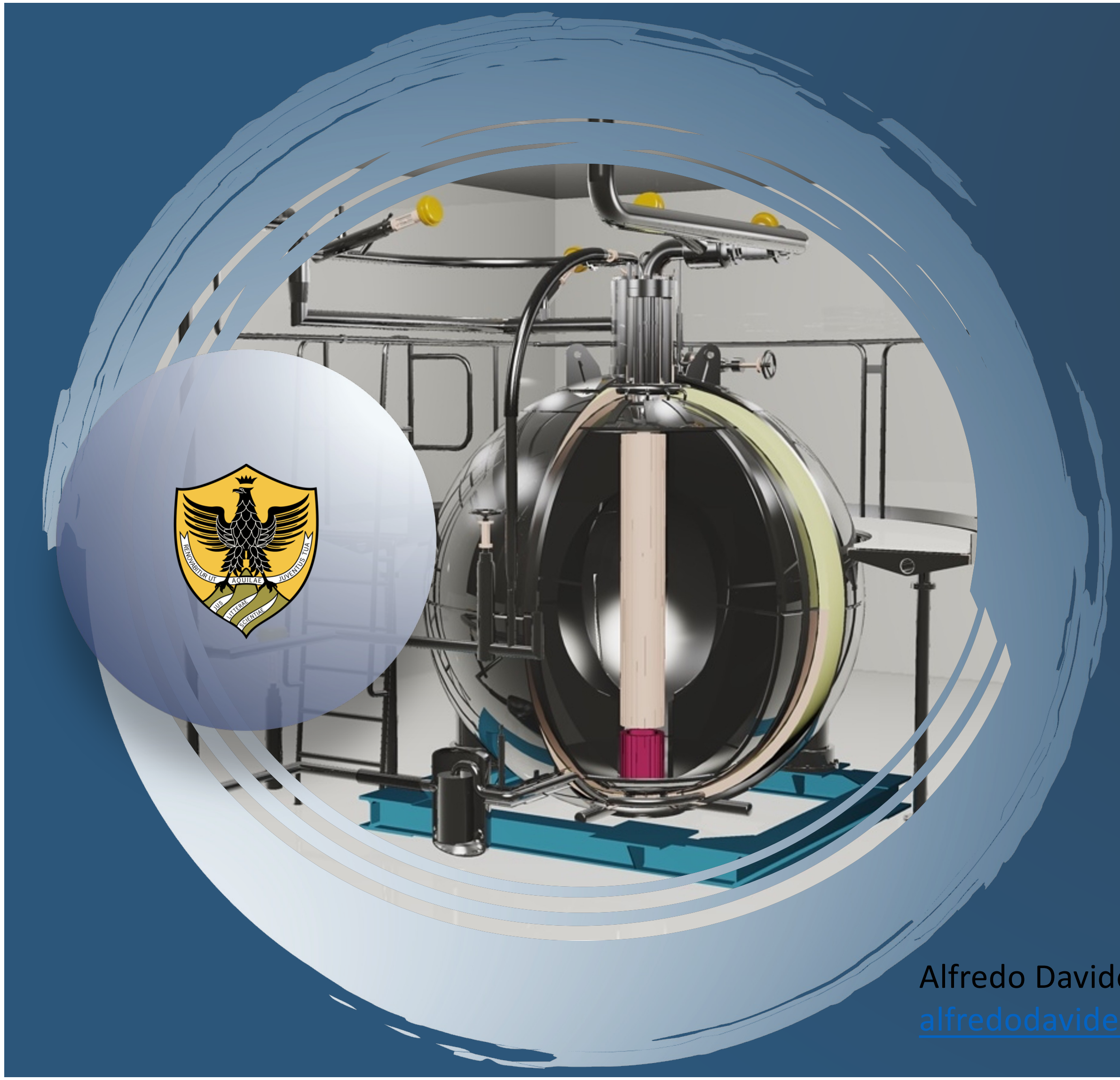

SoUP
The INFN School on Underground Physics

DSFC
Dipartimento
di Scienze Fisiche
e Chimiche

CRYOGENICS

(… MAINLY NOBLE LIQUIDS FOR UNDERGROUND DETECTORS)

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Outline

- Heat transfer
- Producing “cold” (cryogenics)
- Keeping “cold”
- Monitoring “cold”
- Cryogenic liquids as detectors
- Typical operations

Introduction

- Goal: overview of
  - some of the relevant physical effects
  - the many technologies and techniques employed in the
    - Design
    - Installation
    - Operation

  of liquefied noble gas detectors
- Knowledge in many fields is required (prerequisites)
  - Vacuum technology,
  - Mechanical engineering,
  - Process engineering,
  - High purity gas delivery, and others...

Apologies…

From Wikipedia:
The 13th IIR International Congress of Refrigeration (held in Washington DC in 1971) endorsed a universal definition of “cryogenics” and “cryogenic” by accepting a threshold of 120 K (or –153 °C) to distinguish these terms from the conventional refrigeration.

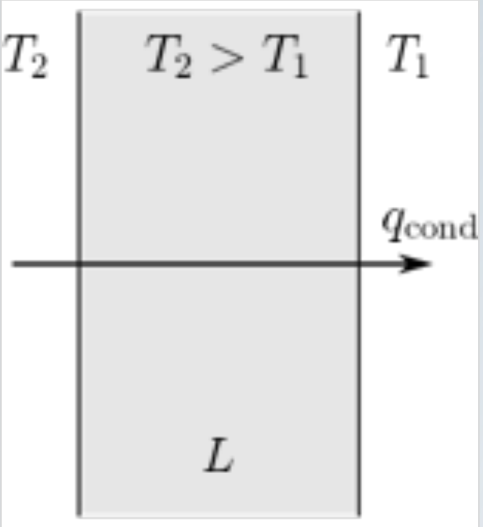
However, what I’ll be focusing on is noble liquids, mainly liquid xenon (LXe)
… and liquid argon (LAr)

Intruduction

- Requirements for cryogenic systems:
  - Safe and not-too-long cool down
  - Stability during operation
  - Purity
  - Radio-purity
  - Emergency handling
    - Cooling
    - recuperation

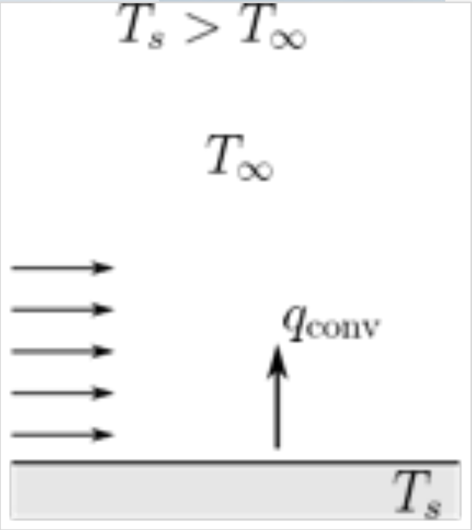
Heat transfer mechanisms

Conduction



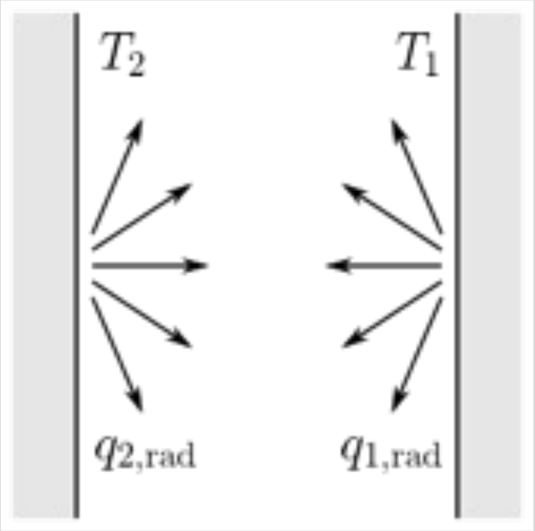
$$q_{cond} = \frac{k \cdot A}{L}(T_2 - T_1)$$

