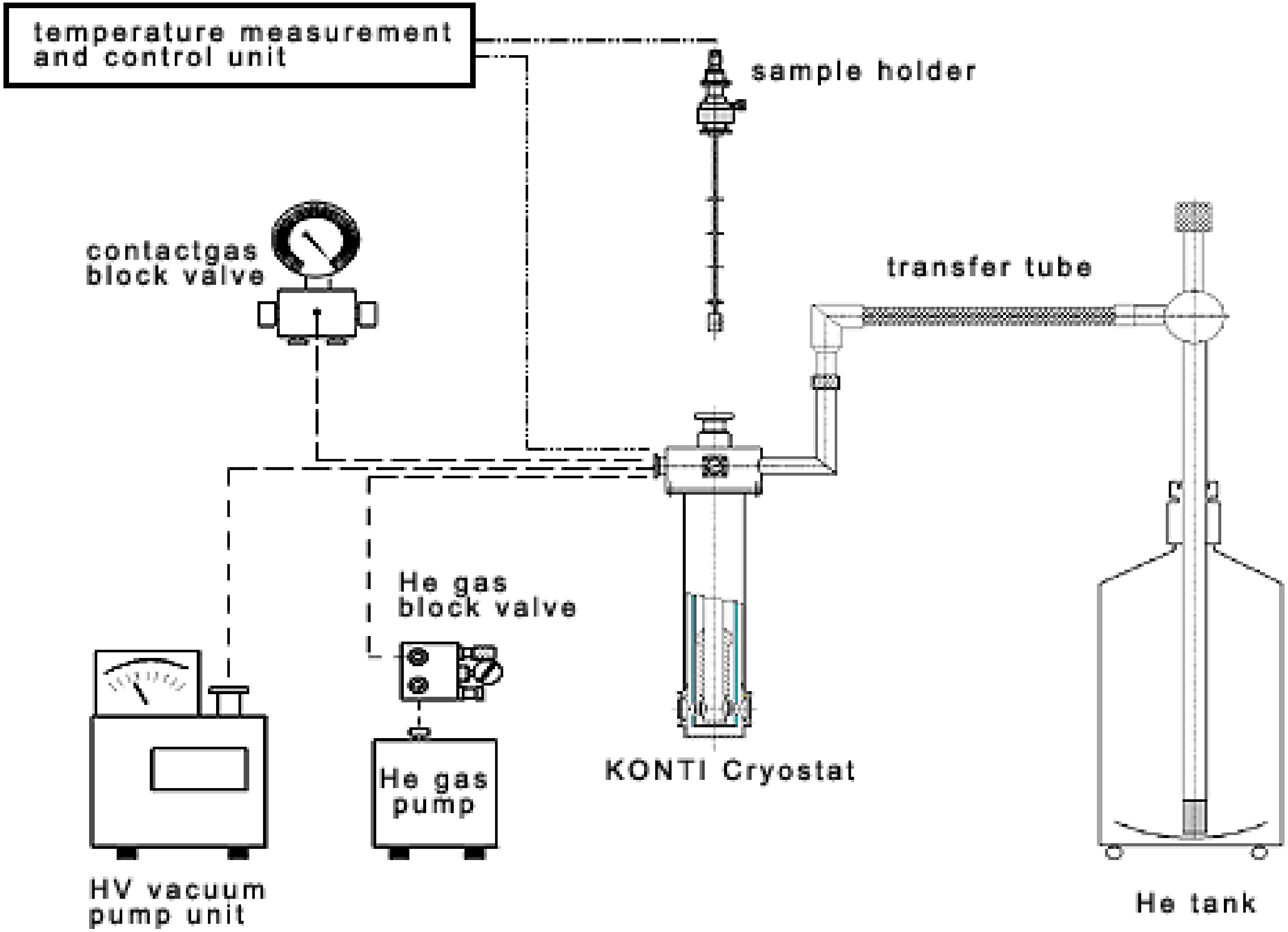
Cryostats - evaporation cryostats 3

- principle …
  - without liquid cryogen baths
- advantages
  - compact
  - low cost
  - flexible orientation
  - fast cool-down
    (in the order of 10 minutes)
- disadvantages
  - high consumption (e.g. 0,5l LHe/h)
  - temperatur e control close to boiling point difficult



Courtesy of Janis Research Company, Inc.

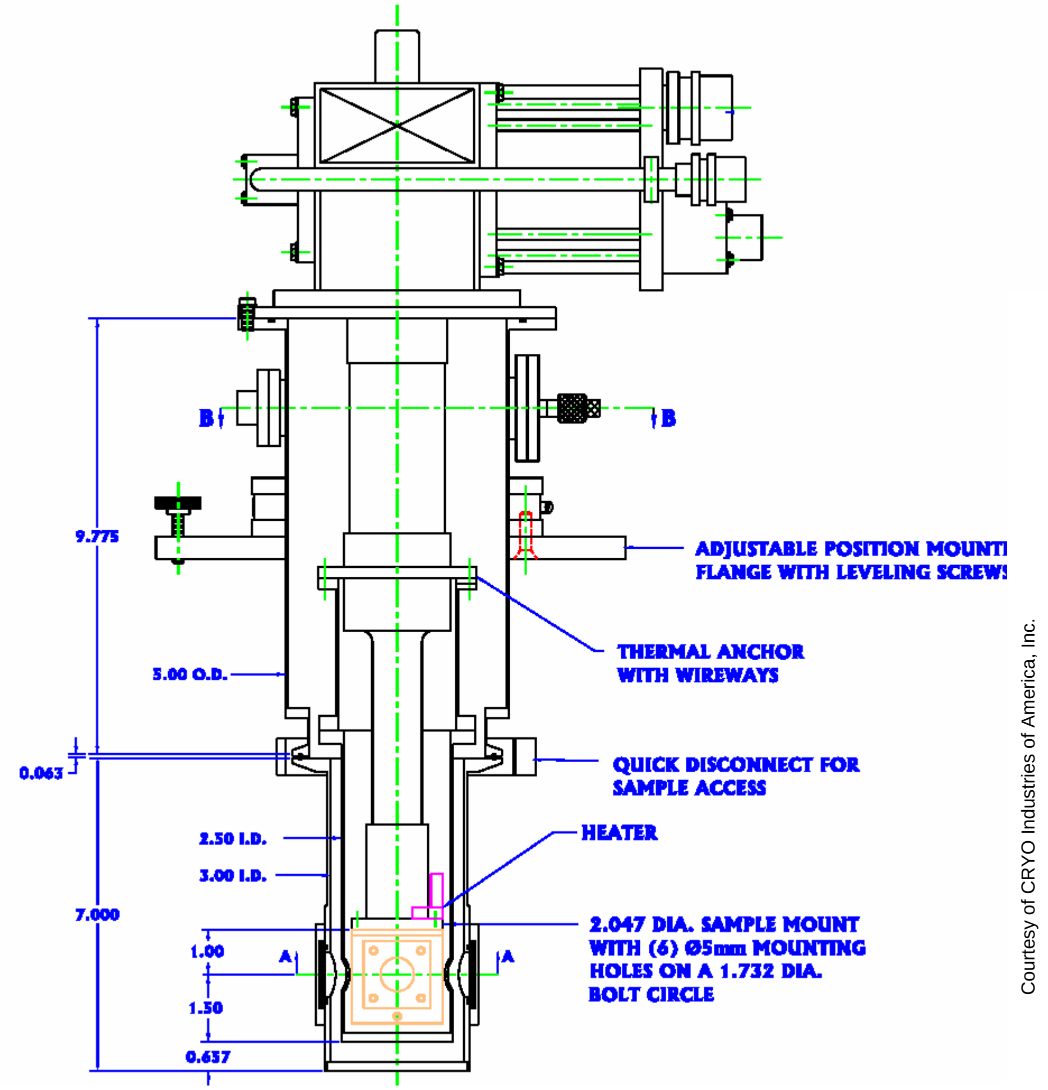
Cryostats - overall system



Courtesy of CryoVac GmbH & Co KG

Cryostats - refrigerator cryostats

- principles
  - operation range 4,5 -300K
- advantages
  - compact
  - no cryogenic liquids
  - low operation costs
  - high autonomy
  - flexible orientation
- disadvantages
  - high investment cost
  - some can create vibrations



Courtesy of CRYO Industries of America, Inc.

Specification

What to specify?

- Refrigeration task and operation conditions

  refrigeration object dimensions, operation temperature and cooling principle, cool-down and warm-up conditions

- Minimum requirements

  capacities, functions, materials, redundancies, measurement points and precision, automation degree

- Installation and environmental conditions

  infrastructure (power supply, cooling, comp. air), accessibility, crane, environ-ment (vibrations, magnetic field, radiation)
  emissions (noise, vibrations, gas emission)

- Interfaces

  infrastructure (gas recovery, cooling water, instrument air, energy), controls

- Quality requirements

- Documentation

  drawings, design calculations, diagrammes, manuals, certificates, maintenance schedule, safety analysis
  - paper form or computer readable

Specification - typical quality requirements

- Materials
  - e.g. special material specifications
  - material certificates
- Joining techniques
  - requirements for weldments
  - requirements for joints
- Surface properties
  - free of ferritic impurities
  - dirt, grease, weld XXX

- Leak rates

  e.g.

  $< 10^{-8}$ mbarls^{-1} individual welds

  $< 10^{-7} - 10^{-6}$ mbarls^{-1} overall leakrate He->Vac

  $< 10^{-6} - 10^{-5}$ mbarls^{-1} overall leakrate air->Vac

  $< 10^{-4}$ mbarls^{-1} valve seats

  $< 10^{-4}$ mbarls^{-1} flanges with non-metallic seals

- Thermal losses

  z.B.

  0,3-2,3% /24h liq. helium transp. vessel

  0,1-0,5% /24h liquid nitrogen tank

  0,5-2 W/m liquid nitrogen transfer line

  5-500 mW/m shielded helium transfer line

Materials

Materials - selection criteria

- mechanical strength
  - $\sigma_{0.2}$, σ_B, E, δ, α
- working properties
  - forming, extrusion, welding
- further properties
  - magnetic properties., electric properties
- thermal properties
  - heat conductivity, heat capacity, thermal contraction
- surface properties
  - corr. resist., emissivity, spec. surf. area, outgassing
- oeconomic properties
  - price, availability

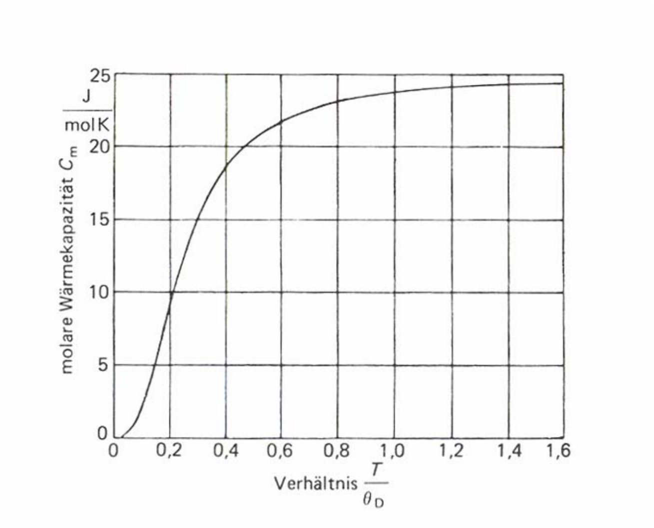
Materials - selection criteria

		1.5662 9% Nickel	1.4306/07 304L	1.4404/35 316L	Al 5083 Al Mg4,5Mn	Cu-OF	3.7165 Ti Al6 V4	GF reinforced epoxy	PTFE
price/kg	CHF	3.5	4.5	4.7	7.3	9	70	35	26.5
price/kg max	CHF		17.3	21.7	6.6	9.5	81	180	26.5
Rp0,2 at RT	MPa	515	175	225	125	200	820	250	18.5
Rm at RT	MPa	690	450	600	275	240	890	250	18.5
elongation	%	20	40	35	17	18	6		530
density	kg/m3	7900	7900	7900	2657	8960	4540	1948	2200
thermal conductivity at 4K	W/(mK)	0.626	0.227	0.2	0.5	320	0.4	0.06	0.043
thermal cond. integral 4K-300K	W/m	5556.3	3031	3031	23460	162000	1416	167.2	70
Rp0,2/price	MPa/CHF	147.14	38.89	47.87	17.12	22.22	11.71	7.14	0.70
th.cond.integral/Rp0,2	W/(MPam)	10.79	17.32	13.47	187.68	810.00	1.73	0.67	3.78
Rp0,2/density	GPam3/kg	65.19	22.15	28.48	47.05	22.32	180.62	128.34	8.41

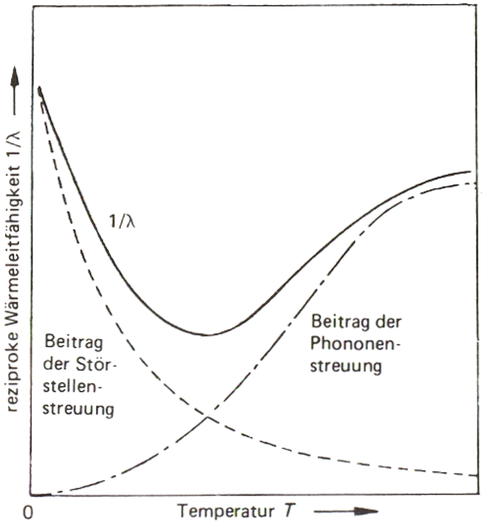
Materials - thermal properties

- heat capacity
  - Debye temperature of metals:

    Fe 453K, Al 398, Cu 343, Pb 88K



- thermal conductivity
  - energy transport by electrons



Materials - steels

austenitic stainless steel

e.g.

1.4301 (304),
1.4306/07 (304L),
1.4311 (304LN),
1.4401 (316),
1.4404/35 (316L),
1.4541 (321),
1.4550 (347)

- properties
  - universally applicable
  - good weldabilty
- reference
  - AD W10

low temperature steel

e.g.

1.3912 (FeNi36, Invar)

1.5662 (X8Ni9, 9% nickel steel)

- properties
  - high strength (1.5662)
  - low thermal contract. (1.3912)
  - cheaper than stainless steel
- remark
  - 1.5662 is not suitable for application below -196°C

Materials - non ferrous materials

Al and Aluminium alloys

e.g. AW3003 (Al-Mn1Cu),
AW1100 (Al99,0Cu),
AW6061 (Al-Mg1SiCu),
AW6063 (Al-Mg),
AW5083 (Al-Mg4,5Mn)

- properties
  - high thermal cond. (1100, 6063)
  - moderate strength (6061, 5083)
  - good vacuum properties, low emissivity
  - extrudable
  - weldable
- reference
  - AD W 6/1

Cu and Copper alloys

e.g.

SF-Cu (99.9)

- high thermal cond. (annealed)

CuZn28Sn1 (2.0470, brass)

CuNi30Mn1Fe (2.0882, Ni-bronze)

CuBe1,9 (Berylliumbronze)

- high strength and good thermal conductivity

- reference
  - AD W 6/2

Materials - polymers

non filled polymers

- thermoplastic polymers
  - PET (Mylar)
    - superinsulation, windows
  - PI (Kapton, Vespel)
    - insulation, seals
  - PTFE (Teflon)
    - seals
- duroplastic polymers
  - epoxy resins
    - electrical insulation

filled + fibre reinforced poly.

- fibre reinforced polymers
  - with glas fibres
    - thermal expansivity like metals
  - with carbon fibres
    - thermal conductivity like steel
    - thermal expansion ~0
  - Kevlar fibres
    - low weight
- powder filled polymers
  - with powders to adjust the themal expansivity
  - with powders to increase the thermal conductivity

- reference
  - G. Hartwig: „Polymer Properties at Room and Cryogenic Temperatures“, 1994, Plenum Press

Materials - others

glass

e.g.

- borosilicate glass
  - cryostats
- quarz glass
  - windows

ceramics

e.g.

- Aluminiumoxide, Zirconiumsilicate
  - filler powders
- Siliziumdioxide
  - Perlite

Materials - mech., opt. and electrical propert.

- mechanical properties
  - Bei tiefen Temperaturen erhöhen sich bei vielen Werkstoffen die Dehngrenze und die Zugfestigkeit, die Bruchdehnung verringert sich jedoch in vielen Fällen. (Tieftemperaturversprödung)

- emissivitity
  - see lecture by G. Vandoni

- electrical properties
  - energy transport by electrons ⇒ analogous to thermal conductivity, in alloys the effect of Störstellenstreuung becomes predominant.

Techniques and Selected Hardware

Methoden und Bauelemente

- Joining technique and seals
- Valves
- Pipework and transfer lines
- Radiation shields
- Adsorbers
- Heaters
- Instrumentation
- Vacuum technique

Joining techniques - overview

- welding (TIG)
    - advantage - excellent leak tightness
    - for precision manufacturing - electron beam welding
    - material transitions with friction welded joints
    - attention - copper forms bubbles
    - provide for eventual cuts

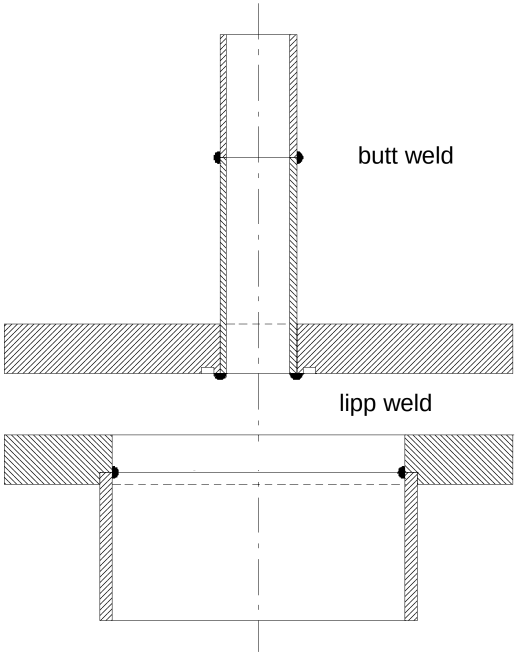
- soldering
  - hard soldering
    - thermal expansivity to be considered
    - good for copper - stainless steel joints
    - disadvantage - ageing possible
  - soft soldering
    - e.g. In97-Ag3, In52-Sn48
    - attention - standard Sn60-Pb40 soft solder becomes brittle at low temp.
    - not applicable for stainless steel
    - special soft solder exists:
      - non superconducting
      - with low thermo-electric potent.

- glueing
    - electrical feed throughs
    - electrical insulation
    - thermal contacts
      e.g. sensor attachement

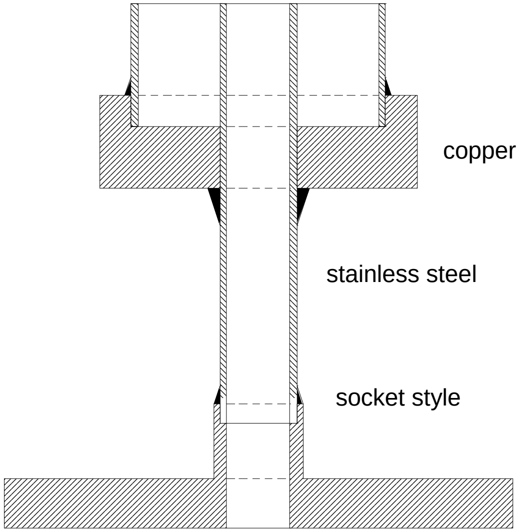
    - e.g.
      Araldite CW1304GB/HY1300GB,
      Eccobond 285 + Härter 24LV,
      Epo-Tek T7110,
      Poxycomet F,
      Scotch-Weld DP190,
      Stycast 2850FT + hardener 9,

Joining techniques - examples

welded joints

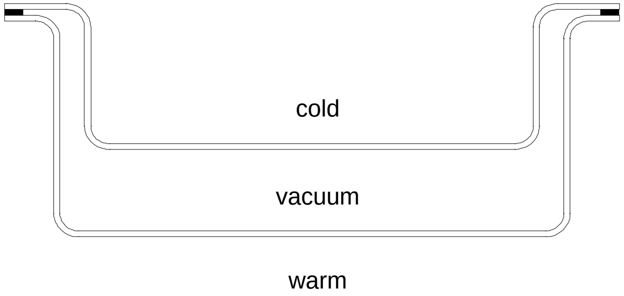


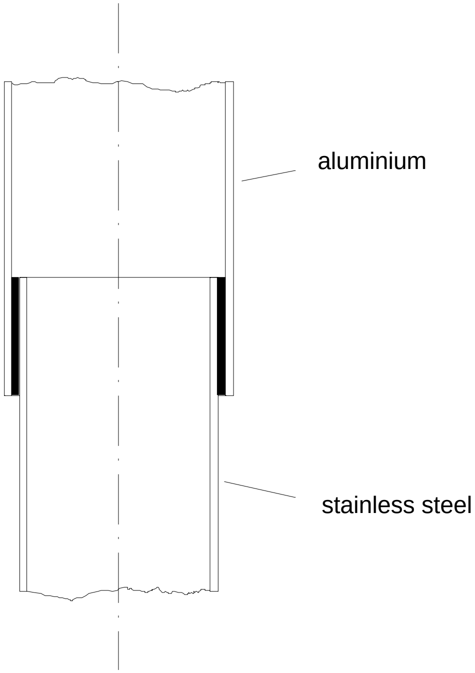
soldered joints



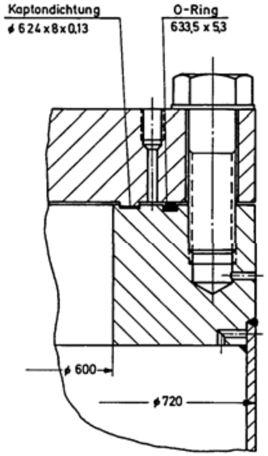
Joining techniques - errors

- thermal contraction
  - identical materials - different temperatures
    - shear load of the joint due to the contraction of the internal part
  - different materials - parallel cooling
    - different thermal expansivity can cause plastic deformation of one component
    - e.g. Aluminium - stainless steel
      Al outside - plastic deformation of Al
      Al inside - extreme load on the joint

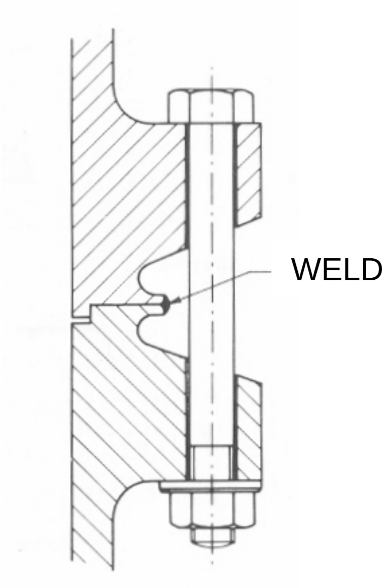




Joining techniques - flanges 1



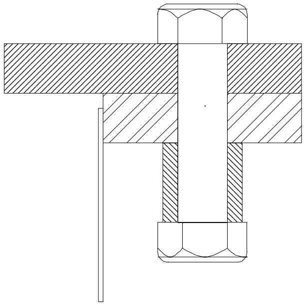
- double seal for leak testing (main seal Kapton)
- separation of sealing function and force is possible
- material combinations



In order to obtain a constant force, the thermal expansivity of flange and bolt must be taken into account.

e.g.:

Flanges of stainless steel and aluminium with stainless steel bolts can be joined with an Invar spacer.



