Science & engineering for cryogenic safety

Philippe Lebrun
CERN, Geneva, Switzerland

European Graduate Course in Cryogenics
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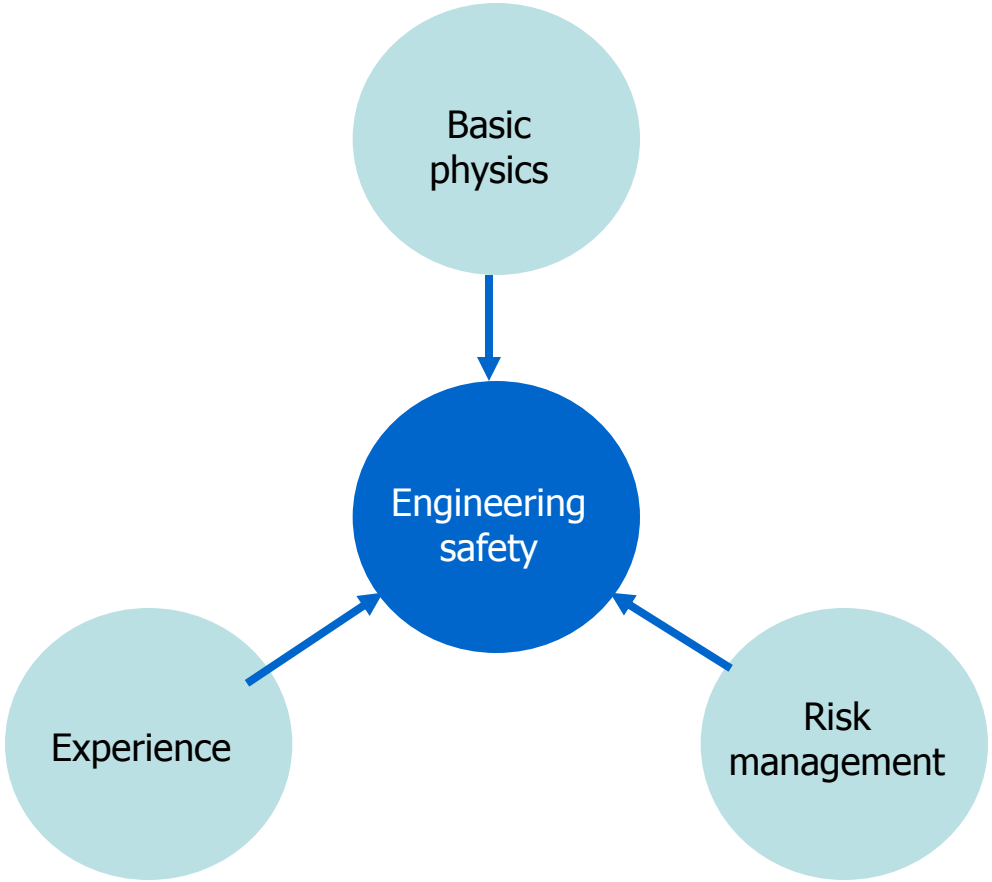
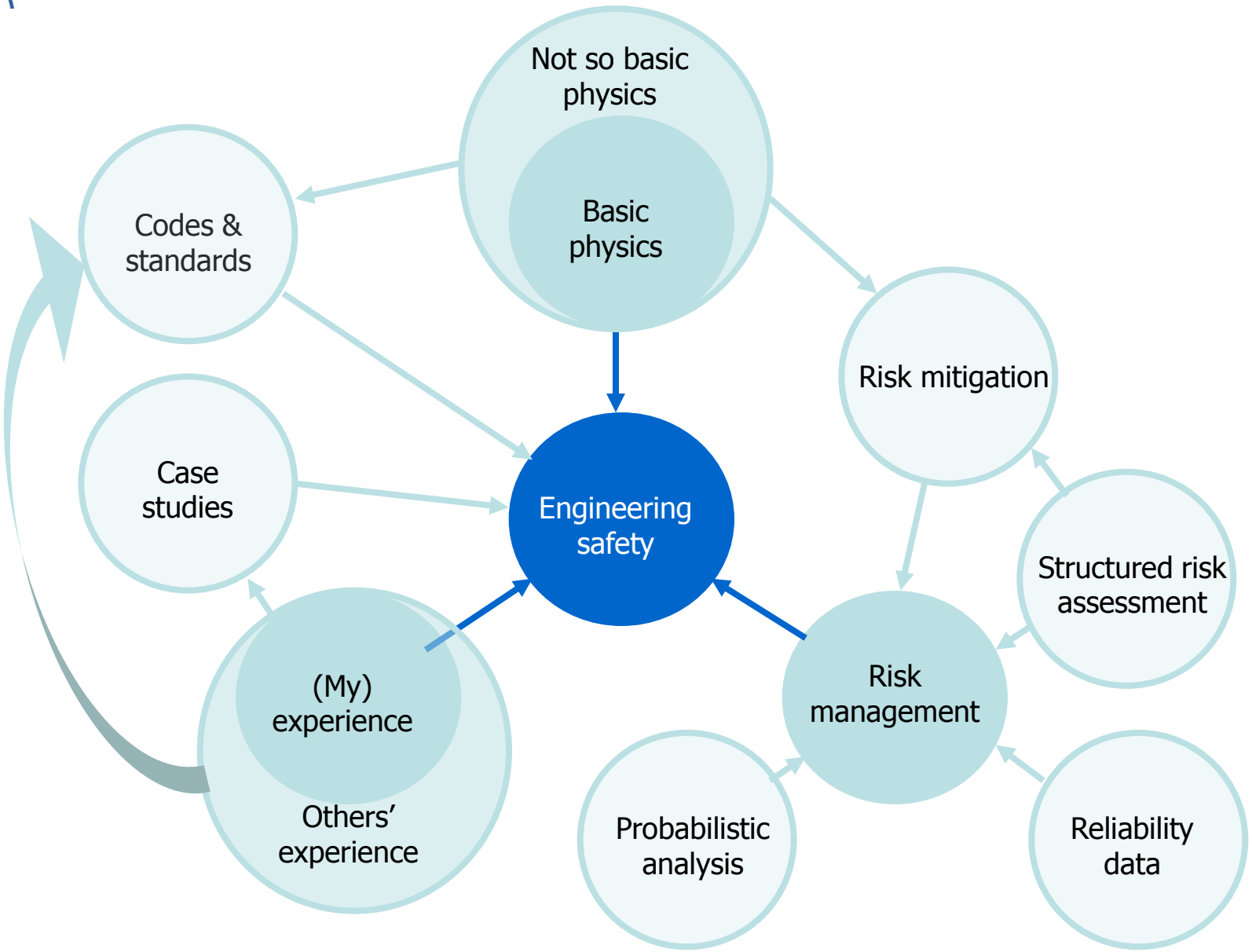
Engineering safety: the simple view



Engineering safety: a more complex pattern



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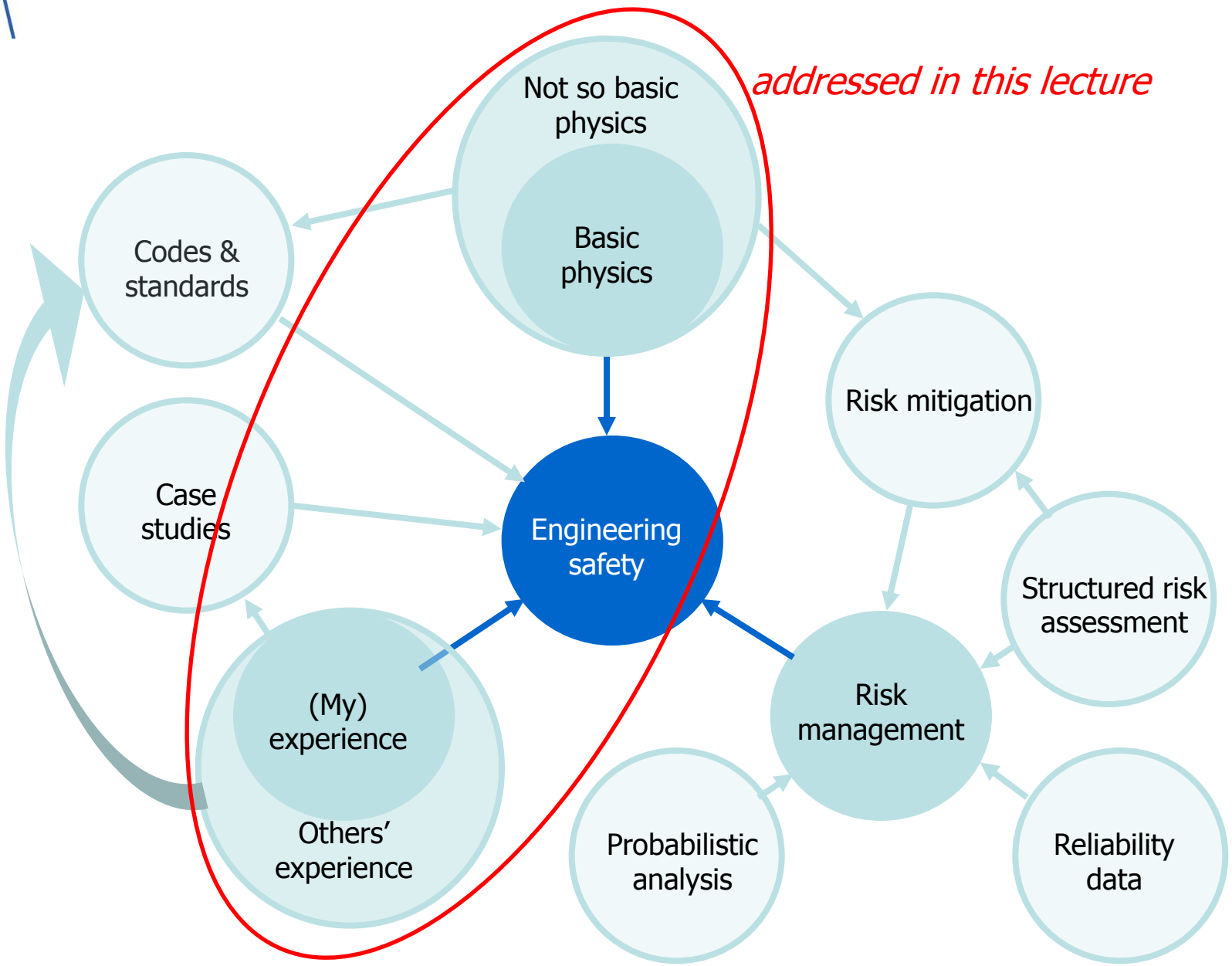

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- Energy release potential of liquid cryogens
  - Thermal energy: cooling of equipment
  - Mechanical energy: damage
- Physiological hazards
  - Freezing of tissue
  - Oxygen deficiency
- Liquid cryogen spillage
  - Mixing and buoyancy
  - Stratified flow in tunnel
- Material properties
  - Thermal contraction
  - Embrittlement
- Mechanical design
  - Combined pressure/temperature regimes
  - Mechanical instabilities (buckling) under pressure or vacuum
- Fluid properties
  - Pressure buildup and relief in cryogenic vessels
  - Air condensation and oxygen enrichment
  - Loss of insulation vacuum
- A compound case: the LHC accident

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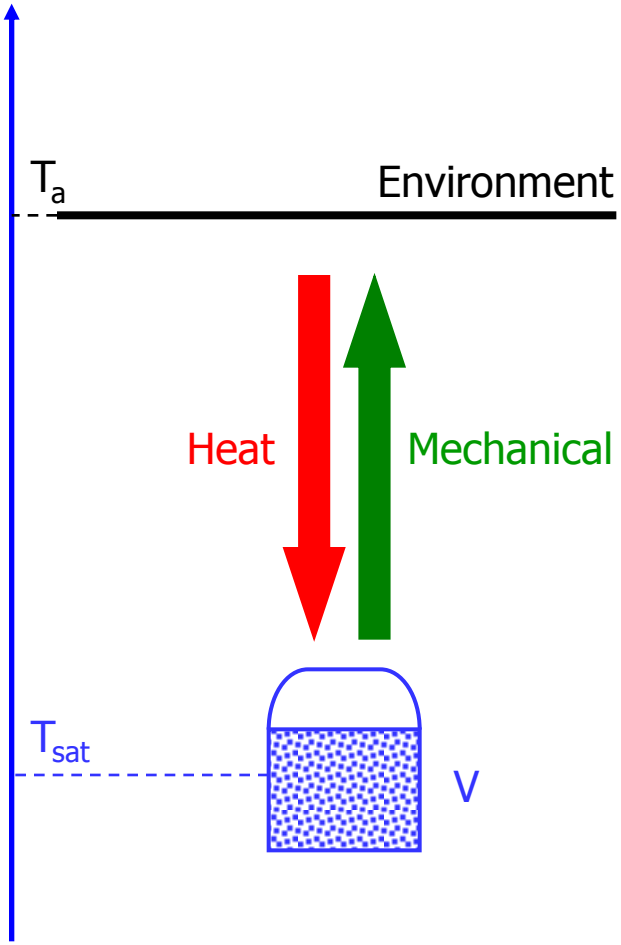
Energy release potential of liquid cryogens



- Consider vessel containing volume V of liquid cryogen at saturation (T_{sat}) and atmospheric pressure, environment at T_a
  - What is the energy release potential of that liquid?
  - How much damage can be done by releasing it to the environment?
- Technical answer depends upon the details of the process, but… thermodynamics can set upper boundaries to answer these questions
  - Cooling of equipment (thermal energy): first principle
  - Mechanical damage (mechanical energy): second principle

Cooling of equipment: thermal energy

- Heat needed to vaporize mass m of liquid and warm resulting vapour up to temperature T

$$Q(T) = m\,L_v + m\,C_p\,(T-T_{sat})$$

  - Case 1: 1000 liter (125.2 kg) liquid helium at 4.2 K, 1 bar
    Lv = 20.8 kJ/kg Cp ≈ 5.2 kJ/kg.K
  - Case 2: 1000 liter (806.6 kg) liquid nitrogen at 77.2 K, 1 bar
    Lv = 199.3 kJ/kg Cp ≈ 1.05 kJ/kg.K

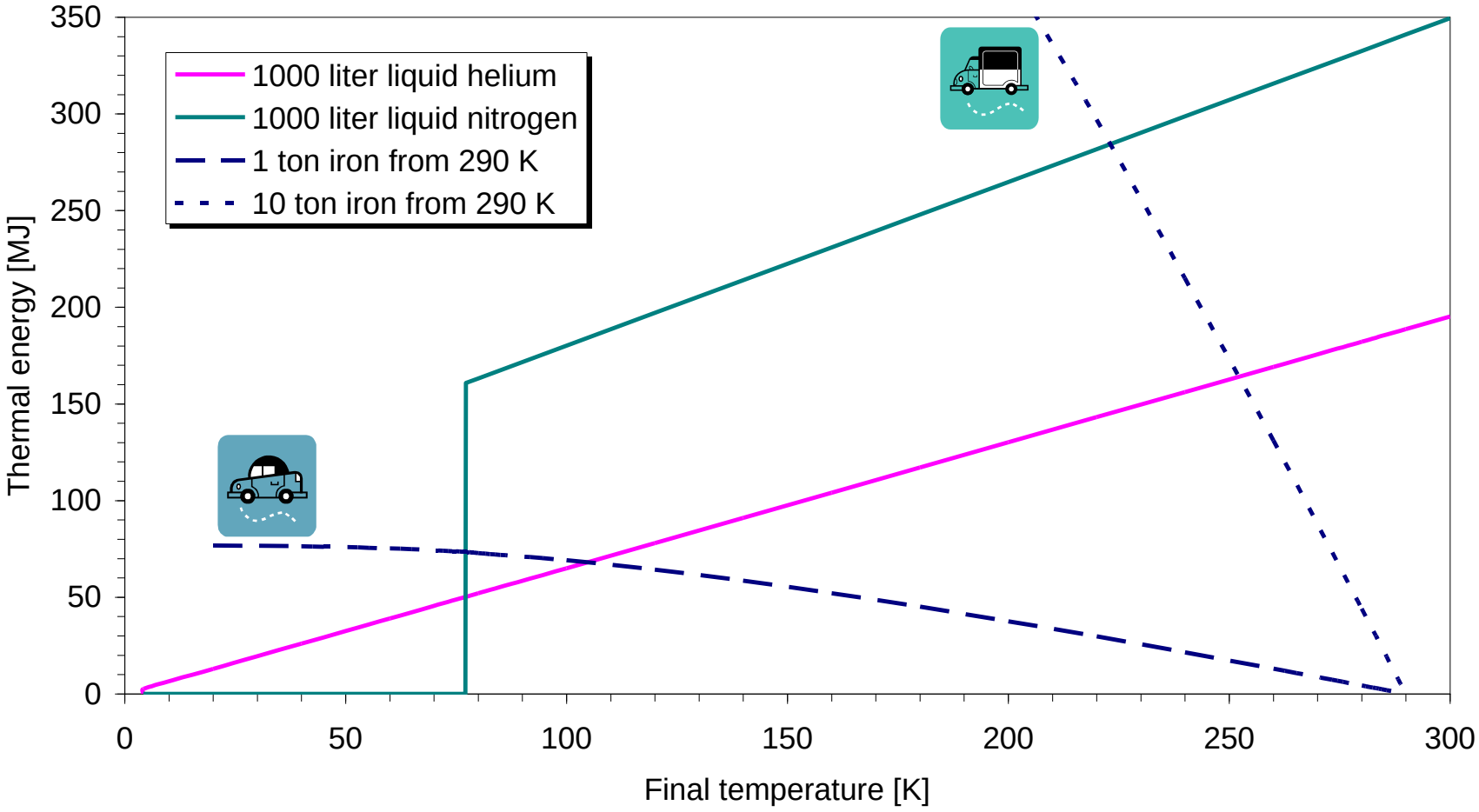
- First principle of thermodynamics (energy conservation): Q is drawn from the environment of the fluid, where it will cool mass M of equipment from T_a down to temperature T

$$Q(T) = M\,[h(T_a)-h(T)]$$

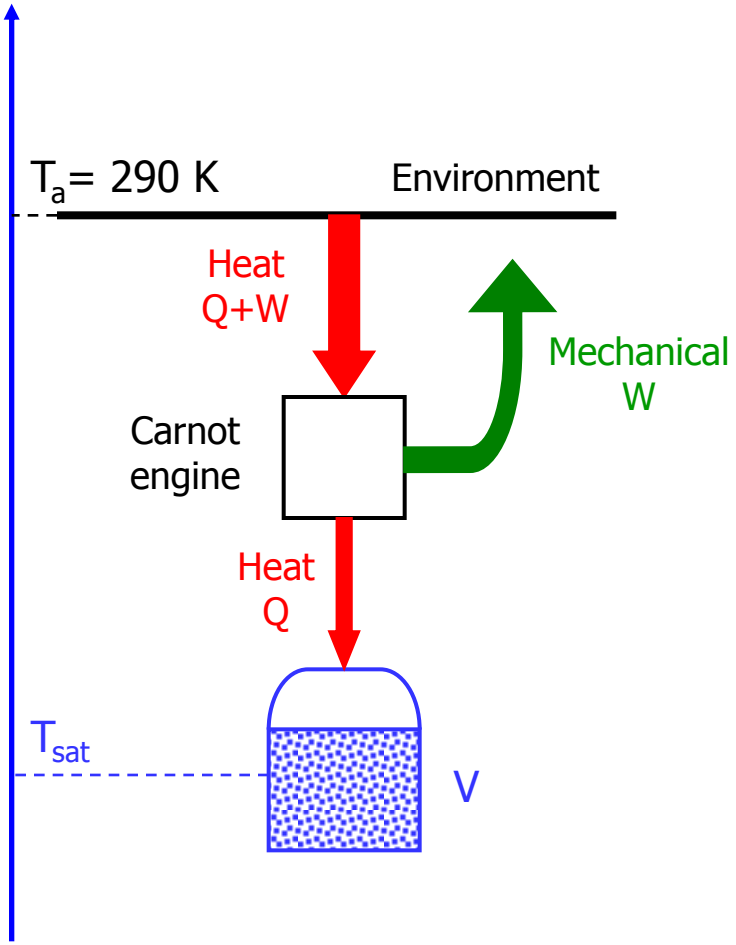
h(T) enthalpy of material

  - Applications: 1 ton of iron 10 tons of iron

Cooling potential of liquid cryogens



Mechanical energy release



- Upper bound set by 2nd principle of thermodynamics (Carnot)
- Mechanical energy W
  - extracted from heat Q at T
  - by Carnot engine rejecting at Ta

  $W = Q\,(T_a/T - 1)$
- Consider only heat of vaporization at T_{sat}

  $W = m\,L_v\,(T_a/T_{sat} - 1)$
  - Case 1: 1000 liter liquid He at 4.2 K
    $(T_a/T_{sat} - 1) \approx 68$
    $W \approx 177$ MJ (~ 65 kg TNT)
  - Case 2: 1000 liter liquid N2 at 77.2 K
    $(T_a/T_{sat} - 1) \approx 2.76$
    $W \approx 443$ MJ (~ 163 kg TNT)
- Real process
  - efficiency < Carnot
  - also include specific heat of vapour
  - see examples later

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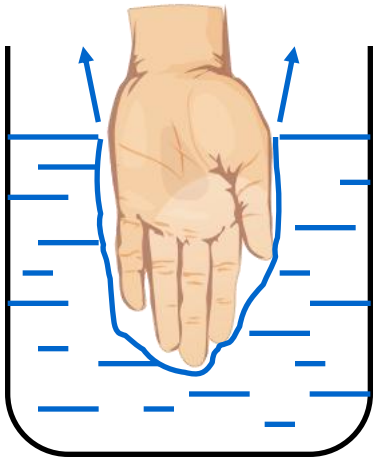
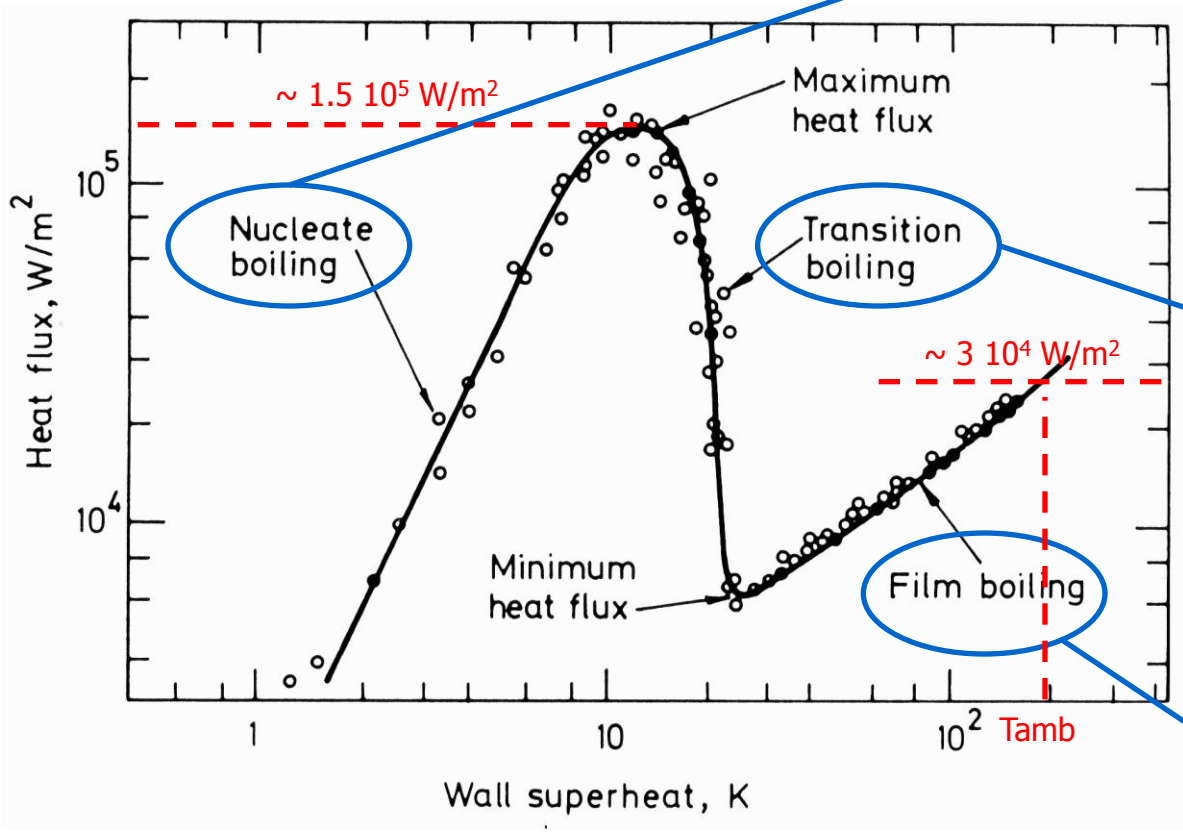
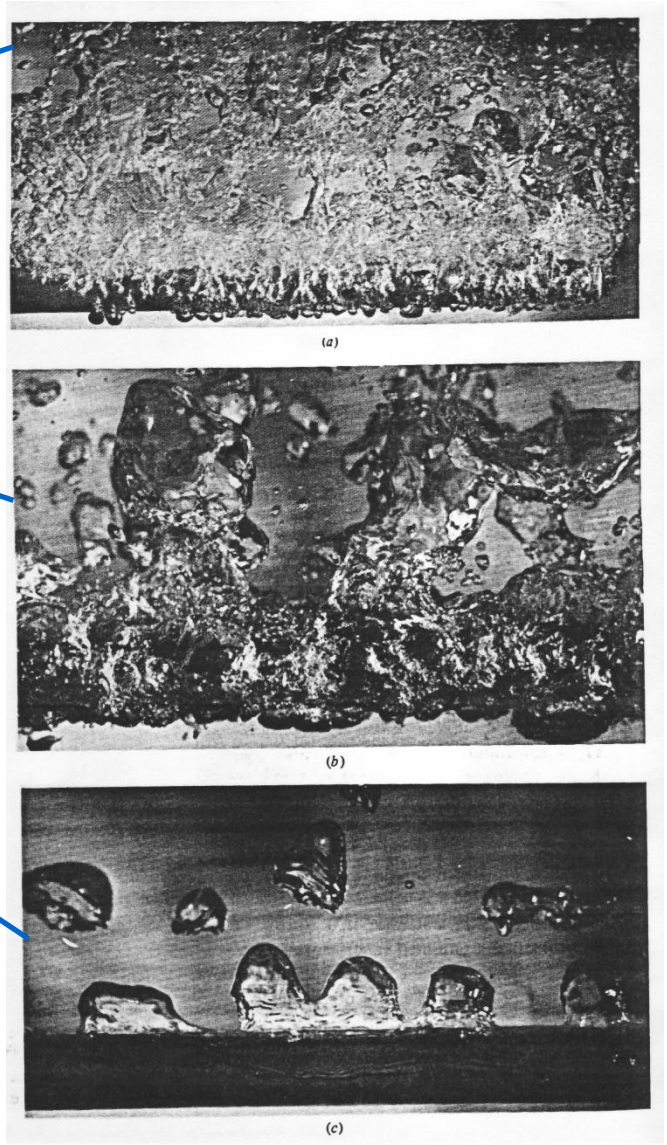
Freezing of tissue by cryogens