Convection



$$q_{conv} = h \cdot A\,(T_s - T_\infty)$$

Radiation



$$q_{rad} = \sigma \cdot F_E F_A A\,(T_2^4 - T_1^4)$$

Conduction

1) Gas conduction

at low pressures (<10Pa or 10^{-4} torr), that is when the mean free path ~ 1m > distance between hot and cold surfaces

$$\frac{Q}{A} = \eta_g P_g \Delta\theta$$

where η_g is the "accommodation coefficient"; typical values for helium ⇒

$\theta_{cold} \sim \theta_{hot}$	η_g (W.m^{-2}.Pa.K)
4 ~ 20K	0.35
4 ~ 80K	0.21
4 ~ 300K	0.12
80 ~ 300K	0.04

not usually a significant problem, check that pressure is low enough

2) Solid conduction

$$\boxed{q_{cond} = \frac{k \cdot A}{L}(T_2 - T_1)}$$

$$\frac{Q}{A} = k(\theta)\frac{d\theta}{dx}$$

a more convenient form is:

$$Q\frac{L}{A} = \int_{\theta_c}^{\theta_h} k(\theta)\, d\theta$$

look up tables of conductivity integrals

Conduction

$$\boxed{q_{cond} = \frac{k \cdot A}{L}(T_2 - T_1)}$$

How to reduce heat transfer through conduction?

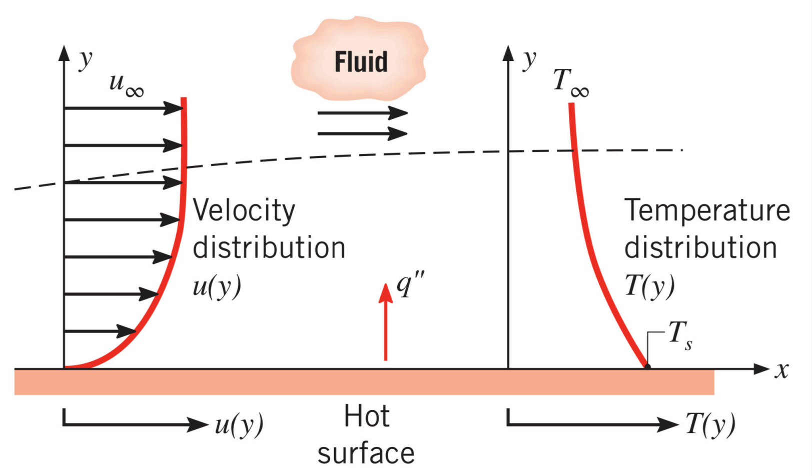
- Evacuate gases
- Material with low thermal conductivity
- Increase the length
- Reduce the cross section

Convection

$$\boxed{q_{conv} = h \cdot A\left(T_s - T_\infty\right)}$$

Two mechanisms:

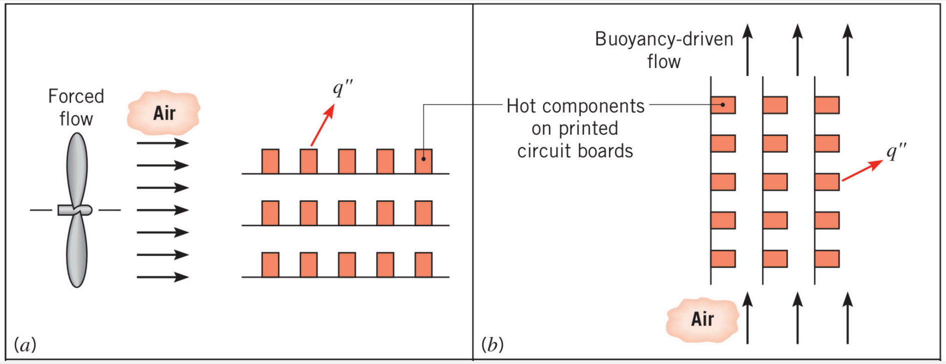
- Random molecular motion (diffiusion) – dominant near surface
- Bulk/macroscopic motion (advection) – increases/enlarges the boundary layer surface



How does the heat get transferred?

- Fluid in motion exchanges heat with the “hot surface”. Two layers (equal? different? We don’t care!):
  - Hydrodynamic/velocity boundary layer
  - Thermal boundary layer

Convection



Can be classified as

- Free/natural convection, buoyancy-driven flow
- Forced convection, pressure-driven flow

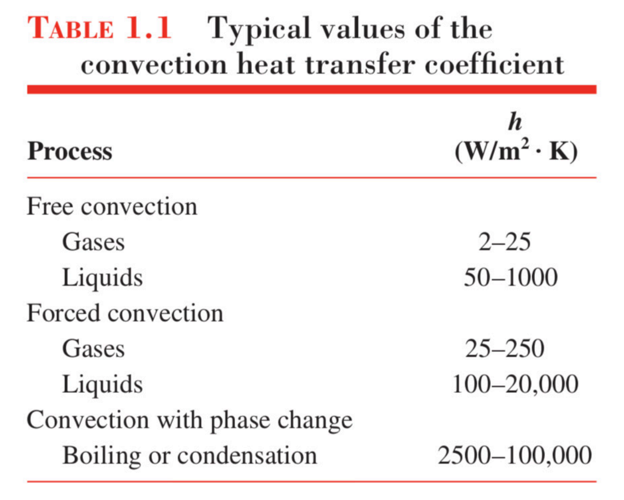


TABLE 1.1 Typical values of the convection heat transfer coefficient

Process	***h*** **($W/m^2 \cdot K$)**
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

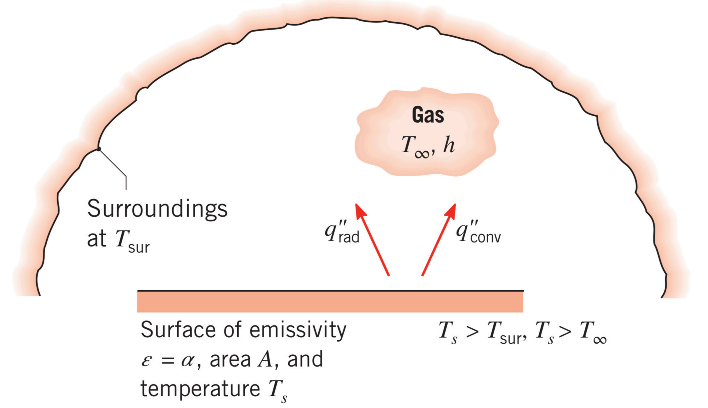
Radiation

$$q_{rad} = \sigma \cdot F_E F_A A \left(T_2^4 - T_1^4\right)$$

- F_A: ”viewing factor”, fraction of radiation leaving one surface that is intercepted by the other surface
- F_E: depends on the emissivity of the surfaces

Note that putting an intermediate surface at an intermediate temperature such radiative power will decrease significantly
In general: n thermally floating shields between the cold and hot surfaces reduce the transmitted power by a factor (n + 1) (super-insulation)

Bergman, “Fundamentals of Heat and Mass Transfer”



$$q_{rad} = \sigma \cdot F_E F_A A \left(T_s^4 - T_{sur}^4\right)$$

Producing "cold" (cryogenics)