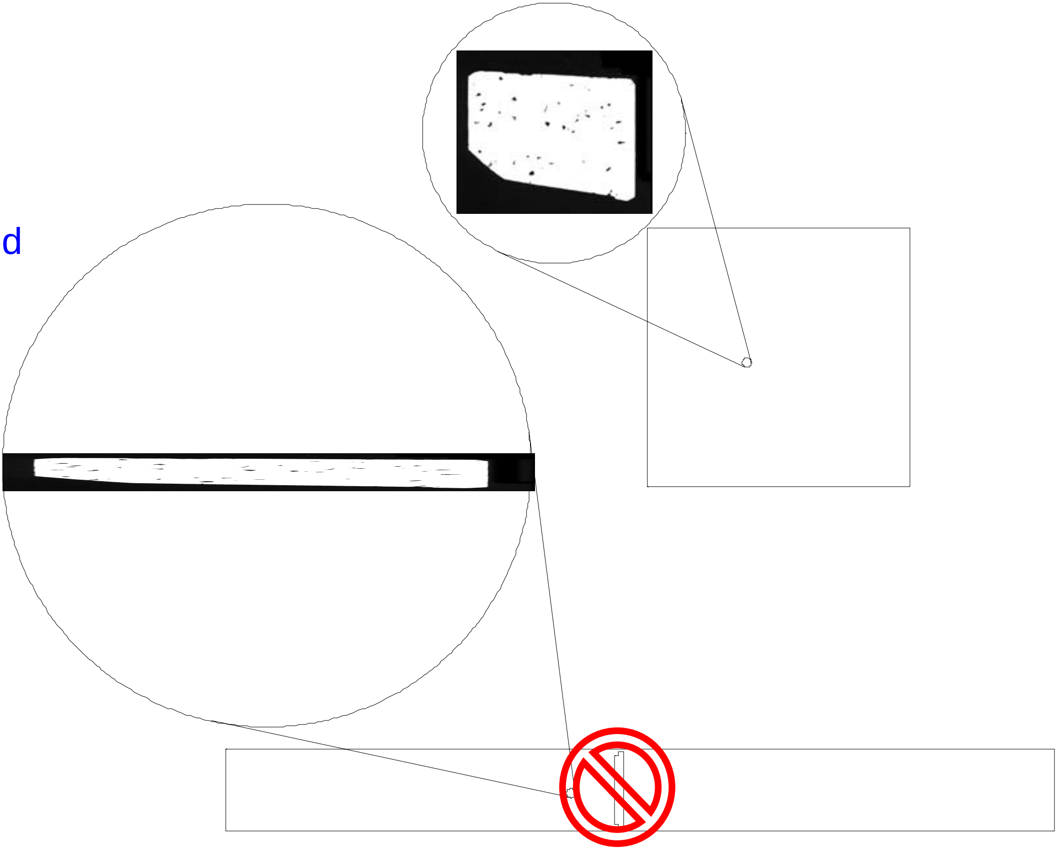
Joining techniques - flanges 2

- Flange
  - risk of leaks by manufacturing

Inclosures from the material manufacturing are lengthened by the forming process. The prevailing inclosure direction must be taken into account as they can otherways lead to leaks.

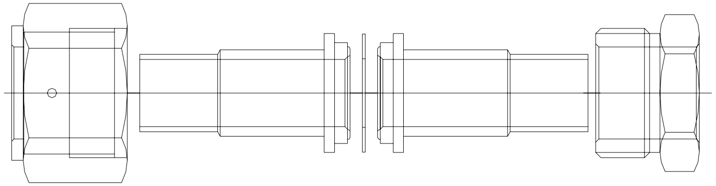
Alternatives:

forged material,
vacuum molten material



Joining techniques - seals 1

- seals
  - copper, aluminium
    → sufficient compression force along the sealing line is required to ensure yield



  - indium
    → e.g. V-groove mit seal cord

    cross section seal cord =
    1.5 x cross section of the groove

  - polyimide (Kapton)
    → compression force of 50N/mm^2

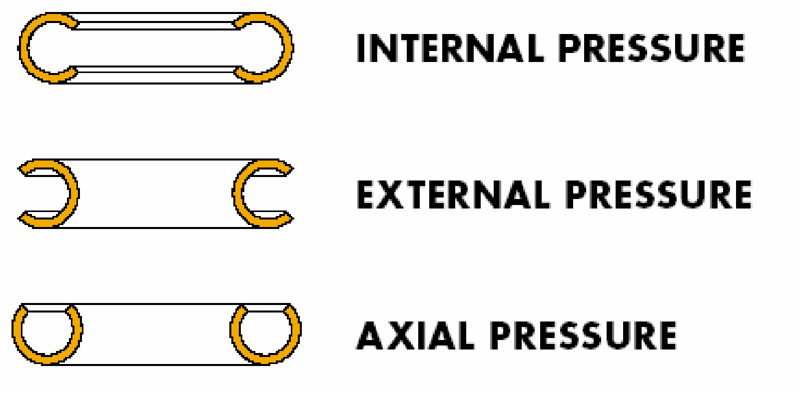
Joining techniques - seals 2

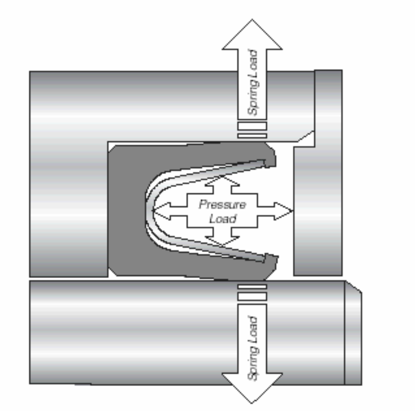
- seals
  - O-rings

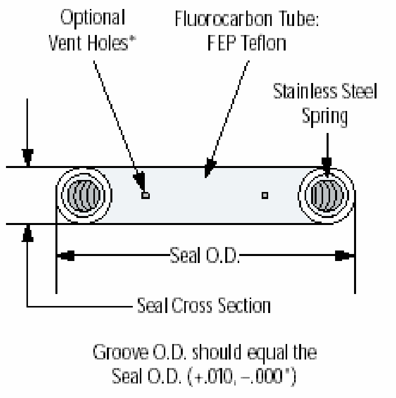
    e.g.
    out of metal - some are coated,

    out of polymers with internal spring

    NOTE: Seals containing polymers cannot be used in a vacuum environment due to their high diffusion rate.







Groove O.D. should equal the Seal O.D. (+.010, –.000")

Joining techniques - heat transfer aspect

Aim - **increase**
the heat transfer

- surface contact
  - $Q \neq f(\text{surface})$;
    $Q = f(\text{contact pressure})$!
    e.g. Cu-Cu at 300K, 500N - 10^{-2}-10^{-1} W/K
    Cu-Cu at 4K, 500N - $3*10^{-3}$-10^{-2} W/K
    Au-Au at 4,2K, 100N - 10^{-1} W/K
    Au-Au at 4,2K, 500N - $4*10^{-1}$W/K
  - Improvement by increased contact pressure, vacuum grease (Apiezon grease) or gold-plated contact surfaces
  - where possible solder or weld
    (silver solder joint 2 W/Kcm^{2})
  - glue with filled epoxy resins
- connectors
  - flexible bands and braids
  - heat pipes

Aim - **decrease**
the heat transfer

- principles
  - reduction of ratio cross section/length
    - tie rods, cables (steel, Kevlar)
  - increase of the number of heat transfer barriers
    - chains, bundle of sheet
- supports

Verbindungen - Wärmeleitung

	Cu 99.999%	Cu 99.98%	Cu OFE-99.95%	Al 99.99%	Al 99%	AW 3003	AW 5083	AW 6061	AW 6063	Saphir Polykrist.	Quarz Einkristall	1.5662 9% Ni St	Be-Cu	Ti 6Al 4V
Wärmeleitung [W/mK]														
4 K	7000	620	320	3150	54	11	0.506	9.53	34	111	582	0.626	1.879	0.403
76 K	570	600	550	430	290	140	57.1	116	241	1030	56.6	12.654	35.991	3.36
300 K	400	420	400	235	220	160	128	160	201	45	7.5	27.827		7.7
Wärmeleitungsintegral [W/m]														
4-76 K	307000	103000	68600	182000	22000	6720	2360	5700	16015	248000	32400	496.2	1478	156
76-300 K	93000	97000	93400	57000	50800	34980	21100	30600	45458	37200	4190	5060.1		1260

1.4301 304	1.4306 304L	Edelstahl 310	1.4436 316	Kevlar	CFK	GFK G-10	GFK G-10	PA (Polyamid)	PTFE	PMMA	PET amorph	PCTFE 50% krist.	PI (Polyimid)	
														Wärmeleitung [W/mK]
0.227	0.272	0.241	0.272	0.060	0.029	0.063	0.072	0.012	0.043	0.058	0.038	0.019	0.011	4 K
8.01	7.854	5.952	7.854	1.271	0.81	0.415	0.279	0.292	0.232	0.215	0.156	0.104	0.125	76 K
14.9	15.309	11.628	15.309		5.05	0.82	0.608	0.337	0.26	0.24		0.142	0.192	300 K
														Wärmeleitungsintegral [W/m]
317	318	247	318	52.5	22.5	19.2	14.7	13.0	12.8	10.1	7.8	5.73	5.6	4-76 K
2760	2713	2040	2713		814	148	97.0	75.1	57.2	52.9		27.9	37.7	76-300 K

$$\text{kleines } \Delta\text{T}: \quad \dot{Q} = \frac{A}{l}\,\lambda\,\Delta T \qquad\qquad \text{großes } \Delta\text{T}: \quad \dot{Q} = \frac{A}{l}\int_{T_1}^{T_2} \lambda(T)\,dT$$

$$\text{mit A} = \text{Querschnitt, l} = \text{Länge, } \lambda = \text{Wärmeleitung und } \int_{T_1}^{T_2} \lambda(T)\,dT = \text{Wärmeleitungsintegral}$$

Ventile - Spezifikationsbeispiel

Specification of Valves operating at Cryogenic Temperature

Cryogenic valves must be able to cover both the control and the shut-off function. Only valves of the extended-spindle type with body and stem in co-axial design are accepted. These valves must be welded to the pipework and to the top plates of the cold boxes. Rotating type valves or valves with actuators inside the cold boxes will generally not be accepted. Proposals of exceptions for specific reasons have to be submitted to CERN with full justification, for approval.

The choice of any non-metallic material must be in accordance with the CERN Safety Instruction 41.

Materials and Design

The valve body must be in austenitic stainless steel AISI 316L or the equivalent DIN type. The spindle may be of the same material as the body or may consist partly of composite material. In case of composite material, the steel-to–composite connection must have a mechanical link in addition to any glued link. This mechanical link must be realised in order not to weaken the structure of the composite part. For valve stems in composite material, the difference in thermal contraction between ambient and liquid helium temperature must be compensated by the design in order stay below two percent of the valve travel.

The spindle-and-bellows assembly must be dismountable from the top and must allow changing either the seat seal or the valve trim without the necessity to break the isolation vacuum.

In order to allow for misalignment introduced by the piping following thermal expansion and contraction, valve plugs for a maximum seat diameter of 15 mm or above, must have a flexible connection to the valve stem. For plugs with a smaller seat diameter this misalignment may be compensated be the elasticity of the valve stem. The stem itself must by its design allow for such misalignments, any guiding of it in the valve body must be protected against friction. Any flexible connection of the valve plug to the valve stem must be designed such that vibration of the plug due to the fluid flow is prevented and no damage of the plug, the seat or the seal occurs.

A flexible and clearance-free clutch device must protect the valve stem from any misalignments introduced from the actuator.

The valve bore and plug must be fabricated with a tolerance allowing for a rangeability of at least 1:100.

Sealing system

The static and the dynamic seal must be placed at the top warm end of the valve, easily available for maintenance or replacement.

The dynamic spindle seal must be welded metallic bellows. The bellows must be protected against twist load. Its lifetime design shall be made for a minimum of 10'000 full travel cycles at full design pressure. The bellows seal must be backed by an additional safety stuffing box with check-connection to the space enclosed in between.

The static seal to the ambient between body and spindle inset must be an O-ring seal. The O-ring seal groove must be designed for pressure and vacuum conditions. For sub-atmospheric operation conditions a double O-ring seal joint, covering static and dynamic sealing, with guard gas connection into the space in-between must be included.

The valve seat must be tightened with a soft seal for the shut-off function that must be placed on an area different from the regulation cone of the plug. For this soft seal only plastic materials proven for operation at liquid helium temperature are accepted.

Tests and material certificates

The chemical and physical qualities of the raw materials for pressure stress parts must be verified and documented by material test certificates.

The following tests, all recorded with a written protocol must be carried out on each ready assembled valve.

A pressure test, following the CERN Pressure Vessel Code D2, which refers to the European Directive CE93/C246.

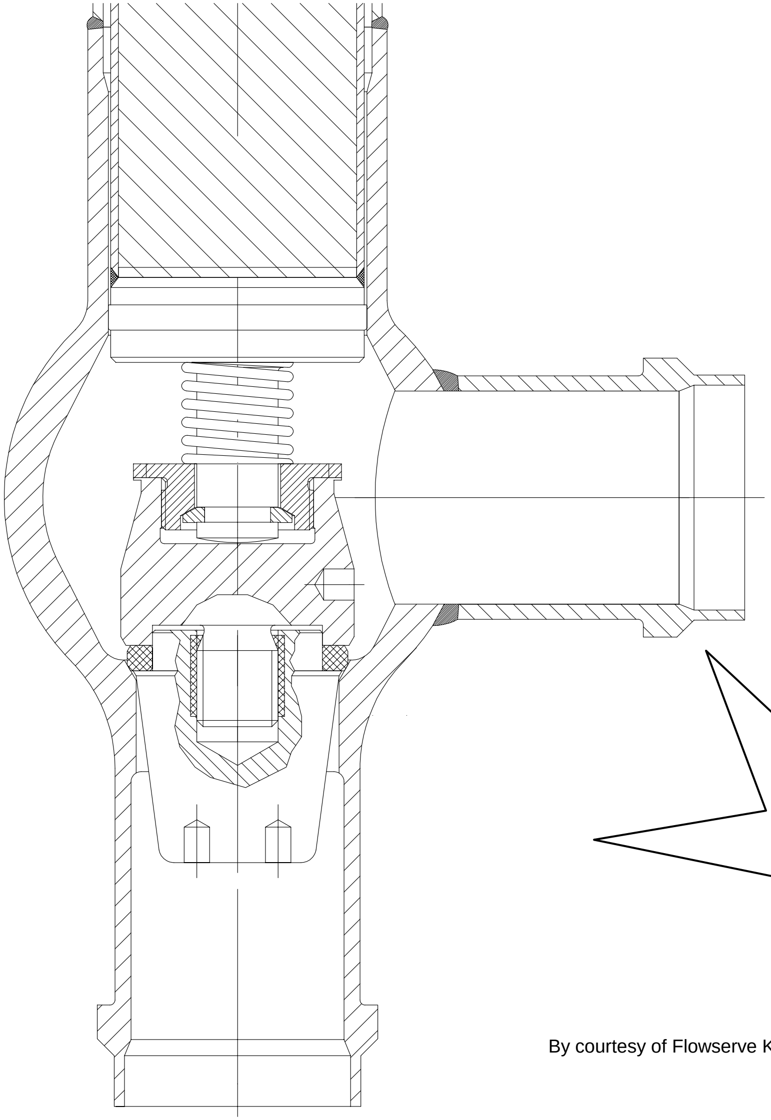
A functional test to verify that the valve stem moves without friction

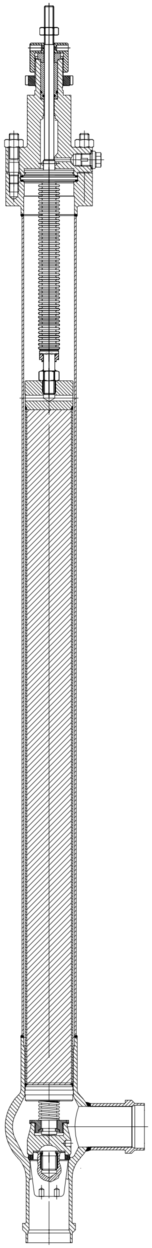
Leak tests to verify the leak rates listed below.

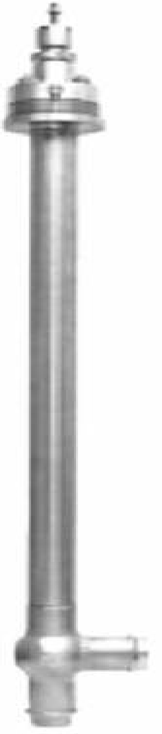
The cryogenic valves must satisfy the following leak rate criteria at maximum working pressure and room temperature.

Individual leak rate to atmosphere10-6 Pa m3/s(10-5 mbar l/s), Individual leakage across valves seat:10-5 Pa m3/s(10-4 mbar l/s), Individual leak rate to the vacuum insulation10-9 Pa m3/s(10-8 mbar l/s).

Valves - design 1

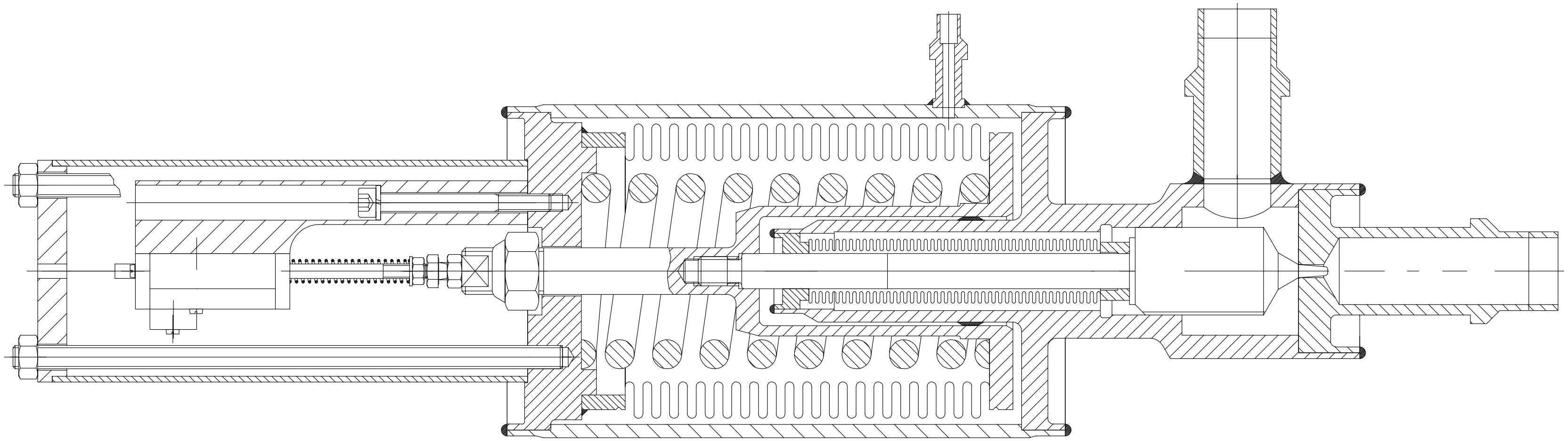






By courtesy of Flowserve Kämmer

Valves - design 2



valve with integrated actuator

By courtesy of Flowserve Kämmer

Valves - design (DIN534)

numerical value equation!