- Dipping one's hand into liquid nitrogen (for limited time)
  - Calefaction (film boiling) limits heat transfer to few W/cm^2
  - No harm

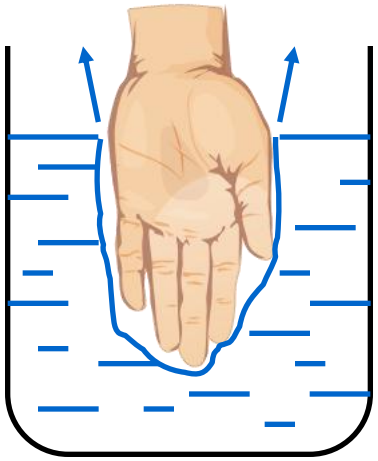
Pool boiling heat transfer for nitrogen

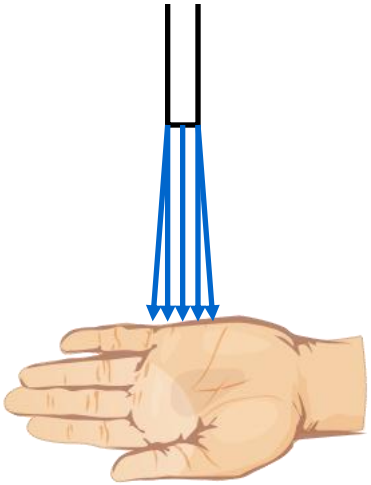


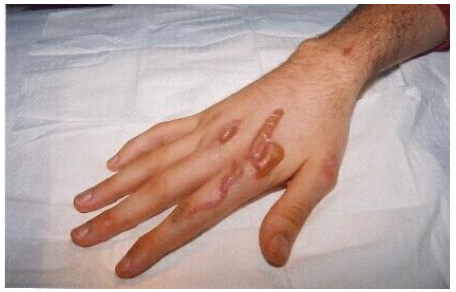


H. Merte & J.A. Clark, *Boiling heat transfer for LN2 at standard and near-zero gravity*, Adv. Cryo Eng. 7 (1962) 546-550

Freezing of tissue by cryogens







- Dipping one's hand into liquid nitrogen (for limited time)
  - Calefaction (film boiling) limits heat transfer to few W/cm^2
  - No harm

- Cryogen jet impinging on hand
  - High convective heat transfer
  - Risk of severe burns

⇒ in all cases, use personal protection equipment

Heat transfer in liquid nitrogen jet

- Object of characteristic dimension D in liquid nitrogen jet, velocity v
- Reynolds number $Re = \rho v D/\eta$
- Heat transfer coefficient $h = k Nu/D$
- Correlation for Nusselt number around cylindrical object D

  $Nu \approx 0.25\ Re^{0.6}\ Pr^{0.38}$ for $10^3 < Re < 10^6$
- Take D ≈ 5 cm
- Liquid nitrogen (1 bar, 77 K) jet of moderate velocity 1 m/s

  $\rho = 807$ kg/m^3

  $\eta = 151$ μPa.s

  $k = 0.133$ W/m.K

  $Pr = 2.3$

  Then Re = 267'000, Nu = 620, h = 1650 W/m^2.K

  Hence $h\,\Delta T \approx 3\ 10^5$ W/m^2, i.e. *10 times more efficient than film boiling*

Properties of cryogens compared to water

Property		He	N_2	H_2O
Normal boiling point	[K]	4.2	77	373
Critical temperature	[K]	5.2	126	647
Critical pressure	[bar]	2.3	34	221
Liq./Vap. density (*)		7.4	175	1600
Heat of vaporization (*)	[$J.g^{-1}$]	20.4	199	2260
Liquid viscosity (*)	[μPl]	3.3	152	278

(*) at normal boiling point

Vaporization of normal boiling cryogens under 1 W applied heat load

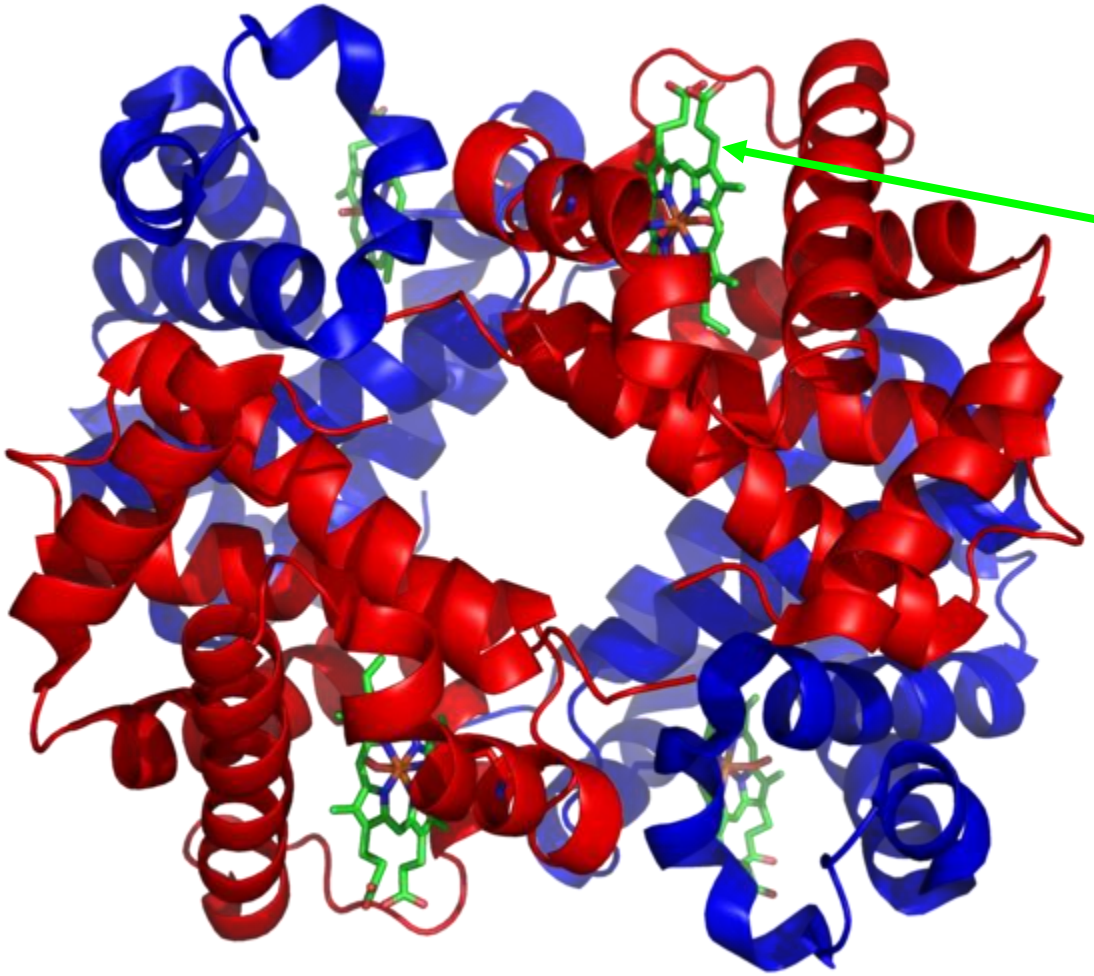
Cryogen	[mg.s^{-1}]	[l.h^{-1}] (liquid)	[l.min^{-1}] (gas NTP)	Liquid-to-gas NTP density ratio
Helium	48	1.38	16.4	748
Nitrogen	5	0.02	0.24	691

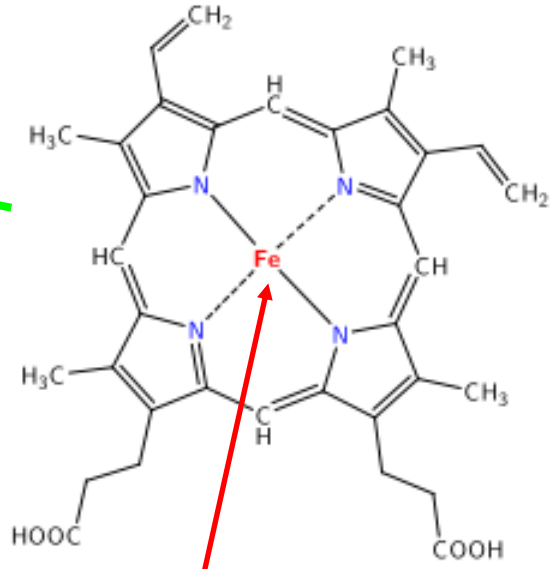
Effect thresholds for ODH

Volume % Oxygen	Effect
17	Night vision reduced
	Increased breathing volume
	Accelerated heartbeat
16	Dizziness
	Reaction time for novel tasks doubled
15	Impaired attention
	Impaired judgment
	Impaired coordination
	Intermittent breathing
	Rapid fatigue
	Loss of muscle control
12	Very faulty judgment
	Very poor muscular coordination
	Loss of consciousness
	Permanent brain damage
10	Inability to move
	Nausea
	Vomiting
6	Spasmatic breathing
	Convulsive movements
	Death in 5-8 minutes

?

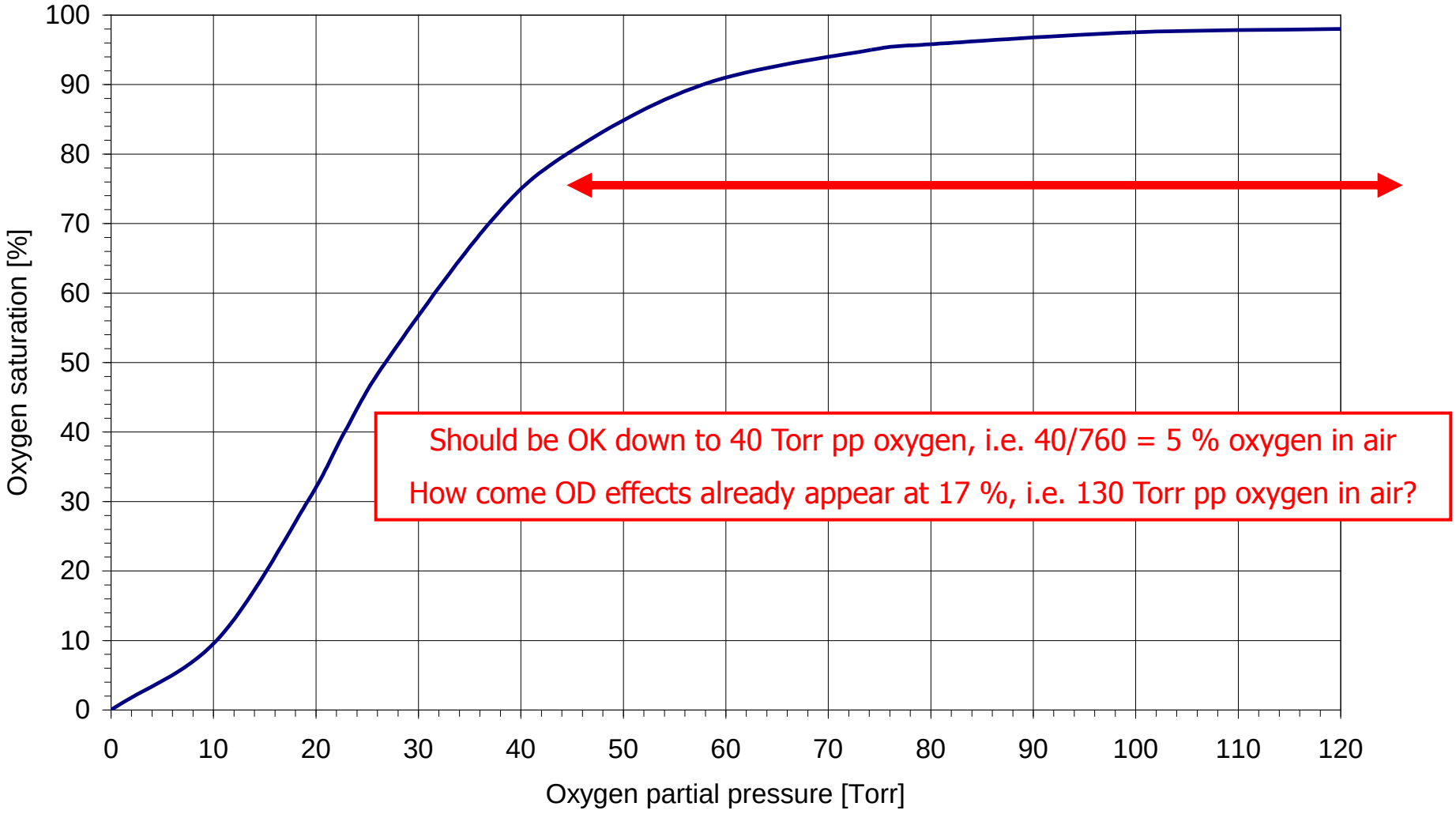
Hemoglobin molecule and oxygen ligand (heme)





Oxygen binding site

Oxygen saturation curve of hemoglobin



Alveolar gas equation

Saturated vapor pressure of water at body temperature (47 Torr at 37 C)

Respiratory quotient = CO_2 rejected/O_2 consumed

(1 for carbohydrates, 0.8-0.9 for proteins, 0.7 for lipids)

$$p_AO_2 = F_IO_2(P_{ATM} - pH_2O) - \frac{p_aCO_2(1 - F_IO_2[1 - RQ])}{RQ}$$

Arterial partial pressure of CO_2 (~ 35 Torr)

Effect of saturated water vapour

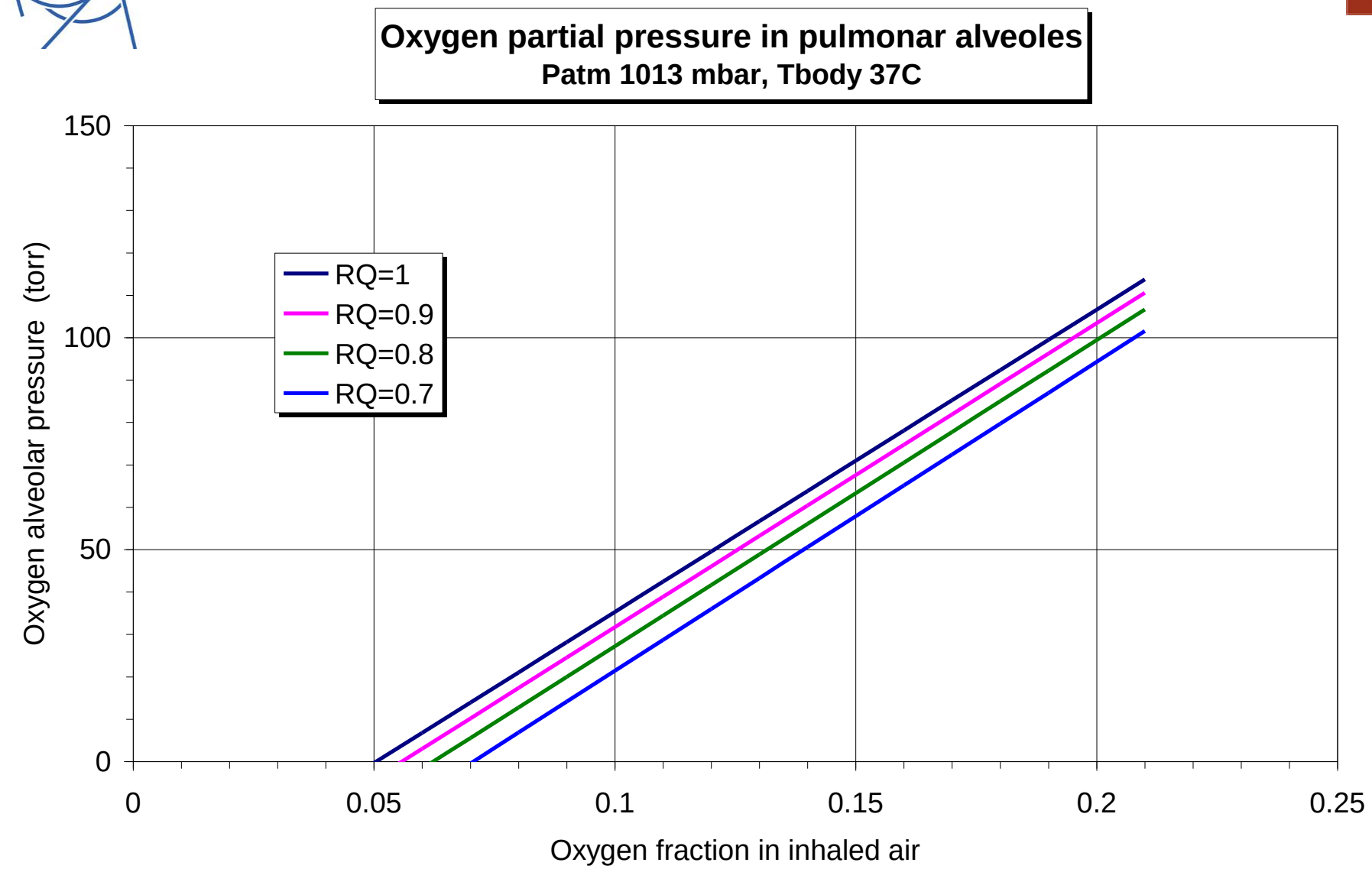
Effect of CO_2 rejection

Alveolar-arterial pressure gradient

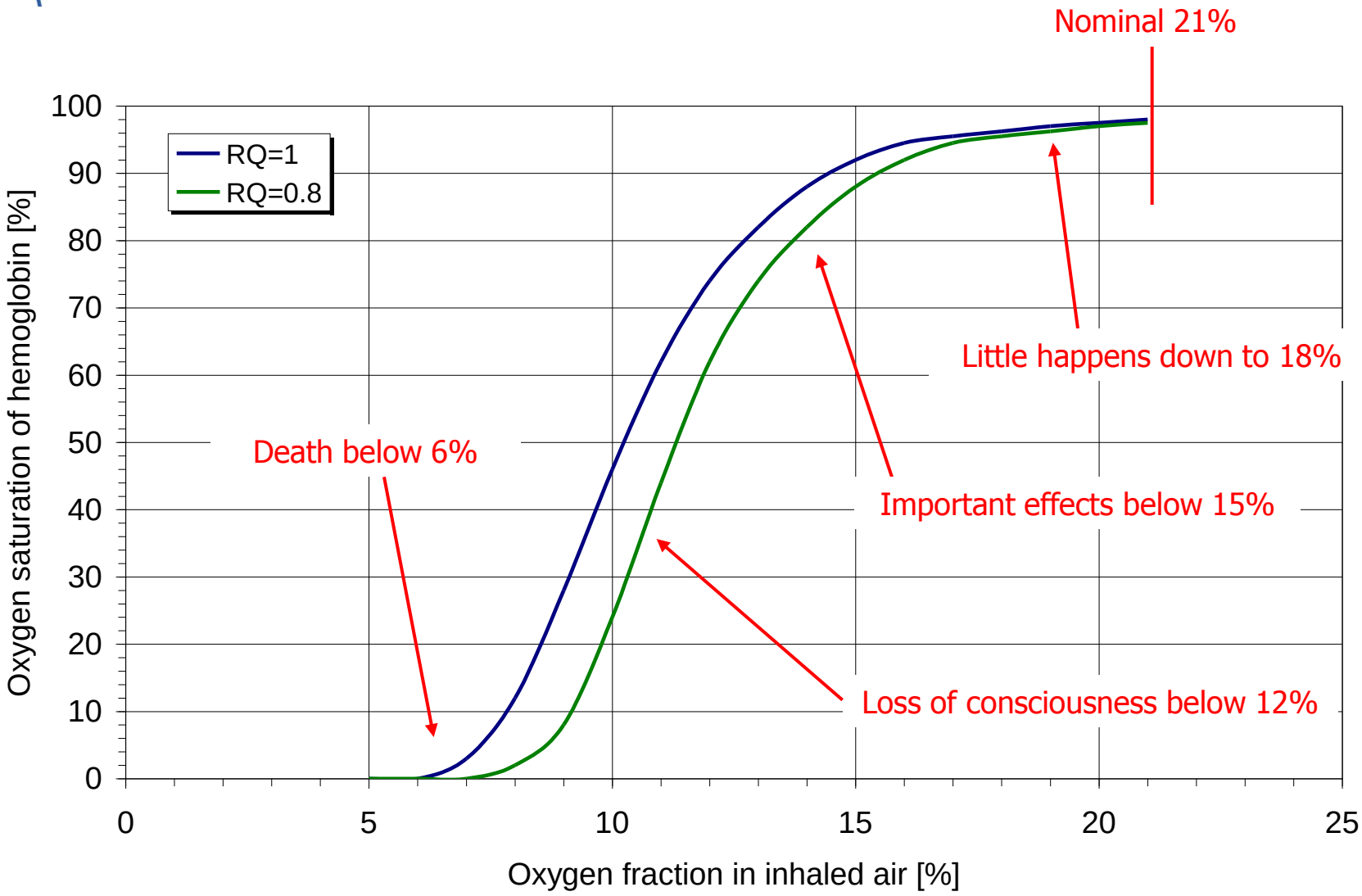
$$\text{A-a gradient} = p_AO_2 - p_aO_2$$

Range 5-20 Torr, normally < 10 Torr

W.O. Fenn, H. Rahn & A.B. Otis, *A theoretical study of the composition of the alveolar air at altitude*, American Journal of Physiology **146** 5 (1946) 637-653


Oxygen partial pressure in pulmonar alveoles
Patm 1013 mbar, Tbody 37C
RQ=1
RQ=0.9
RQ=0.8
RQ=0.7
Oxygen alveolar pressure (torr)
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25
Oxygen fraction in inhaled air

Oxygen in hemoglobin vs oxygen in inhaled air
(Alveolar-arterial gradient = 10 Torr)