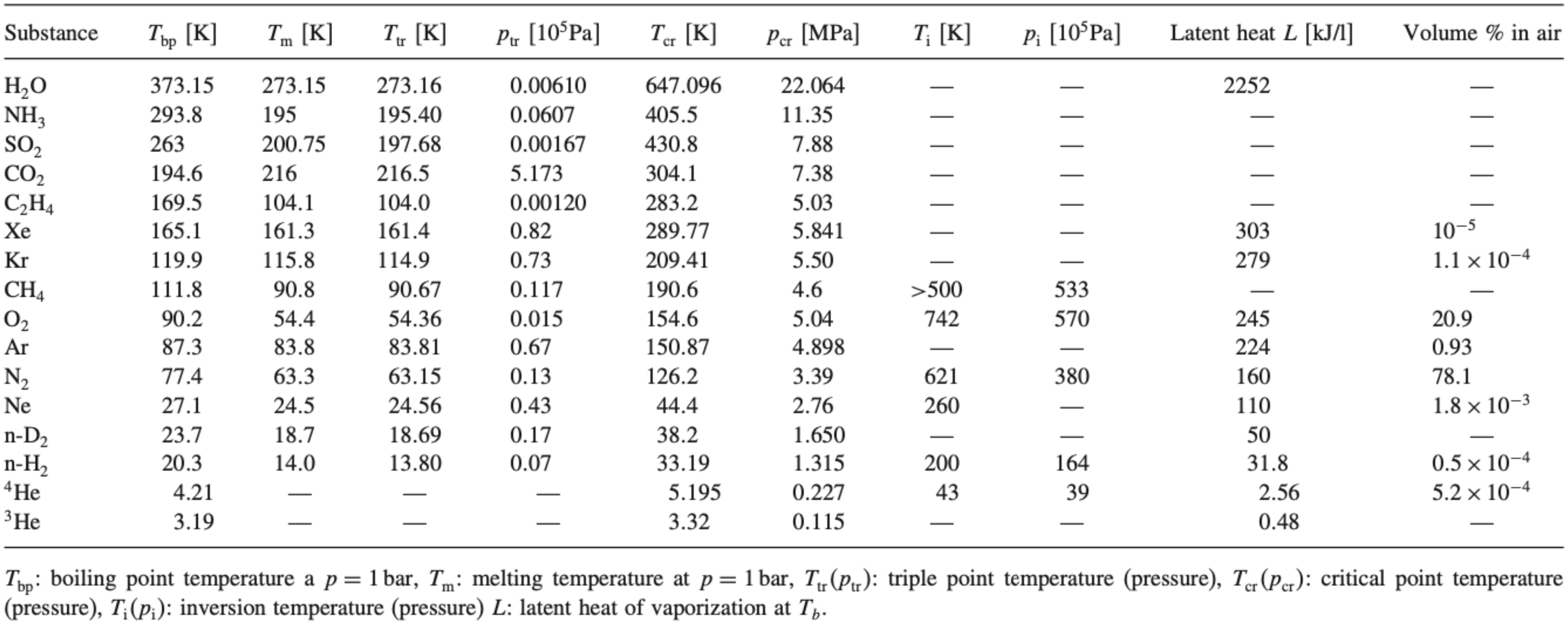
Outline of the section:

- Cryogenic fluids (cryogens)
- Cryocoolers
- Dilution refrigerators (very cold)

Cooling with cryogenic fluids (cryogens)

- Historically, the simplest way to produce low temperature was (and still is) the use of "cryoliquids" (e.g. nitrogen, helium)
- Most most low-temperature lab equipment based on cryogens
- Change to new technologies is expensive
- obtained by the Joule-Thomson process:
  - isothermal compression
  - remove heat from the hot gas
  - let the gas expand → temperature decrease ($T<T_{inv}$)

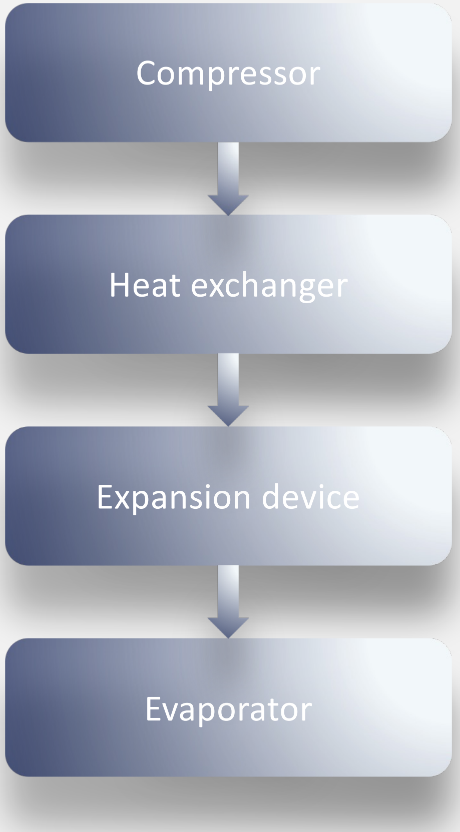
Cooling with cryogenic fluids (cryogens)



Substance	T_{bp} [K]	T_m [K]	T_{tr} [K]	p_{tr} [10^5Pa]	T_{cr} [K]	p_{cr} [MPa]	T_i [K]	p_i [10^5Pa]	Latent heat L [kJ/l]	Volume % in air
H_2O	373.15	273.15	273.16	0.00610	647.096	22.064	—	—	2252	—
NH_3	293.8	195	195.40	0.0607	405.5	11.35	—	—	—	—
SO_2	263	200.75	197.68	0.00167	430.8	7.88	—	—	—	—
CO_2	194.6	216	216.5	5.173	304.1	7.38	—	—	—	—
C_2H_4	169.5	104.1	104.0	0.00120	283.2	5.03	—	—	—	—
Xe	165.1	161.3	161.4	0.82	289.77	5.841	—	—	303	10^{-5}
Kr	119.9	115.8	114.9	0.73	209.41	5.50	—	—	279	1.1×10^{-4}
CH_4	111.8	90.8	90.67	0.117	190.6	4.6	>500	533	—	—
O_2	90.2	54.4	54.36	0.015	154.6	5.04	742	570	245	20.9
Ar	87.3	83.8	83.81	0.67	150.87	4.898	—	—	224	0.93
N_2	77.4	63.3	63.15	0.13	126.2	3.39	621	380	160	78.1
Ne	27.1	24.5	24.56	0.43	44.4	2.76	260	—	110	1.8×10^{-3}
n-D_2	23.7	18.7	18.69	0.17	38.2	1.650	—	—	50	—
n-H_2	20.3	14.0	13.80	0.07	33.19	1.315	200	164	31.8	0.5×10^{-4}
^{4}He	4.21	—	—	—	5.195	0.227	43	39	2.56	5.2×10^{-4}
^{3}He	3.19	—	—	—	3.32	0.115	—	—	0.48	—