Liquid (incompressible fluid) :

$$k_V = \frac{\dot{m}}{\sqrt{1000\ \rho\ \Delta p}}$$

with ρ = density in kg/m^3 , Δp = pressure drop in bar,

ṁ = mass flow in kg/h

Gas :

subcritical flow ($p_2 > p_1/2$)

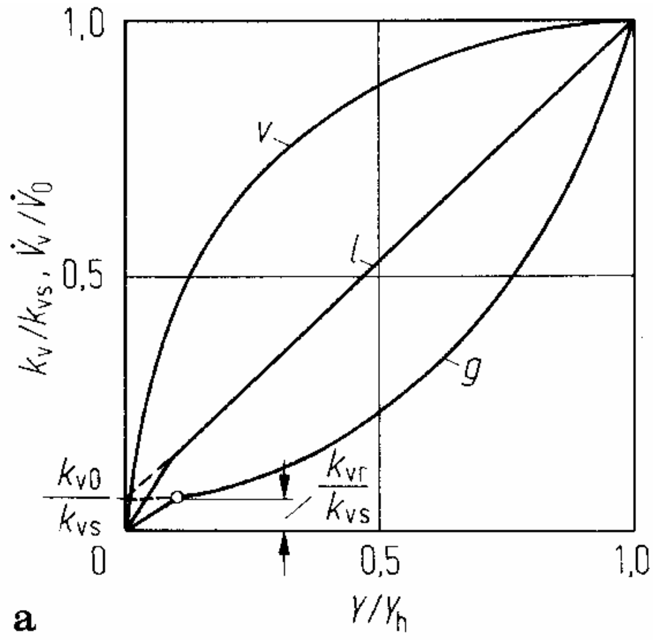
$$k_V = \frac{\dot{m}}{519}\sqrt{\frac{T_1}{\rho_G\ \Delta p\ p_2}}$$

with T_1 = temperature in K, ρ_G = density at normal conditions,

p_2 = pressure in bar

supercritical flow ($p_2 \le p_1/2$)

$$k_V = \frac{\dot{m}}{259.5\ p_1}\sqrt{\frac{T_1}{\rho_G}}$$



Pipework - pressure drop

$$\Delta p = \frac{\rho}{2} v^2 \frac{l}{d} \lambda$$

mit ρ = Dichte, v = Geschwindigkeit, l = Länge, d = Durchmesser

Reynolds Zahl: $\mathrm{Re} = \frac{v\,d}{\nu}$

mit ν = kinematische Viskosität: $\nu = \frac{\eta}{\rho}$, η = dynamische Viskosität

laminare Strömung (Re < 2300):

$$\lambda_{lam} = \frac{64}{\mathrm{Re}}$$

turbulente Strömung ($\mathrm{Re} \geq 2300$):

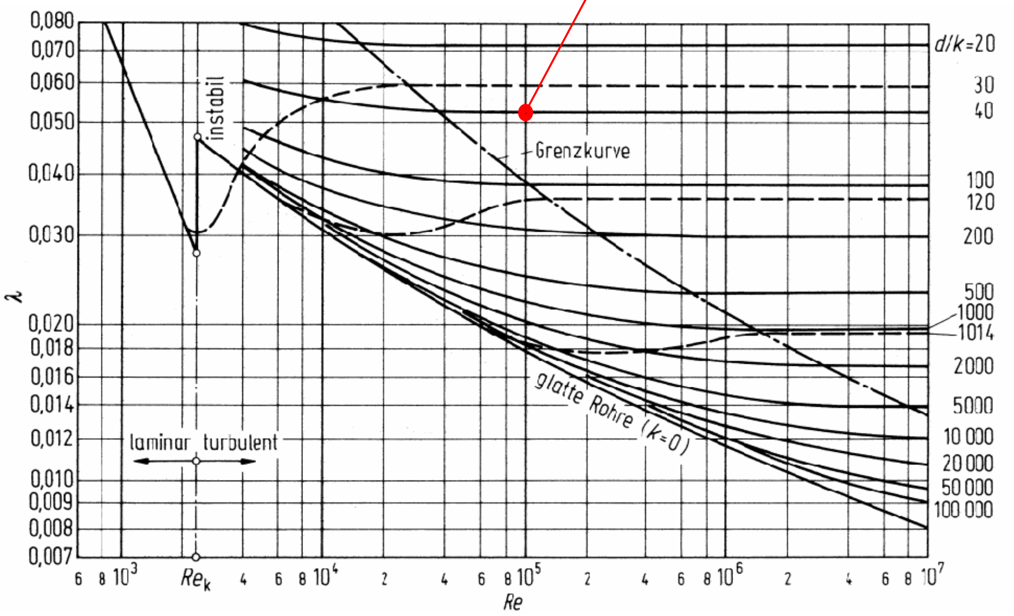
λ_{turb} aus Nikuradse - Diagramm entnehmen oder für glatte Rohre

Formel von Blasius für $2300 < \mathrm{Re} < 10^5$:

$$\lambda_{turb} = \frac{0{,}3164}{\mathrm{Re}^{0{,}25}}$$

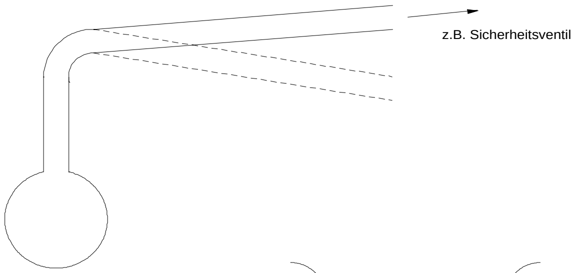
Formel von Nikuradse für $10^5 < \mathrm{Re} < 10^8$

$$\lambda_{turb} = 0{,}0032 + \frac{0{,}221}{\mathrm{Re}^{0{,}237}}$$

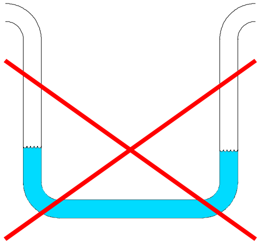


λ – Wellrohr oder
λ – Ringrillenrohr
bei $\mathrm{Re} \sim 10^5$

pipe systems - direction of installation



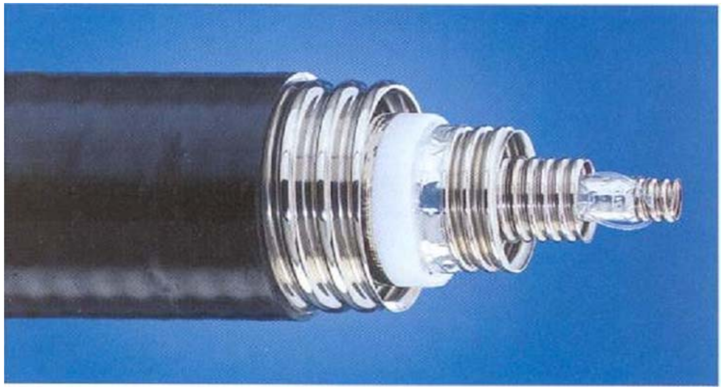
- ascent towards warm end in order to allow thermal stratification
  - otherways - descend after a short ascent

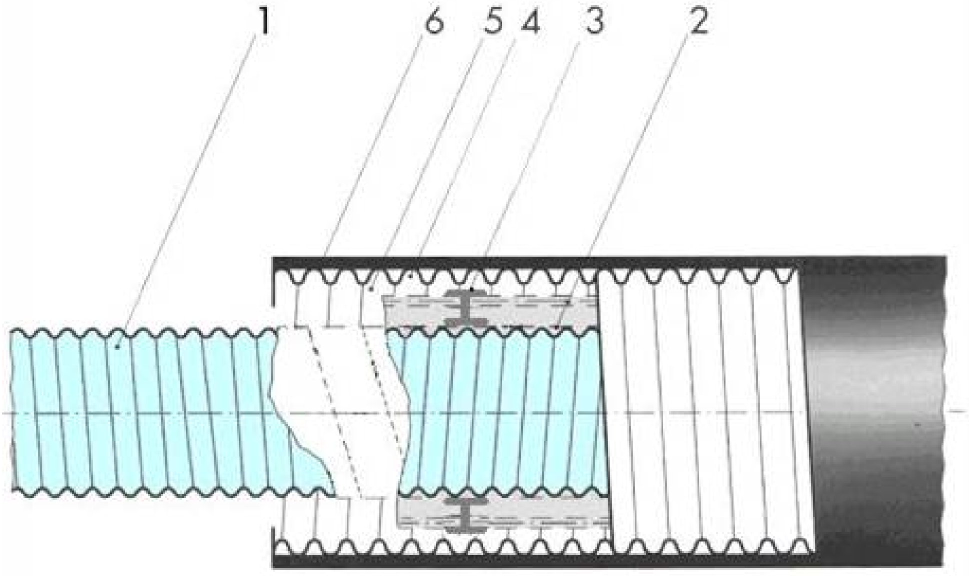


- avoid low points (Siphons) in liquid carrying lines

- take into account thermal contraction

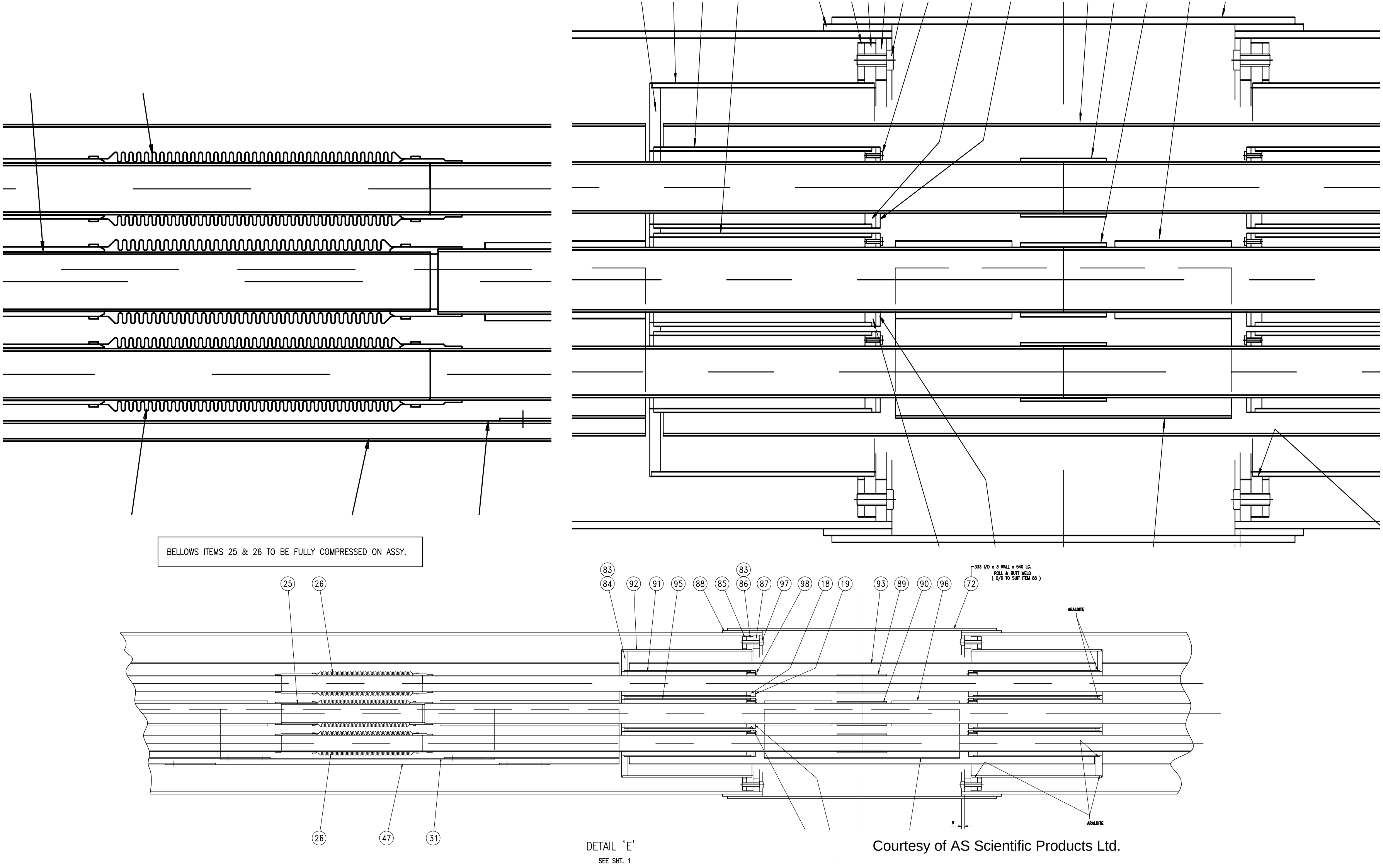
Transfer lines - design 1





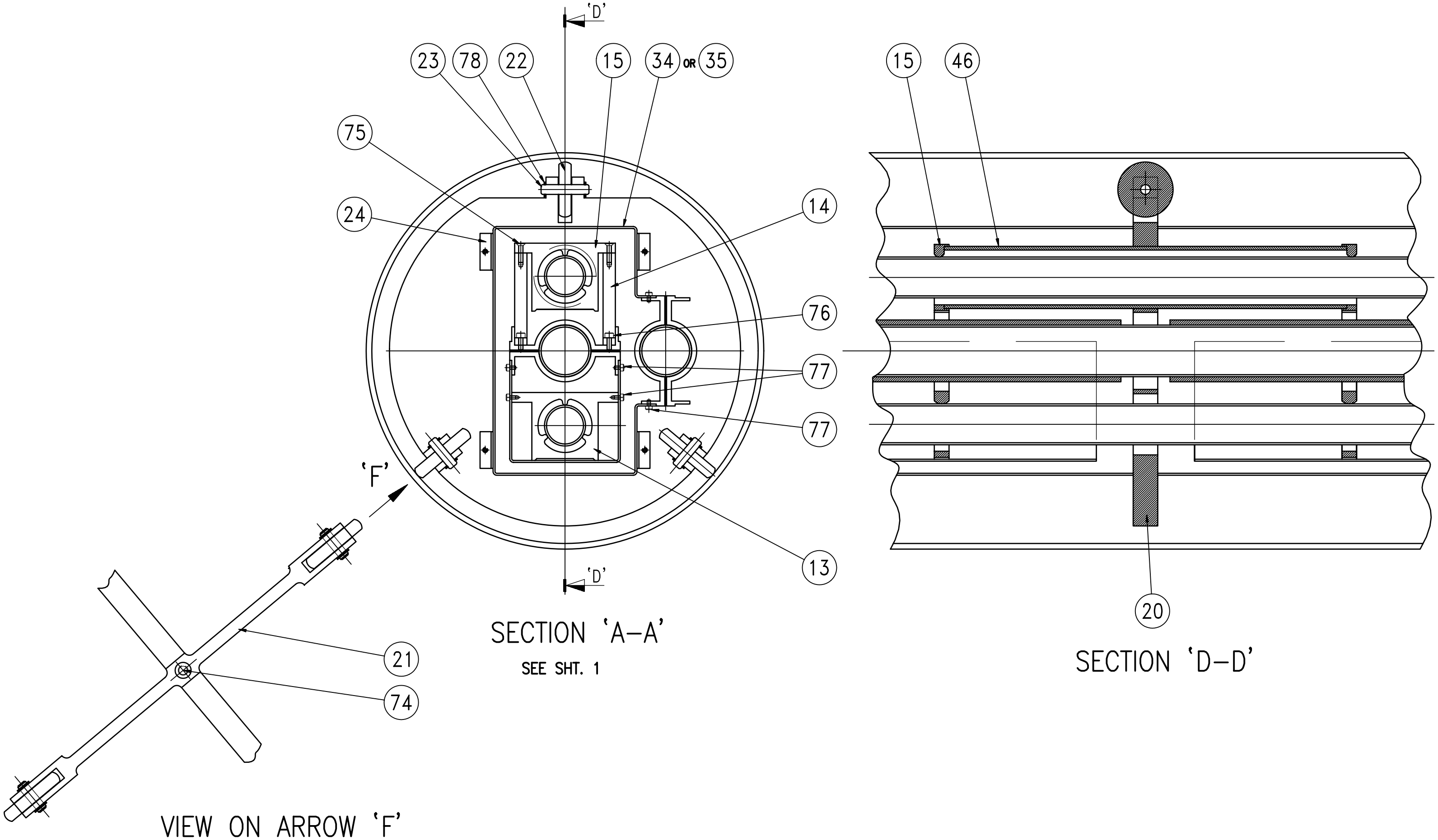
Courtesy of NEXANS Deutschland Industries GmbH & Co. KG

Transfer lines



Courtesy of AS Scientific Products Ltd.

Transfer lines - design 2



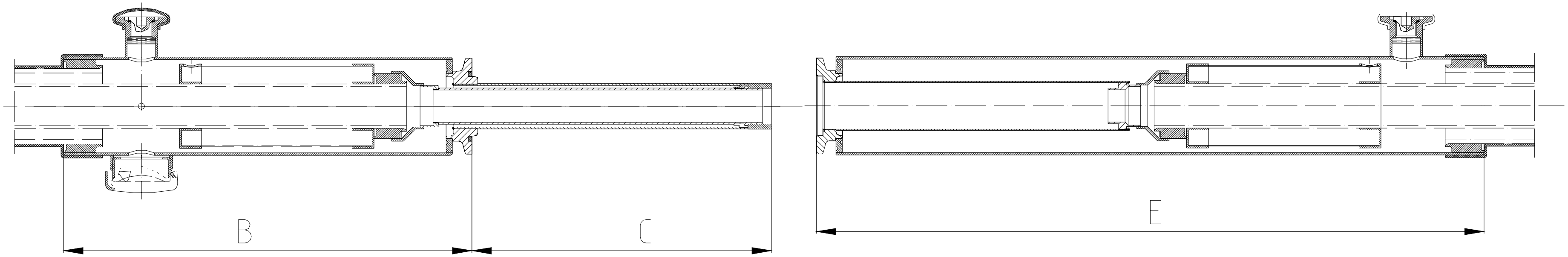
SECTION 'A–A'

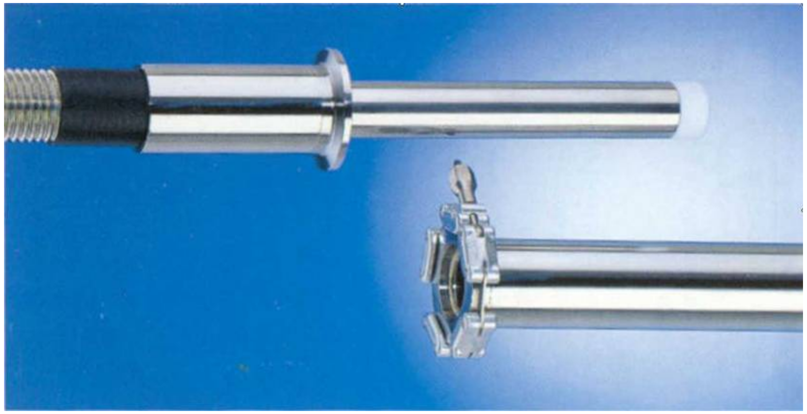
SEE SHT. 1

SECTION 'D–D'

VIEW ON ARROW 'F'