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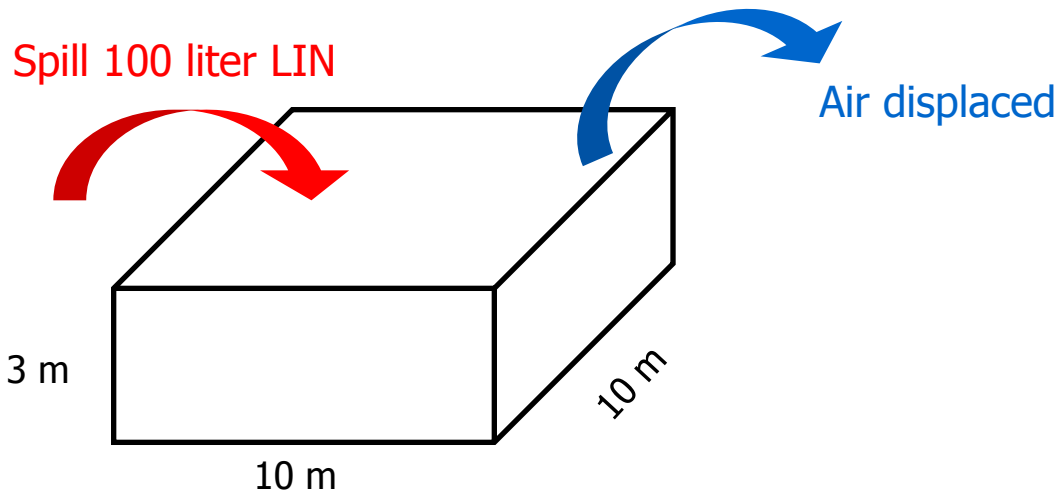
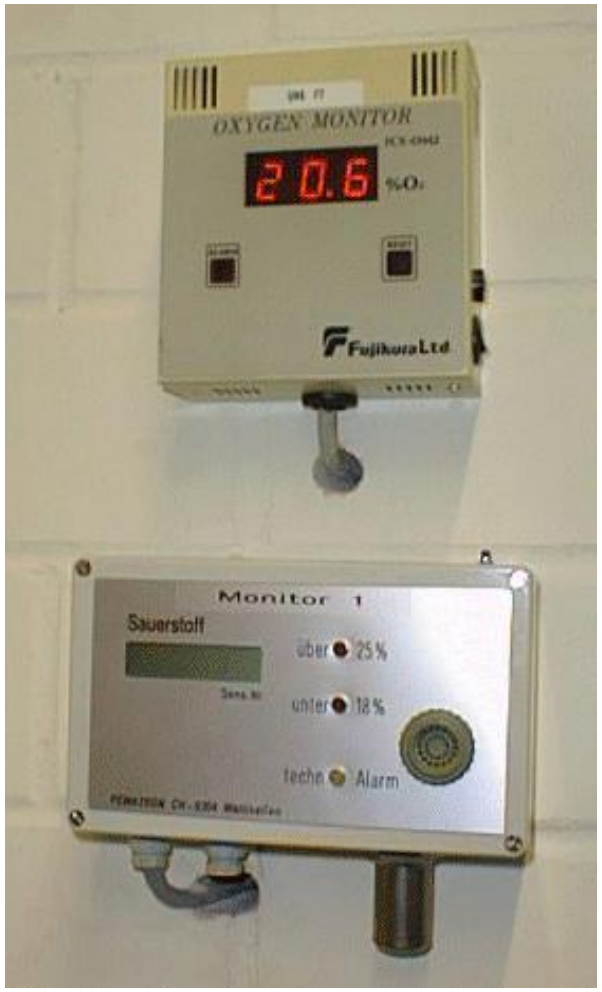
Cryogen spillage and oxygen displacement



- Geometrical volume of laboratory = 300 m^3
- Spilling 100 liter LIN releases 70 m^3 gaseous nitrogen NTP
- Assume air displacement initially without mixing: 70 m^3 air displaced, containing 14.7 m^3 NTP of oxygen
- Remaining oxygen content 48.3 m^3 NTP, i.e. 16.1 volume %

⇒ *Oxygen deficiency hazard*

Oxygen monitors



Fixed

Personal, portable

Buoyancy of cold helium in atmosphere
A simple argument

- Ideal gas approximation (per mole)

  $PV = RT \quad \Rightarrow \quad dV|_P = R\,dT / P$

- Definition of enthalpy (per mole)

  $dH = C_p\,dT$

- Hence

  $dV|_P = R\,dH / P\,C_p$

  $dV/dH \sim 1/C_p$

  For helium (monoatomic), $C_p = 5\,R/2$

  For air (diatomic), $C_p = 7\,R/2$

$\Rightarrow$ dV/dH is always higher for helium than for air

$\Rightarrow$ cold helium will eventually rise in air upon warmup

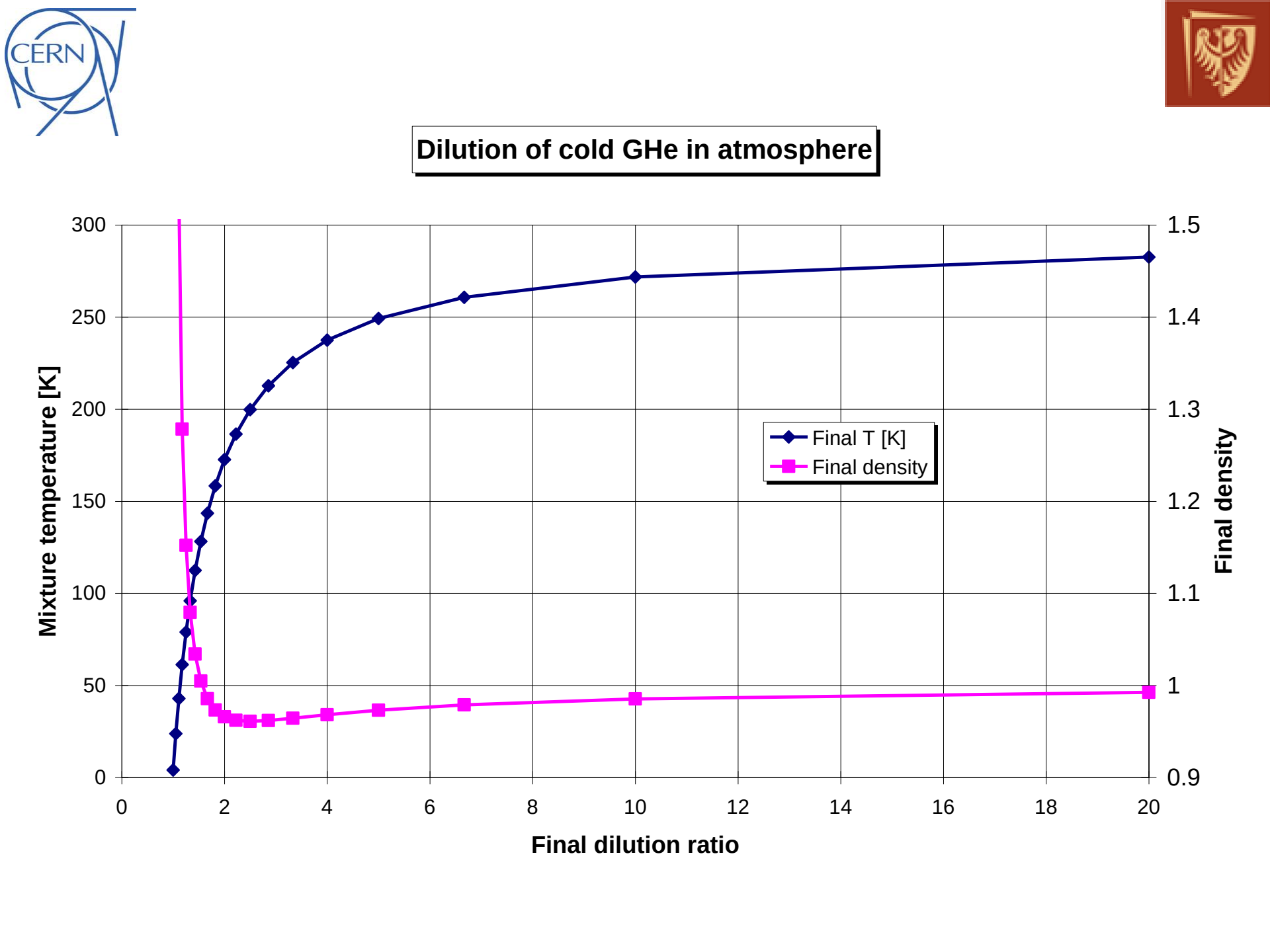
Dilution and buoyancy of cryogen spills in air
A more detailed calculation

- Consider spillage of cryogen at saturation and its dilution in atmosphere at 293 K: under which conditions will it rise or sink?
- Two competing effects
  - Warm up tends to increase buoyancy
  - Dilution tends to decrease buoyancy of lighter gases
- Let x be the molar fraction of the spilled cryogen in mixture
- Energy conservation

  $x\ C\ (T_{mix} - T_{sat}) = (1-x)\ C_{air}\ (293 - T)$
- Mass conservation

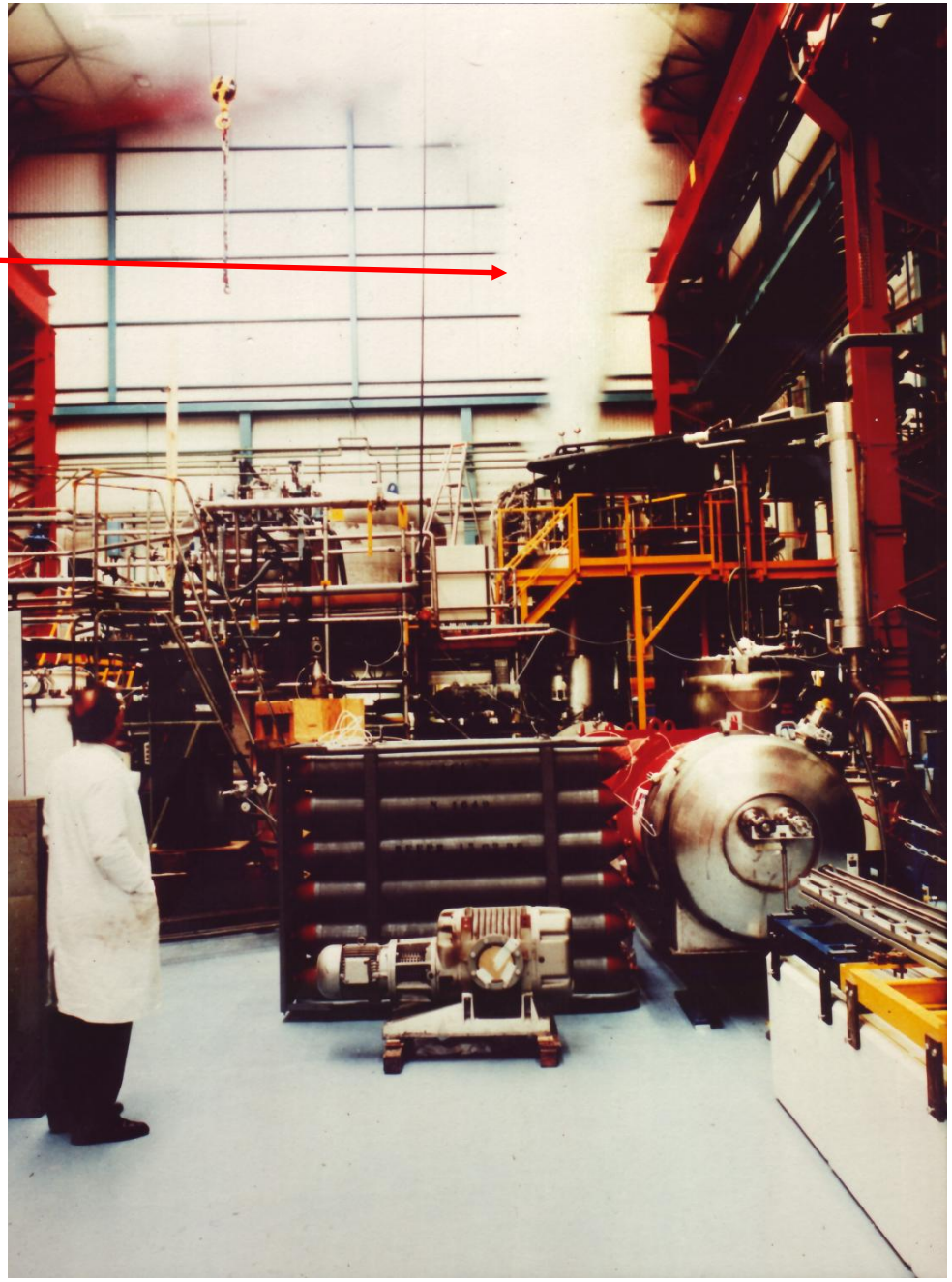
  $M_{mix} = x\ M + (1-x)\ M_{air}$ with $M_{air} = 29$
- Density of mixture (w.r. to atmosphere at 293 K)

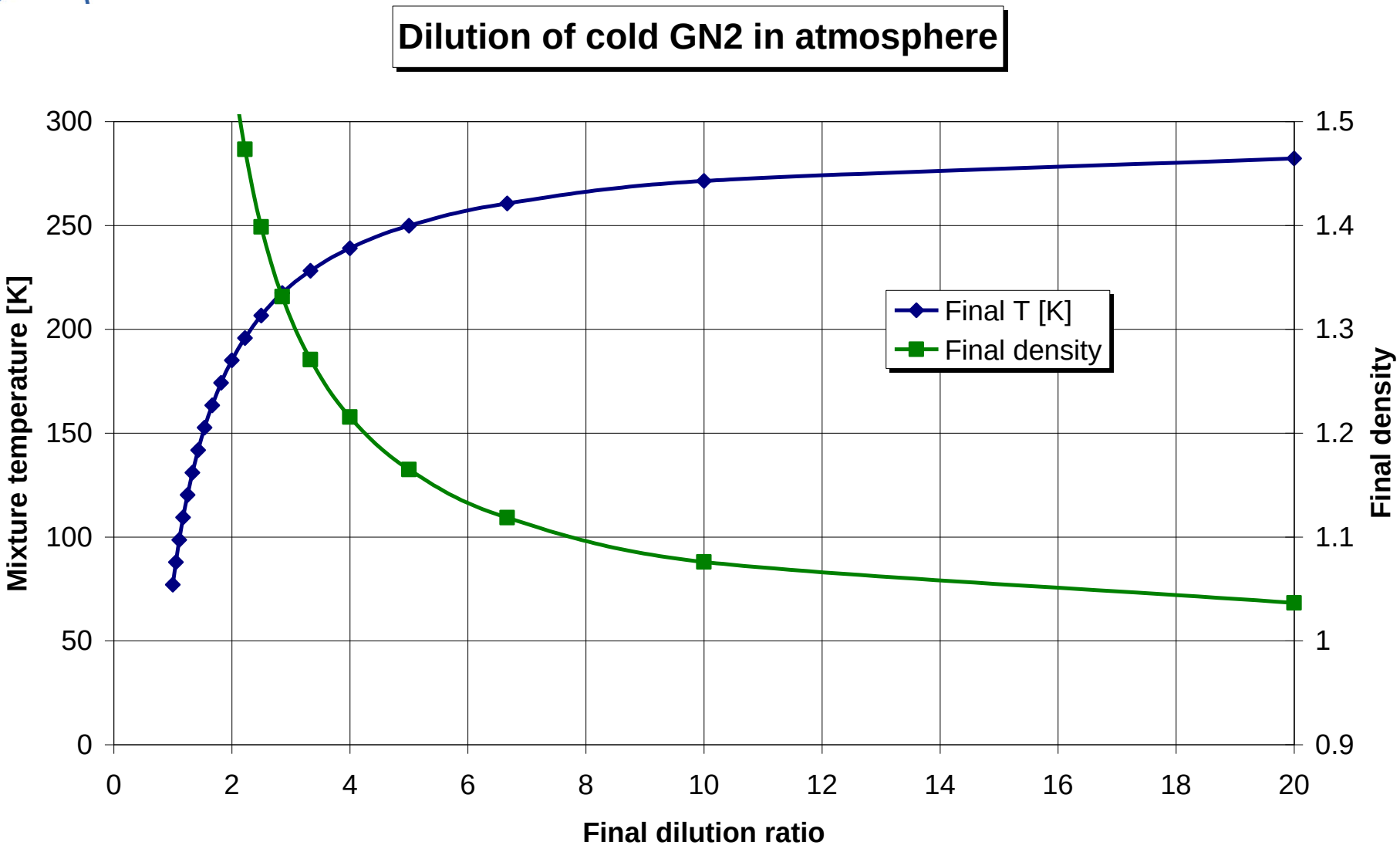
  $d_{mix} = 293\ M_{mix} / 29\ T_{mix}$


Dilution of cold GHe in atmosphere
Mixture temperature [K]
Final density
Final dilution ratio
Final T [K]
Final density
0
50
100
150
200
250
300
0.9
1
1.1
1.2
1.3
1.4
1.5
0
2
4
6
8
10
12
14
16
18
20

The plume rises even at low dilution (low temperature)

Liquid helium discharge upon resistive transition of superconducting magnet

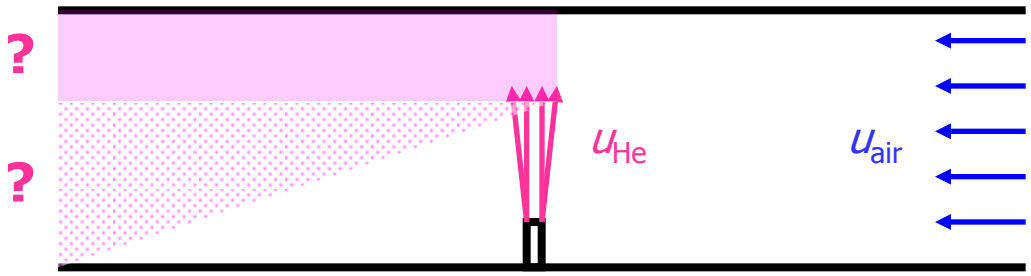



Dilution of cold GN2 in atmosphere
Mixture temperature [K]
Final density
Final dilution ratio
Final T [K]
Final density
300
250
200
150
100
50
0
1.5
1.4
1.3
1.2
1.1
1
0.9
0
2
4
6
8
10
12
14
16
18
20

Venting of cold nitrogen upon dewar refill

Cold helium discharge test in tunnel mock-up

Scaling laws for stratified flow in tunnel



Bakke number

$$(Ba')^3 = \frac{Re^2}{Ar} \cdot \frac{u_{air}}{u_{He}}$$

Reynolds number

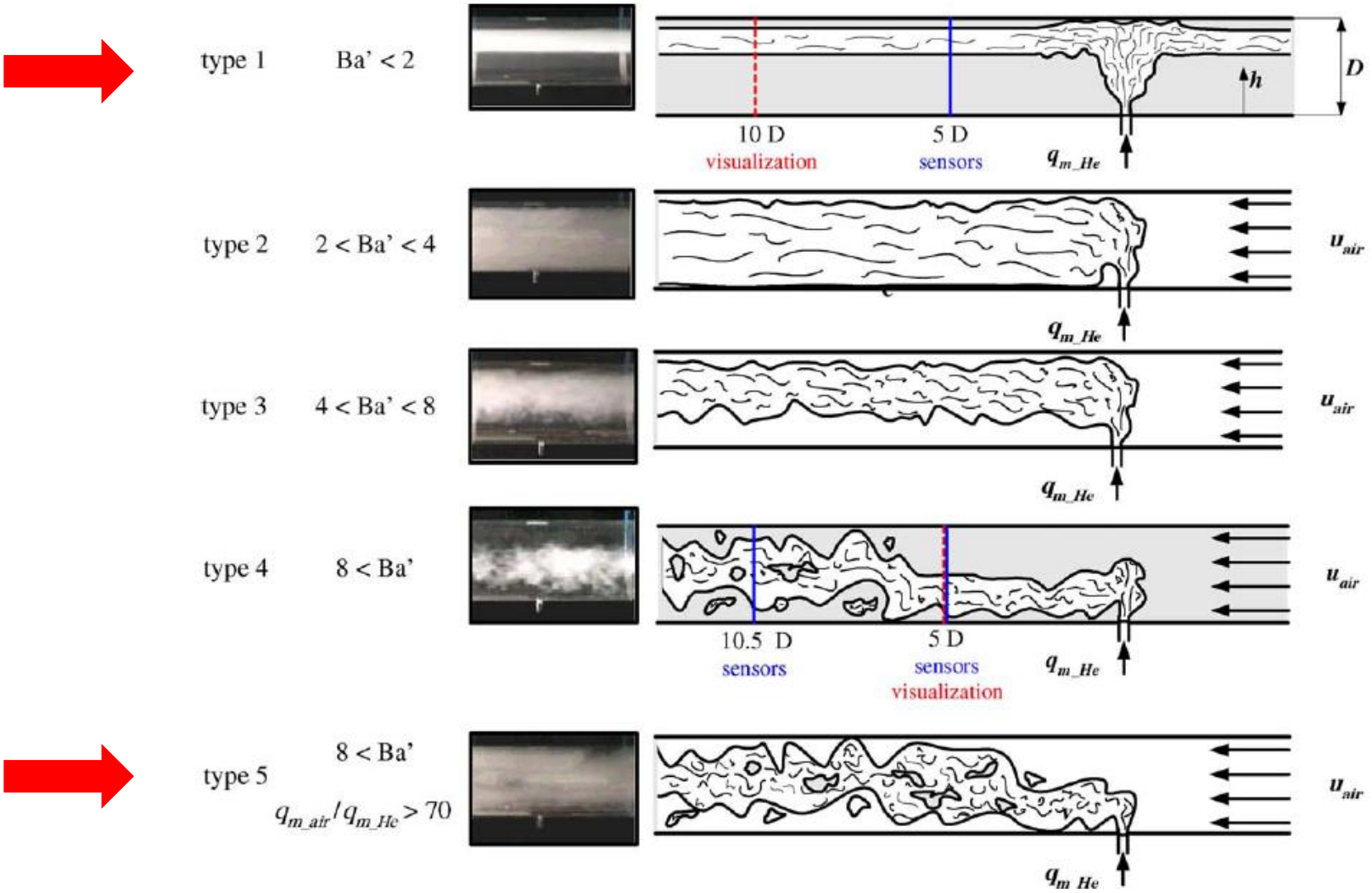
$$Re = \frac{u_{air} D}{\nu_{air}} \sim \frac{F_i}{F_\nu}$$

Archimedes number

$$Ar = \frac{g D^3}{\nu_{air}^2} \frac{\Delta\rho}{\rho_{air}} \sim \frac{F_b}{F_\nu}$$

M. Chorowski, G. Konopka-Cupial & G. Riddone, *Safety-oriented analysis of cold helium-air mixture formation and stratification*, Cryogenics **46** (2006) 262-272

Conditions for stratified flow in tunnel



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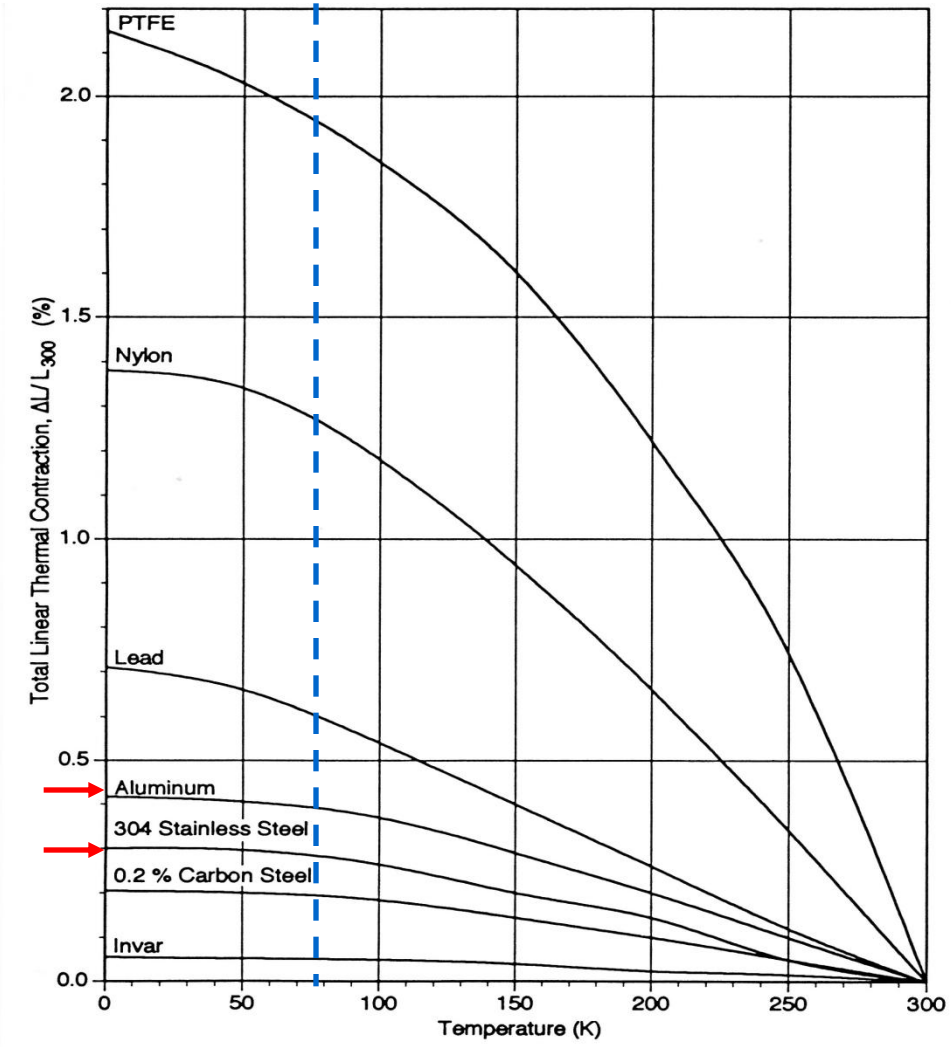
Thermal contraction of materials

Most of the contraction done at LIN temperature



Thermal shock in LIN

Alu-St. steel pipe junction

Stress buildup by impeded thermal contraction

- Free thermal contraction $\Delta L/L = \int \lambda(T)\, dT$
- Impeded thermal contraction builds up stress $\sigma = E\, \Delta L/L$

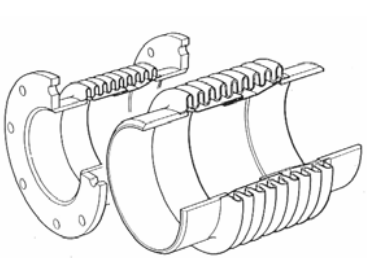
Material	Low-carbon steel	AISI 304 (annealed)	Al 2024	Inconel 718	Ti6Al4V	Invar®
Integral contraction at 4 K [%]	0.20	0.30	0.40	0.24	0.18	0.03
Young's modulus at 4 K [GPa]	210	180	80	200	130	140
Impeded thermal stress [MPa]	420	540	320	480	234	42
Yield strength at 4 K [MPa]	600	400	500	1400	1600	600
Ultimate tensile strength at 4 K [MPa]	1000	1700	800	1800	2000	1000
	High stress	Will plastify	High stress	High stress		O.K.