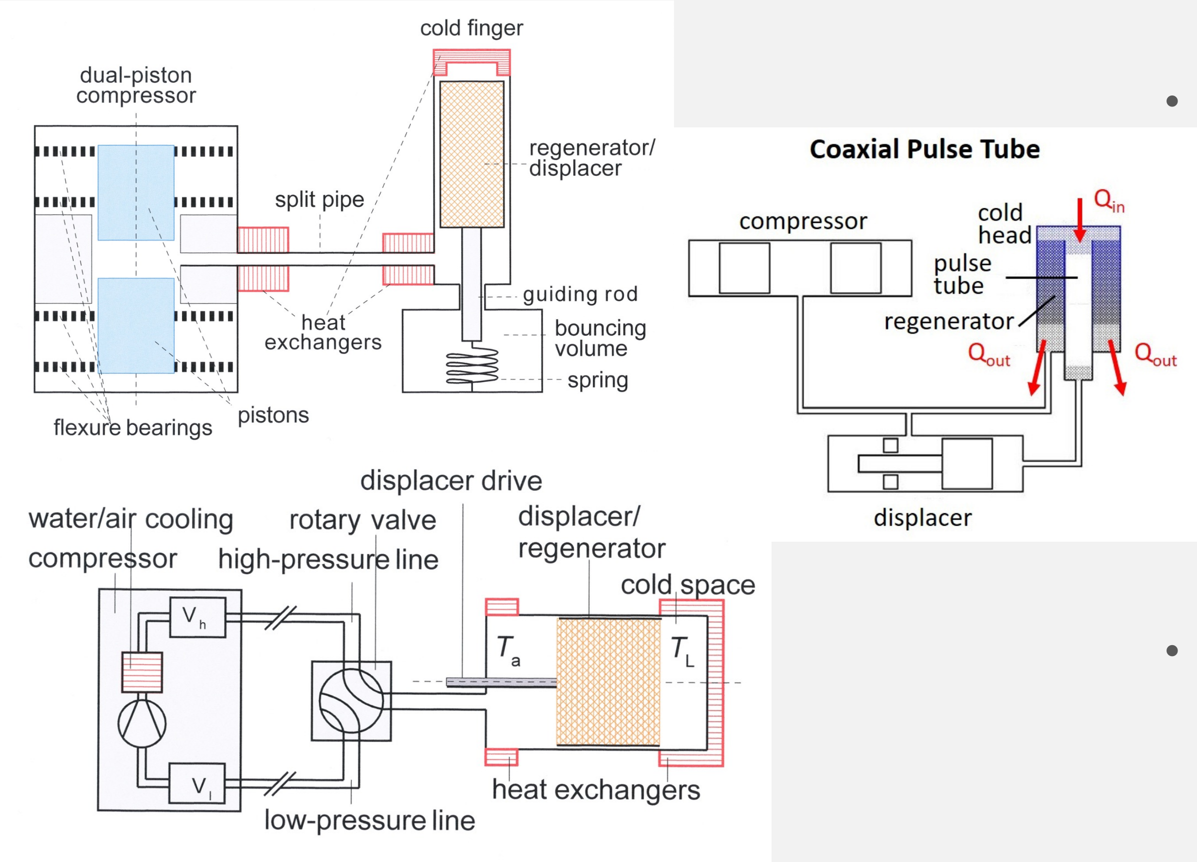
T_{bp}: boiling point temperature a $p = 1$ bar, T_m: melting temperature at $p = 1$ bar, $T_{tr}(p_{tr})$: triple point temperature (pressure), $T_{cr}(p_{cr})$: critical point temperature (pressure), $T_i(p_i)$: inversion temperature (pressure) L: latent heat of vaporization at T_b.

Cooling with cryocoolers



- Mechanical device that generates low temperatures through compression and expansion of a gas
- Operates on a closed cycle (gas mass constant)
- The cold generated in the expander is exchanged between the cold end and the object to be cooled
- Cryocoolers can produce temperatures as low as 4.2K

Cooling with cryocoolers

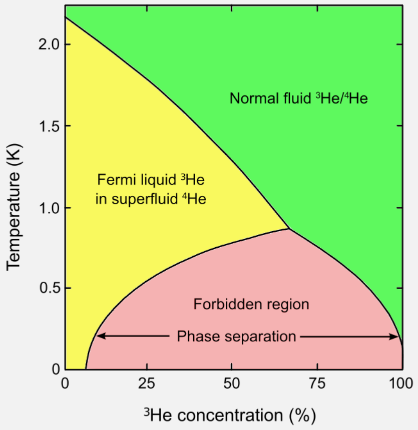


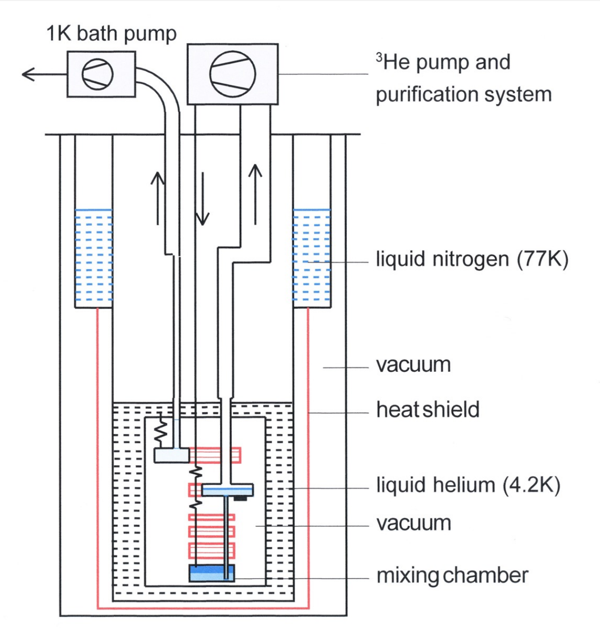
- Different types:
  - Stirling pulse tube
  - Gifford McMahon (GM)
  - Pulse tube refrigerator (PTR)

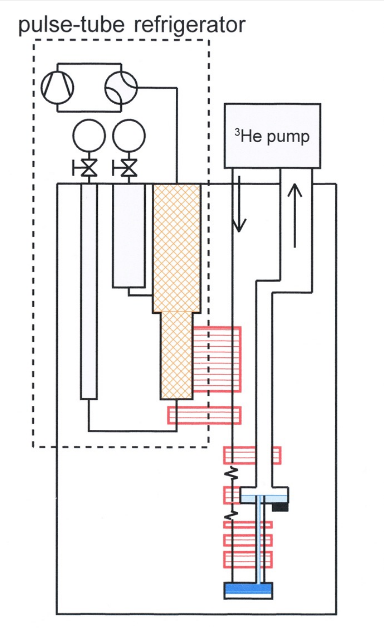
Require some infrastructure and care:
  - Compressor
  - Chiller (maybe)
  - Maintenance
- Not vibration free

Cooling at mK with dilution refrigerators

- Provide continuous cooling to temperatures as low as 2 mK
- No moving parts (i.e. vibration-free)
- First proposed by Heinz London in the early 1950s
- First realization in 1964
- Uses a mixture of ^{3}He and ^{4}He
- Available:
  - Wet
  - Dry (cryogen free)







What are the underground experiments using?

Many different strategies are employed to extract heat from the cryostat:

- Cryocoolers
  - Pulse-tube refrigerators (MEG, XMASS, XENON, PANDA-X)
  - Stirling-type (ICARUS, LN_2 secondary cooling loop)
  - GM-refrigerators (XENON cryogenic distillation column)
- LN_2 cooling
  - LUX/LZ (LN_2 thermosyphon GXe condenser)
  - Darkside-50 (LN_2/GAr condenser)
  - XENON1T/nT LXe/SXe storage,
  - XENONnT cryogenic purification LXe/LN_2 heat exchanger
  - Darkside-20k (LN_2/GAr condensers for AAr and UAr)
  - GERDA/LEGEND (LN_2 evaporators/confenser)
- Dilution refrigerator
  - CUORE, COSINUS, CRESST…

Keeping cold

Outline of the section:

- Insulation
- Multilayer insulation
- Cryostats and tranfer lines

Insulation

Storage of a cryogen is difficult, as it entails a continuous boil off due to heat leaks

Boil off causes pressure to rise (remember the liquid-to-gas volume ratio)

The need for insulation is vital

We need to minimize the heat leaks due to any any of the processes discussed earlier by means of **insulation**

Insulation can be:

- Mass insulation (cellular, granular, fibrous materials)
- Reflective insulation (metal foils, multilayer)
- Vacuum insulation

Examples:

- Foam (Mass)
- Vacuum alone (Vacuum)
- Evacuated powder (Mass+Vacuum)
- Opacified powder (Mass+Vacuum+Raflective)

Vacuum insulation

Eliminating matter (ideal vacuum) we can avoid conduction and convection

However, in vacuum only radiative heat transfer is still occurring

Moreover, vacuum is usually not ideal… as we already saw

Vacuum alone doesn’t work: too much radiation!

Radiated power goes as T^4

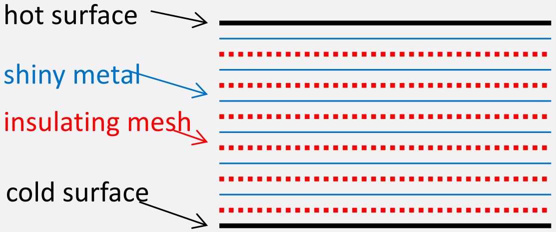
Can reduce it by subdividing the gap between hot and cold surface using alternating layers of shiny metal foil or aluminized Mylar and insulating mesh.