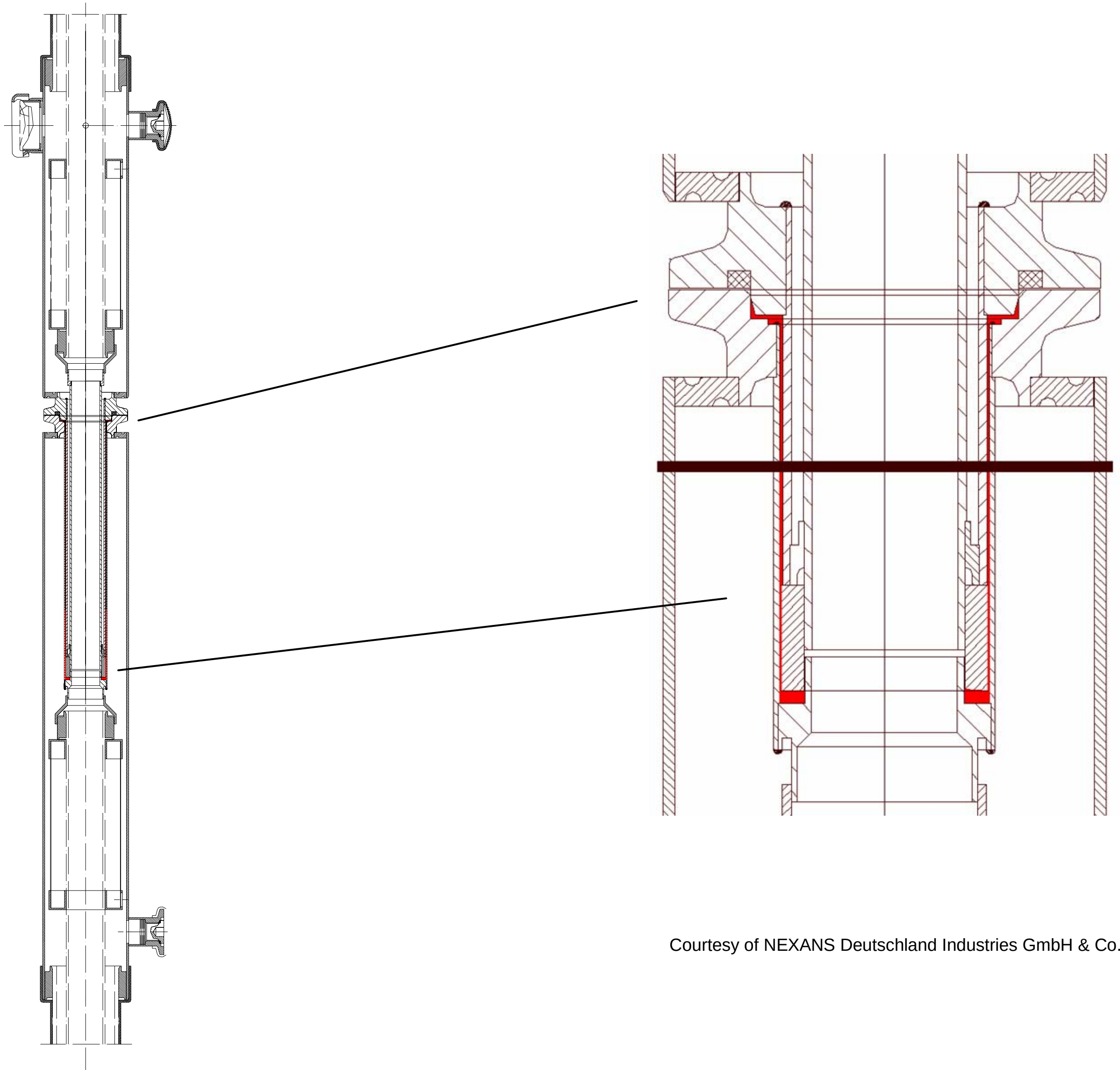
Transfer lines - couplings 1





Courtesy of NEXANS Deutschland Industries GmbH & Co. KG

Transfer lines - couplings 2



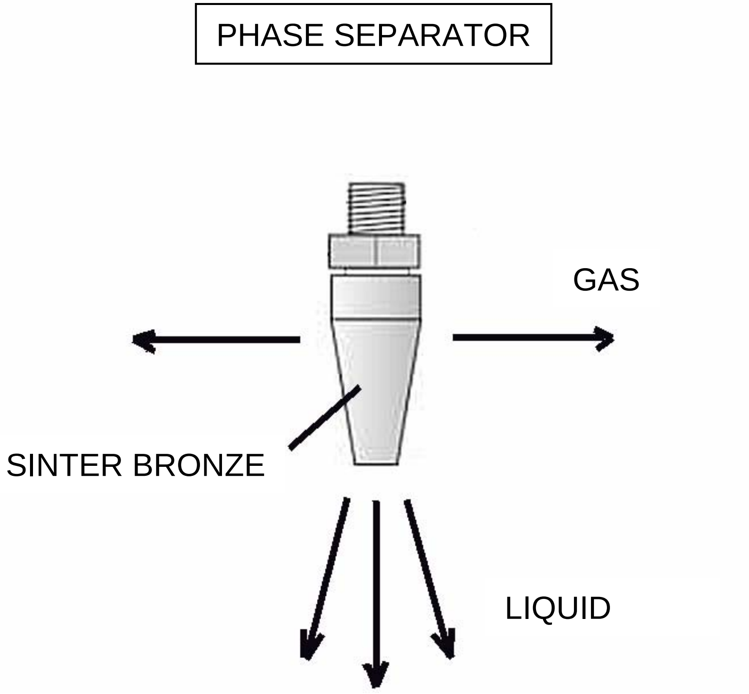
Courtesy of NEXANS Deutschland Industries GmbH & Co. KG

Transfer lines - phase separator

- phase separator

The installation of a phase separator at the delivery end of a siphons can improve the transfer of liquid.

NOTE: As these filters can clog, they should only be installed in accessible places.



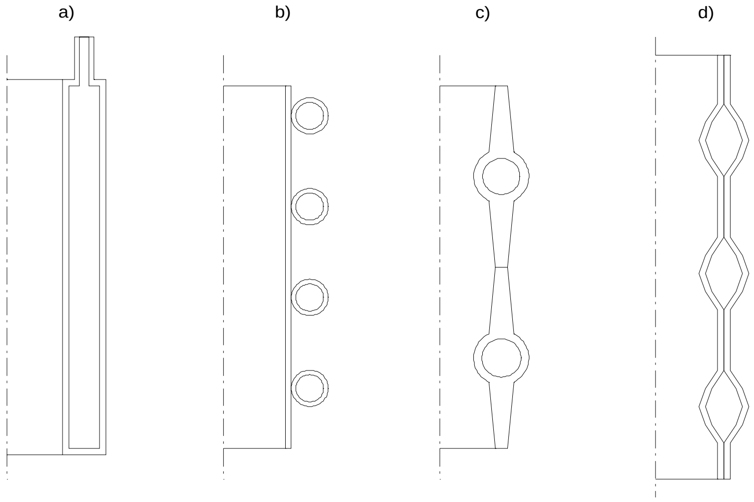
Shield - design

a) shield out of two concentric cylinders

b) shield with brazed cooling pipes

c) shield assembled from extruded elements (e.g. finned pipes)

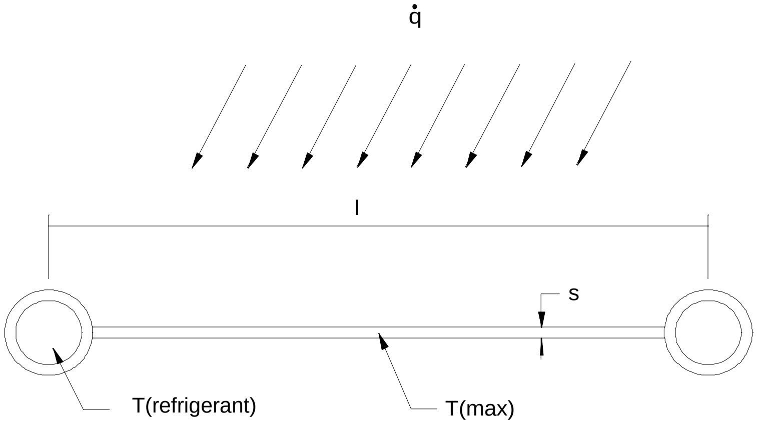
d) quilted panel type shield
(made by 1. spot welding two plates
and 2. hydraulically forming them)



Shield - design

Distance of the cooling pipes:

$$l = \sqrt{\frac{8\,\lambda\, s\,(T_{\max} - T_{refrigerant})}{\dot{q}}}$$



with

λ = thermal conductivity,

s = thickness of the shield,

$T_{\max}$ = maximum temperature of the shield in between two cooling pipes,

$\dot{q}$ = specific heat flux

Adsorber - design

- Capacity

$$V_{Adsorber} = \frac{x\,\dot{m}\,T}{\rho\,\beta}$$

with

x - concentration of impurities

$\dot{m}$ - mass flow

T - up time

ρ - density of the impurities at RT

β - adsorption capacity

- Pressure drop - Ergun equation

$$\Delta p = \frac{150(1-\varepsilon)^2\,\mu\,u_0 L}{\varepsilon^3 D_p^2} + \frac{1.75\,\rho\,L\,u_0^2}{D_p^2}\,\frac{1-\varepsilon}{\varepsilon^3}$$

with

D_p - particle diameter

L - length of the adsorber

u_0 - gas velocity $= \frac{\dot{V}}{A}$

ε - void fraction

μ - viscosity

ρ - gas density

Attention – Avoid the formation of a turbulence layer!

Adsorber - data

Material properties	activated charcoal				silica gel				Source
bulk density	[kg/m^3]	480			[kg/m^3]	720			[2]
solid density	[kg/m^3]	1920			[kg/m^3]	2200			[2]
particle density	[kg/m^3]	750			[kg/m^3]	1200			[2]
void fraction ε	[-]	0.64			[-]	0.6			
maximum regenertaion temperature	[K]	410			[K]	590			[2]
	per unit of mass		*per unit of bulk volume*		*per unit of mass*		*per unit of bulk volume*		
specific heat capacity at RT	[kJ/kgK]	0.84	[kJ/m^{3}K]	403.2	[kJ/kgK]	0.92	[kJ/m^{3}K]	662.4	[2]
specific surface area	[10^{6}m^2/kg]	1.2	[10^{6}m^2/m^3]	576	[10^{6}m^2/kg]	0.78	[10^{6}m^2/m^3]	561.6	[2]
Adsorption properties									
monolayer capacity for N_2 at 90.1K following BET	[m^3/kg]	0.173	[m^3/m^3]	83	[m^3/kg]	0.127	[m^3/m^3]	91	[1]
monolayer capacity for O_2 at 90.1K following BET	[m^3/kg]	0.235	[m^3/m^3]	113	[m^3/kg]	0.132	[m^3/m^3]	95	[1]
monolayer capacity for Ar at 90.1K following BET	[m^3/kg]	0.216	[m^3/m^3]	104	[m^3/kg]	0.122	[m^3/m^3]	88	[1]
monolayer capacity for N_2 at 77.3K following BET	[m^3/kg]	0.182	[m^3/m^3]	87	[m^3/kg]	0.135	[m^3/m^3]	97	[1]
adsorption capacity for N_2 at 76K	[m^3/kg]	0.240	[m^3/m^3]	115	[m^3/kg]	0.250	[m^3/m^3]	180	[3,4]
adsorption capacity for N_2 at 77,4K	[m^3/kg]	0.246	[m^3/m^3]	118	[m^3/kg]	0.196	[m^3/m^3]	141	[5]

Sources:

[1] Cryogenic Process Engineering, Timmerhaus; Plenum Press, New York, 1989.

[2] Cryogenic Fundamentals, Haselden; Academic Press, London, 1971.

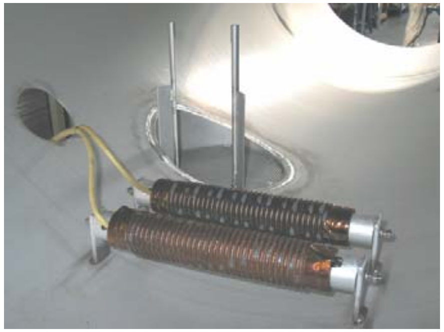
[3] Hiza and Kidnay, The Adsorption of Methane on Silika Gel at Low Temperatures, Adv. Cryog. Eng., **6**, 1961, 457-466.

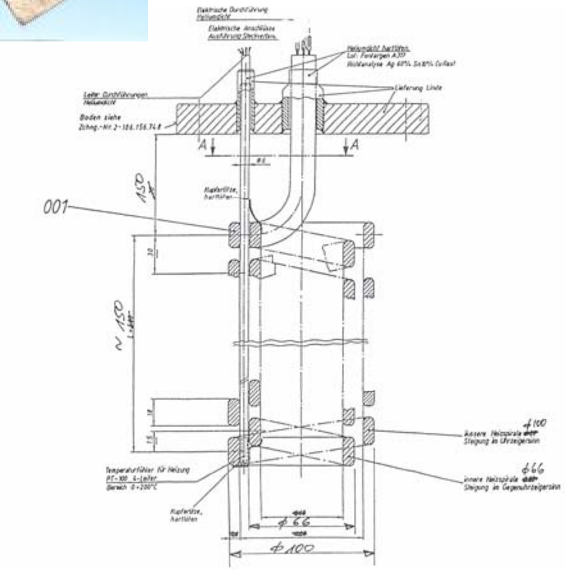
[4] Kidnay and Hiza, The purification of Helium Gas by Physical Adsorption at 76K, AIChE Journal, **16**, 6, 1970, 949-954.

[5] Unpublished measurements by Air Liquide: Adsorption from a 99,5% He + 0,5% N2 mixture at 70-150bar (activated charcoal) and 30bar (silica gel), respectively.

Heater elements

- Heater wire
  - e.g. constantan wire (CuNi), manganin wire (CuMnNi)
  - tension up to 50V
  - advantage – no inertia
- Foil heaters
  - e.g. on polyimide foil (=Kapton foil)
  - typical power 2W/cm^2
  - on cryogen side or on vacuum side
  - advantage – equally distrib. power
- encapsulated heater elements
  - Tension up to 400V
  - advantages
    - high heating powers are possible
    - no electrical feedthroughs
- Attention!
  - For heaters in the liquid – safety interlocks are required for low level and for vacuum pressure!

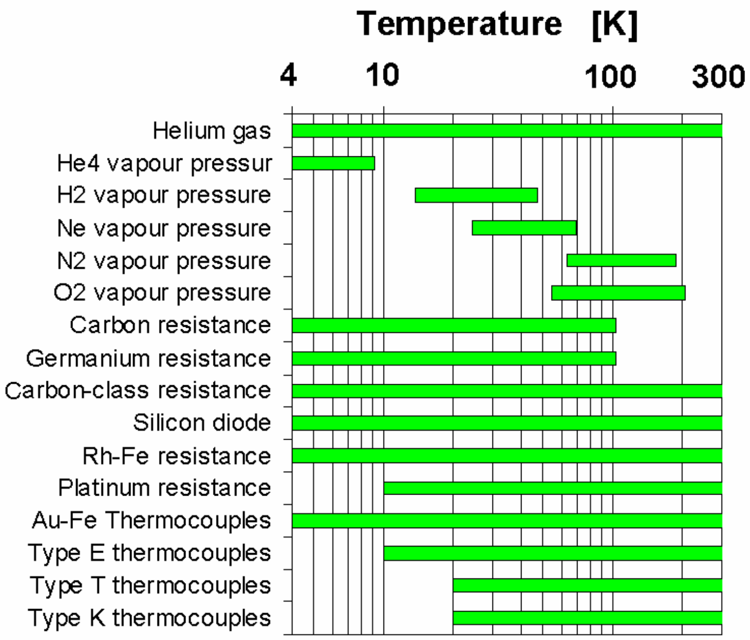


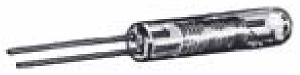


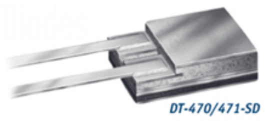
Instrumentation - temperature measurement

- Primary thermometers
    - gas thermometer
    - vapour thermometer
- Secondary thermometers
    - metallic resistances
    - non-metallic resistances
    - thermocouples

    - others: capacitance t,; resonance t.; inductance t.
- Precision factors
    - sensitivity (e.g. Ω/K)
    - reproducability (factors - installation, self heating, ageing)
    - magnet field dependence




PT 100

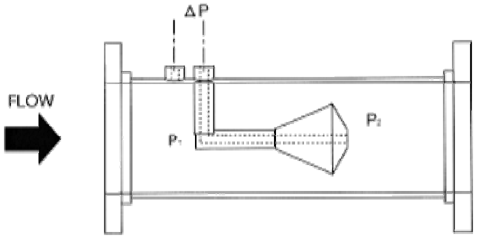


Silicon diode

Instrumentation - level and flow

- Level measurement
  - Differential pressure
  - Superconducting wire
  - Capacitance based
    - not for LHe

- Flow measurement
  - Differential pressure method
    - orifice
    - Venturi tube
    - V-cone
  - Other physical principles
    - Coriolis
    - Turbine



V-cone

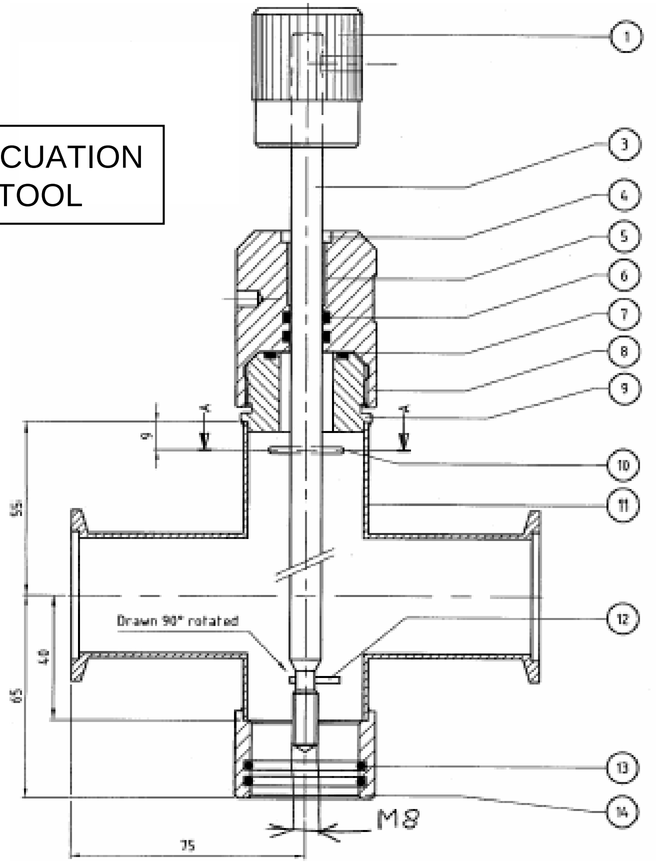
Insulation vacuum - permanent vacuum

- Operation range
  10^{-3}mbar (RT) - 10^{-5}mbar (cold)
  (i.e. 10^{-1}Pa - 10^{-3}Pa)

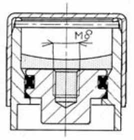
- Privilege weld connections
- Avoid elastomer joints (diffusion)

- Extension of the up-time by installation of adsorber packages on the cold surfaces
  → activation (regeneration) is important

EVACUATION TOOL



PUMPING PORT



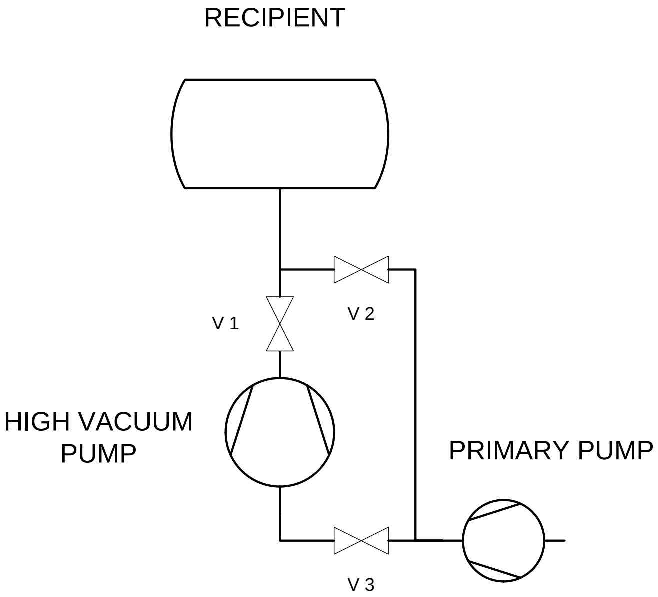
Insulation vacuum - pumped vacuum

- Operation range
  10^{-5}mbar (=10^{-3}Pa) and better
- Primary pump
  rule of thumb for pumping speed

  $S_{\text{Primary Pumop}} > 0.005 \times S_{\text{High Vacuum Pump}}$
- Secondary pump (high vac. pump) types

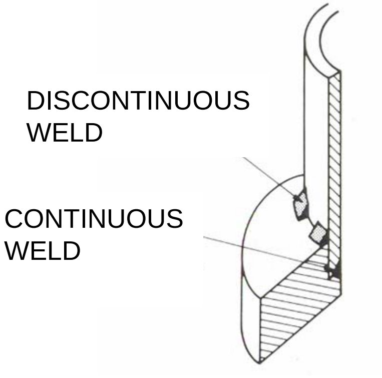
  Diffusion pump
  advantage - cheap

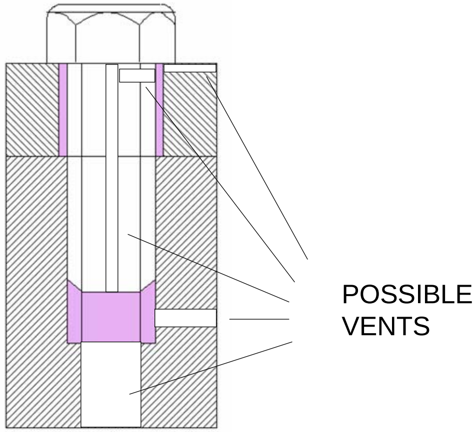
  Turbomolecular pump
  the pumping speed depends on the molecular weight ⇒
  advantage - hydrocarbon free vacuum
  disadvantage - low pumping speed for He and H_2



Insulation vacuum - vacuum technique

- avoid trapped volumes
  - trapped volumes can create virtual leaks





Day 3

Introduction to Cryogenic Engineering

MONDAY   From History to Modern Refrigeration Cycles   (G. Perinić)

TUESDAY   Standard Components, Cryogenic Design   (G. Perinić)

WEDNESDAY   Heat Transfer and Insulation   (G. Vandoni)

THURSDAY   Safety, Information Resources   (

Physiological hazards

Sources of accidents and failures

Information resources

FRIDAY   Applications of Cryogenic Engineering   (T. Niinikoski)

Safety

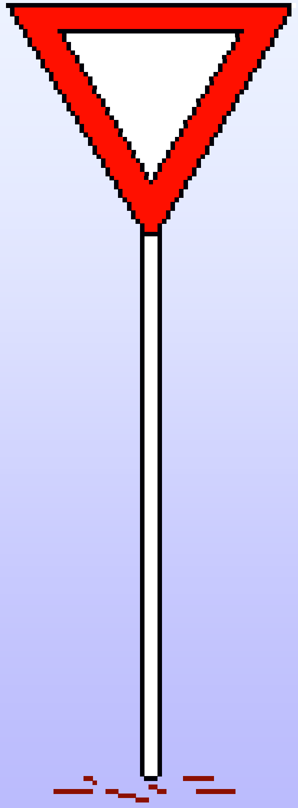
Physiological Hazards

Cold Burns - Asphyxiation - Toxicity

- Cold Burns
  - Contact with cryogenic liquids or cold surfaces

- Asphyxiation
  - Reduction of oxygen content

(- Toxicity
  - CO, F_2, O_3)



Physiological Hazards

Cold Burns - Asphyxiation - Toxicity

- **Effects:**

  Similar to burns

- **First Aid:**

  = identical procedure as in the case of burns

  - rinse injured part with lukewarm water
  - cover injured skin with sterile gaze
  - do not apply powder or creams

- **Protection:**
  - eye protection
  - gloves of insulating and non combustible material which can be easily removed
  - high, tight-fitting shoes
  - trousers (without turn-ups) which overlap the shoes

Physiological Hazards

Cold Burns - **Asphyxiation** - Toxicity

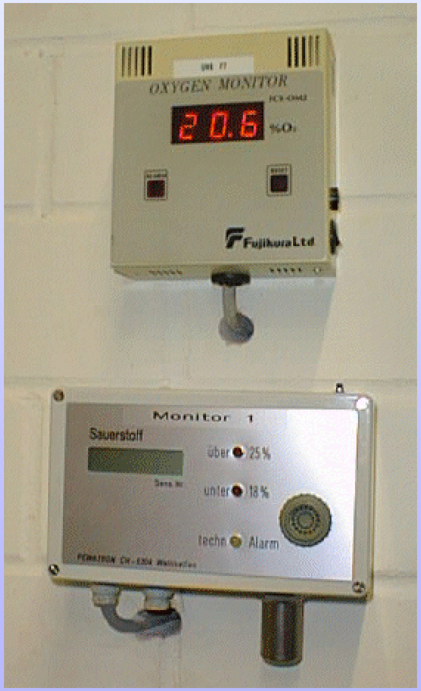
- **Effect:**

19% - 15%	pronounced reduction of reaction speed
15% - 12%	deep breaths, fast pulse, co-ordination difficulties
12% - 10%	vertigo, false judgement, lips slightly blue
10% - 8%	nausea, vomiting, unconsciousness
8% - 6%	death within 8 minutes, from 4-8 minutes brain damages
4%	coma within 40 seconds, no breathing, death

- **First Aid:**

In case of indisposition - remove person from the danger area.
In case of unconsciousness - call doctor immediately.