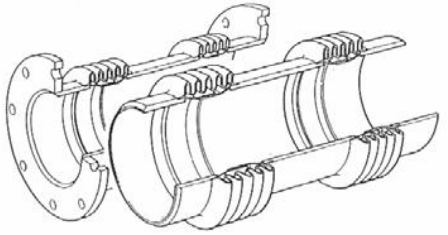
⇒ *compensation bellows, flexible tubes, pipe lyras*
⇒ *Invar® construction*

Invar® membrane tank for LNG carrier
(Gaz Transport + Technigaz)

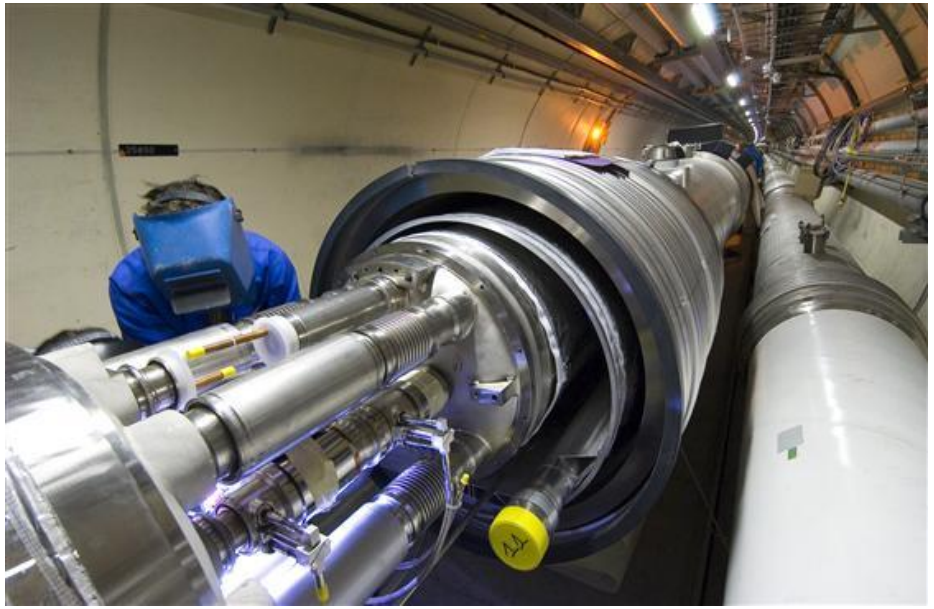
Compensation of thermal contraction: bellows

The LHC ring contracts by 80 m upon cooldown!





20’000 compensator bellows in the machine



Bellows cryogenic low-cycle fatigue lifetime

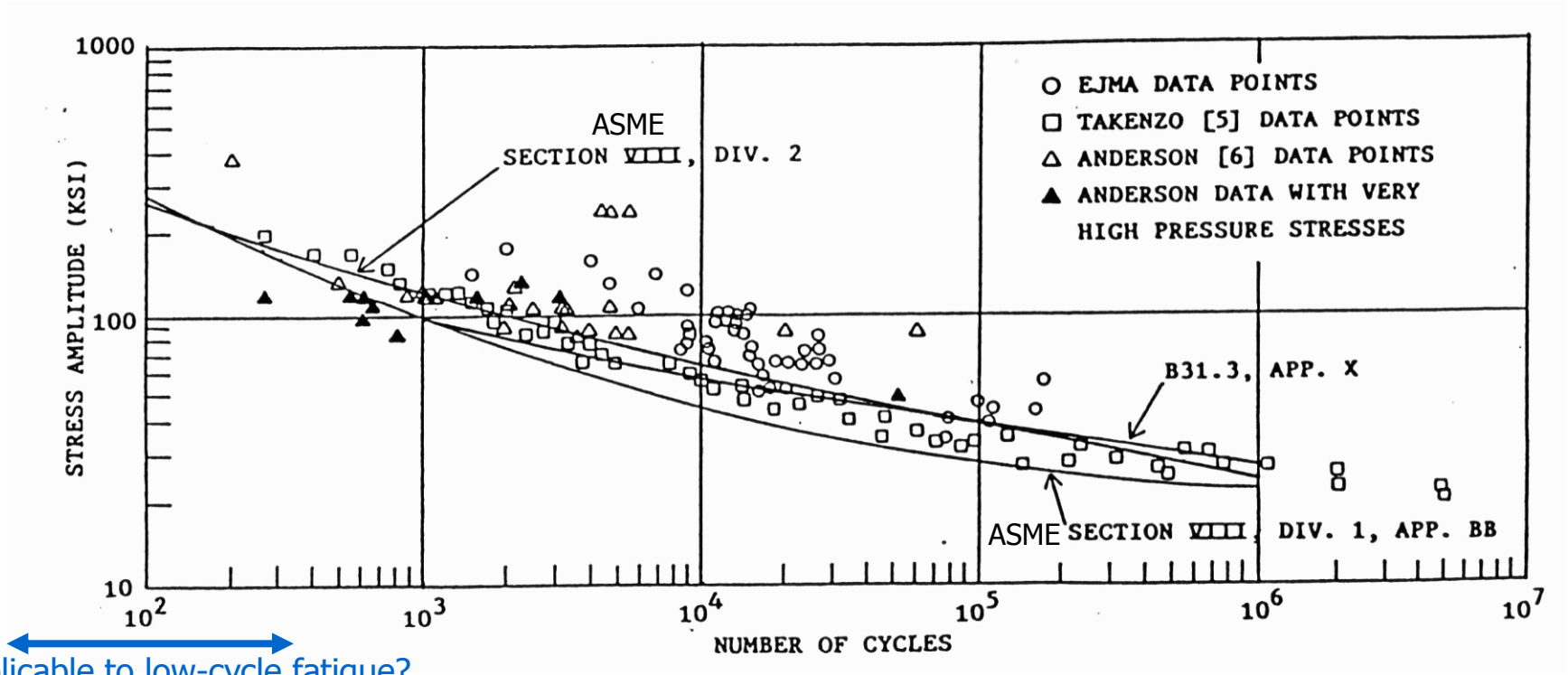
Temperature correction factor

$$N_f = \left(\frac{12824 T_f}{S_t - 372.3} \right)^{3.4}$$

[EJMA]

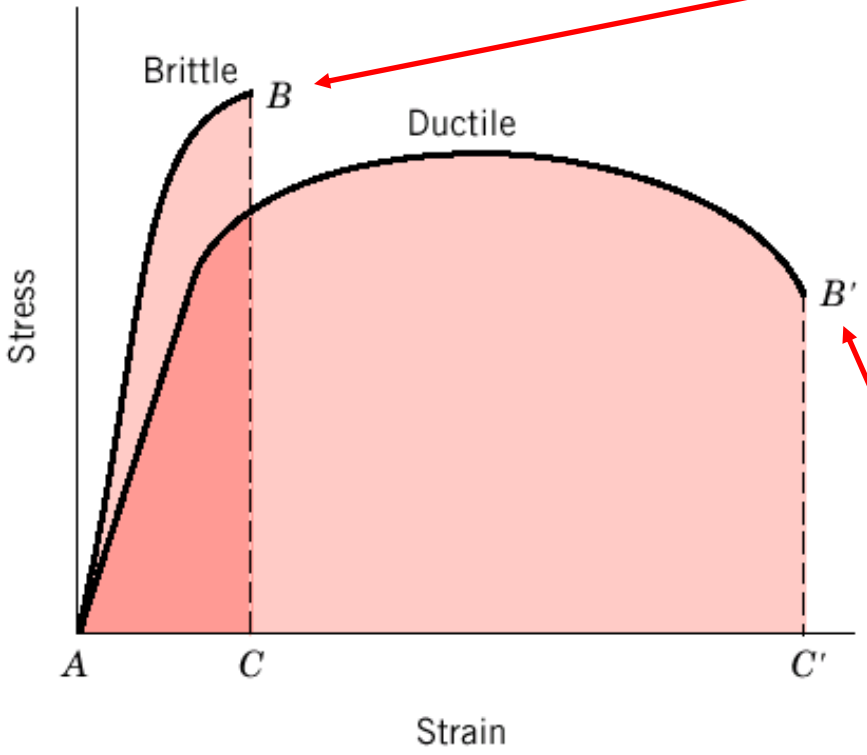
Cycles to failure

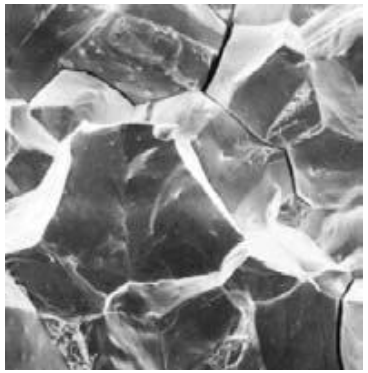
Equivalent stress



Applicable to low-cycle fatigue?

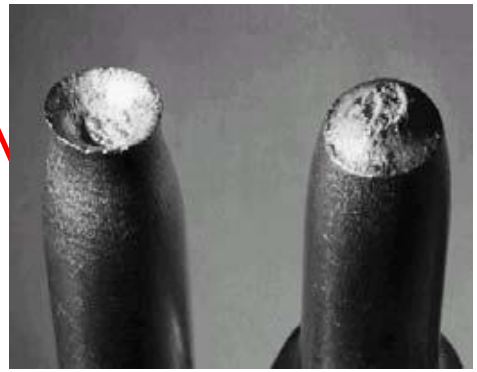
Fracture mechanics, brittle vs ductile

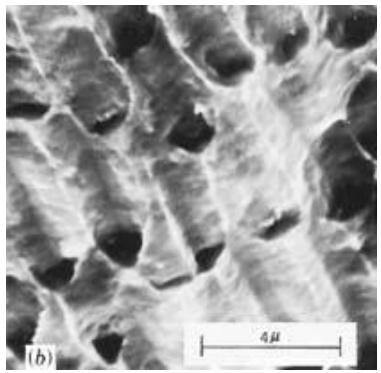




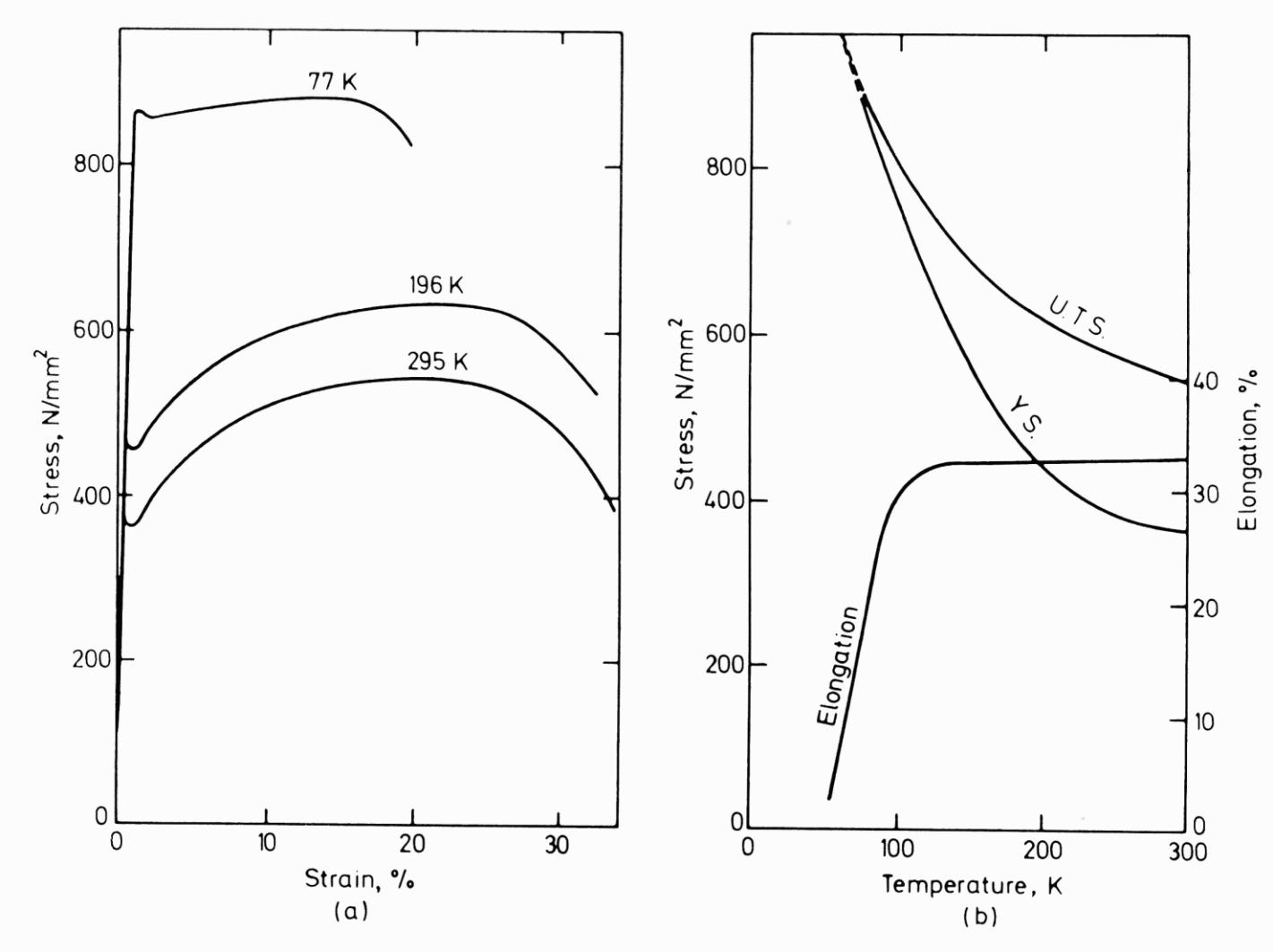
Mild steel, brittle fracture (intergranular)

Aluminium, ductile fracture, « cup-and-cone »



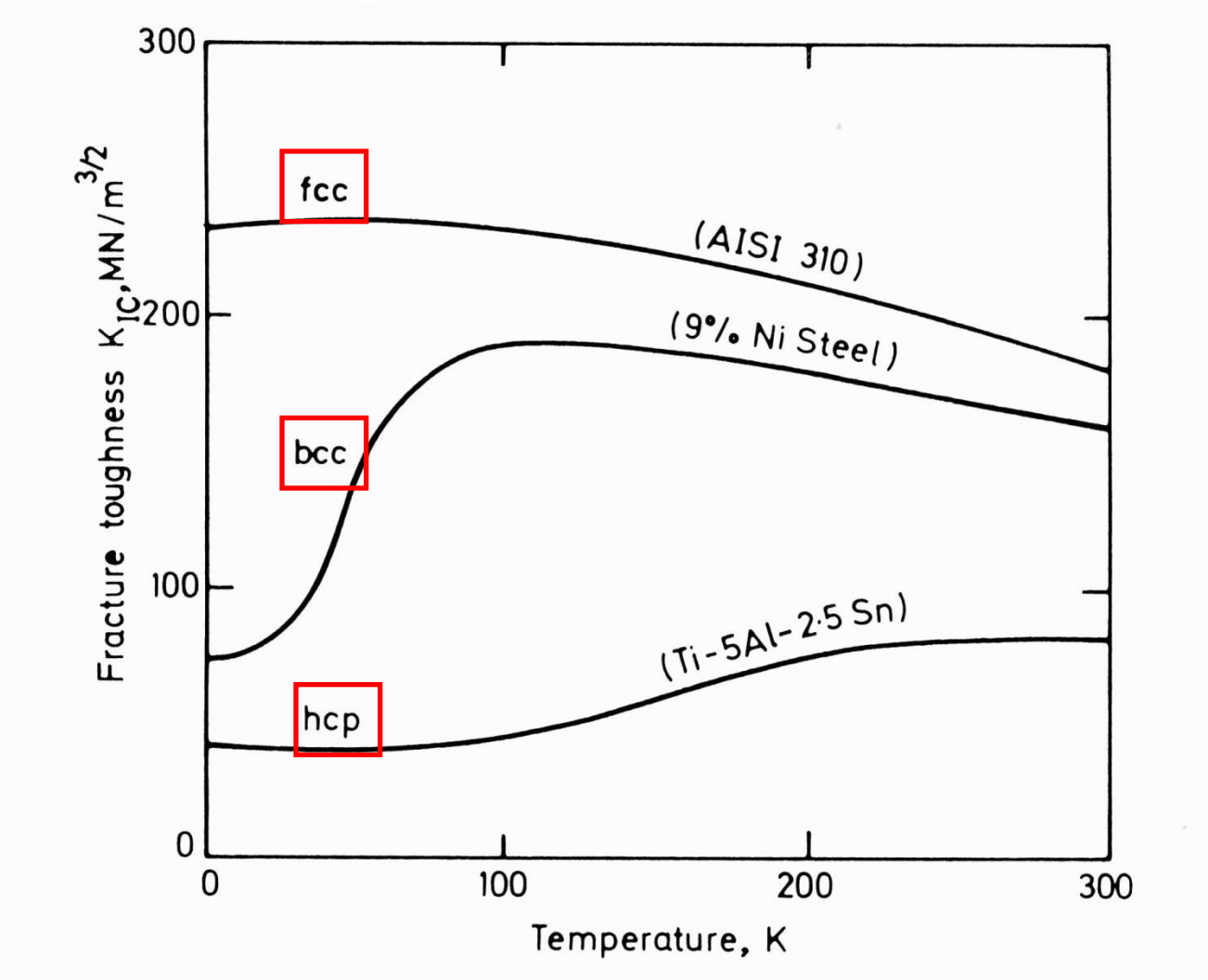


Typical tensile data for 0.2% carbon steel (bcc)



D.A. Wigley, *Mechanical properties of materials at low temperatures*, Plenum Press (1971)

Variation of fracture toughness with temperature



R.P. Reed, A.F. Clark & E.C. van Reuth, *A research program on the properties of structural materials at 4 K*, Adv. Cryo. Eng. **22** (1977) 1-8

Liberty ships

- 2710 ships series built in 18 U.S. shipyards betwee 1941 and 1945
- Manufacturing time 42 days (record 4 days, 15 hours & 30 minutes!)
- Standardized, all welded (vs. riveted) construction

⇒ *more than 1000 showing cracks, 190 fractured, 12 broken!*

Catastrophic brittle fracture

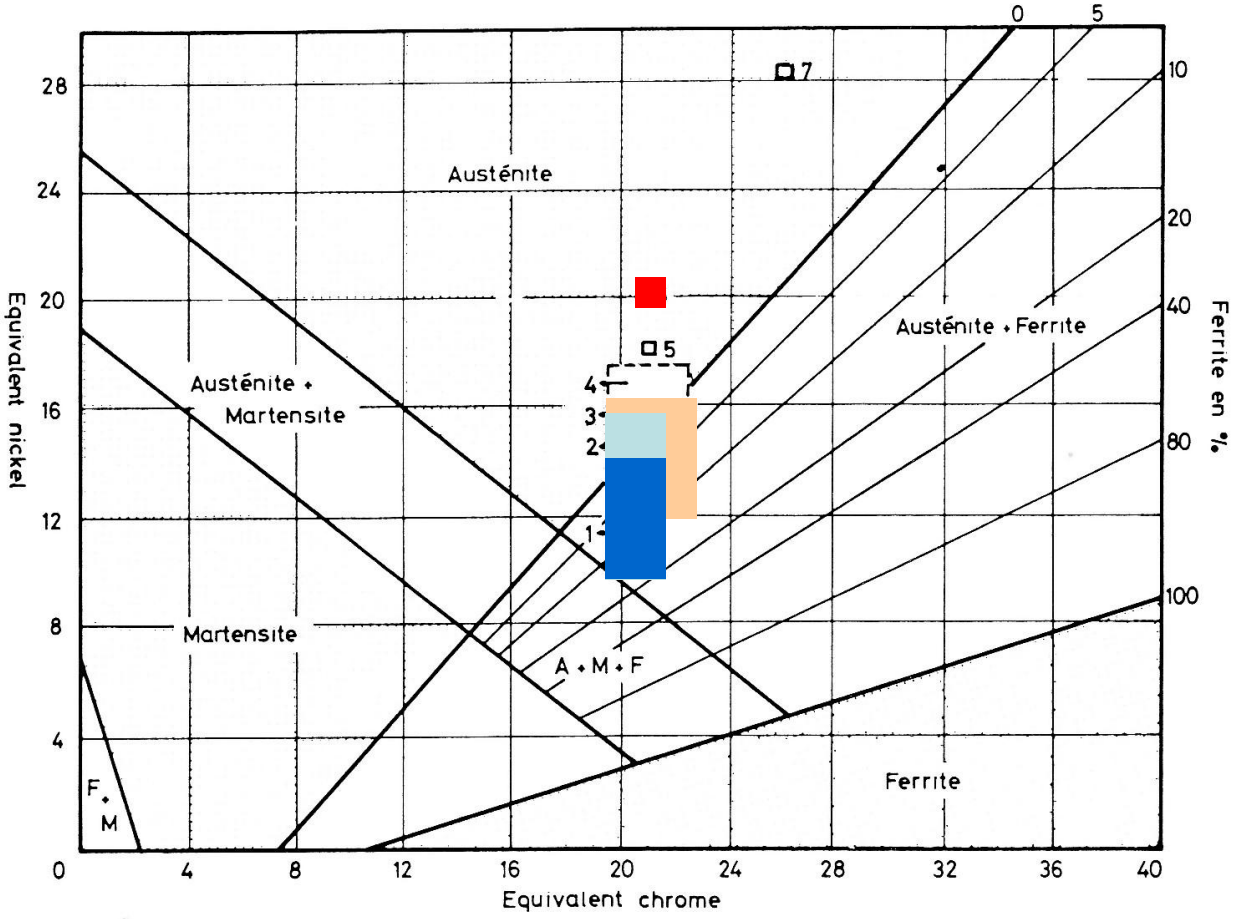
The general technological fraternity was unaware of Fracture Mechanics principles when these ships were designed, and the reason for the disastrous fractures was a mystery since conventional safety assessments were unremarkable and the extremely short lives ruled out conventional fatigue as the culprit. It later became clear that the failures could be attributed to:

- the all-welded construction which eliminated crack-arresting plate boundaries which are present in riveted joints,
- the presence of crack-like flaws in welded joints performed by inexperienced operators pressed into service by the exigencies of the programme,
- the use of materials whose low resistance to crack advance (toughness) was further reduced by low temperatures.