Structure must be open for vacuum pumping

Multilayer insulation

$$q_{rad} = \sigma \cdot \epsilon_r A \left(T_1^4 - T_2^4\right)$$

1 layer of aluminized Mylar	0.028
5 layers of crinkled aluminized Mylar	0.017
10 layers of crinkled Mylar interleaved with glass fibre mesh	0.0072
5 layers of aluminium foil interleaved with glass fibre mesh	0.0094
10 layers of aluminium foil interleaved with glass fibre mesh	0.017
20 layers of NRC2	0.005
200 layers of NRC2	0.004
2 x 24 layer Jehier* blankets	0.002

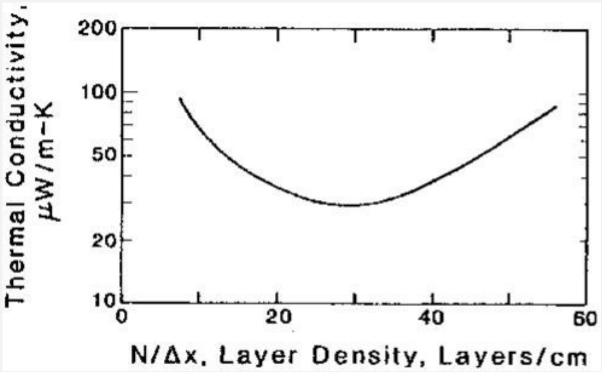


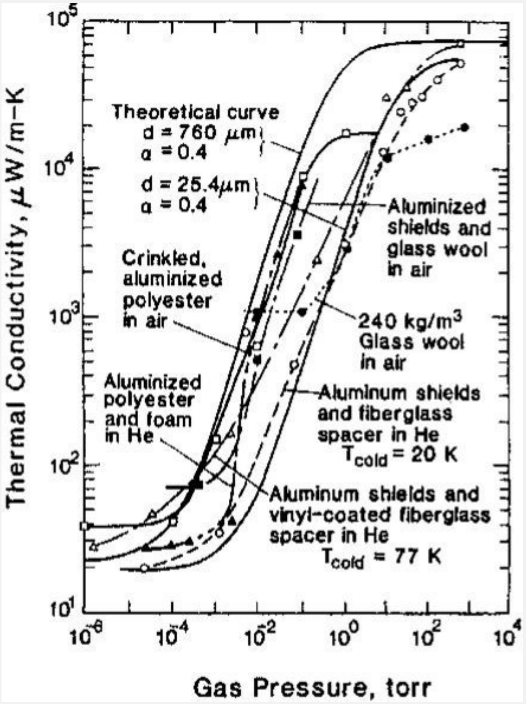
hot surface

shiny metal

insulating mesh

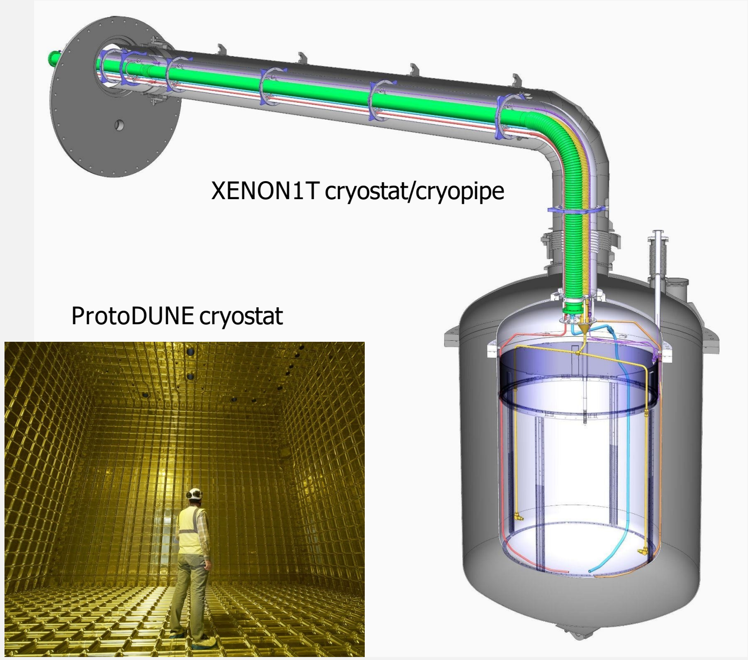
cold surface





Cryostats

- Where the cryogenic liquid is kept cold
- Commonalities
  - Minimize heat influx to the cryogenic liquid
  - Insulation (vacuum, MLI, passive insulation)
  - Minimize conduction through supports
  - Manage thermal contractions
- In the case of low-background experiments
  - Minimize the mass (pressure resistance diminished)
- With very large detectors, bigger challenges
  - Large thermal contractions
  - Vacuum insulation impractical

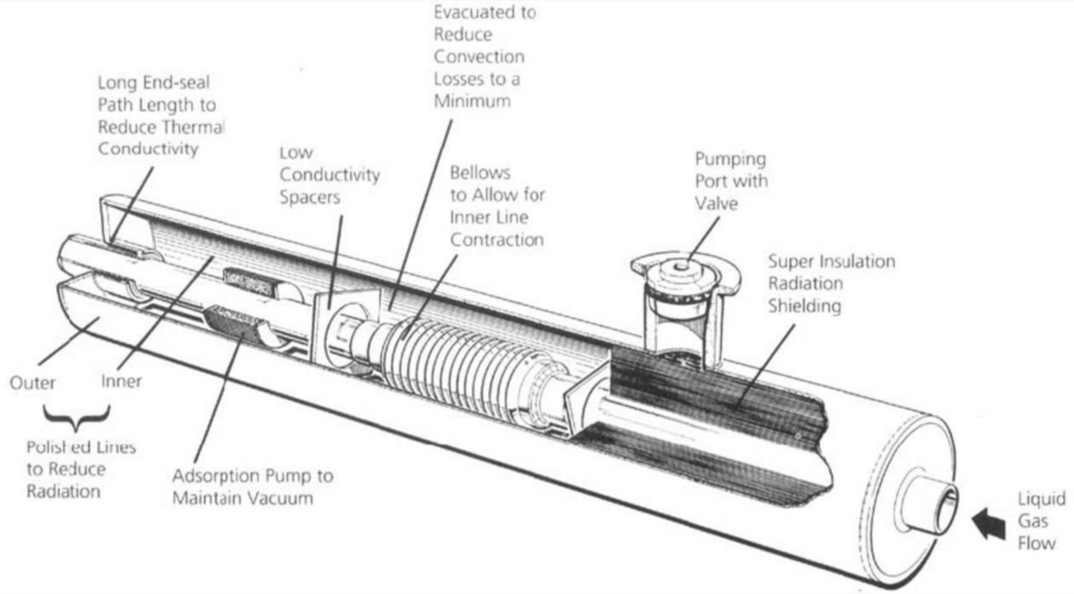


XENON1T cryostat/cryopipe

ProtoDUNE cryostat

Transfer lines

- Vacuum-jacketed piping to reduce heat flow to cryogenic fluid
- Low conductive heat flow
  - G10 supports keep inner tube centered
  - Point contact to outer tube
- Low convective heat flow
  - Vacuum insulation
  - Getter pumps
- Low radiative heat flow
  - Multi-layer insulation
  - Low emissivity tubing
- Sizing is important and should be determined from flow requirement



What are the underground experiments using?