- **Protection / Prevention:**
  - ensure sufficient ventilation + oxygen monitors
  - Dewar content [l] < laboratory content [m^3] / 4
  - Feed exhaust into stack or into recovery pipeline
  - Decanting stations only in large halls or outside
  - Observe rules for confined spaces
  - Observe the rules for transport of dangerous goods



Physiological Hazards

Cold Burns - **Asphyxiation** - Toxicity

Physiological Hazards

Cold Burns - Asphyxiation - **Toxicity**

- **Effect:**
  - *Carbon monoxide* – Poisoning by replacement of oxygen in the blood
  - *Ozone* - Irritation of eyes and skin already by concentrations as low as 1ppm.
  - *Fluorine* - Irritation of eyes and skin.
- **First Aid:**
  - *Carbon monoxide* – same as asphyxiation
  - *Ozone and Fluorine* - Rinse thorougly the affected areas of skin with tap water.
- **Protection / Prevention:**
  - *Carbon monoxide and Ozone* – same as asphyxiation.
  - *Fluorine* - The pungent smell is already detected by the human nose at concentrations of 0.2ppm.

Physiological Hazards

Marking/identification

➔ Warning of „cold“:

➔ Storage and transport vessels (EN DIN 1251):

for example –

LIQUID NITROGEN

➔ Pipes, pipelines and exhausts - recommendation (DIN 2403):

for example -

HELIUM ➔

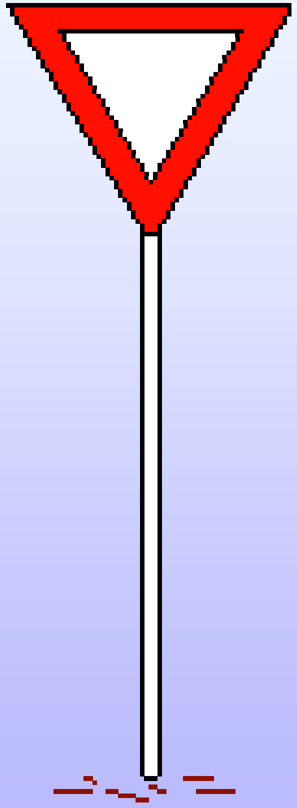
HELIUM ➔

Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

- Embrittlement
- Thermal stress

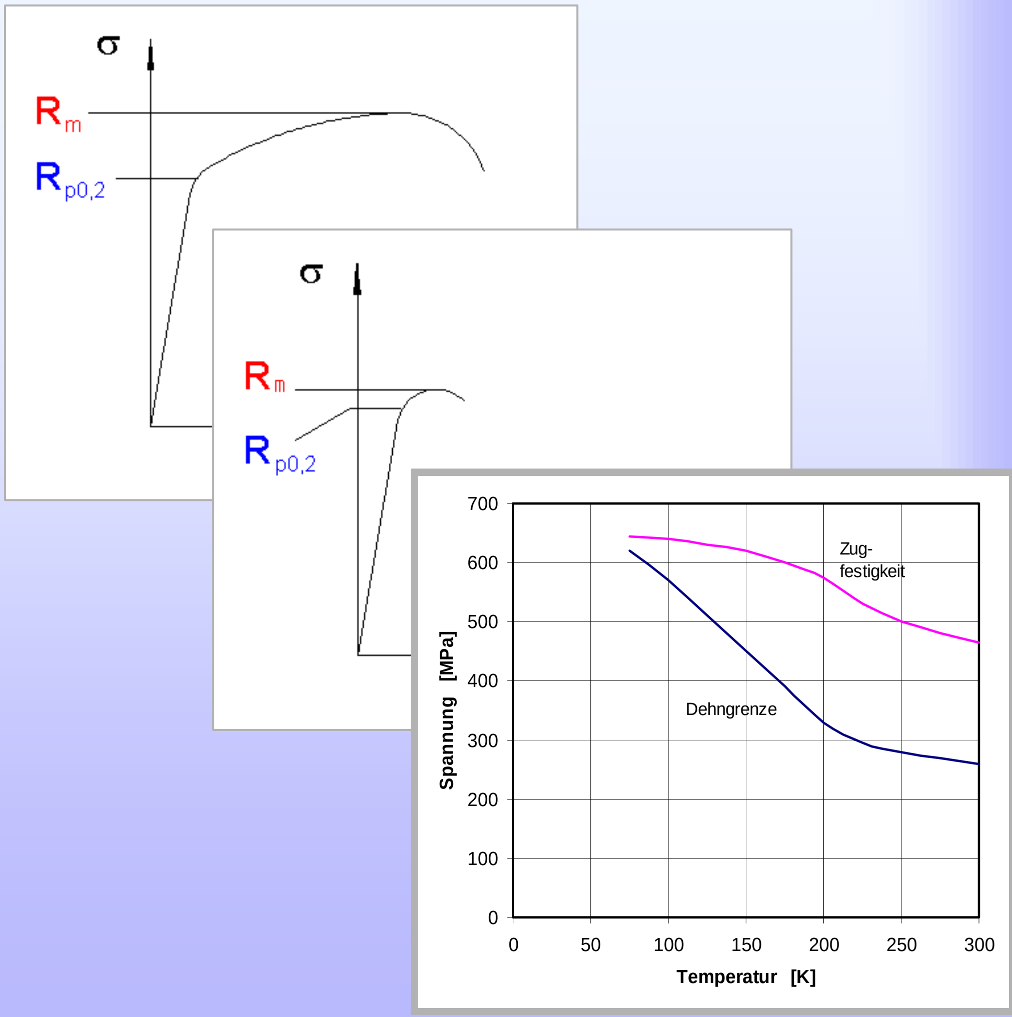
- Pressure build-up by evaporation
- Condensation
- Combustion and explosion hazard
- Electric breakdown



- Accidents and failures due to operation

Sources of accidents and failures

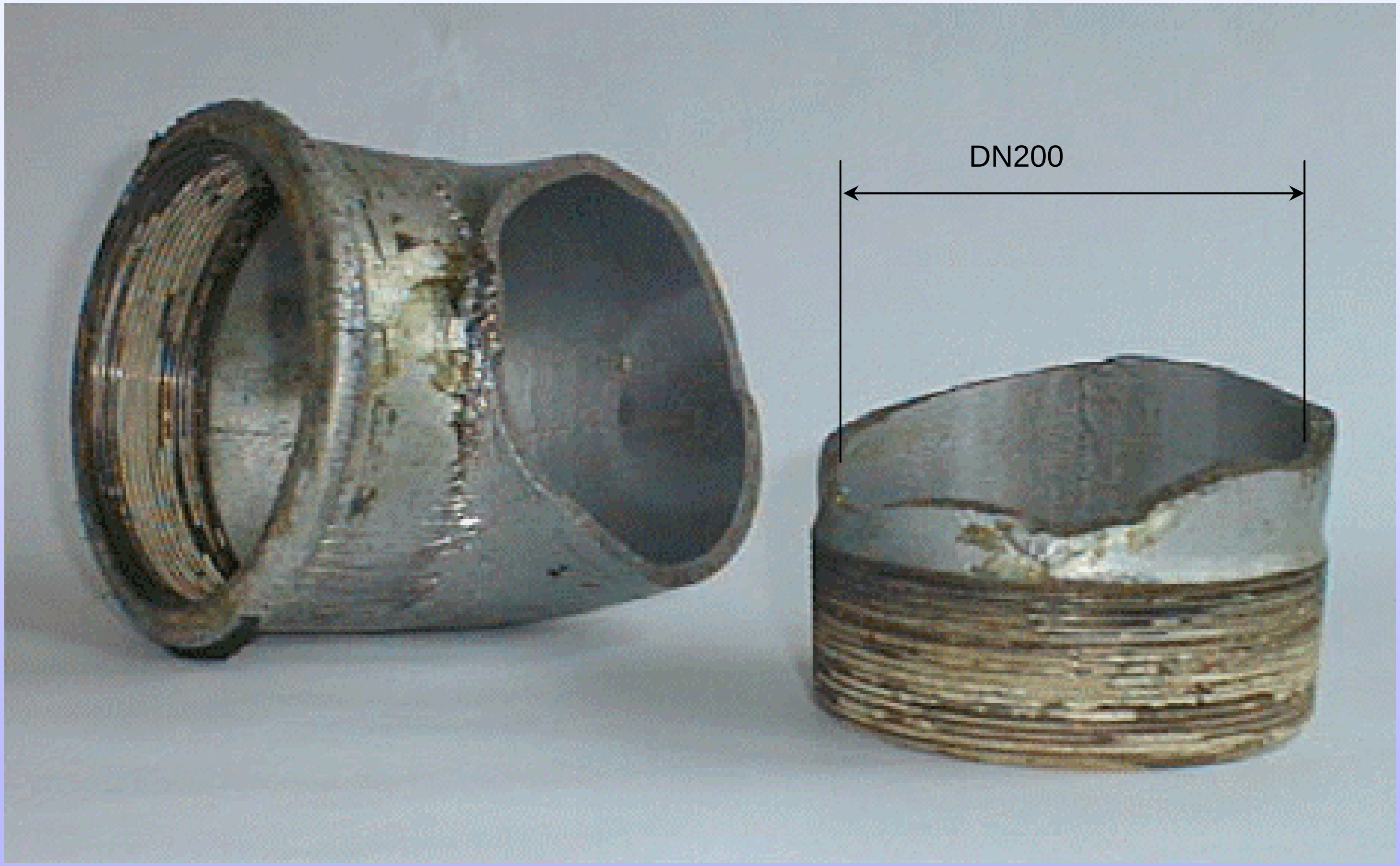
- **Low temperature embrittlement**
  - Affects most materials more orless pronounced
  - Is measured by
    → charpy impact tests
  - Suitable for low temperatures are materials with fcc structure
    → e.g.Cu, Ni, Cu Ni, Al, Al-alloys, Zr, Ti, stainless steels see AD W10



Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

- **Low temperature embrittlement**



Sources of accidents and failures

Properties of materials **–** Properties of refrigerants - Operation

- **Hydrogen embrittlement**
  - Several mechanisms exist, can originate from material production or from operation
  - At risk are:
    - Metals with bcc-structure (e.g. ferritic steels),
    - High tensile steels used in the range 200-300K,
    - Materials under loads close to their limit of elasticity
  - Means of protection:
    - linings or coatings with other metals,
    - over dimensioning

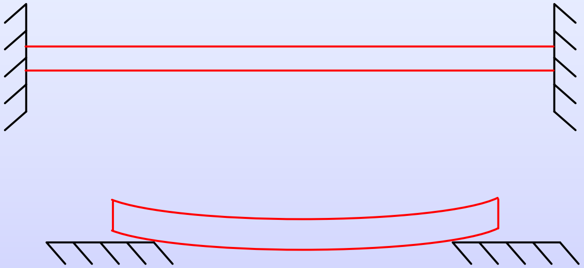
Sources of accidents and failures

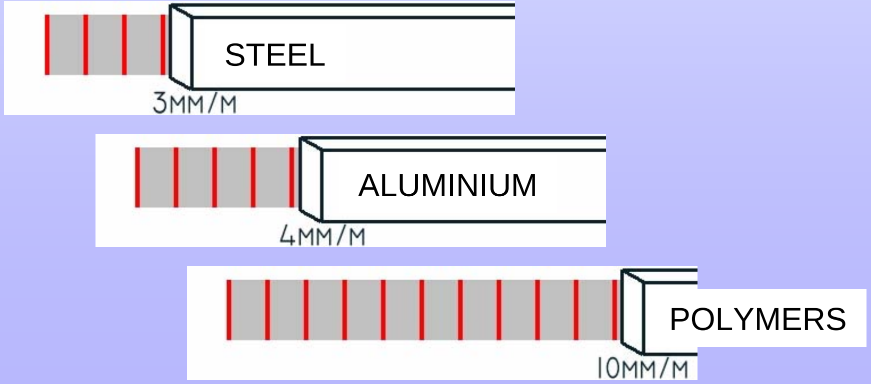
Properties of materials **–** Properties of refrigerants - Operation

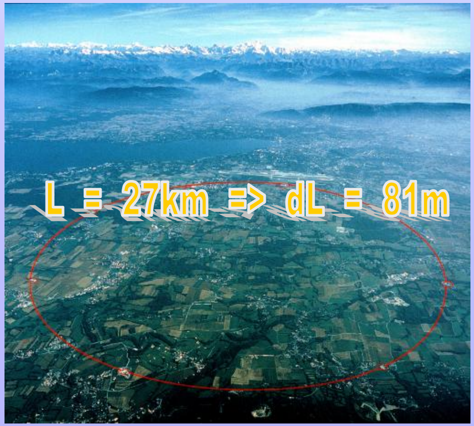
- **Thermal Stress**
  - Contraction due to cool-down

⇨ permanent loads in operation,
e.g. in pipes

⇨ temporary loads,
e.g. during cool-down of
thick walled components







Sources of accidents and failures

Properties of materials **–** **Properties of refrigerants** - Operation

- **Pressure build-up by evaporation**

- due to excessive heat load
  - Cool-down of a component, of an installation
  - Heating components – heaters, quenching magnet
  - Loss of insulation vacuum
  - thermo-acoustic oscillations (Taconis)

- due to other physical effects
  - Boiling retardation
  - stratification
  - roll-over (LNG only)
  - desorption of cryopumped gas

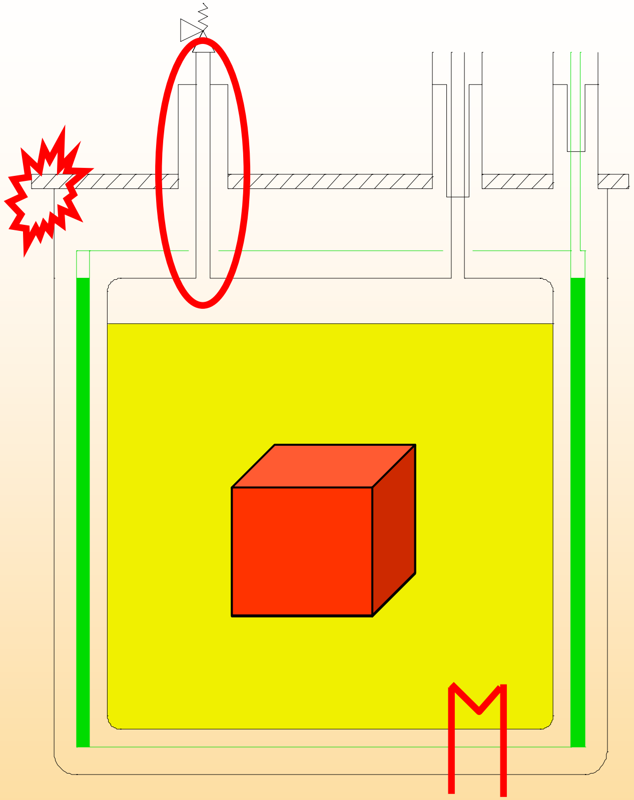
1l liquid refrigerant (T_S)

⇔

500-1500 l gas (300K)

Pressure build-up

Evaporation by excessive heat load



– fast cool-down of
→ a component or
→ a part of the installation

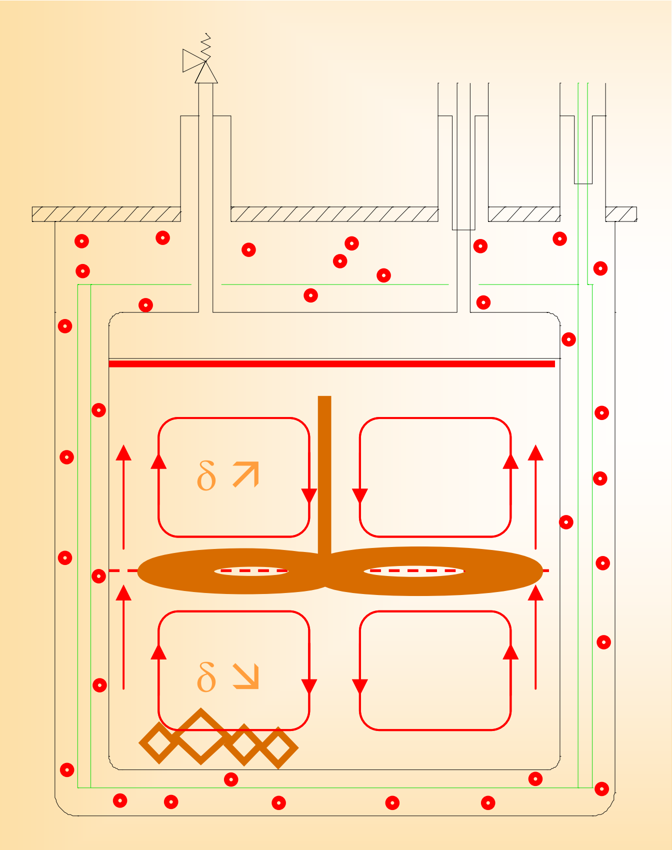
– excessive heating by
→ a component e.g. quench
→ by installations e.g. heaters

– loss of the insulation vacuum

– thermoacoustic oscillations

Pressure build-up

other physical effects



- – boiling retardation
- – stratification
- – rollover in LNG tanks
- – release of cryopumped gas

Sources of accidents and failures

Properties of materials **–** **Properties of refrigerants** - Operation

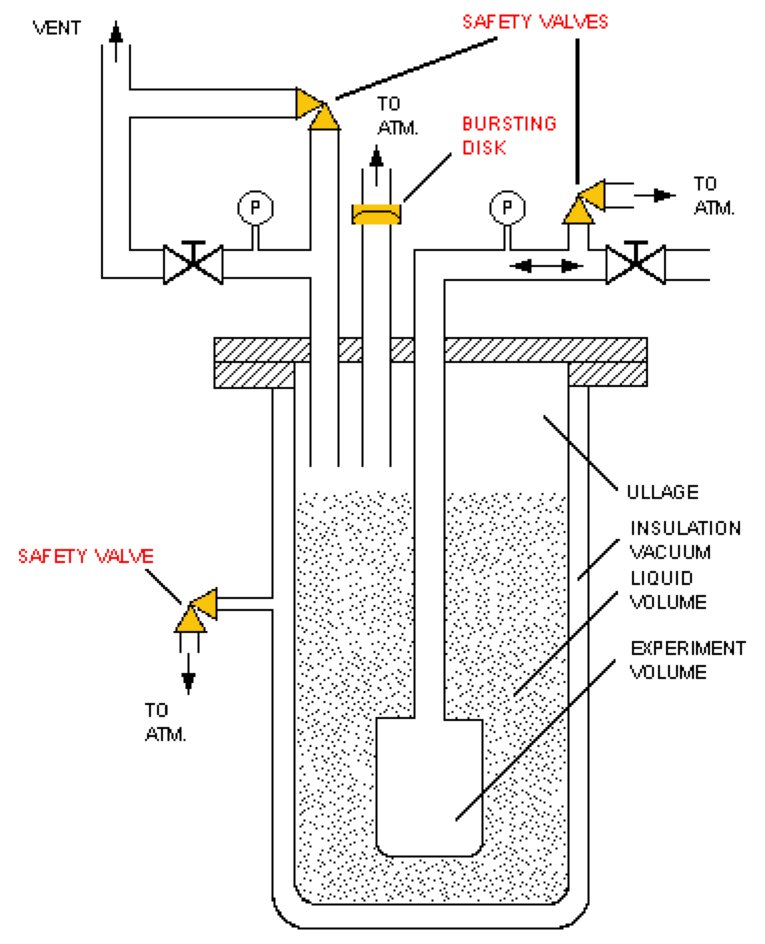
- **Pressure build-up**

Means of protection:

  - safety devices

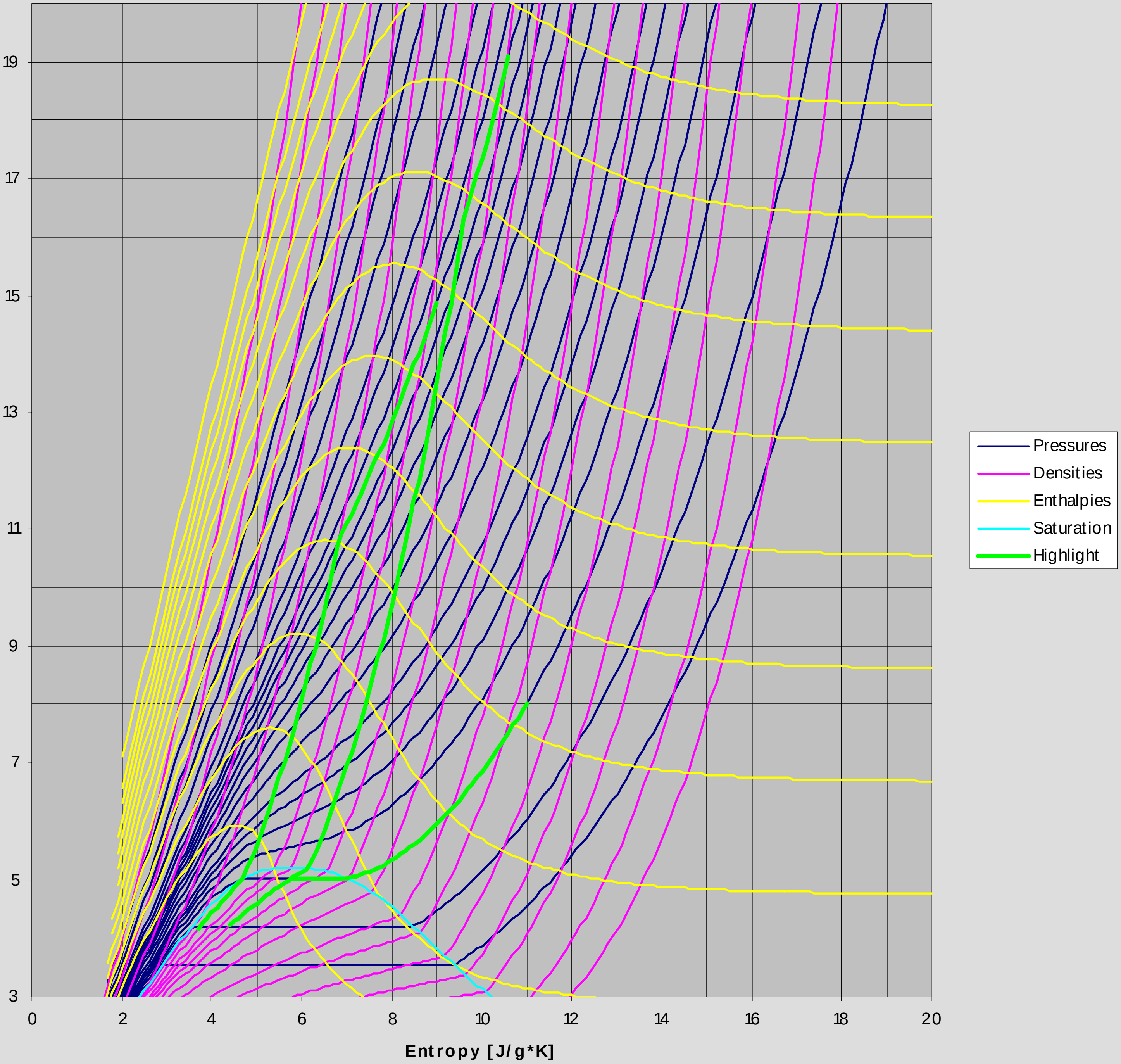
Principles:

  - redundancy and
  - diversity



Calculation of safety valves:

- AD-Merkblatt A1/A2
- DIN EN 13648 (=ISO 21013)


19
17
15
13
11
9
7
5
3
0
2
4
6
8
10
12
14
16
18
20
Entropy [J/g*K]
Pressures
Densities
Enthalpies
Saturation
Highlight

[redacted]

Calculation of safety valves for LHe-containers

1. Determination of the maximum heat flux

Possible heat sources:

- loss of vacuum,
- fire,
- electrical heaters,
- quench in superconducting coils, etc.

typical heat flux in case of insulation vacuum loss:

0.6W/cm2	LHe-cryostat with 10 layers superinsul.
3.8W/cm2	LHe-cryostat without superinsulation

from W. Lehmann, G. Zahn, "Safety aspects for LHe cryostats and LHe containers", *Proc. of the Int. Cryog. Eng. Conf.*, **7** (1978) 569-579.

2. Determination of the gas flux

a) Blow-off pressure below critical pressure

$$\dot{m}_{blow-off} = \frac{\dot{Q}_{surface}}{q}\left(1-\frac{\rho_{gas}}{\rho_{liquid}}\right)$$

with $q = \Delta h_{evaporation}$

(in general $\Delta h_{He} \approx \Delta h_{He}$(1,01325bar, 4,222K) = 20.91J/s)

b) Blow-off pressure above critical pressure

$$\dot{m}_{blow-off} = \frac{\dot{Q}_{surface}}{q}$$

with $q = v\left(\frac{dh}{dv}\right)_{p=const.}$

(up to 5bar V(dh/dV) ≈ Δh_{He}(1,01325bar, 4,222K) = 20.91J/s)

$$\dot{m}_{blow-off} = \max \quad \text{for} \quad v\left(\frac{dh}{dv}\right) = \min$$

Minima of the pseudo-evaporation enthalpy of helium as a function of the pressure

blow-off pressure [bara]	minimal pseudo-evaporation enthalpy [J/g]	temperature at which the pseudo-evaporation enthalpy is at its minimum [K]
5	22.5	6.4
6	25.5	6.8
8	31.2	7.4
10	36.7	7.9
12	41.9	8.4
14	46.8	8.8
18	56.2	9.4
22	65.1	9.7
26	73.3	9.9
30	81.0	9.6
40	95.9	6.6

3. Determination of the minimum blow-off aperture

following AD Merkblatt A1, Verband der Technischen Überwachungs-Vereine e.V. (1995).

a) outflow function ψ

If $$\frac{p_{gegen}}{p_{Kryostat}} > \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}}$$

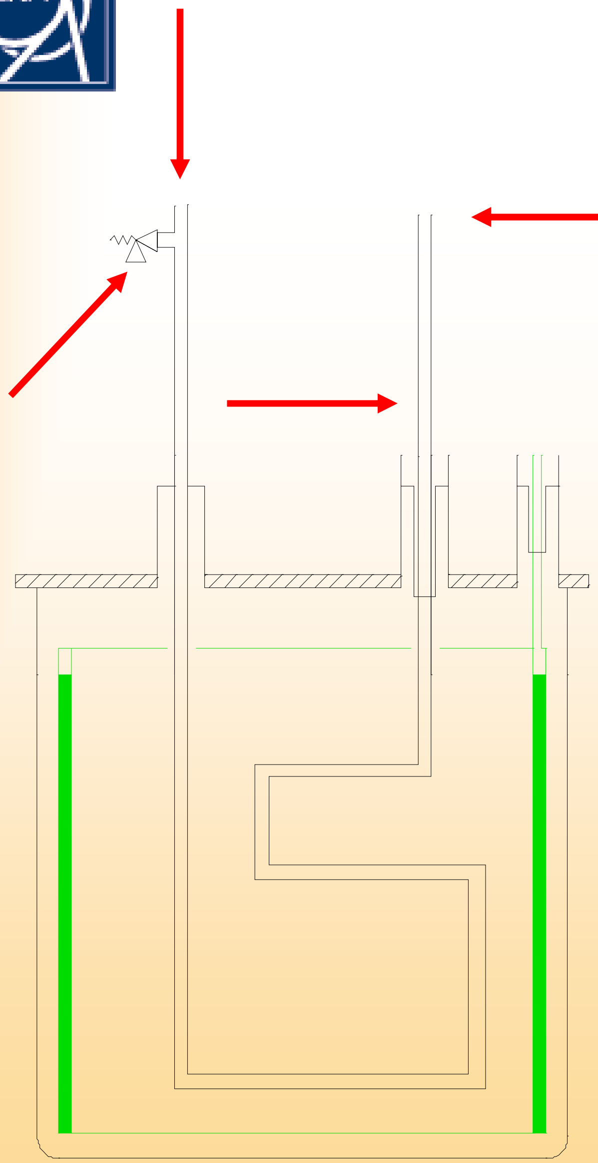
then (subcritical) $$\psi = \sqrt{\frac{\kappa}{\kappa-1}} * \sqrt{\left(\frac{p_{gegen}}{p_{Kryostat}}\right)^{\frac{2}{\kappa}} - \left(\frac{p_{gegen}}{p_{Kryostat}}\right)^{\frac{\kappa+1}{\kappa}}}$$

else (supercritical) $$\psi = \sqrt{\frac{\kappa}{\kappa+1}} * \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}}$$

b) minimum blow-off surface

$$A_{\min.} = \frac{\dot{m}}{\psi\ \alpha\ \sqrt{2\ p_{cryostat}\rho}}$$ with α = outflow coefficient $\in \{0..1\}$

Condensation



Causes

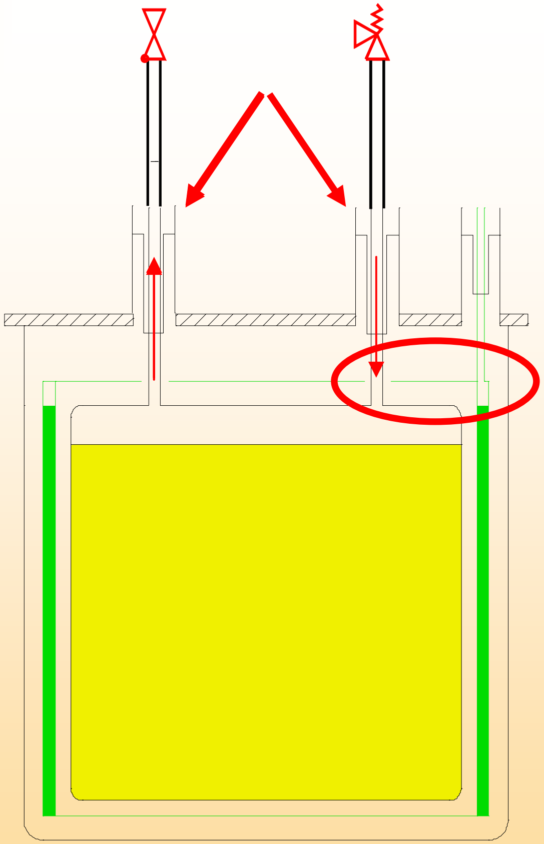
- **impurities in refrigerant (air, neon, oil)**
- **leaks, especially in sub-atmospheric conditions**
- **open exhaust pipes**
- **not insulated or badly insul. surfaces leaks into the insulation vacuum**

Prevention

- ⇨ extensive purging and repeated evacuation before cool-down
- ⇨ operation with slight overpressure
- ⇨ use of vacuum insulation where possible – otherways use only non-combustible insulation material equipped with a vapour barrier in order to stop air and oxygen from reaching the cold surface

Condensation

Plugging of exhaust pipes



- **open or leaky exhaust pipes**

  Attention: acceleration by two exhausts!

- **thermally connected LN2-screens**
- **leaks when pumping on cryogen baths**

Prevention:

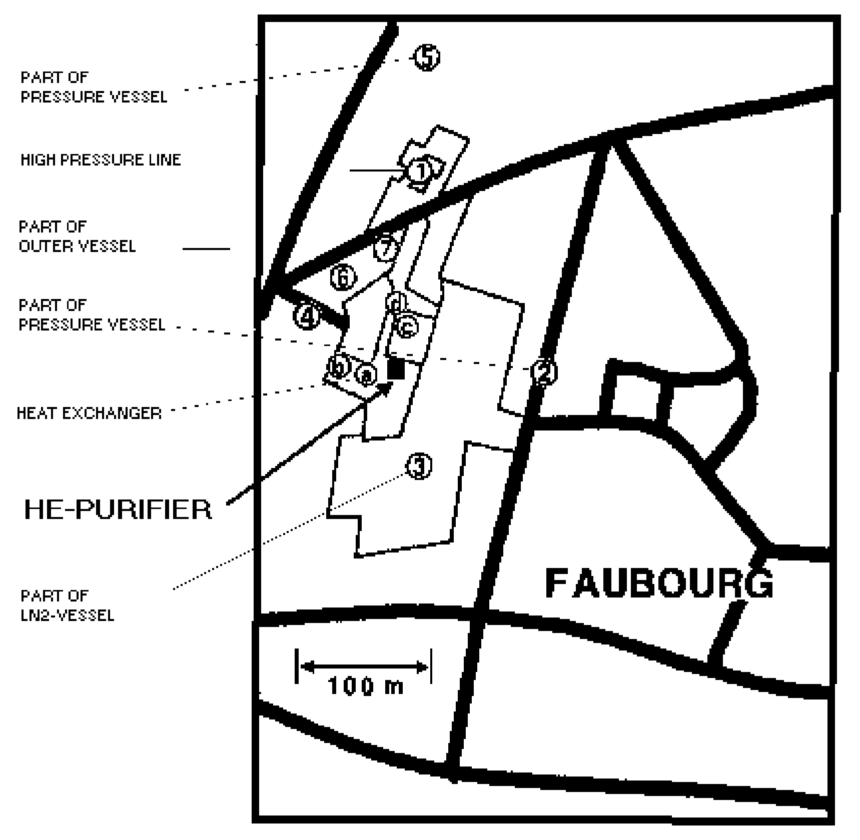
- ⇨ do not leave open dewars
- ⇨ non-return valves in exhaust lines
- ⇨ use only containers with separated exhaust and safety lines

Sources of accidents and failures

Properties of materials **– Properties of refrigerants** - Operation

- **Fire and explosion risk:**

Methane, LNG, Hydrogen



Other combustion dangers:

Superinsulation foils on Polyester base (Mylar®) can be ignited easily!

– Protect when welding!

Sources of accidents and failures

Properties of materials **–** **Properties of refrigerants** - Operation

- **Electric breakdown**

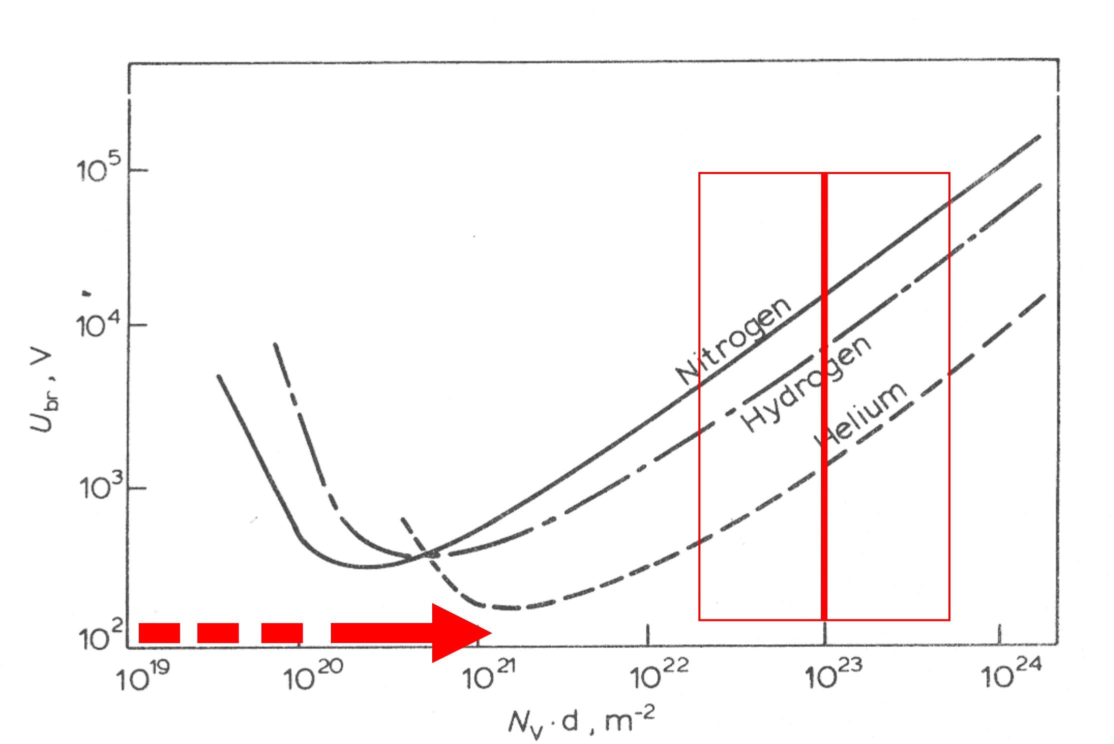


Fig. 8 Generalized Paschen curves

Sources of accidents and failures

Properties of materials **–** Properties of refrigerants - **Operation**

- **Plant operation**
  - operator errors
  - usage of unsuitable equipment
  - operating system errors
  - malfunctioning or failures of components
  - failure of safety equipment
  - Transport accidents
  - etc.

Preventive measures:

- Safety analysis and safety management

Information

Sources

Information sources - literature 1

Titel	Autor	Verlag	Jahr	lieferbar	Kryogene	Werkstoffe	Wärmeübertragung	Thermodynamik Prozesse	Komponenten Kälteanlagen	Kryostatenbau	Instrumentierung	Sicherheit	weitere Themen
Cryocoolers I	G. Walker	Plenum Press	1983					+++	++				
Cryocoolers II	G. Walker	Plenum Press	1983		+			+	+++				++
Cryogenic Engineering	T.M. Flynn	Dekker	1997	X	++	++	+	++	++		++	+	++
Cryogenic Engineering	R. Scott	Met Chem. Research	1989										
Cryogenic Engineering	B.A. Hands	Academic Press	1986	X	+	+	++	++	++	++	+	+	
Cryogenic Process Engineering	K.D.Timmerhaus, T.M.Flynn	Plenum Press	1989	X	+	++		+++	++++		++		
Cryogenic Processes and Equipment		ASME	1993	X									
Cryogenic Regenerative Heat Exchangers	R.A. Ackermann	Plenum Press	1997	X									
Cryogenic Systems	R.F. Barron	Oxford Univ. Press	1985	X									
Cryogenics	W.E. Bryson	Hanser	1999	X	nicht wissenschaftlich								
Handbook of Cryogenic Engineering	J.G.Weisend II	Taylor & Francis	1998	X	+	++	+	+	++	+	++	+	+
Helium Cryogenics	S.W.Van Sciver	Plenum Press	1986		++	+	+++	++					
Low-capacity Cryogenic Refrigeration	G. Walker, E.R. Bingham	Clarendon	1994			+		+++	++	+			
Min. refrig. for cryo. sensors and cold electr.	G. Walker	Clarendon	1989					++	+++				
Separation of gases	W.H. Isalski	Clarendon	1989										

+ 0- 50 Seiten; ++ 50-100 Seiten; +++ 100-200 Seiten; ++++ 200+ Seiten

Information sources - literature 2

Titel	Autor	Verlag	Jahr	lieferbar	Kryogene	Werkstoffe	Wärmeübertragung	Thermodynamik Prozesse	Komponenten Kälteanlagen	Kryostatenbau	Instrumentierung	Sicherheit	weitere Themen
Cryogenic Discharges	E.I. Asinovsky	Taylor & Francis	1999	X									
Cryogenic Fluids Databook	P. Cook		2002	X									
Cryogenic Two Phase Flow	N.N. Filina, J.G. Weisend II	Cambridge Univ. Pre	1996	X									
Cryogenic Heat Transfer	R.F. Barron	Taylor & Francis	1999	X			++++						
Heat Cap. and Thermal Exp. at Low Temp.	T.H.K. Barron	Plenum Press	1999	X		++++							
Thermod. Prop. of Cryogenic Fluids	R.T. Jacobsen, S.G. Penoncello,	Plenum Press	1997	X	++++								
Polymer Prop. at Room and Cryog. Temp.	G. Hartwig	Plenum Press	1994	X		++++							
Safety in the Handl. of Cryog. Fluids	F.J.Edeskuty, W.F.Stewart	Plenum Press	1996	X								++++	
Kryotechnik	W.G. Fastowski, J.W. Petrowski,	Akademie Verlag	1970			+	++	++	++	+	+		+
Tieftemperaturtechnik	H. Hausen, H. Linde	Springer	1985		+		++	+++	+++		+		+++
Tieftemperaturtechnologie	H. Frey, R.A. Haefer	VDI-Verlag	1981		++	++	++	+		+	+		+++
History and origins of cryogenics	R.G. Scurlock	Clarendon	1992										++++

+ 0- 50 Seiten; ++ 50-100 Seiten; +++ 100-200 Seiten; ++++ 200+ Seiten

Information sources - journals/conferences

- Journals
  - Cryogenics http://www.elsevier.nl/locate/cryogenics
- Conferences
  - Listing http://cern.ch/Goran.Perinic/conf.htm