Pr. D. Wright, *School of ME, Univ. Western Australia*

Austenite stability of AISI 300 stainless steels

Schaeffler diagram



304L

304

316L

316L+N

Contents

- Energy release potential of liquid cryogens
  - Thermal energy: cooling of equipment
  - Mechanical energy: damage
- Physiological hazards
  - Freezing of tissue
  - Oxygen deficiency
- Liquid cryogen spillage
  - Mixing and buoyancy
  - Stratified flow in tunnel
- Material properties
  - Thermal contraction
  - Embrittlement
- **Mechanical design**
  - **Combined pressure/temperature regimes**
  - **Mechanical instabilities (buckling) under pressure or vacuum**
- Fluid properties
  - Pressure buildup and relief in cryogenic vessels
  - Air condensation and oxygen enrichment
  - Loss of insulation vacuum
- A compound case: the LHC accident

Cryostat mechanical design
Operating modes and pressure/temperature regimes

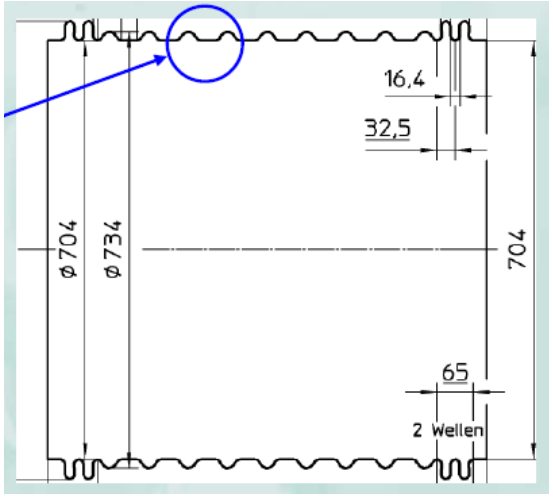
- Cryostat = cryogen vessel + insulation vacuum enclosure
- Design must accommodate all pressure and temperature regimes

⇒ *vessels will have to work with internal and/or external overpressure*

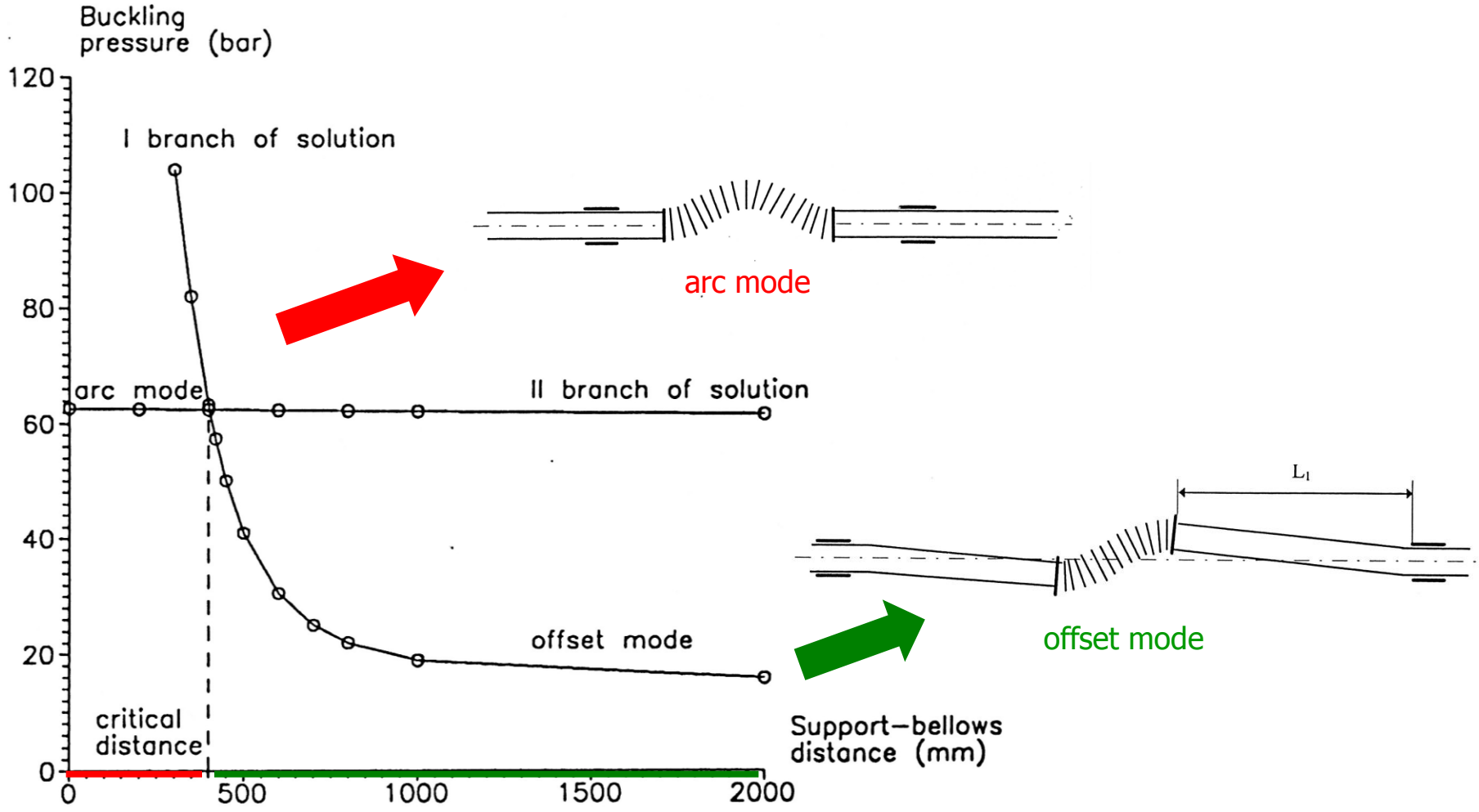
Mode	Cryogen vessel	Vacuum enclosure	Atmosphere
Leak testing I	Vacuum, RT	P_{atm}, RT	P_{atm}, RT
Leak testing II	P_{atm} to P_{design}, RT	Vacuum, RT	P_{atm}, RT
Pressure test	1.5 P_{design}, RT (1.25 P_{design}, RT)	Vacuum, RT	P_{atm}, RT
Purge	Vacuum, RT to Cold	Vacuum, RT	P_{atm}, RT
Normal operation	P_{op}, Cold	Vacuum, RT	P_{atm}, RT
Overpressure	1.1 P_{design}, Cold	Vacuum, RT	P_{atm}, RT
Loss of insulation vacuum	P_{op} to 1.1 P_{design}, Cold	P_{atm}, RT to Cold	P_{atm}, RT
Cold leak	P_{op}, Cold	$P_{atm}+\Delta P$, Cold	P_{atm}, RT

Buckling of corrugated sleeve on vacuum enclosure

- Nominal height of corrugations 15 mm
  ⇒ withstand >12 bar external pressure (ASME code)
- Drift in manufacturing process
  ⇒ height of corrugations reduced to ~ 6 mm
  ⇒ buckling under atmospheric pressure



Buckling of piping/bellows system under pressure

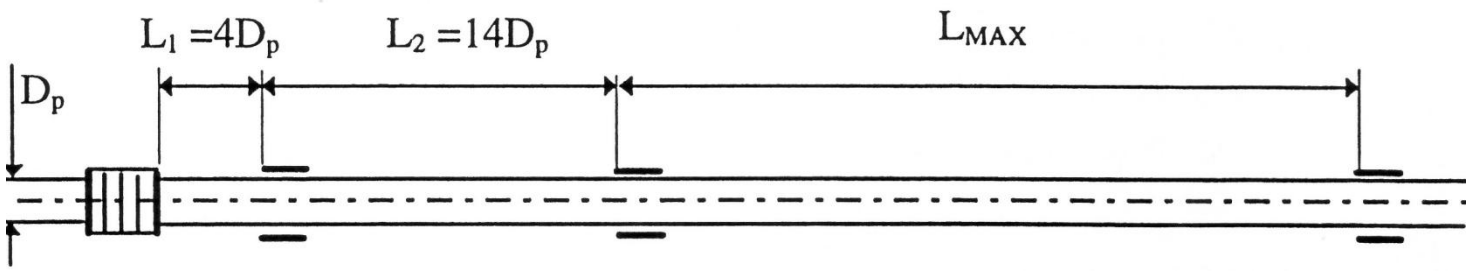


B. Skoczen, *Material and structural stability issues at cryogenic temperatures*, Mechanika **88**, Politechnika Krakowska (2002)

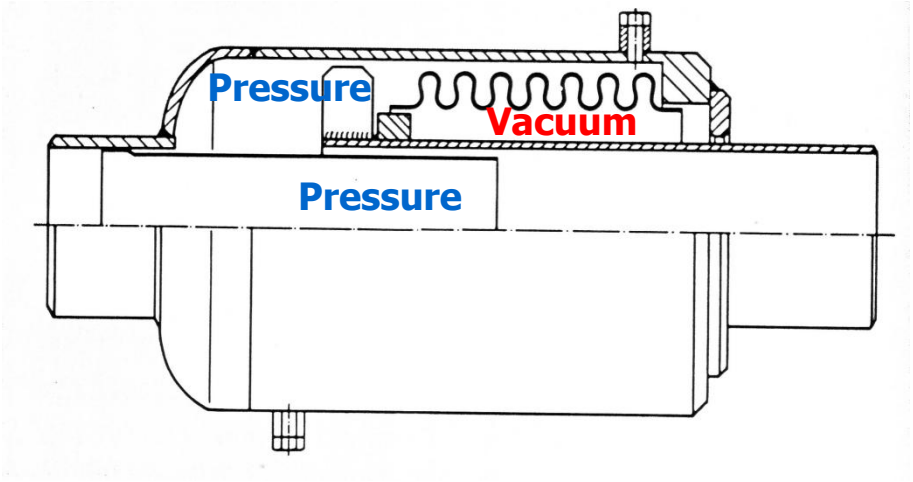
Buckling of unsupported piping/bellows system

Two approaches to good practice

- Adequate guiding of piping



- « Inverted » bellows under external pressure



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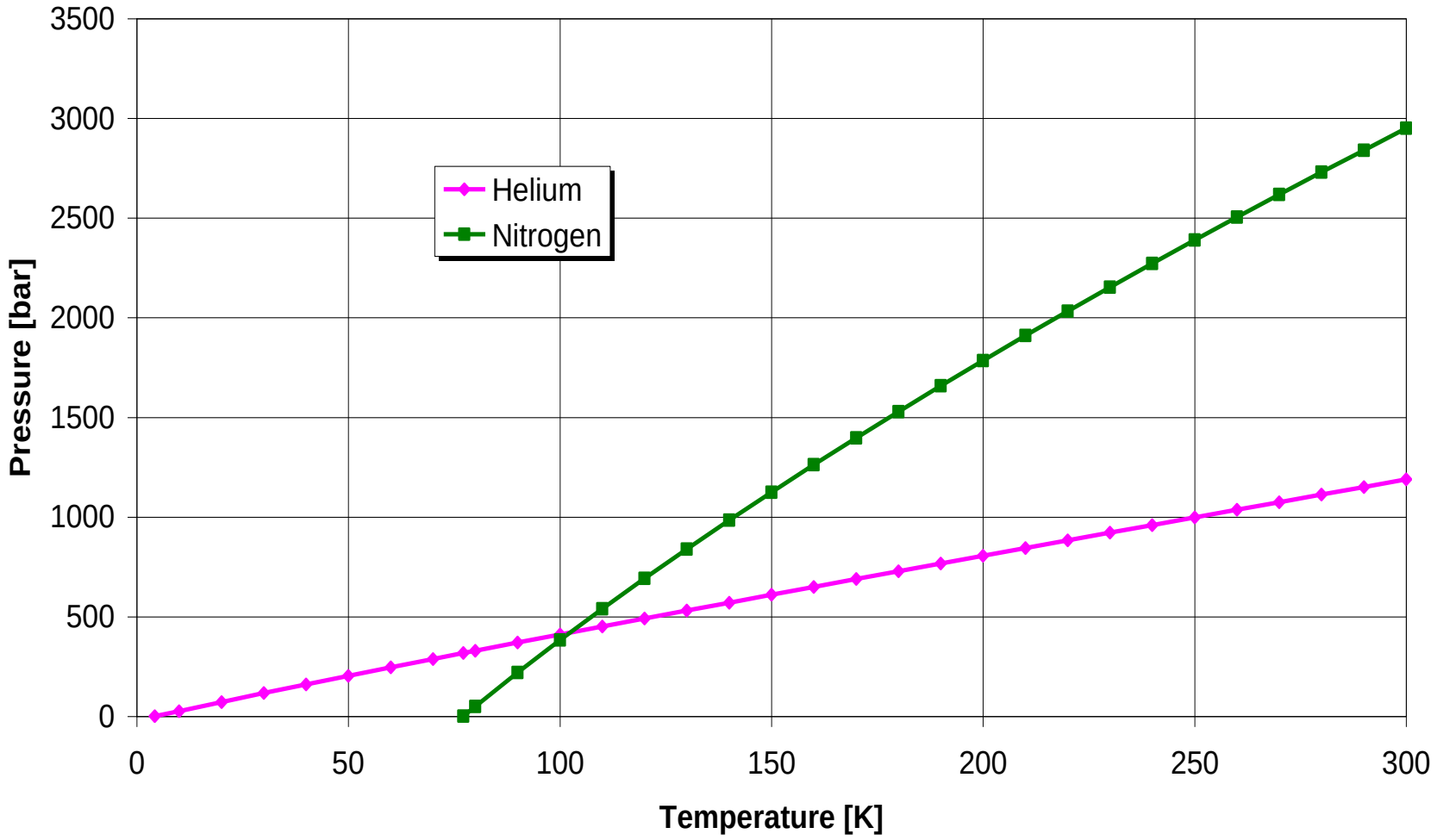

Pressure Buildup in Closed Liquid Cryogen Volume
(Initial conditions: no ullage, saturated liquid @ 1 bar)
Helium
Nitrogen
Pressure [bar]
Temperature [K]
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
200
250
300

Mechanical energy stored in pressurized vessel

- W [Joules] = P [Pa] x V [m3]
- 1000 liter helium dewar, initially at saturation, no ullage
  - At 290 K, P = 1150 bar
  - W = 115 MJ ~ 42 kg TNT
- 1000 liter nitrogen dewar, initially at saturation, no ullage
  - At 290 K, P = 2840 bar
  - W = 284 MJ ~ 104 kg TNT

Explosion of a plugged liquid nitrogen dewar (~100 liter ?) at a university laboratory

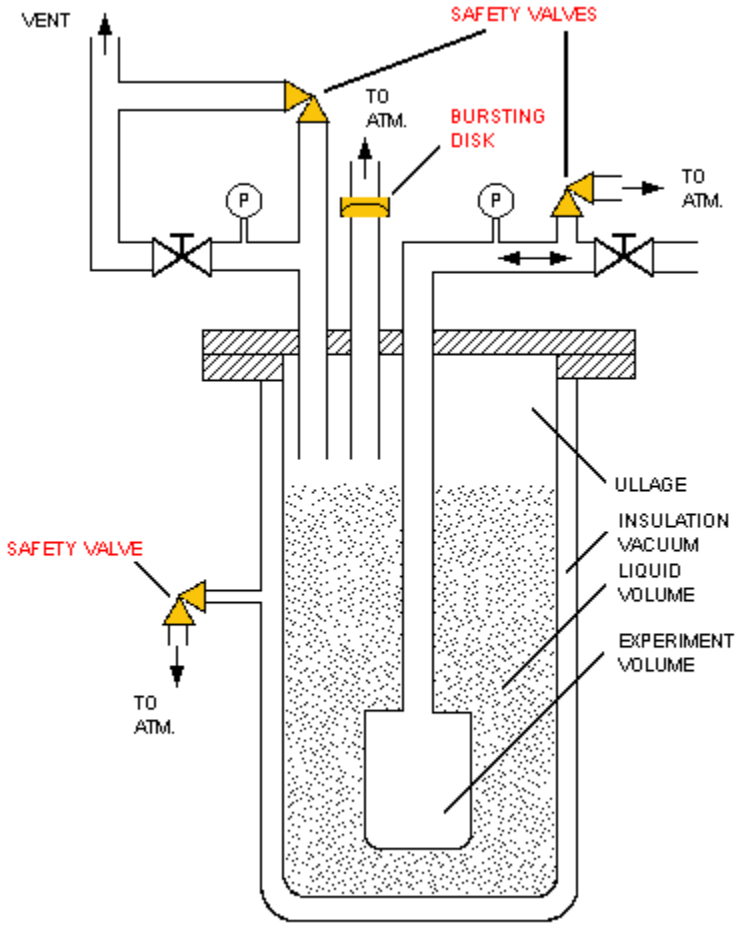
« The failure permitted rapid expansion of the nitrogen gas, blowing out the bottom of the tank and propelling the cylinder upwards… The examination revealed that the cylinder's pressure release valve and rupture disc had been replaced by two brass plugs… The cylinder ruptured when its internal pressure rose above 1000 psi (~ 67 bar) »

Figure 1 -Effect of Explosion on Dewar Cylinder Compared to unaffected cylinder

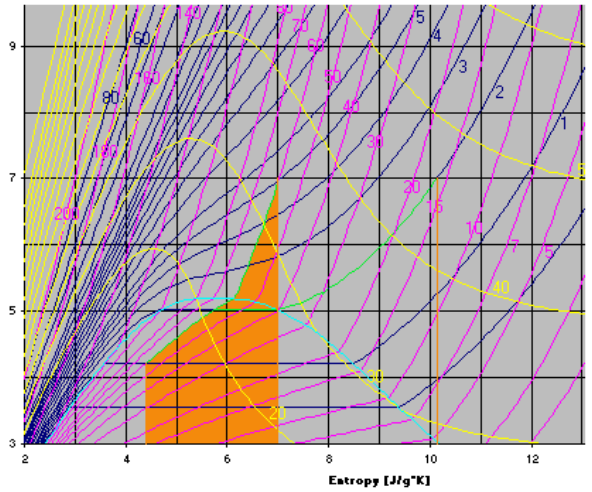
Figure 2 - Hallway Outside Laboratory Showing Explosion Damage

Figure 3 - Inside the Laboratory after Explosion

Protection of cryogenic vessels from overpressure

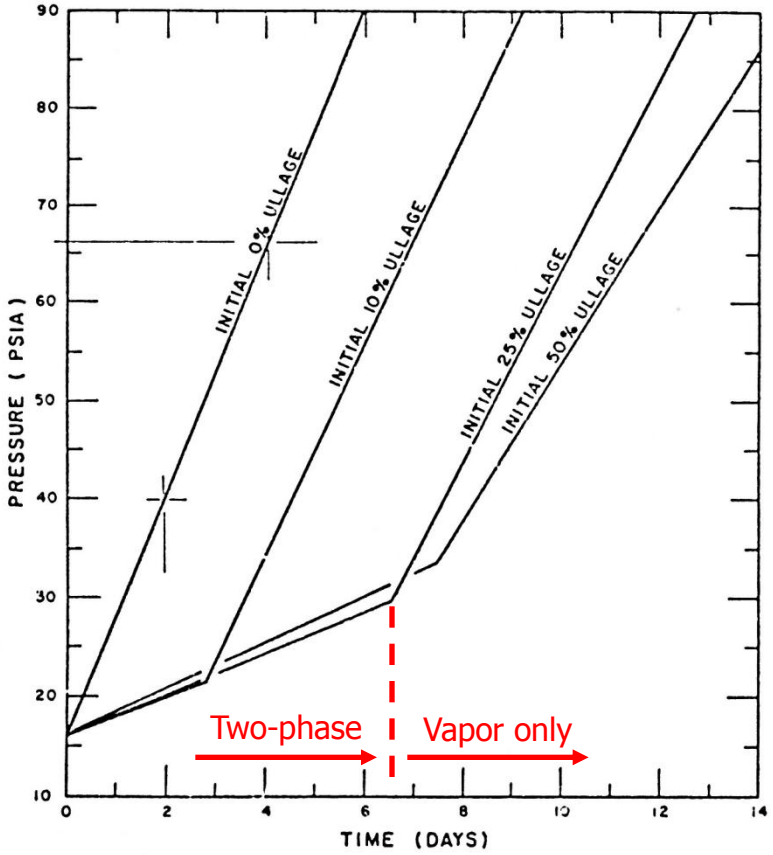


Pressure rise in sealed liquid helium container

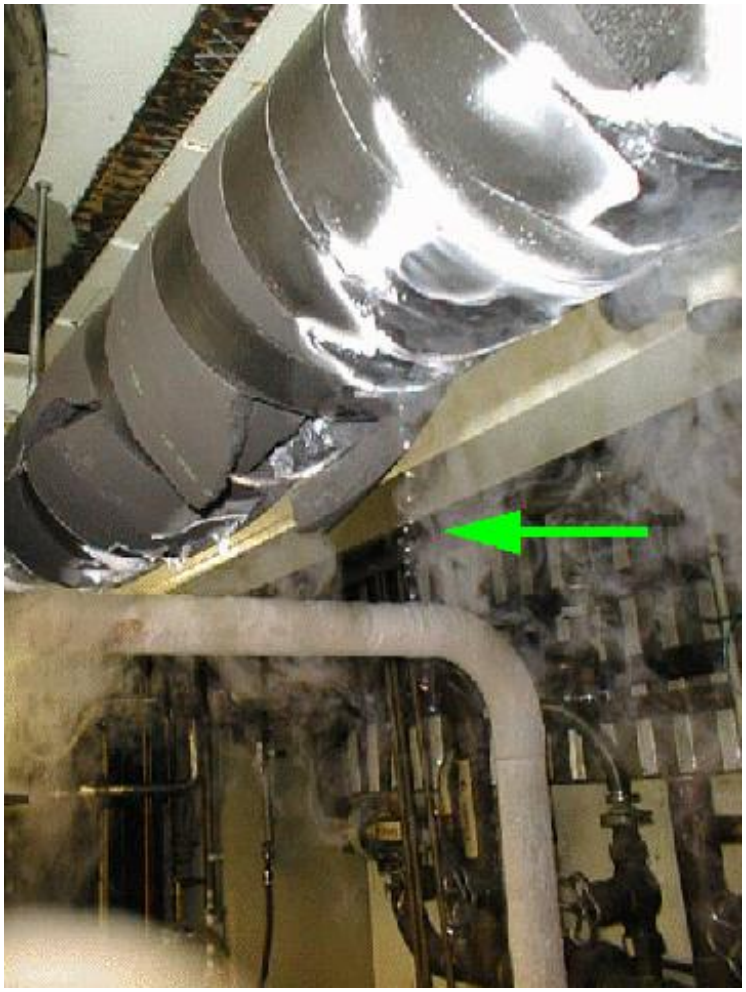


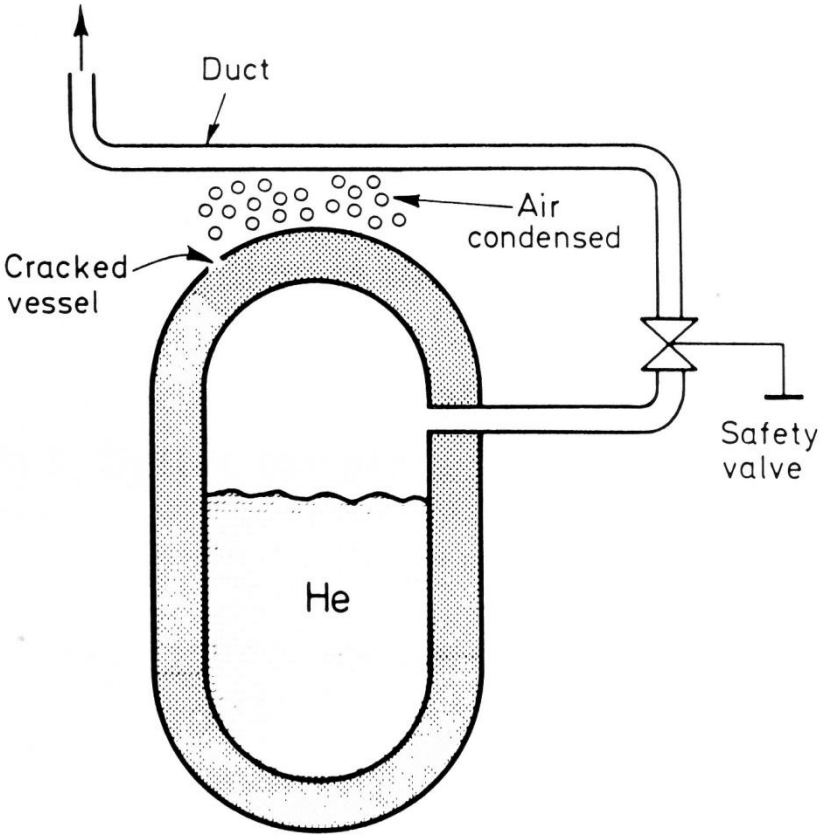
- At constant total volume, heat inleak equals increase in internal energy U
- Average density fixed by initial filling (ullage volume)

11'000 gallon liquid helium container on semi-trailer



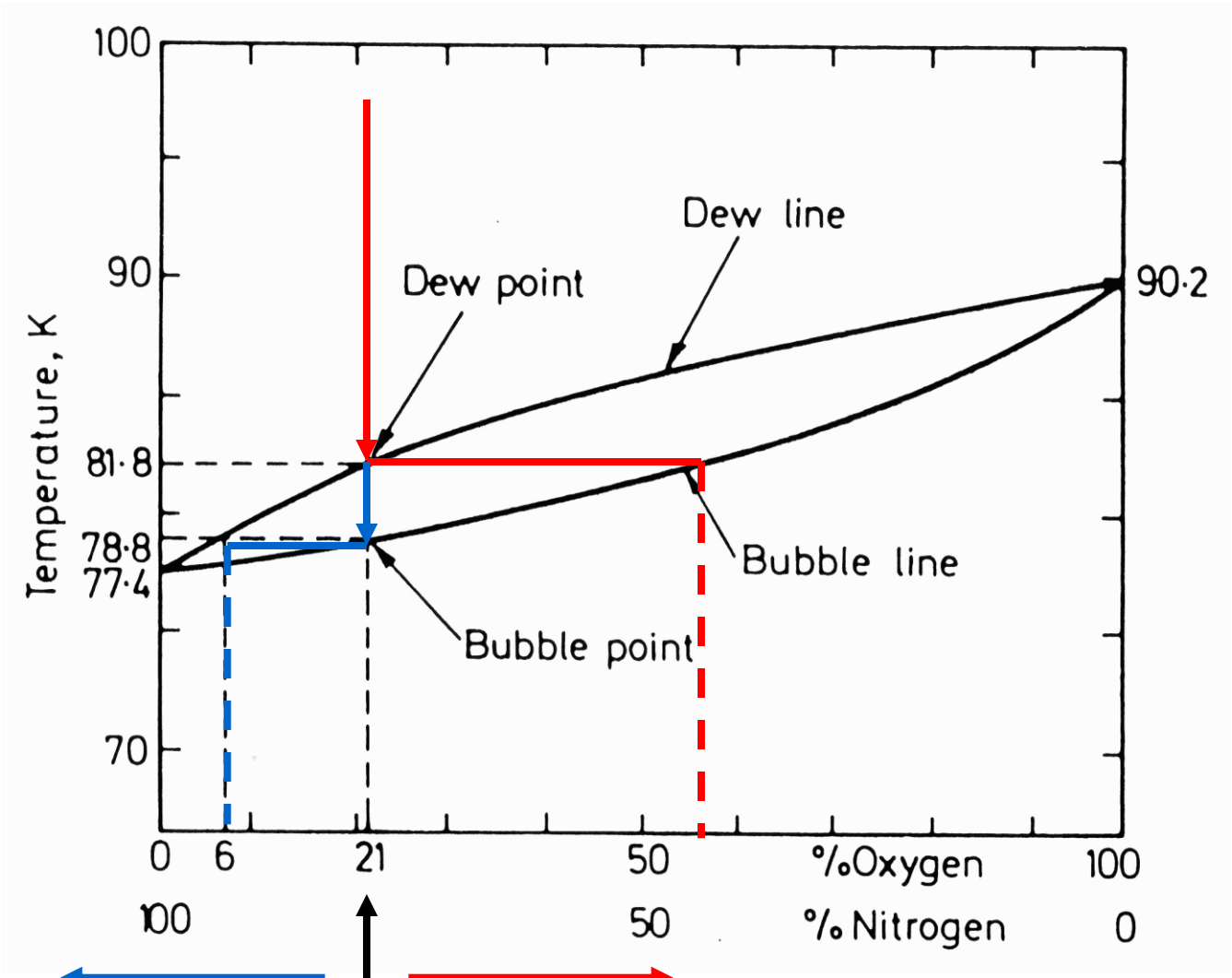
Air condensation on cold helium discharge pipe