All use multilayer insulation

Monitoring the “cold”

Outline of the section:

- Measurements of:
  - Temperature
  - Pressure
  - Flow
  - Vapor fraction
  - Level
  - Insulation vacuum quality

Measure the temperature

- In cryogenic liquid noble detectors one usually needs to measure the temperature of gases, liquids, and surfaces
- In general, three critical aspects for an optimal performance of cryogenic temperature sensors
  - Mounting of the sensor
    - Sensor must be able to dissipate the Joule heating
    - Minimize thermal contact resistance
    - Match thermal expansion coefficients (sensor/adhesive/surface)
  - Joining of sensor leads and electrical cables
    - 4-lead measurement (RTDs)
    - Voltage difference across dissimilar metals (thermocouple sensors)
  - Thermal anchoring of wires
    - Heat flowing to the sensor from the cables can induce a temperature offset
    - Wind wires to a thermal mass so heat does not flow to the sensor itself

Measure the temperature

Many different types of sensors to choose from:

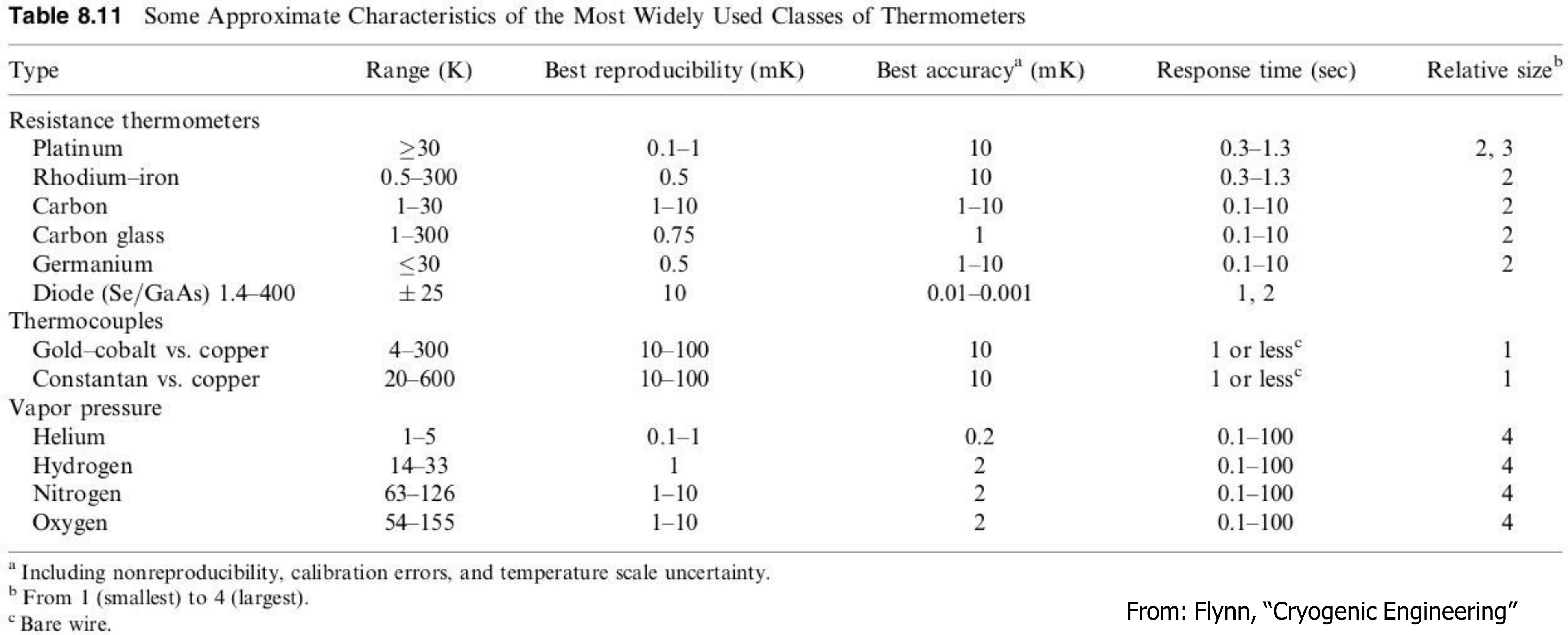


Table 8.11 Some Approximate Characteristics of the Most Widely Used Classes of Thermometers

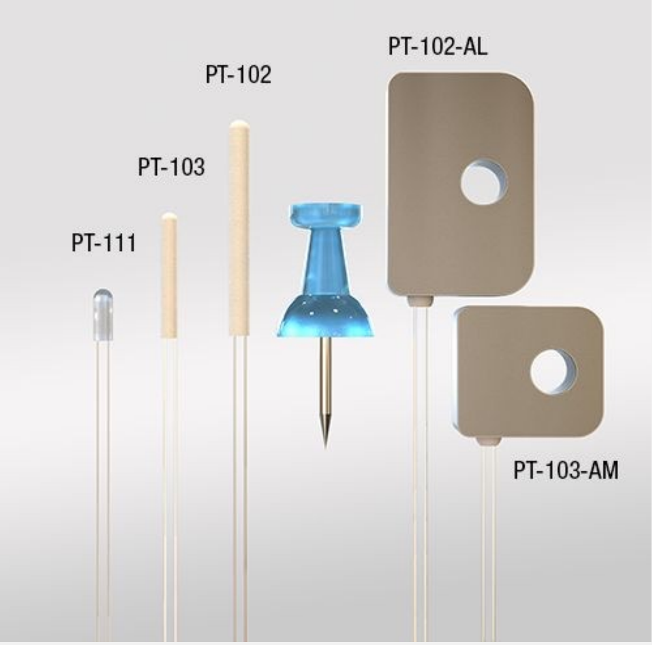
Type	Range (K)	Best reproducibility (mK)	Best accuracy[a] (mK)	Response time (sec)	Relative size[b]
Resistance thermometers					
Platinum	≥30	0.1–1	10	0.3–1.3	2, 3
Rhodium–iron	0.5–300	0.5	10	0.3–1.3	2
Carbon	1–30	1–10	1–10	0.1–10	2
Carbon glass	1–300	0.75	1	0.1–10	2
Germanium	≤30	0.5	1–10	0.1–10	2
Diode (Se/GaAs) 1.4–400	±25	10	0.01–0.001	1, 2	
Thermocouples					
Gold–cobalt vs. copper	4–300	10–100	10	1 or less[c]	1
Constantan vs. copper	20–600	10–100	10	1 or less[c]	1
Vapor pressure					
Helium	1–5	0.1–1	0.2	0.1–100	4
Hydrogen	14–33	1	2	0.1–100	4
Nitrogen	63–126	1–10	2	0.1–100	4
Oxygen	54–155	1–10	2	0.1–100	4

[a] Including nonreproducibility, calibration errors, and temperature scale uncertainty.
[b] From 1 (smallest) to 4 (largest).
[c] Bare wire.

From: Flynn, “Cryogenic Engineering”

Measure the temperature

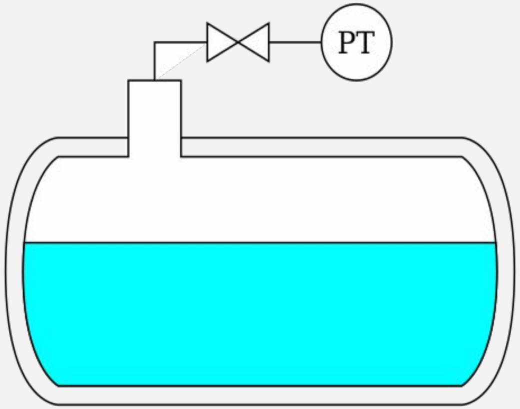
- For liquid noble gas detectors, a very common choice is wire-wound Pt100 RTDs
  - For example, LakeShore Cryotronics PT-102/3 (ceramic) or PT-111 (glass)
  - Available in a bolted surface mount package (-AL)
  - Large temperature range (14 K - 873 K) (673 K for PT-111)
  - Very high reproducibility (±5 mK @ 77K)
  - Fast response time (≈2 s @ 77 K)
- Sensor compatibility with high vacuum environment