Information sources - data bases/formulas

- free information sources
    - UIDAHO Center for Applied Thermodynamic Studies -
cryogen property program http://www.webpages.uidaho.edu/~cats/software.htm
    - NIST Cryogenic Technologies Group -
material property equations http://cryogenics.nist.gov/NewFiles/material_properties.html
    - ITS-90 -
vapour pressure - temp. equation for helium http://www.its-90.com/its-90p3.html
- commercial information sources
    - NIST - Thermodynamic and Transport Properties of Pure Fluids Database
http://www.nist.gov/srd/nist12.htm
    - CRYODATA -
cryogen and material database http://www.htess.com/software.htm/
    - Cryogenic Information Center -
cryogen and material database and bibliography http://www.cryoinfo.org/

End

Extras

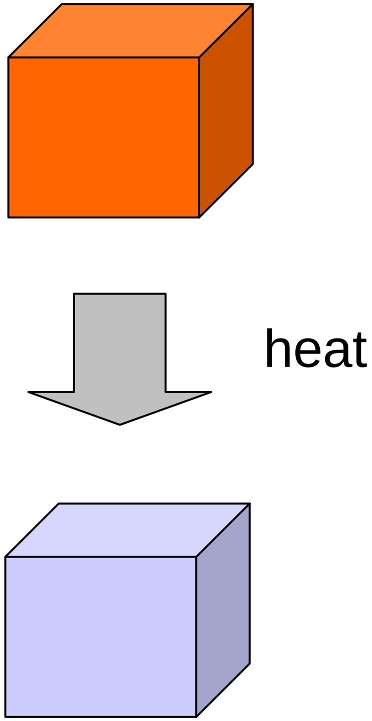
The cryogenists toolbox

- Internal Energy and Enthalpy
- Energy conservation
- Entropy Exergy
- Diagrams TS,
- Cycles
- Efficiency

Energy conservation

- Bernoulli
- static system

Principles of refrigeration

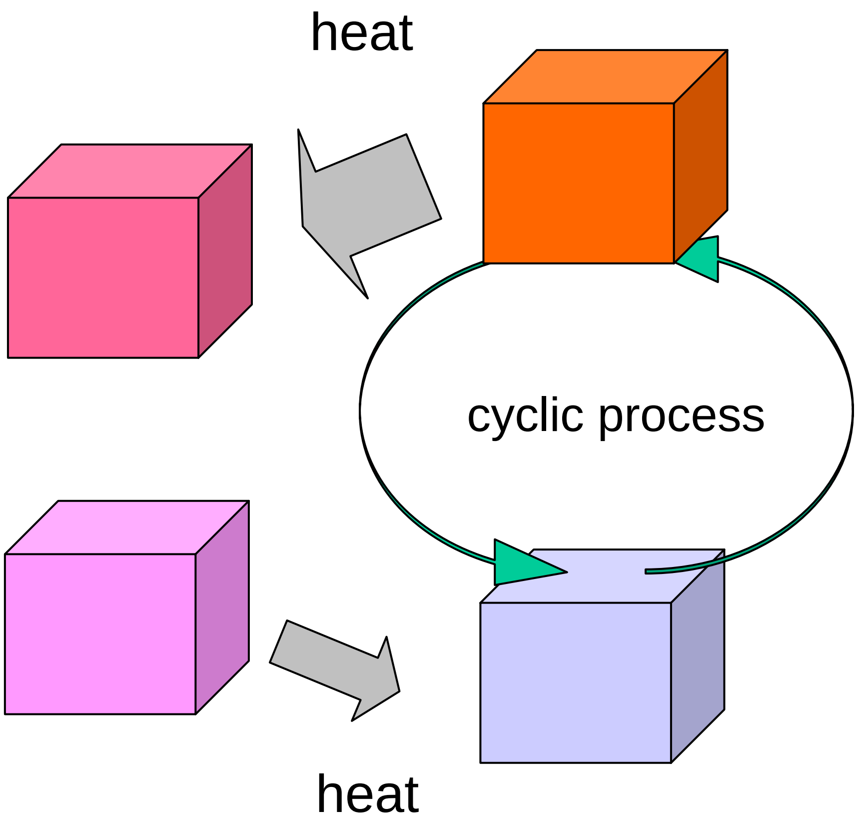


2nd law of thermodynamics

Entropy

- $dQ/T = S = \text{const}$
- state variables p,T,V, U,H,S

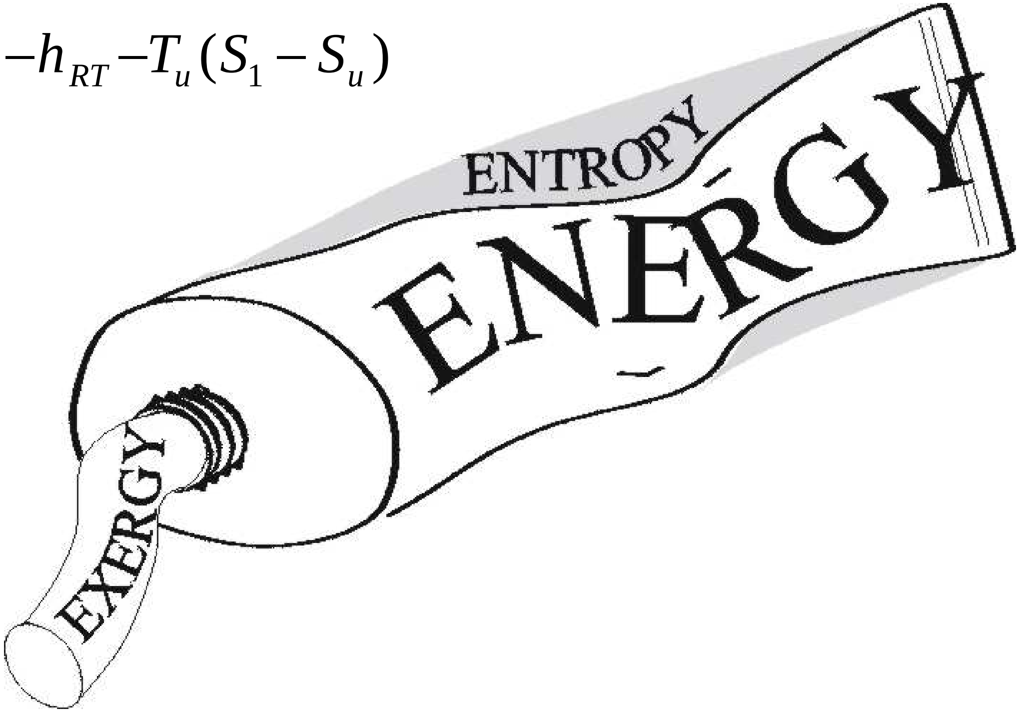
Principles of refrigeration

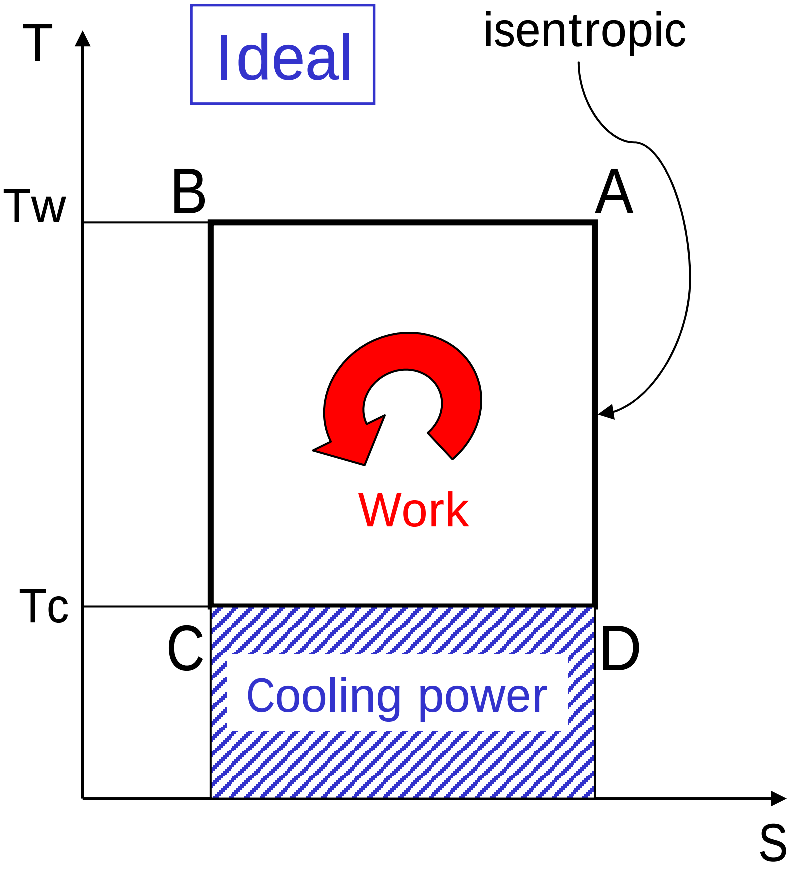


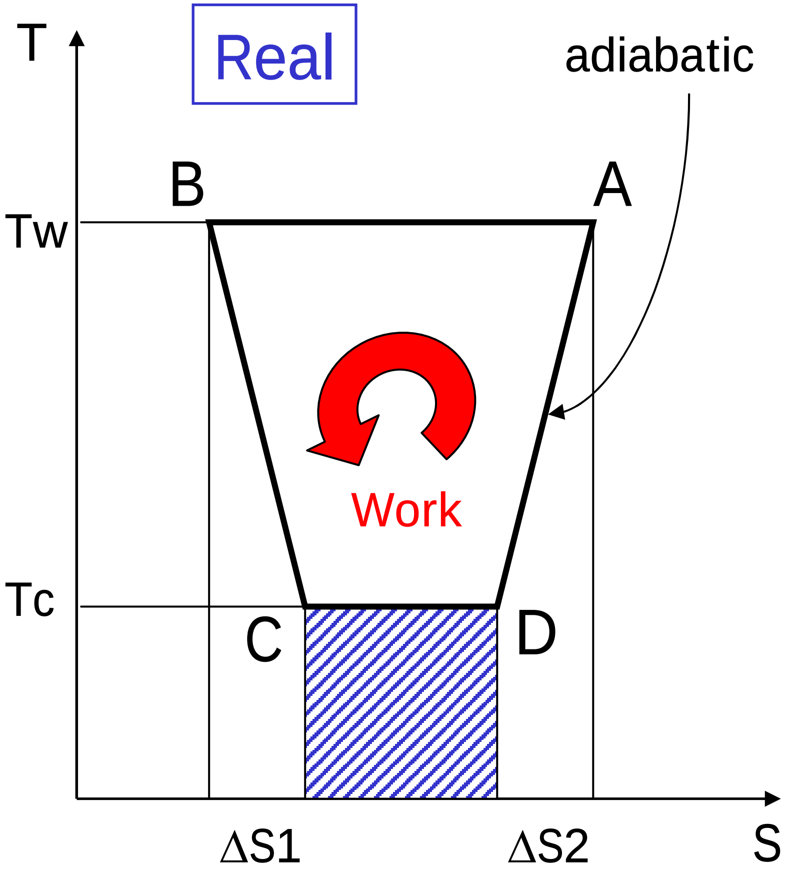
2nd law of thermodynamics

Exergy

$$-W_{ex} = h_1 - h_{RT} - T_u(S_1 - S_u)$$




T
Ideal
isentropic
Tw
B
A
Work
Tc
C
D
Cooling power
S


T
Real
adiabatic
B
A
Tw
Work
Tc
C
D
ΔS1
ΔS2
S

Summary

- throttling

- work

Cryogenics past to present

- time of I. Newton (1642 - 1727)

- R. Boyle (1627 - 1691); E. Mariotte (1620 - 1684) pV=constant
- J J Becher (1635 - 1682), G.E Stahl (1660 - 1734) phlogiston
- G. Amontons (1663 - 1705) absolute zero

Other talks

- VDI
  - Thermodynamics
  - Refrigerants
  - Material properties
  - Heat transfer
  - Thermal insulation
  - Measurement and controls
  - Safety
  - Microcoolers -- Large refrigerators
  - Cryopumps

Other talks

- Weisend
  - basics
  - cryogens
  - materials
  - refrigeration
  - He II
  - cryostat design
  - instrumentation
  - safety

- Quack
  - temperature reduction by throttling or mixing
  - temperature reduction by work extraction
  - refrigeration cycles
  - cryogens
  - cooling principles
  - applications

Throttling - as seen by a thermodynamist

- first law

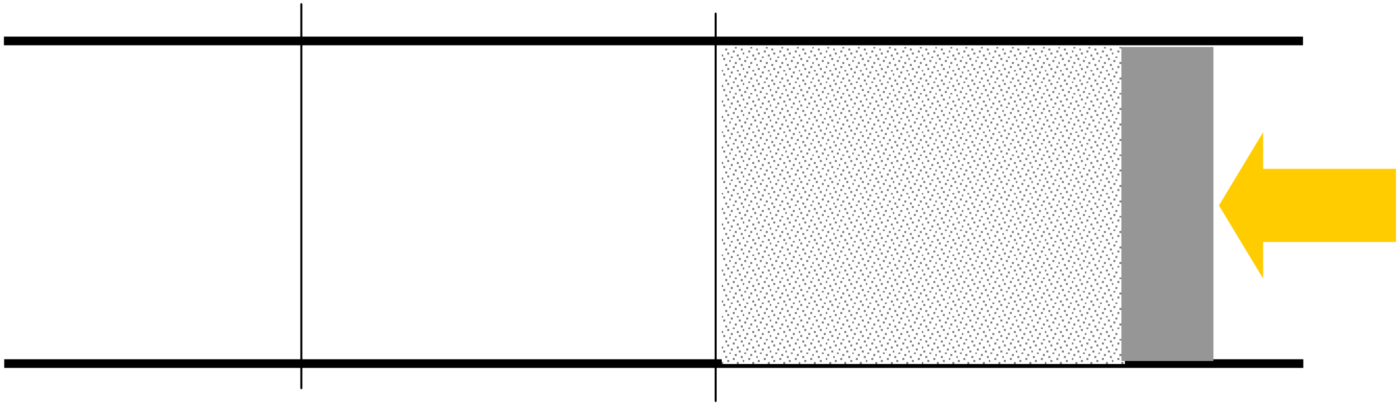
$$dU = dQ + dW = 0$$

- energy content

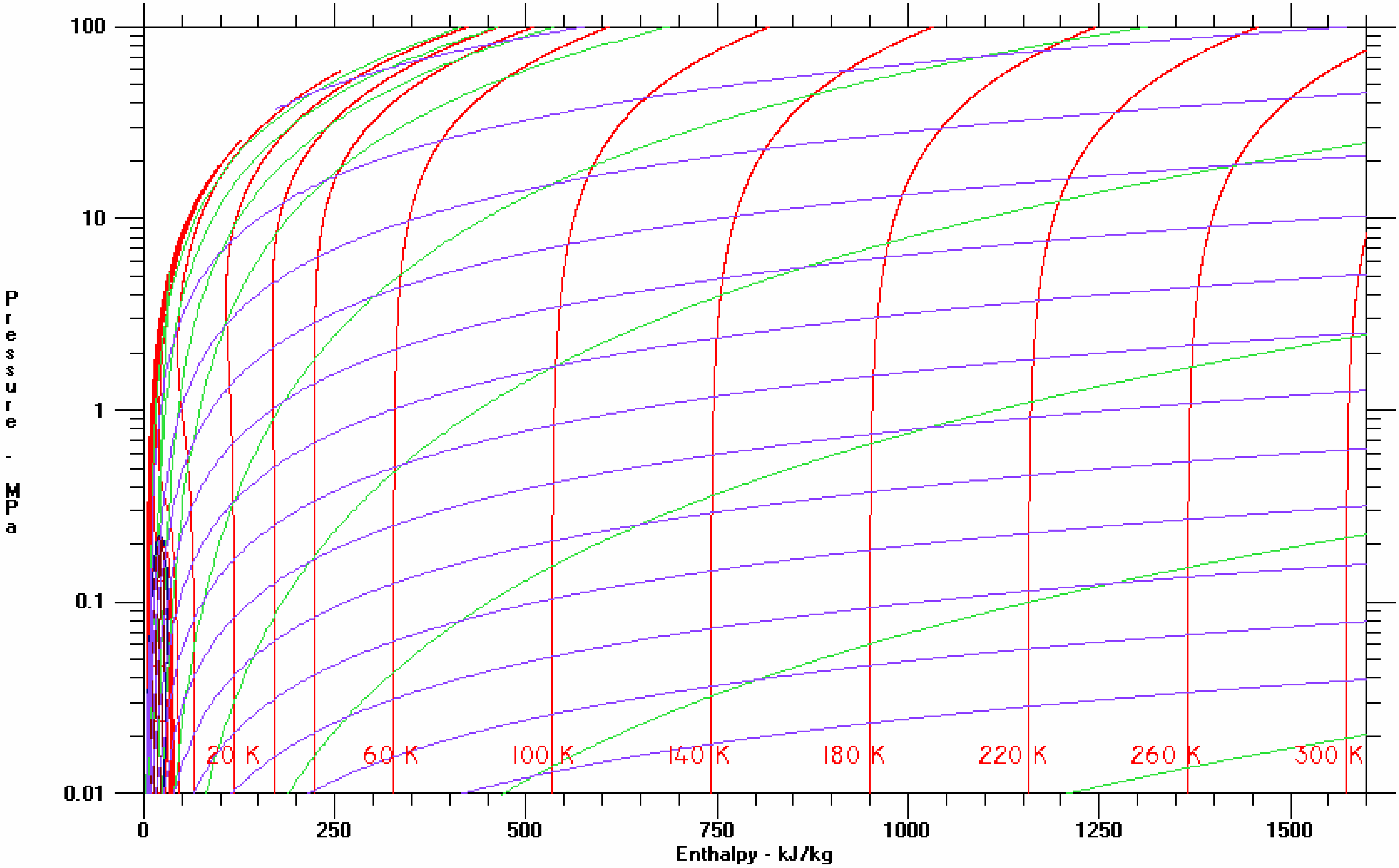
$$E = U + pV + E_{kin} + E_{pot} = H$$

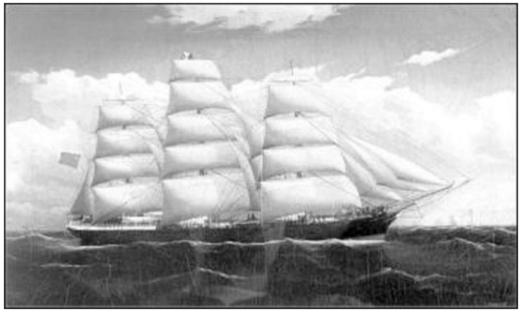
$$m*u_1+p_1*A_1*w_1 = m\,(u_1+p_1v_1) = m*h_1$$

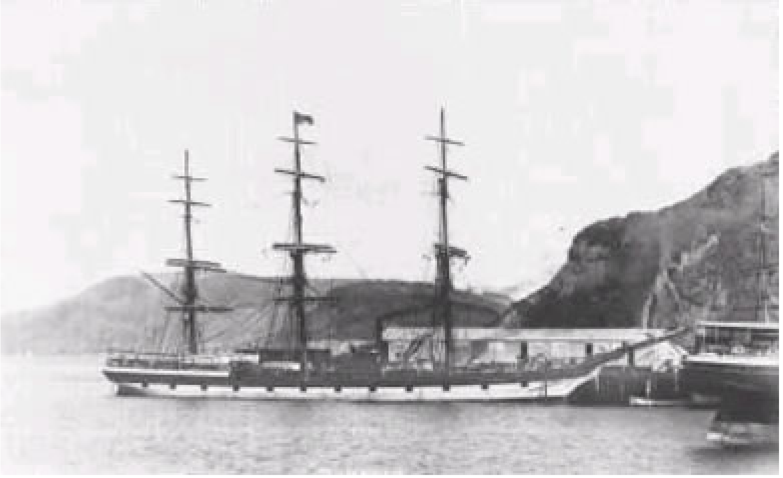
$$mu_1 + p_1A_1w_1 = m(u_1 + p_1v_1) = mh_1$$



$$mu_1 + p_1A_1w_1 = m(u_1 + p_1v_1) = mh_1 \qquad mu_2 + p_2A_2w_2 = m(u_2 + p_2v_2) = mh_2$$


100
10
1
0.1
0.01
Pressure - MPa
0
250
500
750
1000
1250
1500
Enthalpy - kJ/kg
20 K
60 K
100 K
140 K
180 K
220 K
260 K
300 K





Sailing ship Dunedin, equipped with a Bell-Coleman air cycle refrigerator. The ship left Port Chalmers on 15 February and arrived in England on 14 May 1882.