- mechanical risk: embrittlement by low temperature
- chemical risk: combustion/explosion in enriched oxygen atmosphere

Initial oxygen enrichment of condensed air



Multi-layer reflective insulation with loss of vacuum

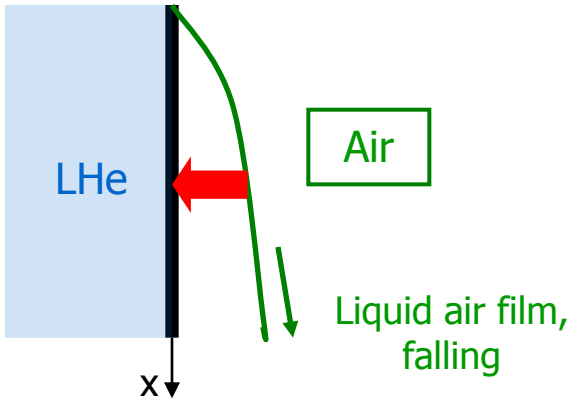
10-layer blanket

Aluminized Mylar
+ PE spacer

Designed to operate under vacuum (10^{-6} mbar) with residual heat flux of about 1 W/m^2, MLI also provides efficient limitation of heat transfer in case of loss of vacuum

Heat transfer by condensation of air on cold wall

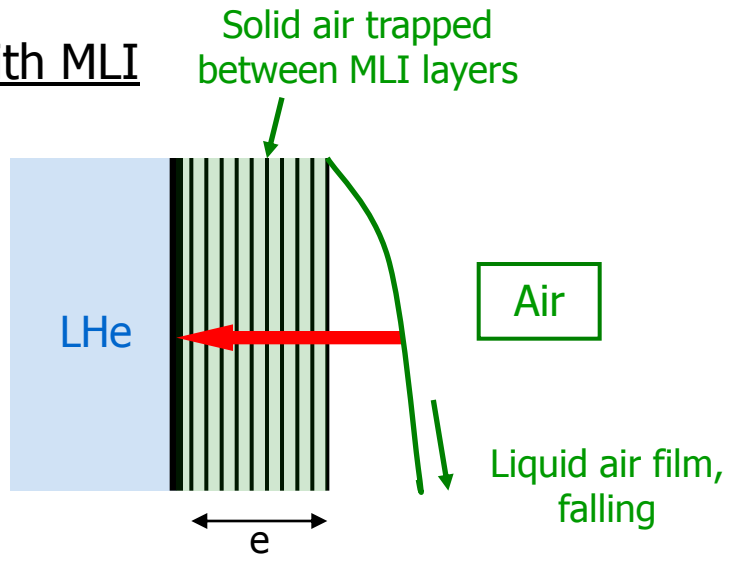
Bare wall



Heat transport limited by conduction across falling film

- From a calculation by Nusselt
  - $h \approx 0.943\ (\rho^2\ g\ k^3\ L_v/\eta\ x\ \Delta T)^{0.25}$
- Assimilating air to nitrogen
  - $h \approx 680\ W/m^2\ K$
  - heat flux $h\ \Delta T \approx 50'000\ W/m^2$
  - average thickness of film ≈ 0.2 mm

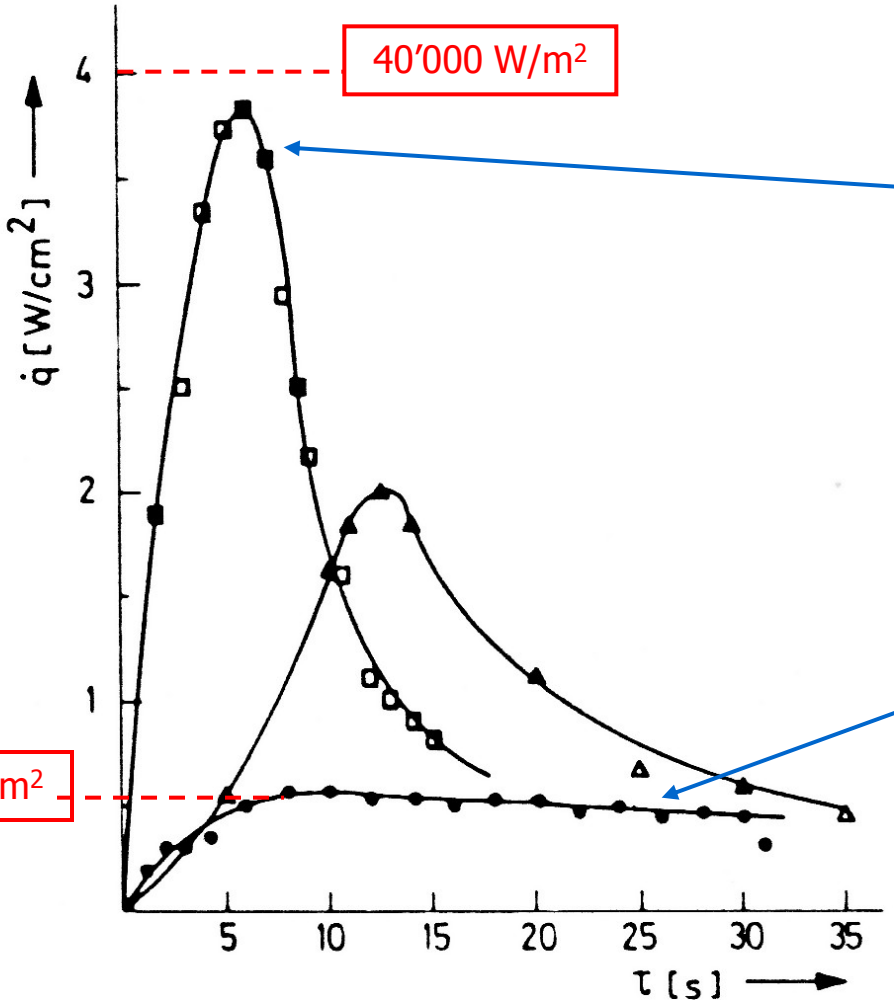
with MLI



Heat transport limited by conduction across solid air

- Multi-layer insulation
  - take e = 10 mm
- Conduction in solid nitrogen
  - conductivity integral from 77 to 4 K ≈ 50 W/m
  - Heat flux $h\ \Delta T \approx 5'000\ W/m^2$

Broken vacuum experiment on LHe cryostat



W. Lehmann & G. Zahn, *Safety aspects for LHe cryostats*, Proc. ICEC7, IPC Science & Technology (1978) 569-579

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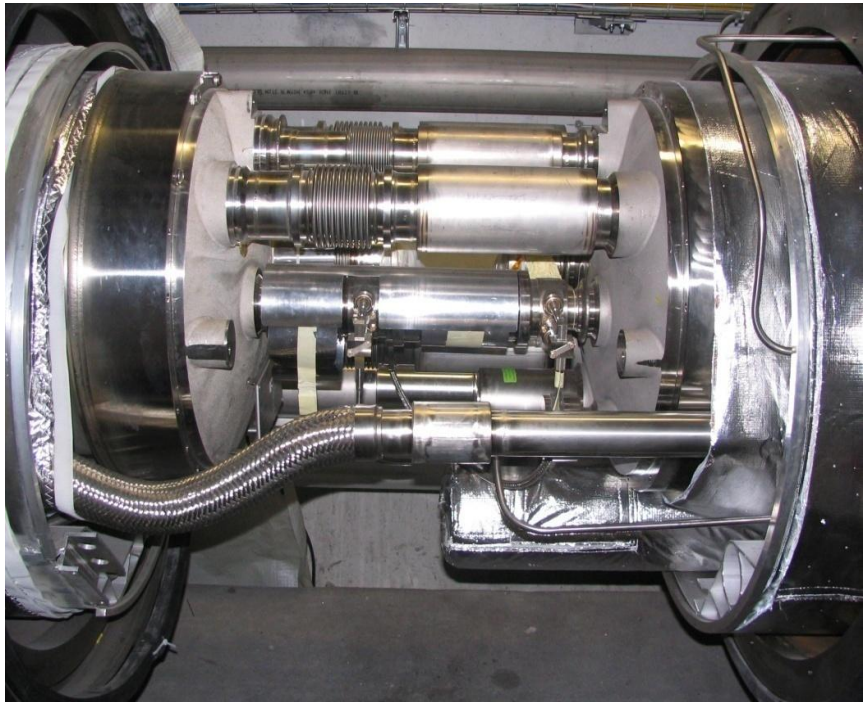
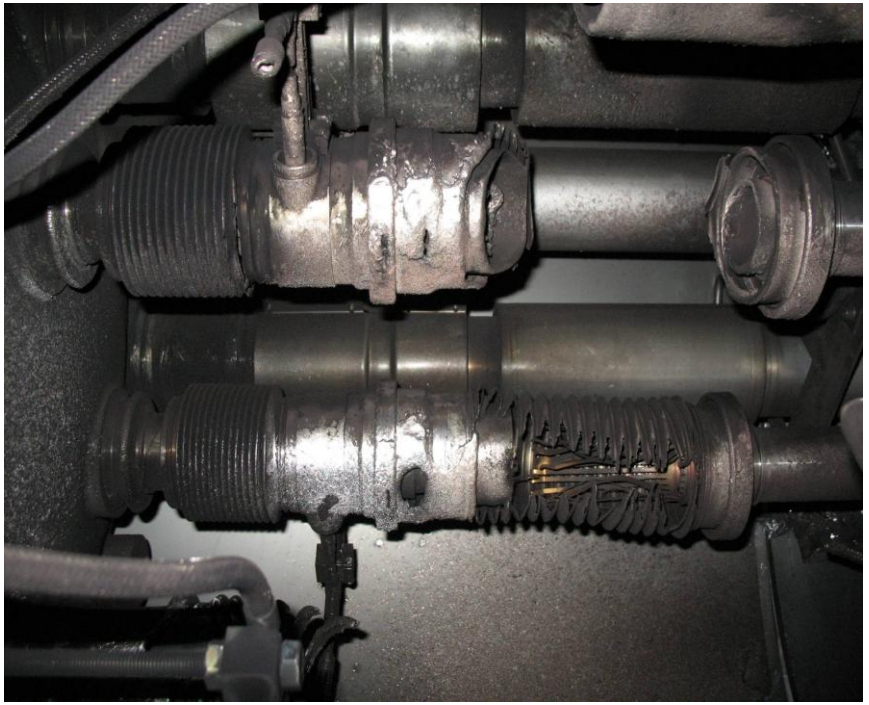
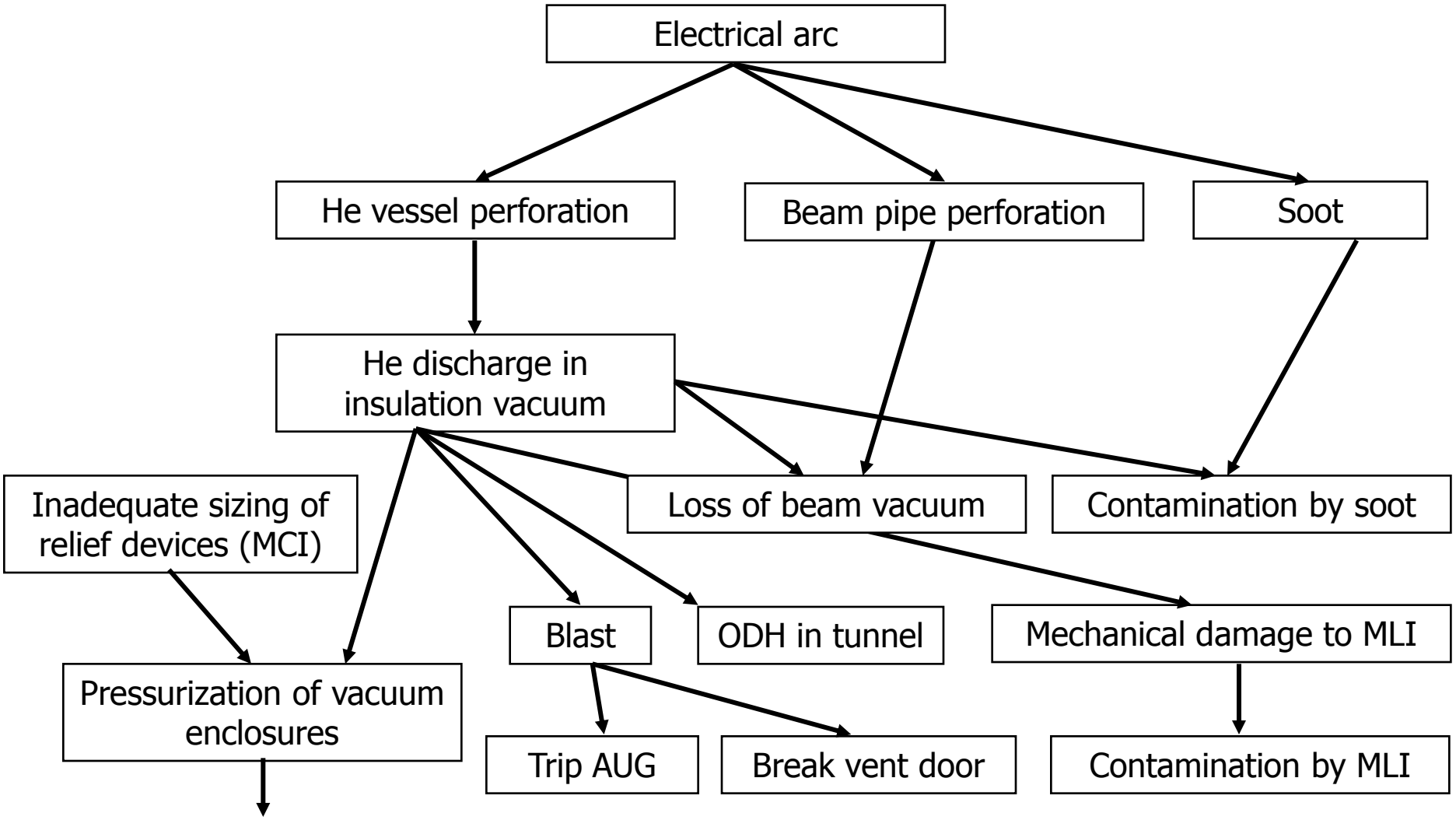
Electrical arc between two magnets



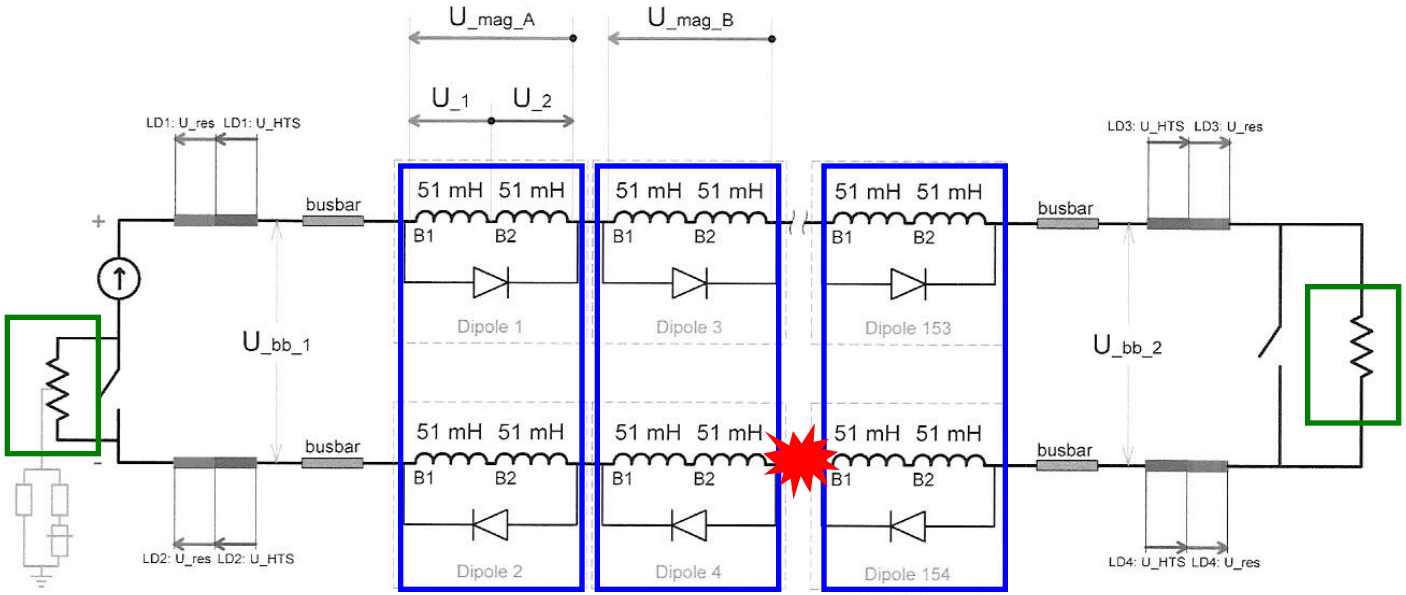


Fault tree of 19 Sept 2008 incident at the LHC

Cryogenic effects [1/2]

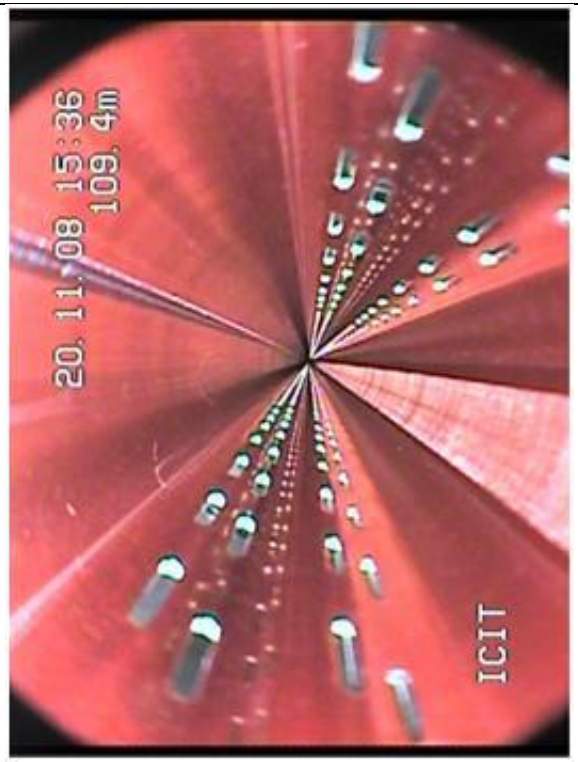
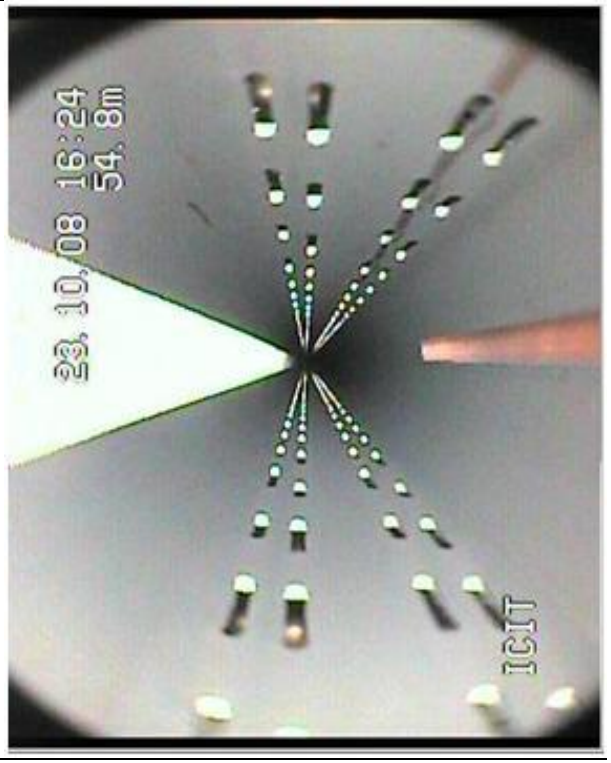


Balance of energy dissipation during the incident

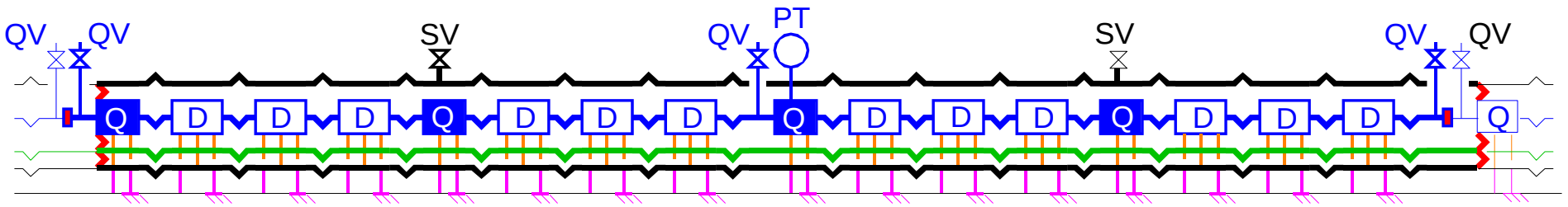


Energy	MJ	%
Stored in the magnets	595.0	100
Dissipated in UJ33 discharge resistor	71.0	12
Dissipated in UA43 discharge resistor	104.8	18
Dissipated in cold mass	144.4	24
Dissipated in electrical arcs	274.8	46

Beam vacuum contamination

Beam Screen (BS) : The red color is characteristic of a clean copper surface	BS with some contamination by super-isolation (MLI multi layer insulation)	BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.
		