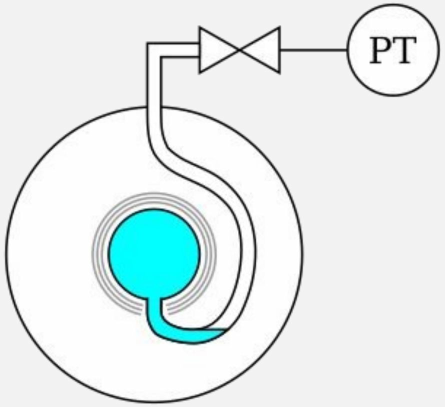


www.lakeshore.com

Measure the pressure

- Possible to use room temperature transducers with increased distance for thermal decoupling from the cryogenic fluid
- Many types of commercial transducers for high-purity gases that are adequate:
  - Capacitance or strain gauge type, ≈0.25% FS accuracy
  - Small cavity volume, low Ra stainless steel 316L wetted surface, VCR fitting
- In the case of cryogenic liquids, use a sensing tube (also called “impulse line”) to the measurement point
- The sensing tube geometry should
  - Ensure the transducer is exposed to gas only (do not insulate)
  - Look for a stable equilibrium liquid position with acceptable heat leak
  - Try to minimize any hydrostatic pressure error

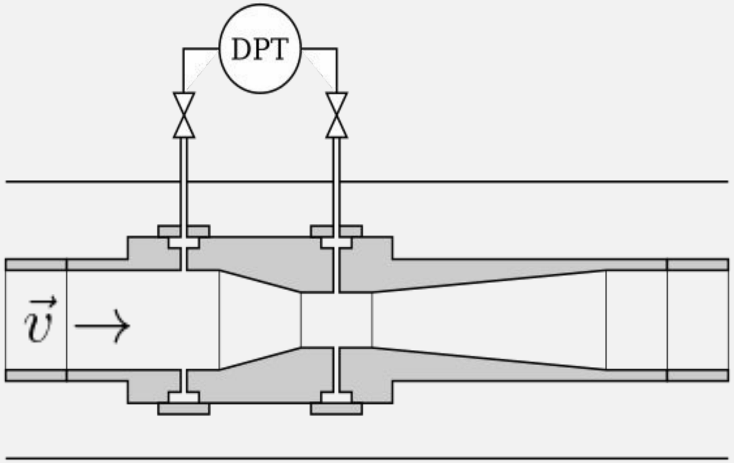




Measure the flow

Venturi flow meter

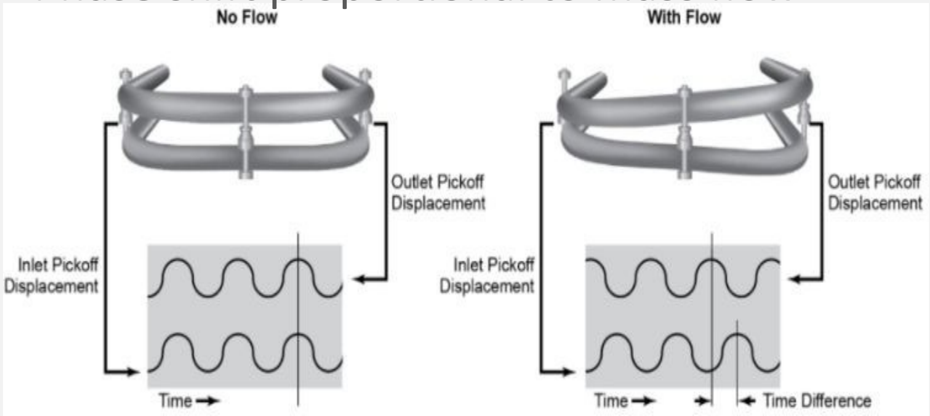
- Restriction leads to velocity dependent pressure drop



$$\dot{V} = f(\Delta p)$$

Coriolis flow meter

- Vibrating (accelerating) tube twists with flow inside (recall that the coriolis force goes as $-\vec{\omega}\times\vec{v}$)
- Phase shift proportional to mass flow



$$\dot{m} \propto \Delta t, \;\; \rho \propto f^{-2}$$

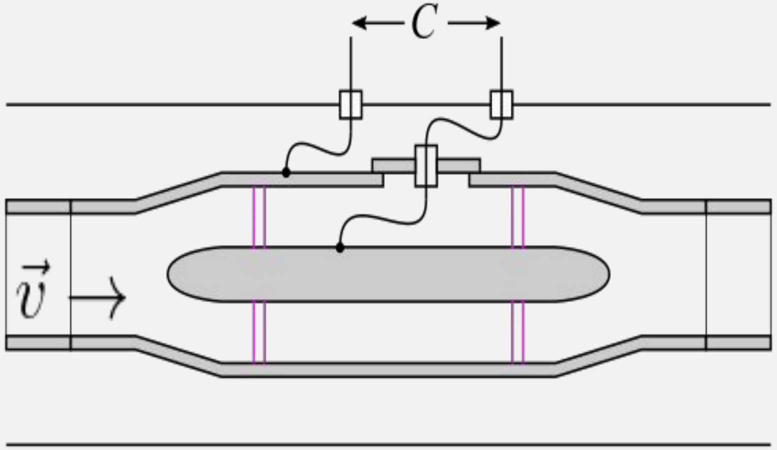
Measure the vapor fraction

- Cryogenic liquids are often near saturated conditions, two-phase flow conditions possible
- Useful to be able to measure the vapor fraction in the fluid
- Capacitance measurement is a common technique
  - Dielectric constant (ϵ) varies with vapor fraction (ϕ)
  - Vapor fraction can be obtained from capacitance (C)
  - Be careful as ϵ depends on pressure and temperature

$$\epsilon = \varphi \epsilon_g + (1 - \varphi) \epsilon_l$$

  - Can also be used to measure two-mixture density

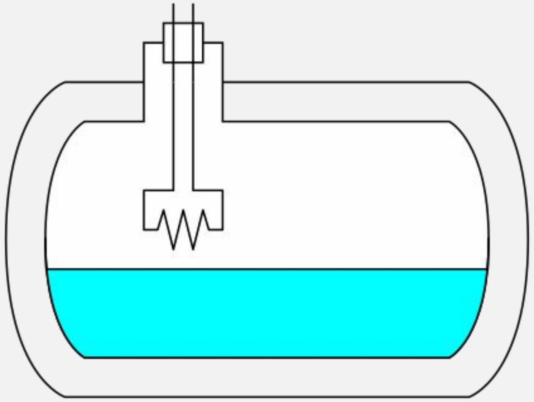
$$\rho = \varphi \rho_g + (1 - \varphi) \rho_l$$



$$\frac{C}{L} = \frac{2\pi\epsilon\epsilon_0}{\ln(r_o/r_i)}$$

Measure the liquid level

- Various techniques to measure the level of a cryogenic liquid
  - Hydrostatic pressure
  - Capacitance
  - Electrical resistance
  - Ultrasonic
- Hydrostatic and capacitance methods are the most commonly used
- Capacitance used when greater precision is required
- The electrical resistance method often used for level "switches"