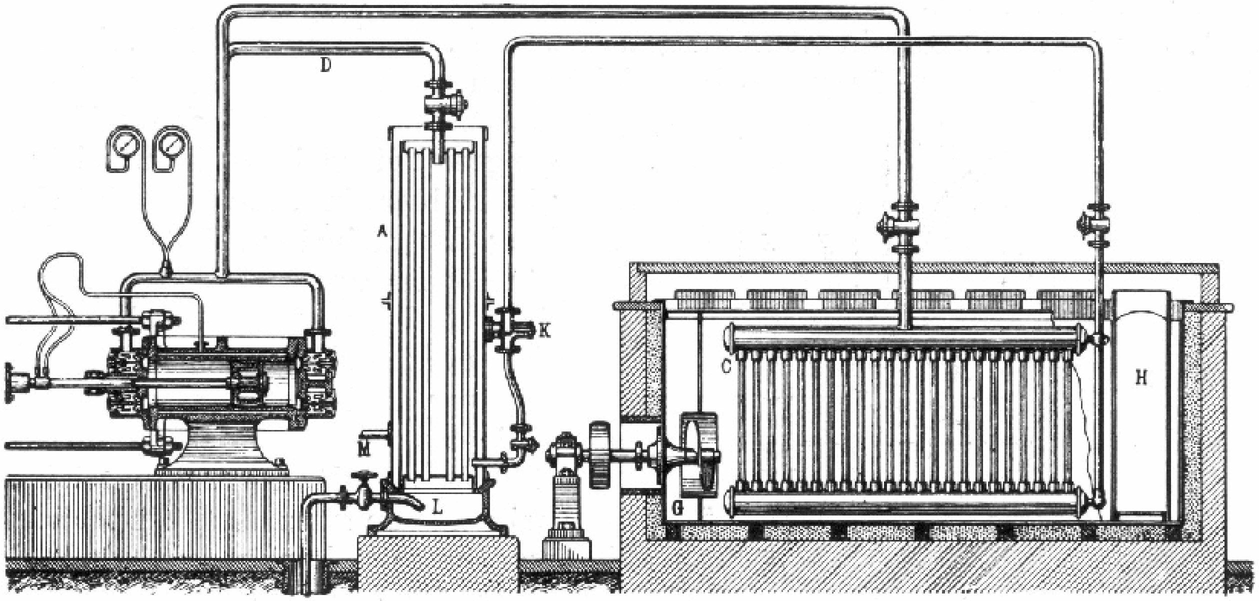
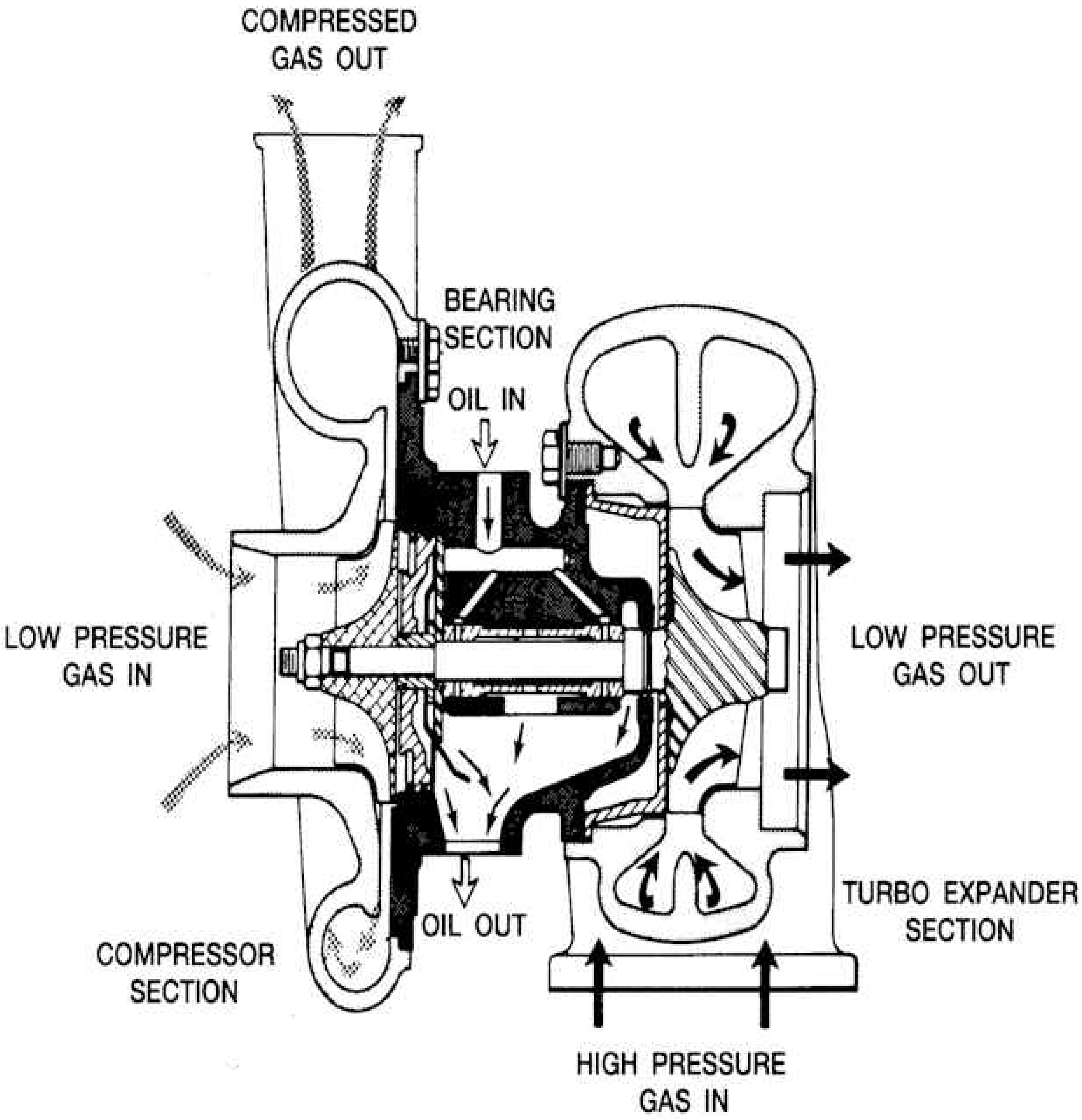
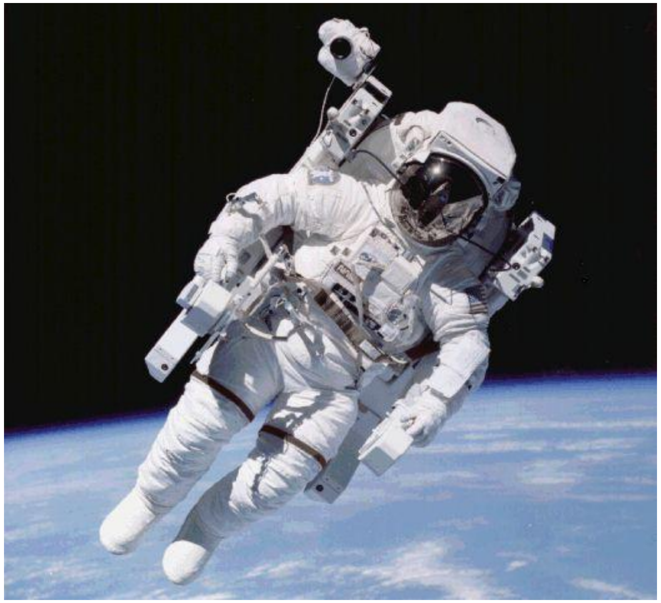


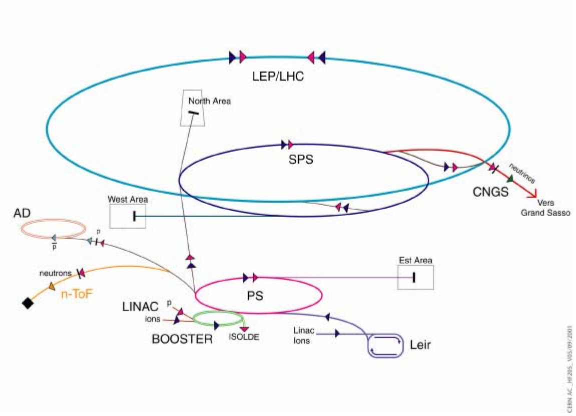
Abb. 44. SO_2-Eismaschine von RAOUL PICTET.

A Kondensator, *C* Verdampfer, *D* Druckrohr, *G* Rührwerk, *H* Eiszelle, *K* Drosselventil, *L* Wassereintritt in den Kondensator, *M* Wasseraustritt.


COMPRESSED GAS OUT
BEARING SECTION
OIL IN
LOW PRESSURE GAS IN
LOW PRESSURE GAS OUT
OIL OUT
COMPRESSOR SECTION
TURBO EXPANDER SECTION
HIGH PRESSURE GAS IN

What is cryogenics?

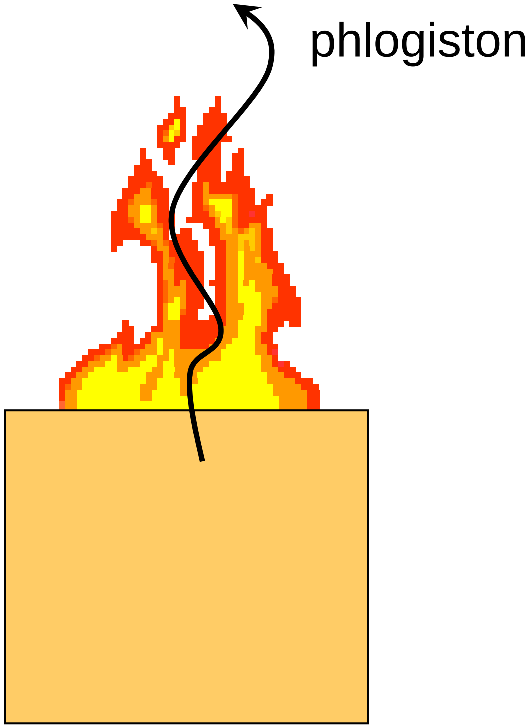




Time of I. Newton

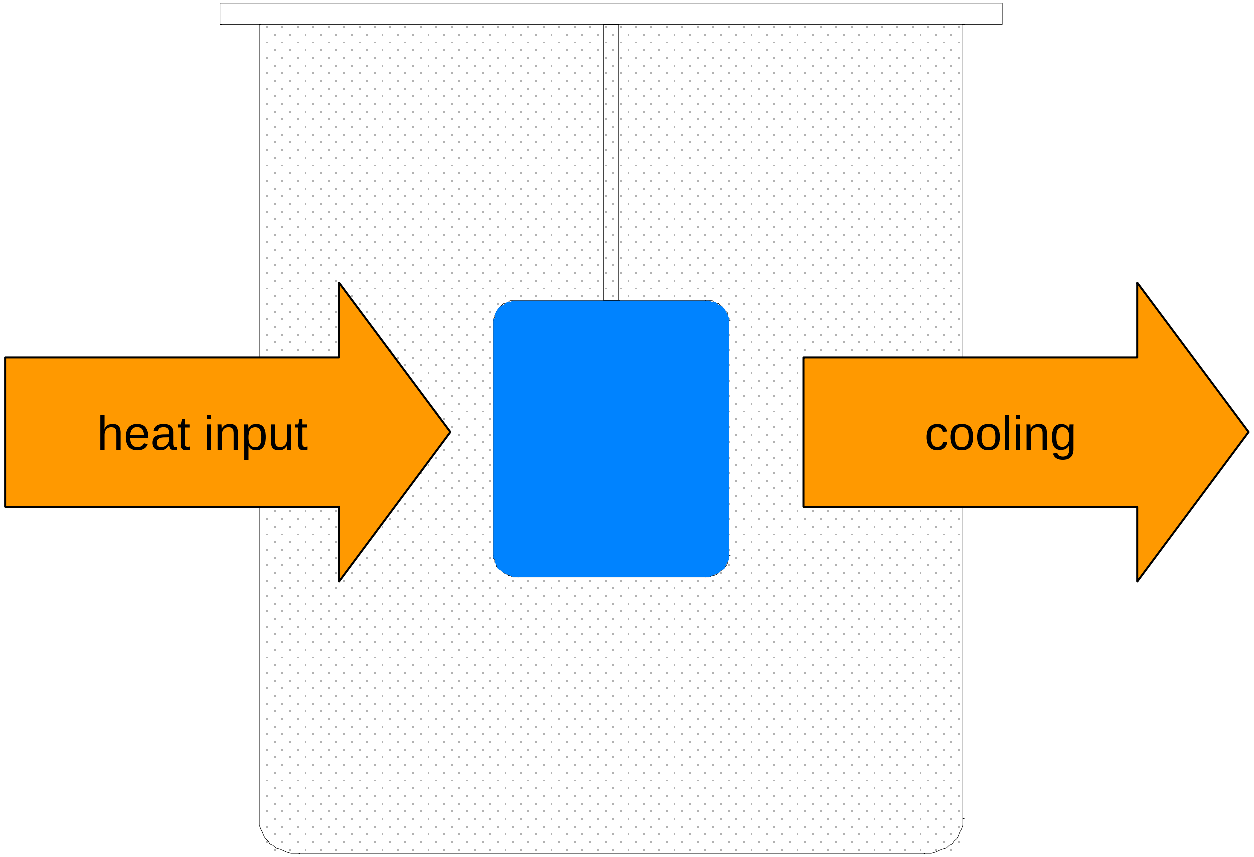
I. Newton
1642 - 1727

- J J Becher (1635 - 1682), G.E Stahl (1660 - 1734)

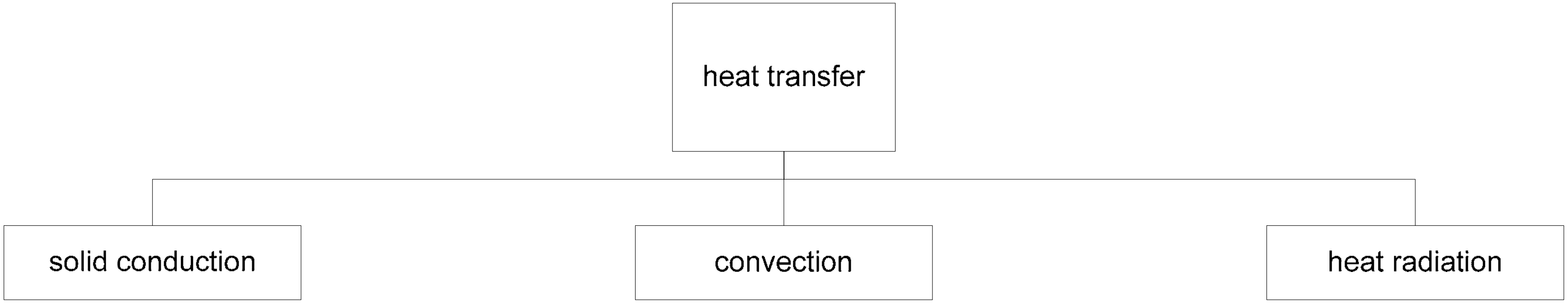


Heat transfer and insulation

Cool and keep cold



cooling or heat removal



heat transfer

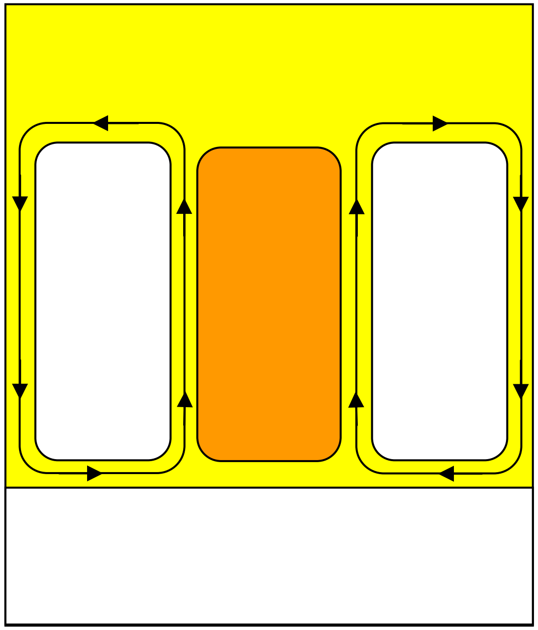
solid conduction

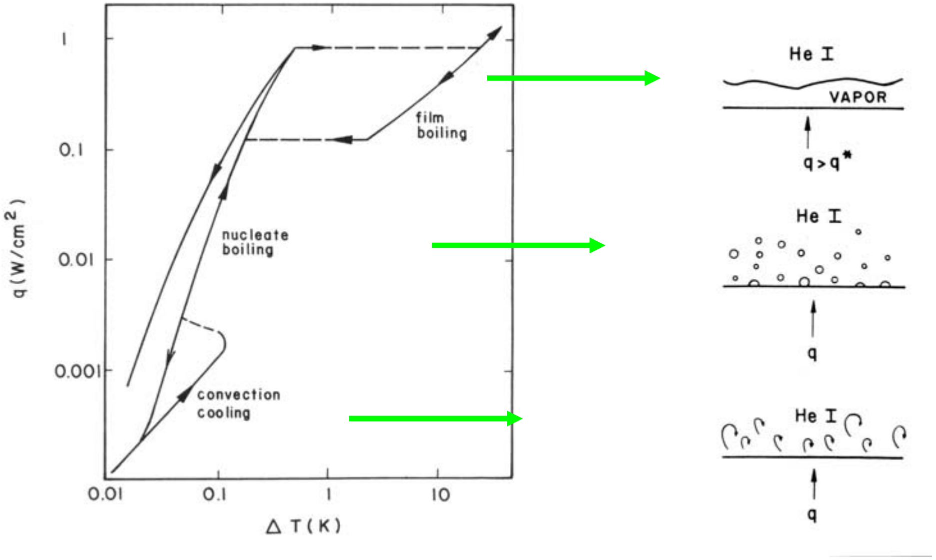
convection

heat radiation

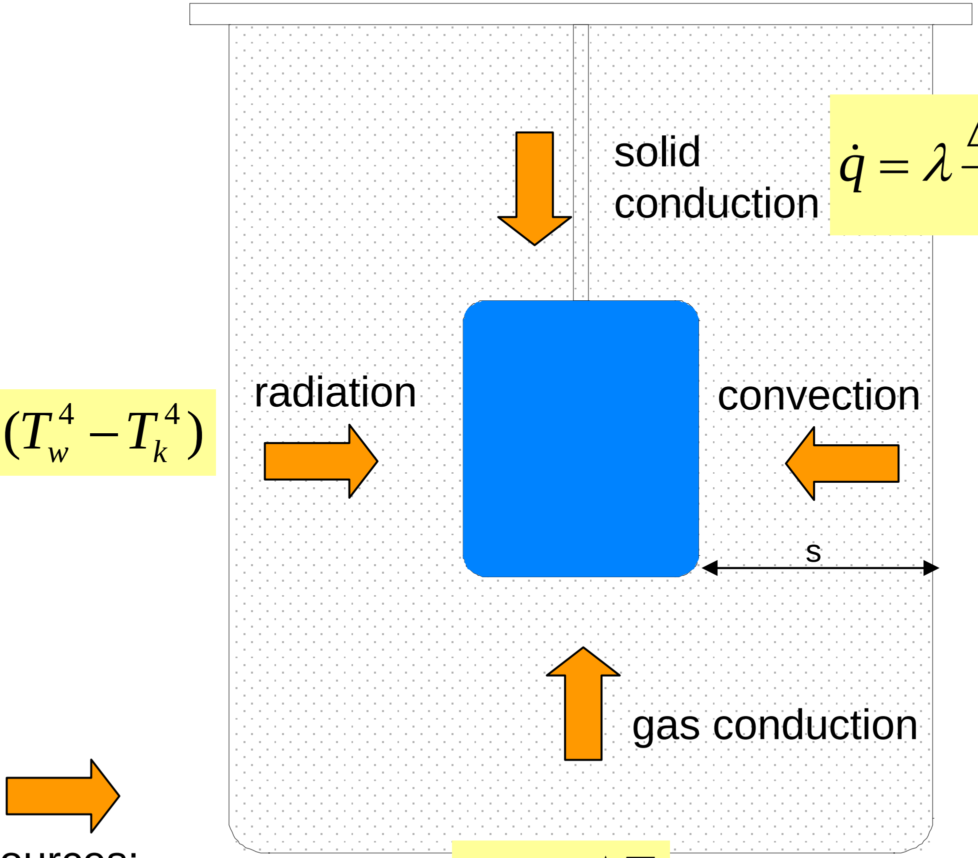
choice of the
refrigerant

Bath cooling





Sources of heat input



solid conduction

$$\dot{q} = \lambda \frac{\Delta T}{s}$$

radiation

$$\dot{q} \sim \varepsilon (T_w^4 - T_k^4)$$

convection

gas conduction

further sources:
- nuclear radiation
- induction

$$\dot{q} = \lambda \frac{\Delta T}{s} \qquad \Lambda << s$$

$$\dot{q} \sim p \Delta T \qquad \Lambda >> s$$

λ - heat conductivity
Λ - free path length

- solid conduction

$$\dot{q} = \lambda \frac{\Delta T}{s}$$

- convection

$$\dot{q} = \lambda \frac{\Delta T}{s}$$

$$\dot{q} \sim p\,\Delta T$$

$$\dot{q} \sim \varepsilon\,(T_w^4 - T_k^4)$$

Introduction to Refrigerators and Cryogens

Wärmequellen im Vakuum

- Festkörperleitung durch
  - Kryostatenhals,
  - Rohrleitungen,
  - Ventile,
  - Aufhängungen,
  - Abstützungen,
  - elektrische Leitungen
- Wärmeübertragung durch
  - Restgas im Isolationsvakuum

$$p >\sim 10^{-4}\ \text{mbar} \quad \dot{Q} \sim 1/L$$

$$p <\sim 10^{-4}\ \text{mbar} \quad \dot{Q} \sim p$$

(bei konstanter Temperaturdifferenz)

- Strahlung

$$\dot{Q} = \varepsilon\, \sigma\, A\, T^4$$

- Sonstige
  - Heizungen
  - Quench
  - induzierte Ströme