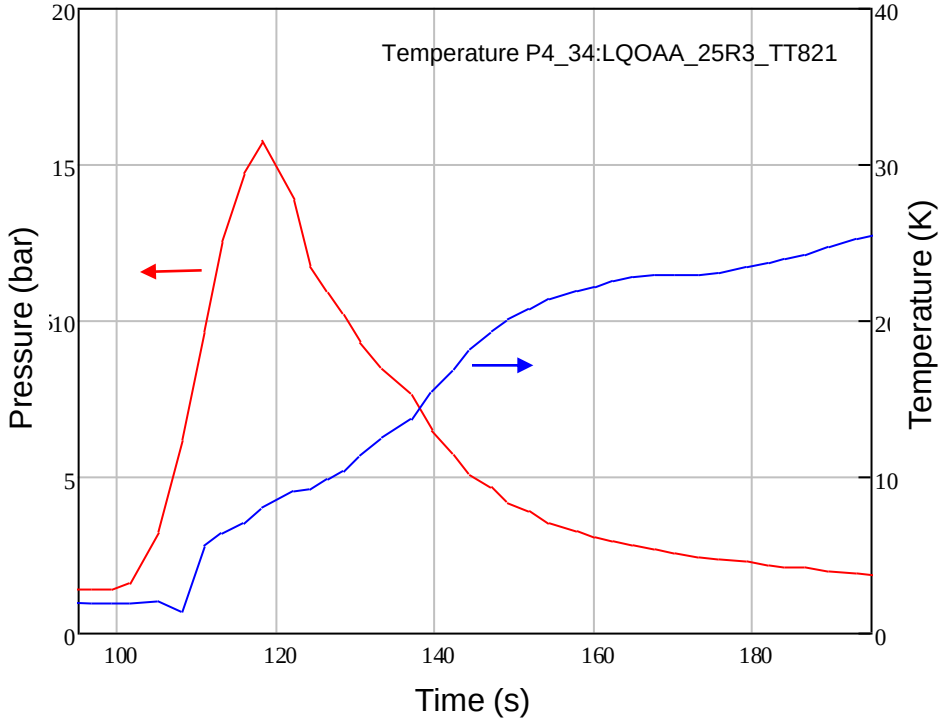
Simplified scheme of a LHC sub-sector (~ 200 m)



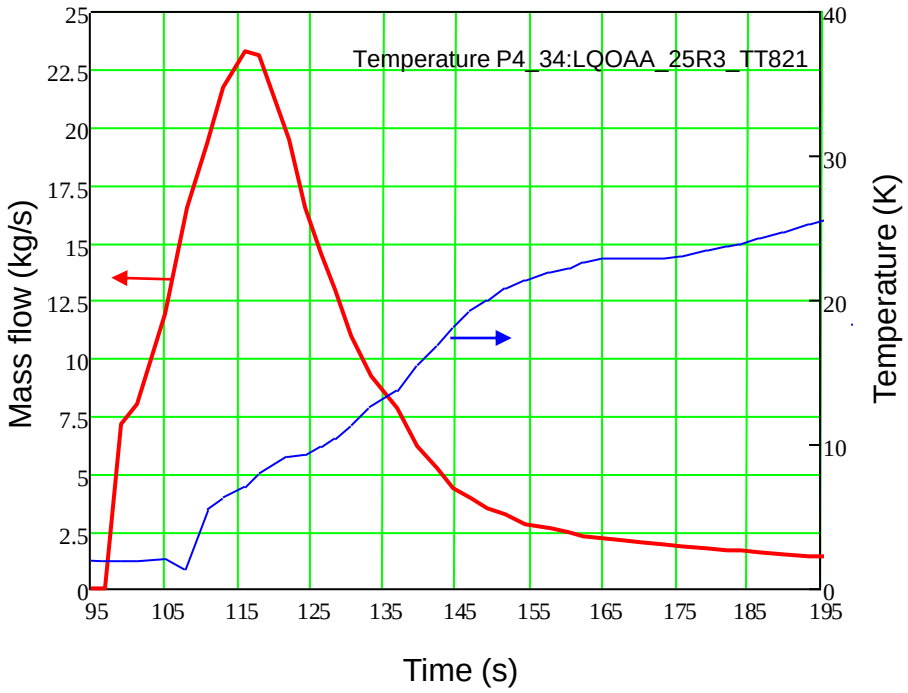
- Cold-mass
- Vacuum vessel
- Line E
- Cold support post
- Warm Jack
- Compensator/Bellows
- Vacuum barrier

Estimation of helium discharge from cold mass

Recorded data

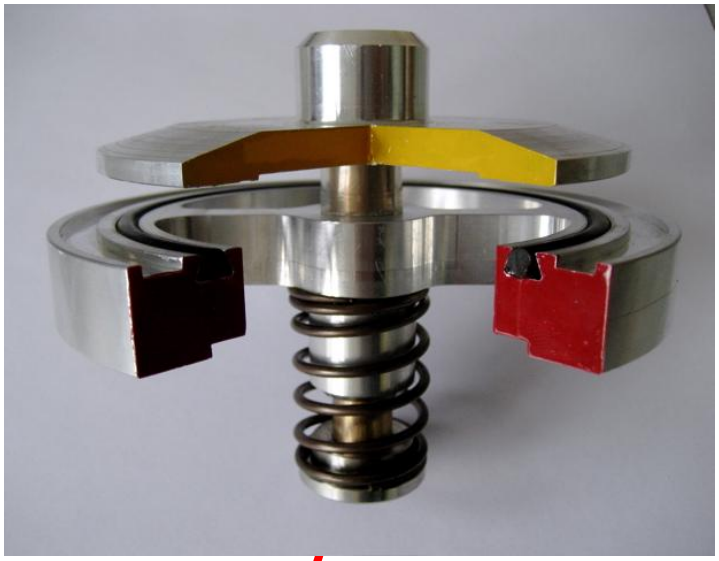


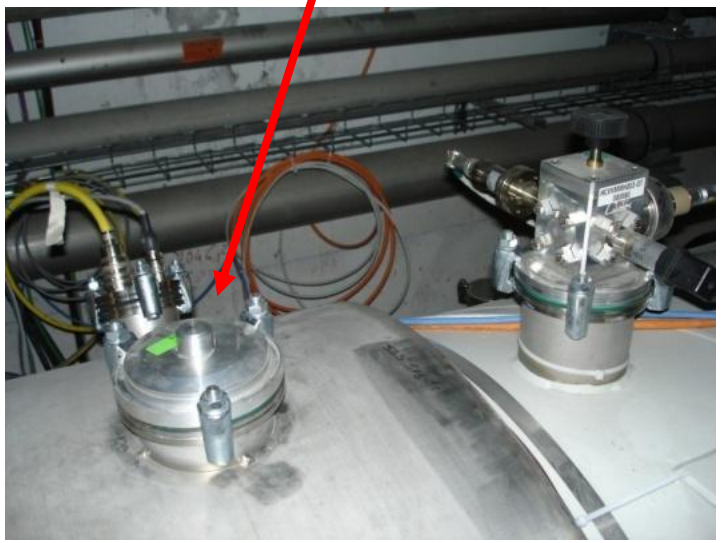
Estimated mass flow

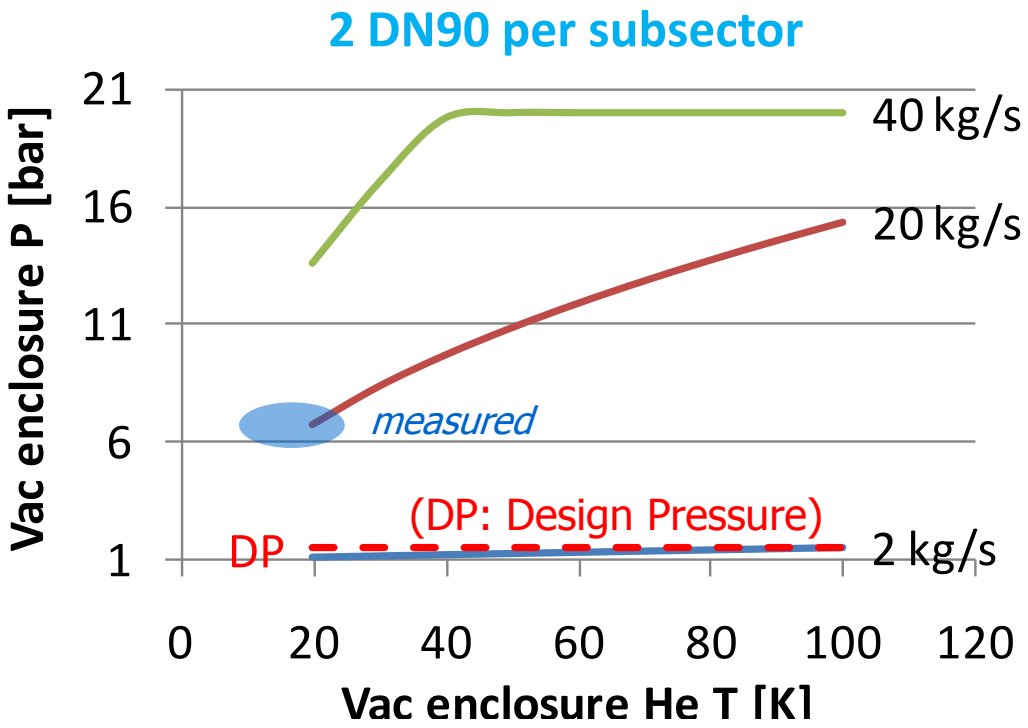


Helium temperature given by sensor P4_34:LQOAA_25R3_TT821
All helium discharged through 1 hole.
Constant hydraulic diameter 54 mm
Total mass of helium = 214 m x 0.026 m3/m x 147.8 kg/m3 = 822 kg

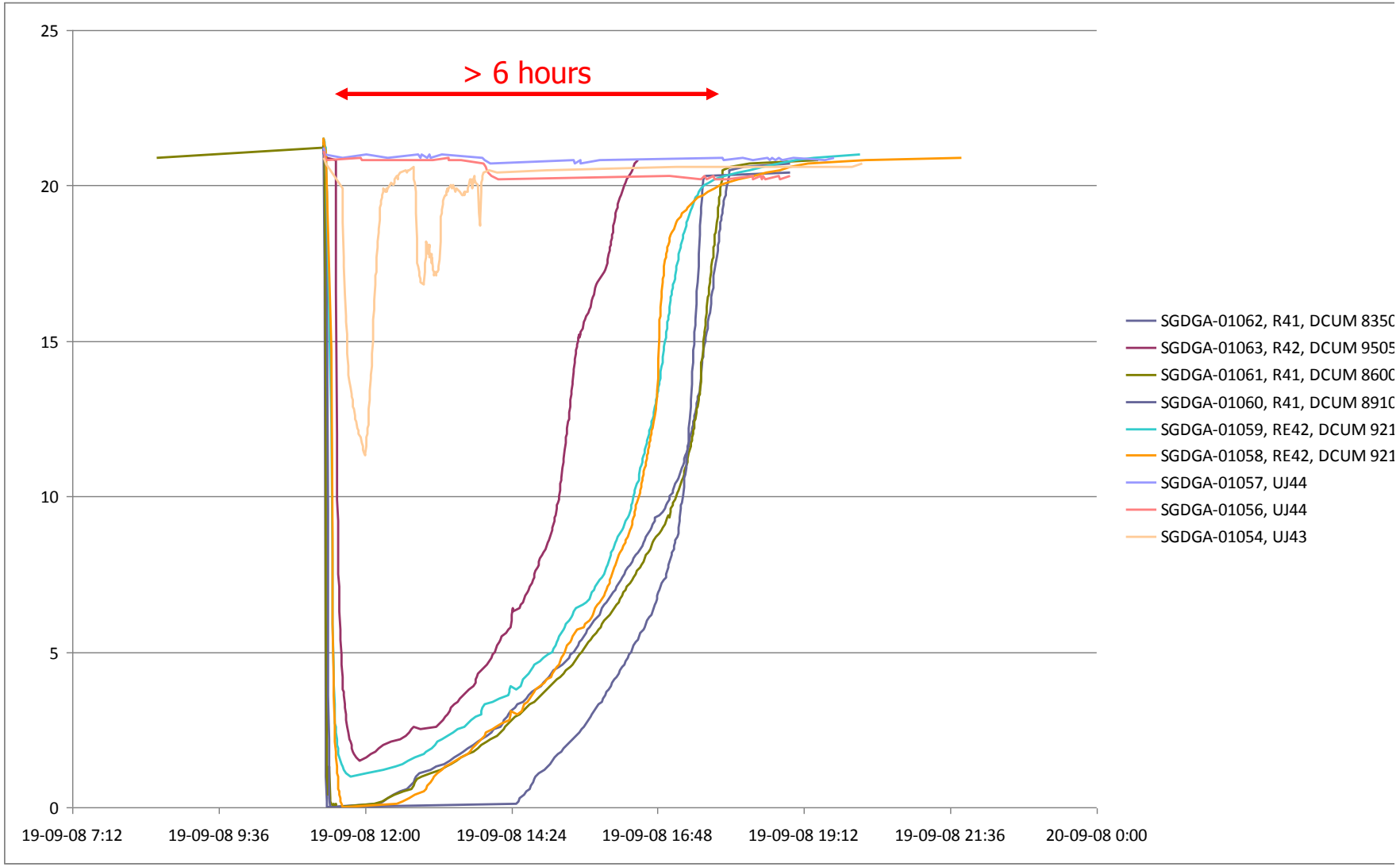
Relief devices on insulation vacuum enclosure

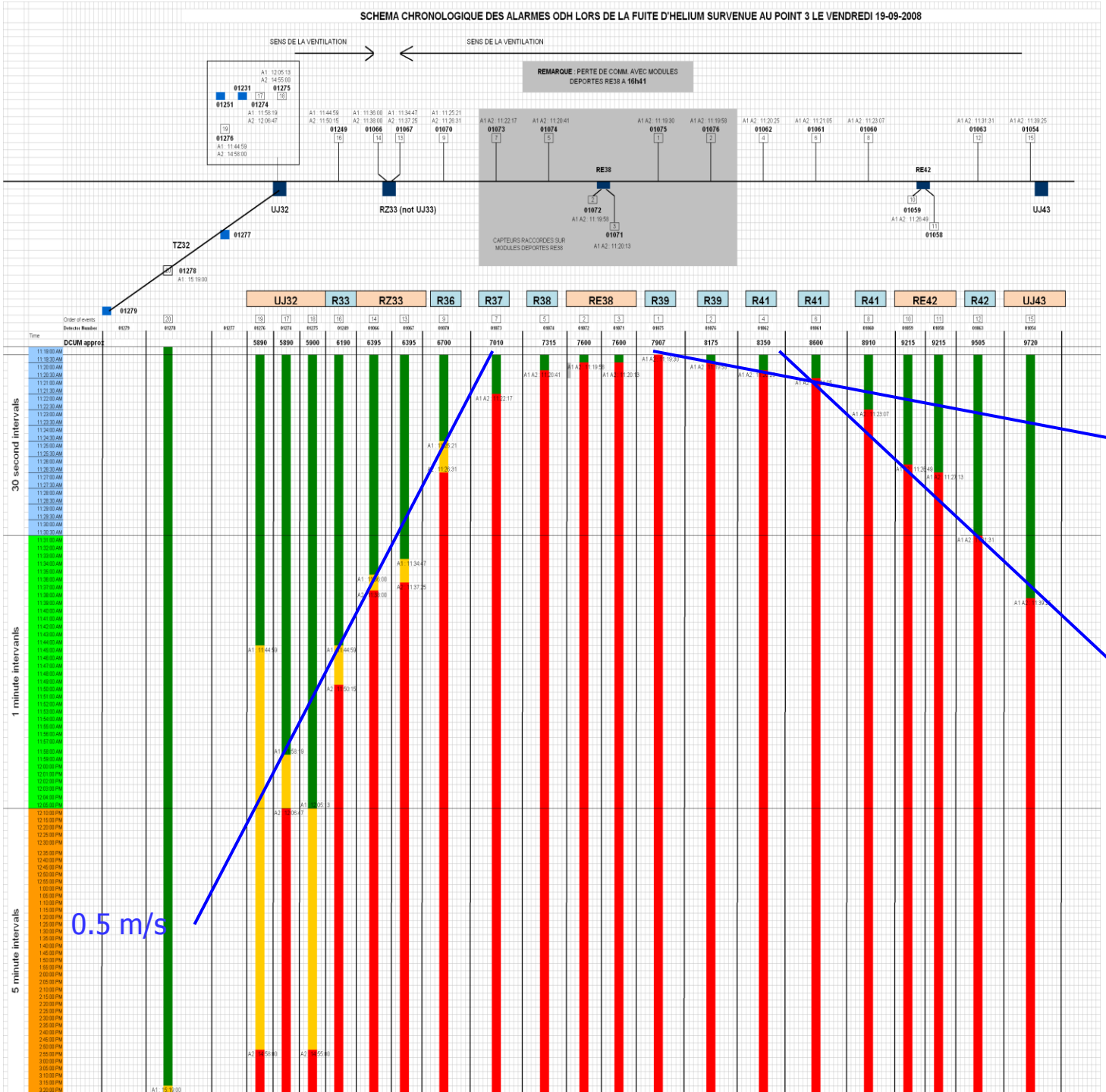






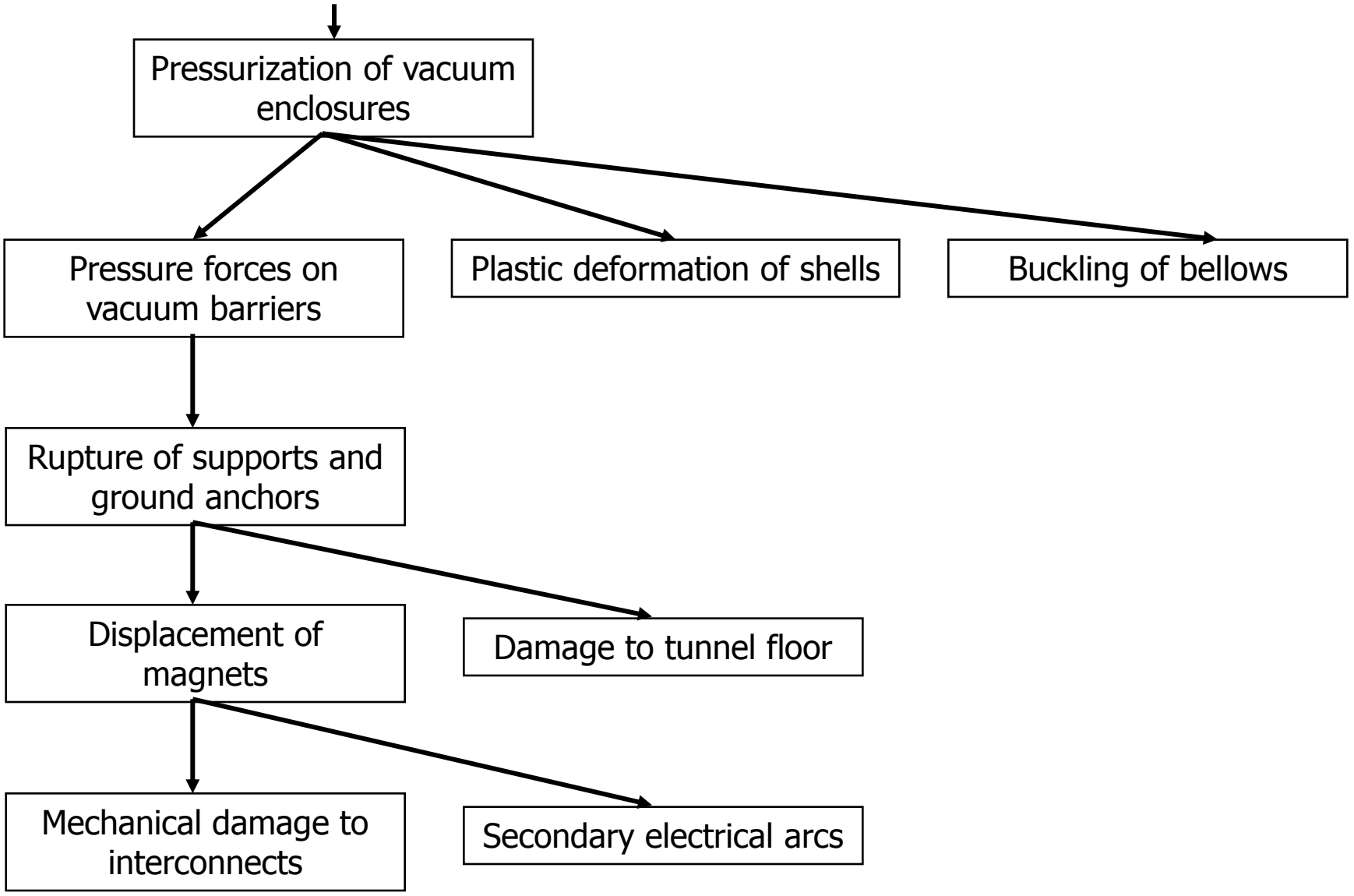
Oxygen content [%] in tunnel (at ceiling)



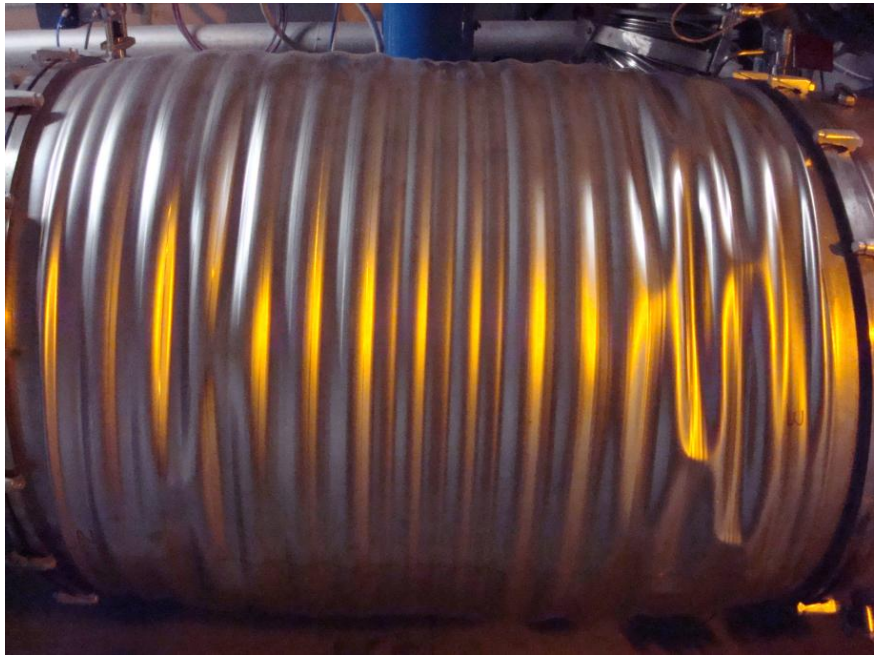

SCHEMA CHRONOLOGIQUE DES ALARMES ODH LORS DE LA FUITE D'HELIUM SURVENUE AU POINT 3 LE VENDREDI 19-09-2008
SENS DE LA VENTILATION
SENS DE LA VENTILATION
REMARQUE : PERTE DE COMM. AVEC MODULES DEPORTES RE38 A 16h41
UJ32
RZ33 (not UJ33)
RE38
RE42
UJ43
TZ32
CAPTEURS RACCORDES SUR MODULES DEPORTES RE38
UJ32
R33
RZ33
R36
R37
R38
RE38
R39
R39
R41
R41
R41
RE42
R42
UJ43
30 second intervals
1 minute intervals
5 minute intervals
0.5 m/s
7.3 m/s
1.5 m/s

Fault tree of 19 Sept 2008 incident at the LHC

Cryogenic effects [2/2]



Assessment of maximum pressure in vacuum enclosure from deformation of W sleeve



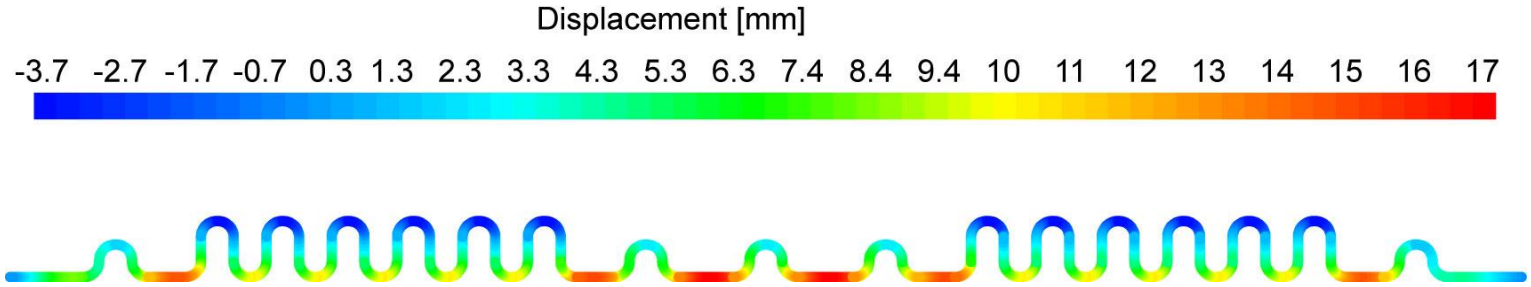
Corrugated sleeve of 1 mm thick AISI 316 L

Yield stress 275 MPa

Nominal diameter 1016 mm

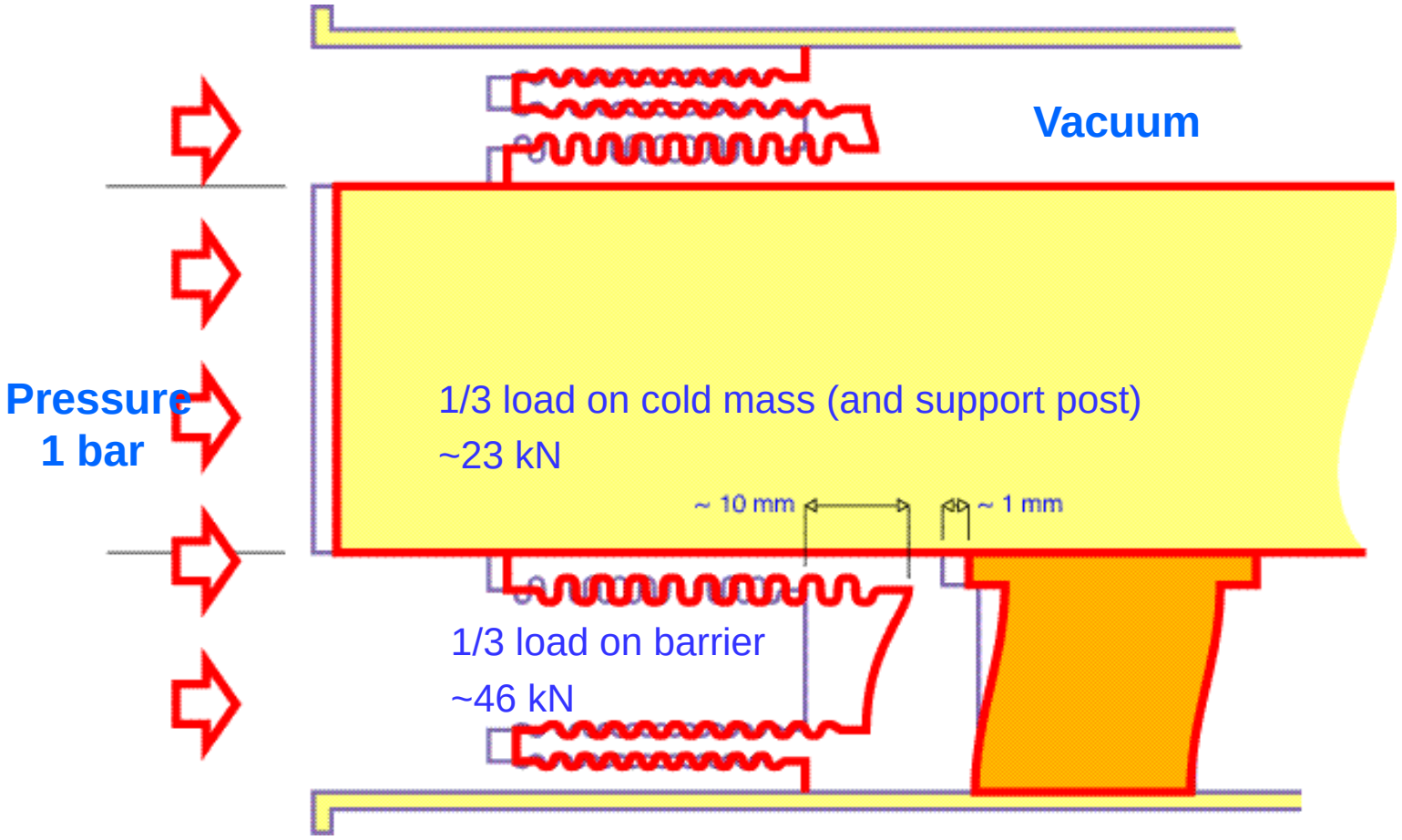
Maximum diameter 1055 mm

FE calculation in large displacement case (iterative geometry) gives 7 bar overpressure



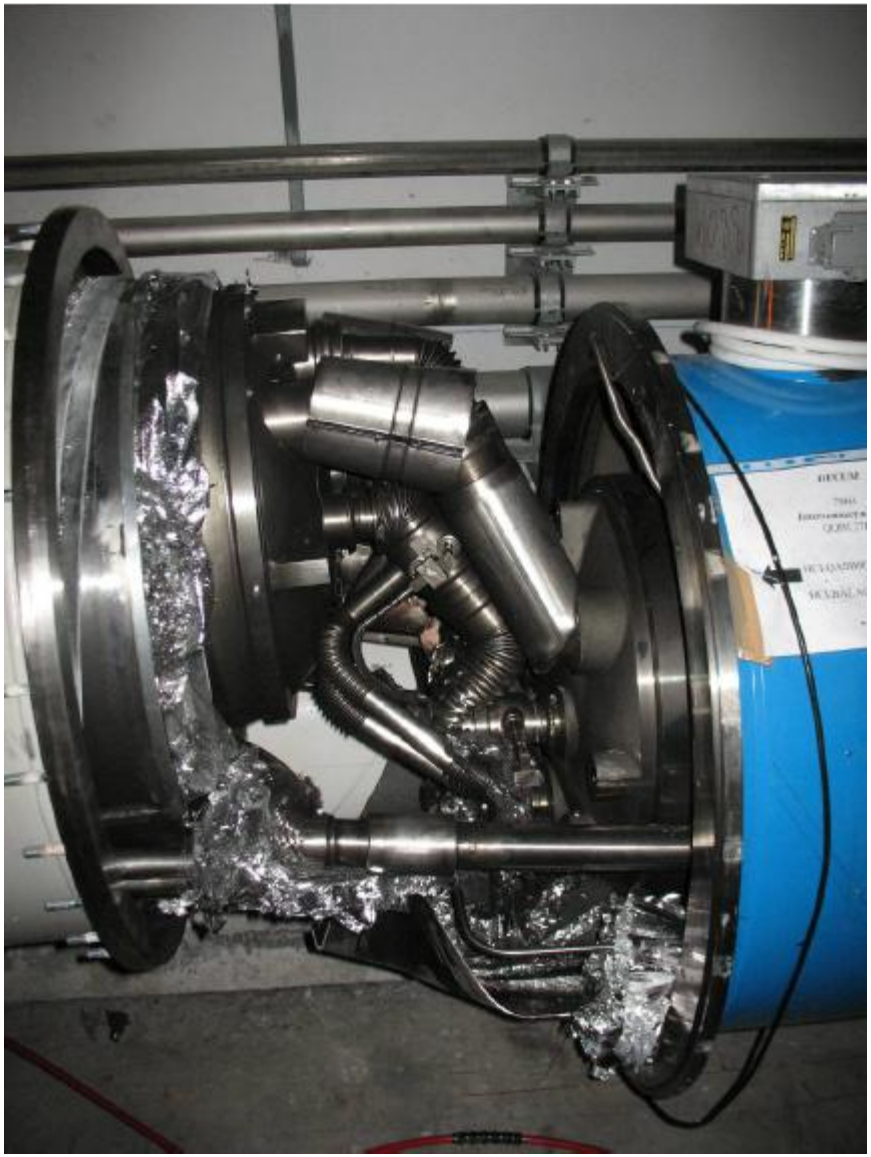
C. Garion

Pressure forces on SSS vacuum barrier
at nominal pressure differential (1 bar)



Total load on 1 jack ~70 kN

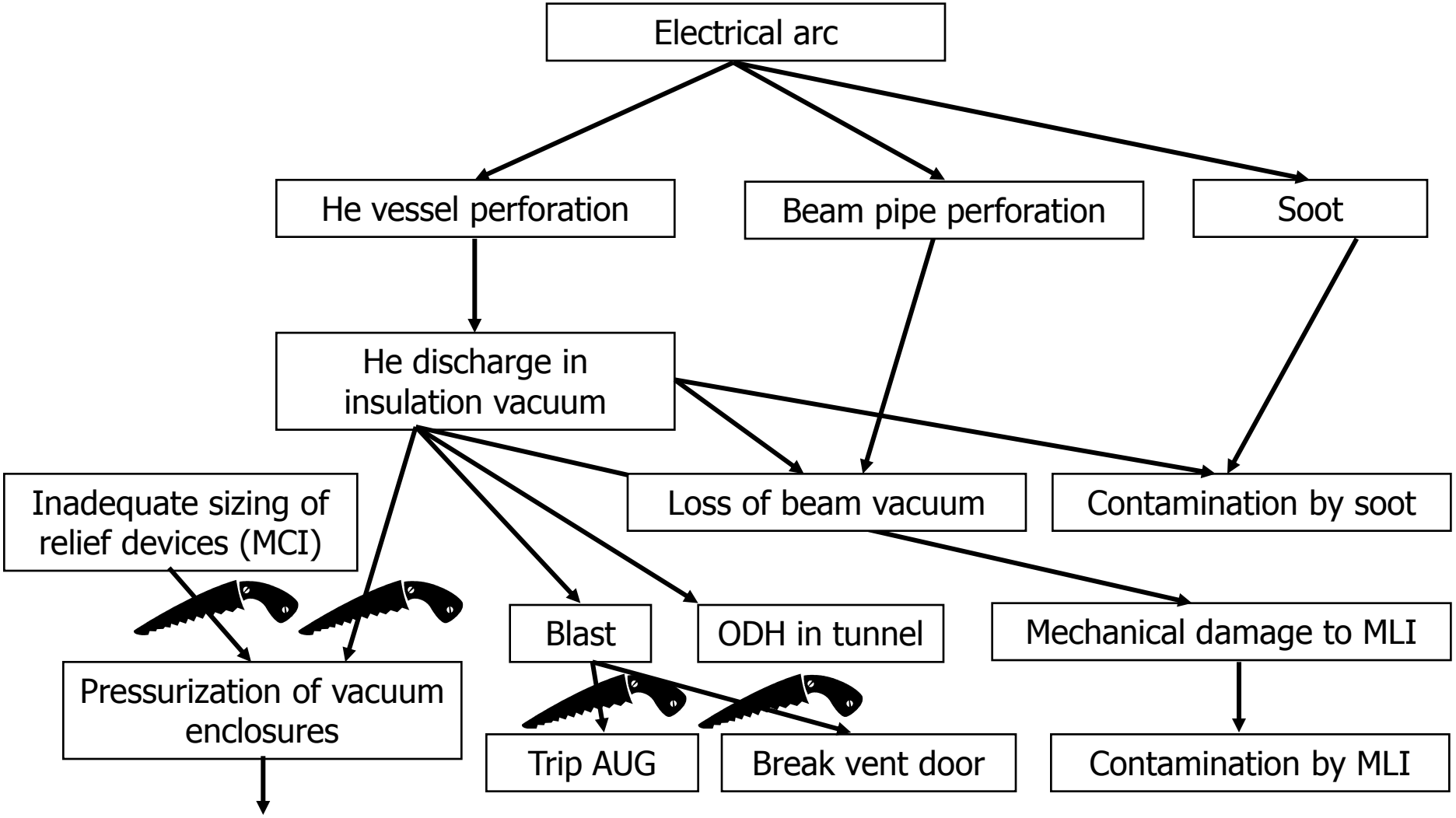
Collateral damage: magnet displacements



Collateral damage: ground supports

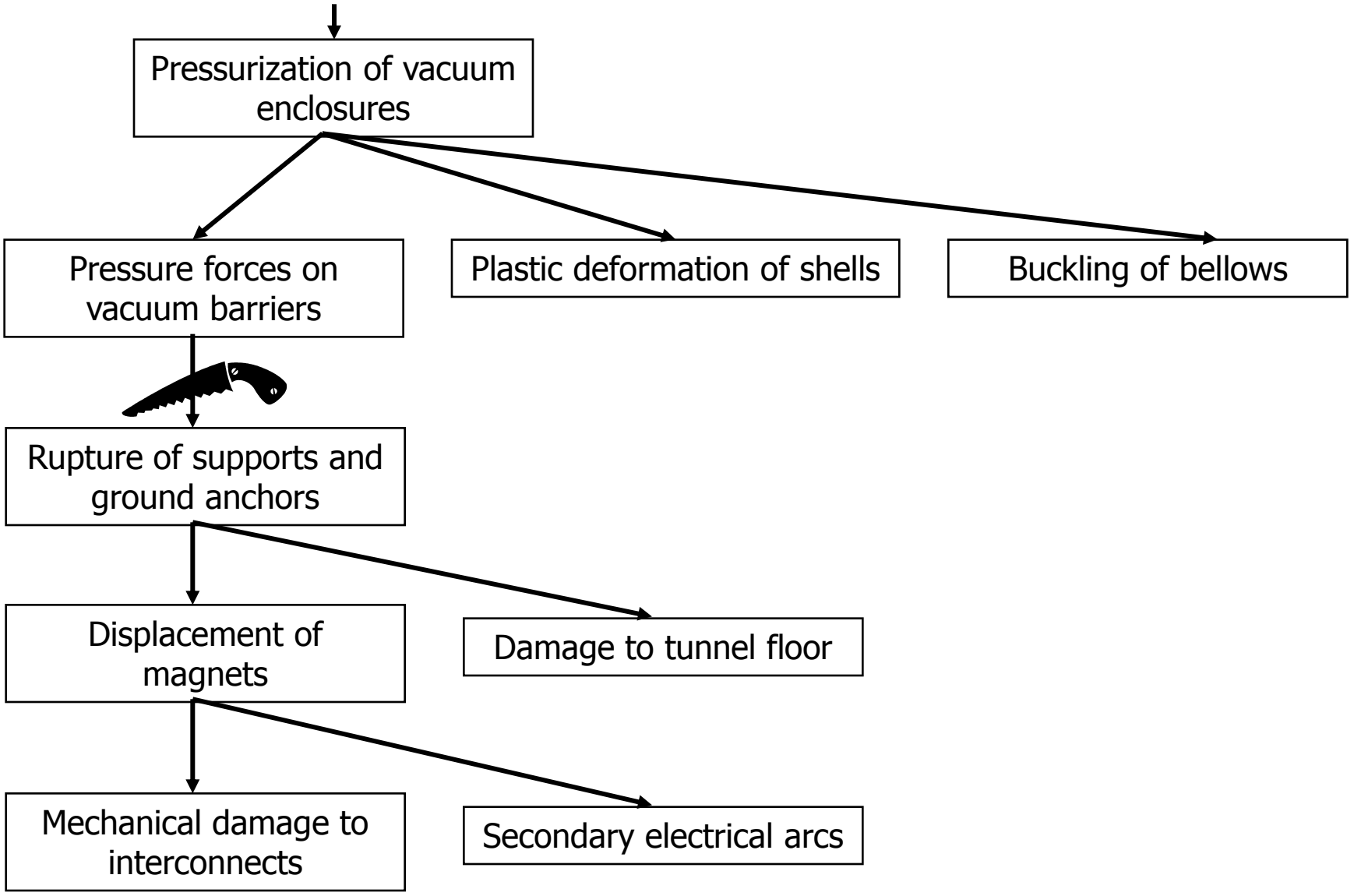
Fault tree of 19 Sept 2008 incident at the LHC

Cryogenic consolidation actions [1/2]

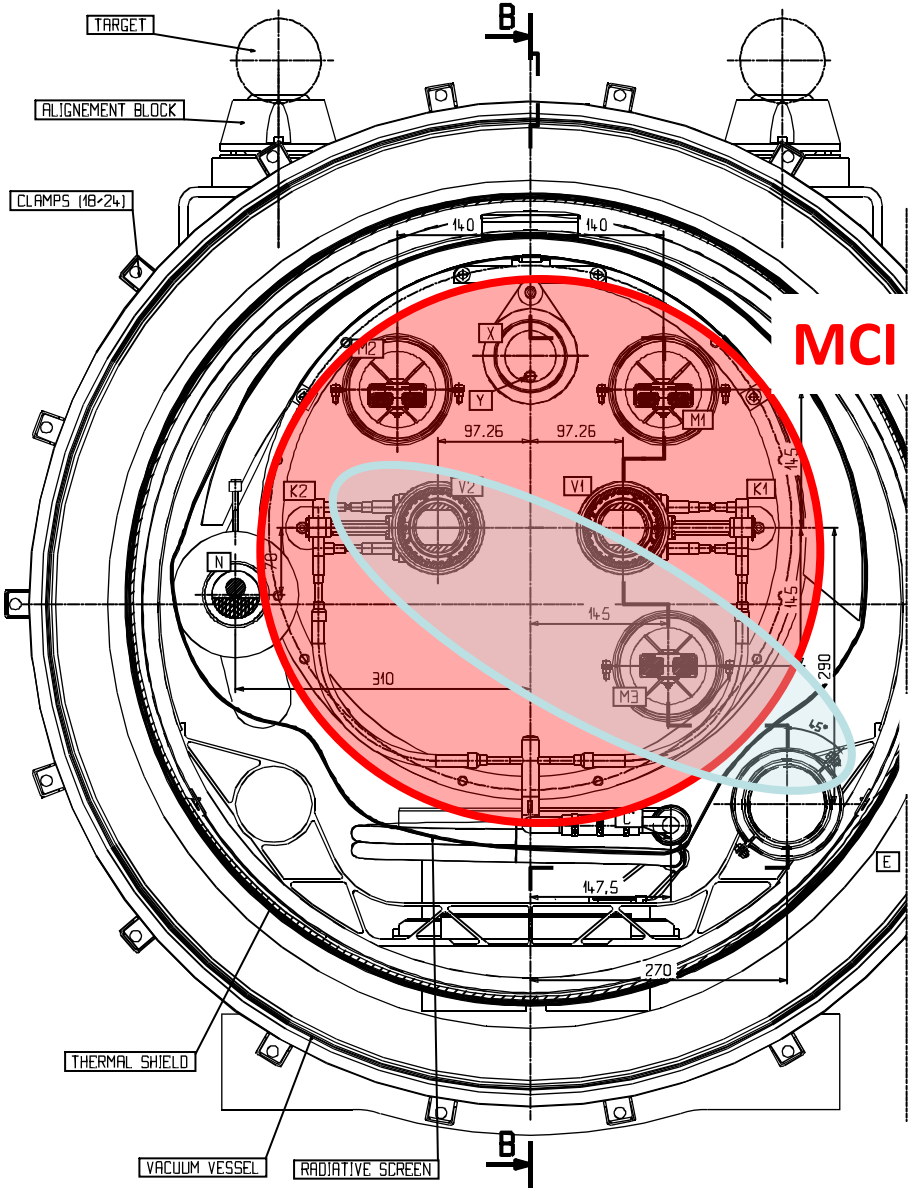


Fault tree of 19 Sept 2008 incident at the LHC

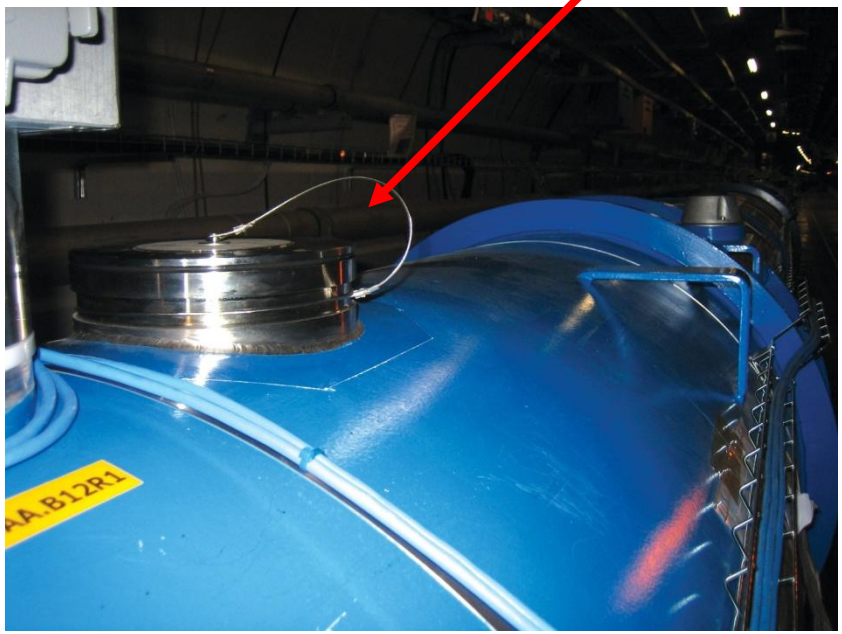
Cryogenic consolidation actions [2/2]

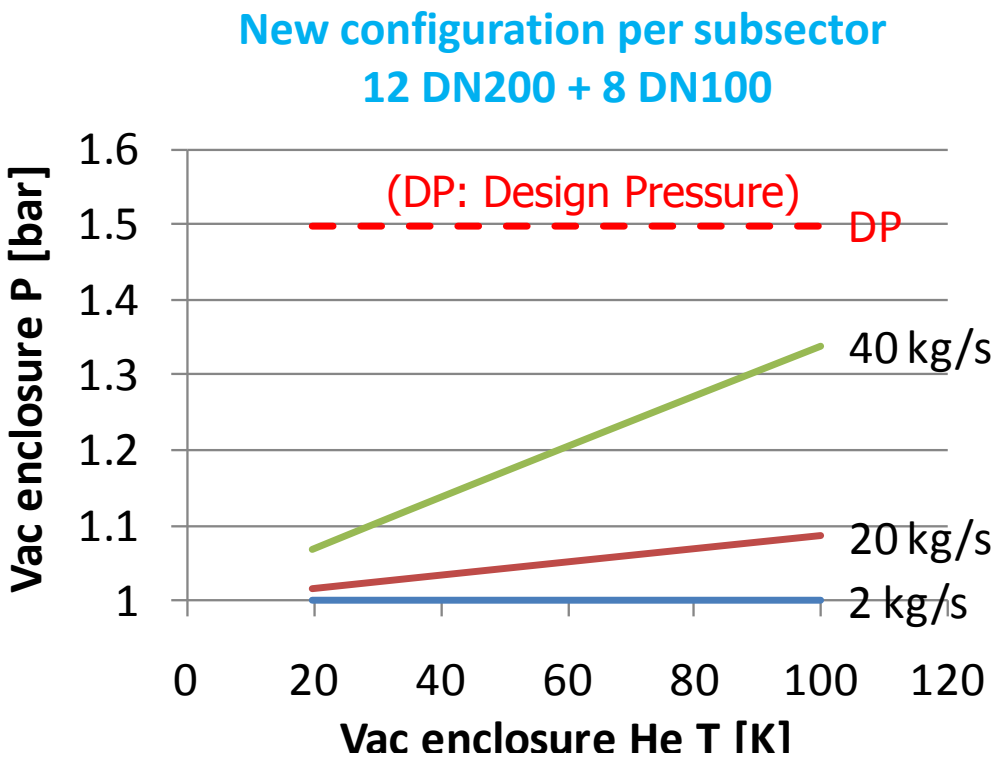


Revision of MCI in case of electrical arc

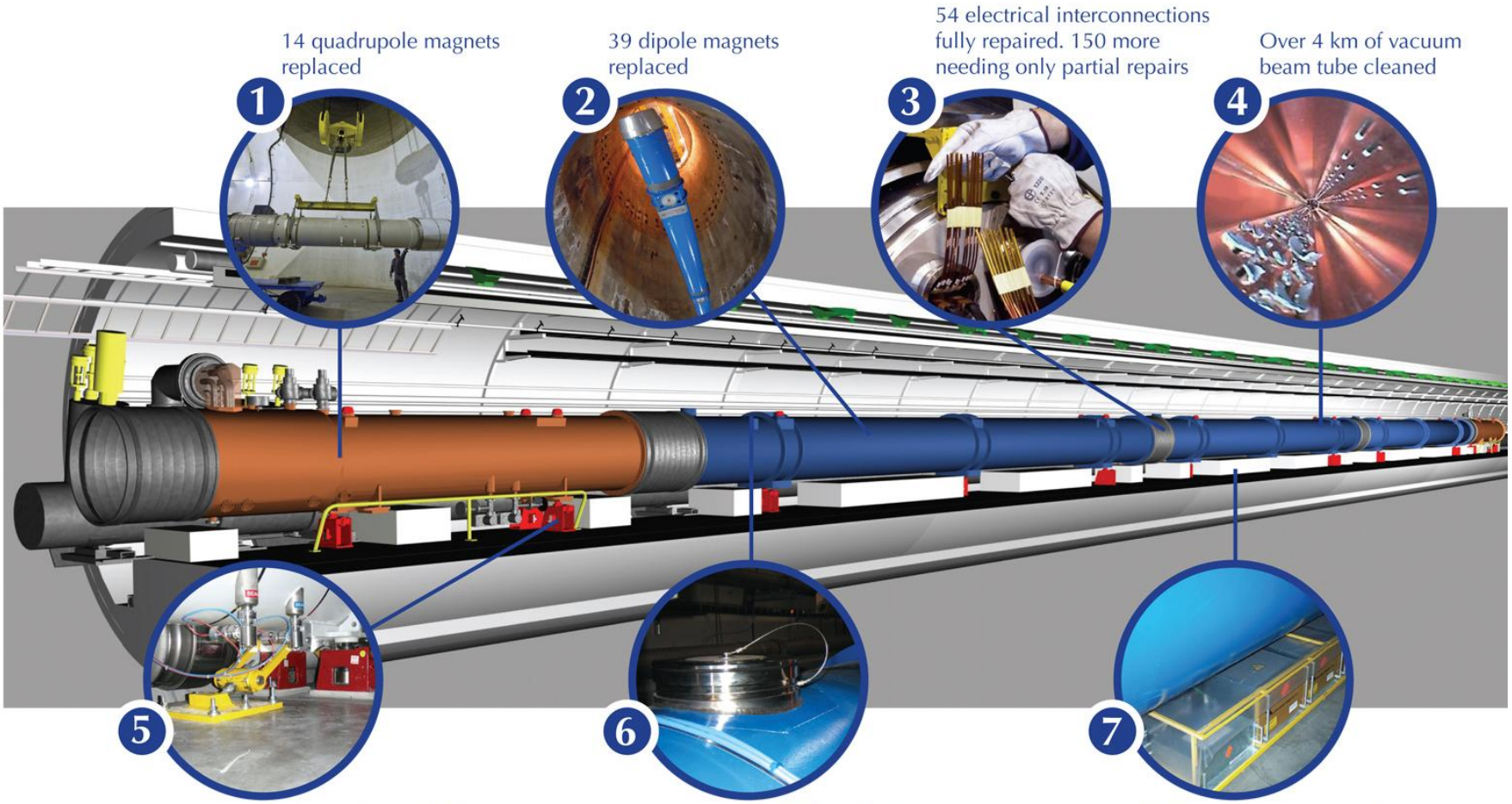


Additional relief devices on vacuum enclosure





Summary of repair & consolidation in tunnel



Conclusions

- Cryogenics, the science and technology of low temperatures and liquefied gases, exhibits diverse safety issues in a variety of domains
- Pluridisciplinary approach to cryogenic safety is therefore essential
- The effects in complex systems are often compounded, so that a thorough analysis of the independent processes and of their interrelations is necessary
- The existing design codes and standards do not generally address the cryogenic domain, so that engineering judgment is required in order to apply them relevantly
- Many issues can however be addressed from basic knowledge of applied physics and engineering science