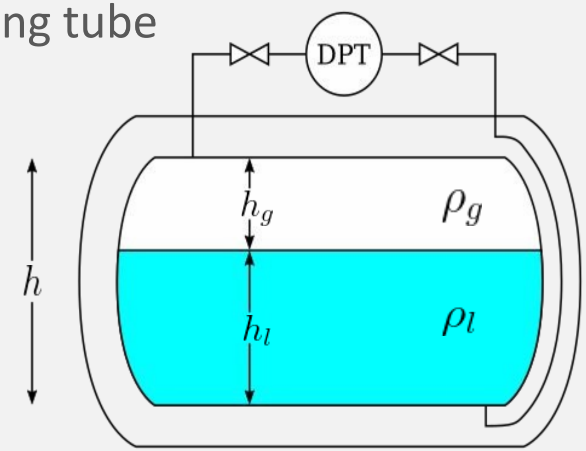


$h_{\text{conv},l} \gg h_{\text{conv},g}$

Measure the liquid level

Hydrostatic pressure level measurement

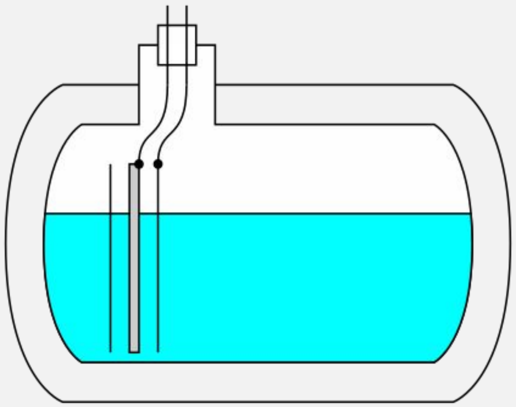
- Room temperature differential pressure transducer
- One gas-phase and one liquid-phase sensing tube



$$\Delta p = (\rho_l - \rho_g) g h_l + \rho_g g h$$

Capacitance level measurement

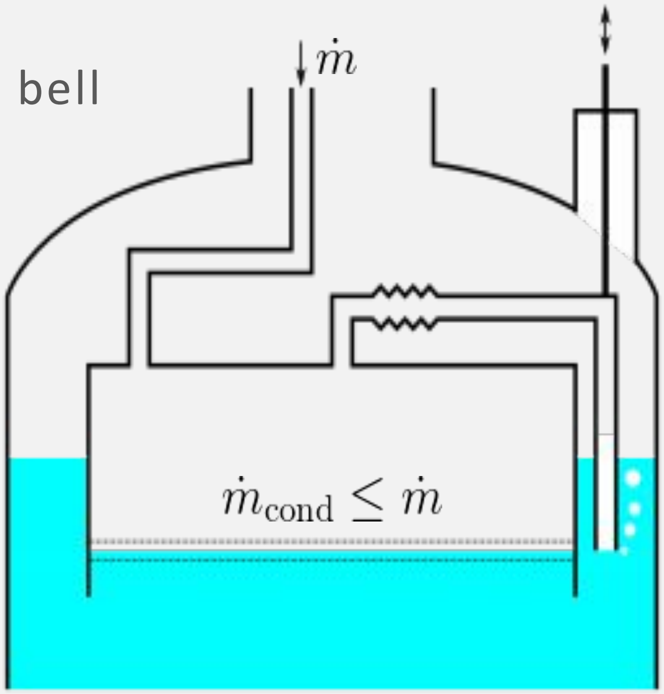
- Cylindrical capacitor geometry
- Sub-millimeter precision level measurement



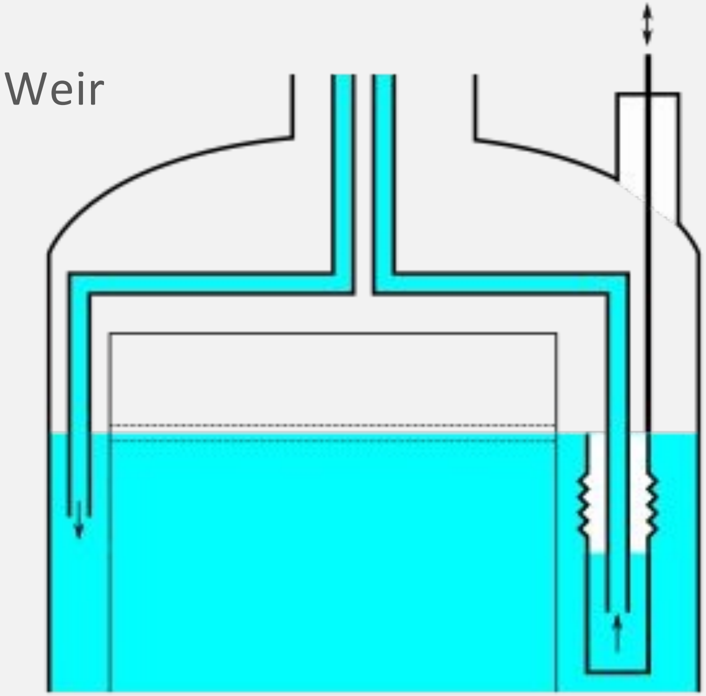
$$C = C_l + C_g = \frac{2\pi \left[L_l(\epsilon_l - \epsilon_g) + L\epsilon_g \right] \epsilon_0}{\ln(r_i/r_o)}$$

Adjust the liquid level (dual-phase TPC)

Diving bell



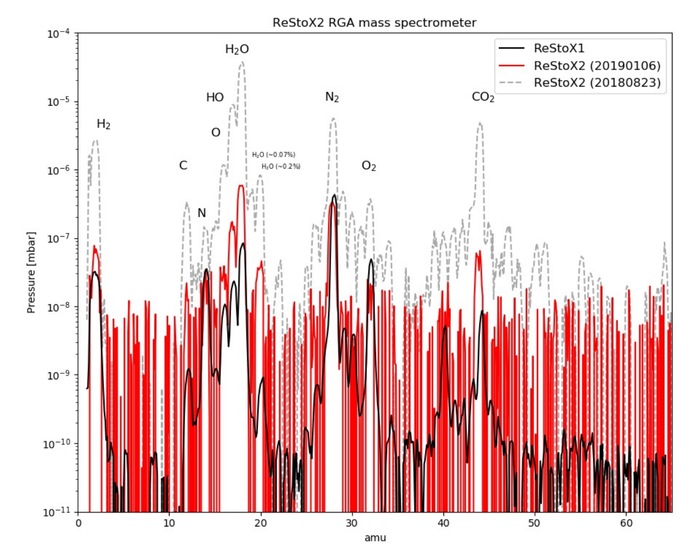
Weir



Measure the quality of the insulation vacuum

If vacuum worsens we may get problems:
- Monitor the vacuum pressure (prevent convection)
- Monitor the vacuum content (RGA)
- Monitor the vacuum pumps performances

Long list of cryogenic devices that need regular maintenance → procure spare when/where possible



Cryogenic liquids as detectors

Outline of the section:

- Purification techniques
  - Liquid and gas phase
    - From electronegative impurities
    - From radioactive impurities

Purification techniques

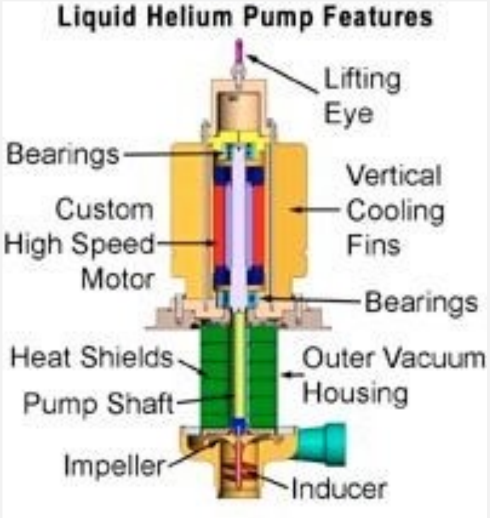
- A broad subdivision can be defined as
  - Batch purification, for the removal of impurities present in the source of noble gas used
  - Continuous purification, for the removal of impurities that are constantly released into the target
- Furthermore, we can subdivide the types of impurities to be removed
  - Electronegative impurities (O_2, H_2O)
    - Minimize the outgassing rate (material selection, preparation)
    - Measure material properties, model expected impurity load
  - Radioactive impurities (mainly ^{222}Rn but also ^{85}Kr, …)
    - ^{222}Rn
      - Minimize with mitigation techniques
      - Prevent it from reaching the target, remove it before it decays in the target
    - ^{85}Kr not produced continuously but can outgas/leak in

Purify in gas phase

- “Traditional” gas-phase purification of the cryogenic liquid via heat exchangers
- Desired system features
    - Large mass flow rates
    - Continuous operation
    - Pump maintenance while detector remains full
    - No down time from purifier replacement
    - Small contribution from radioactive impurities
- Commercial gas purifiers for large flow rates available
    - Outlet purity <0.1 ppb for O_2, H_2O, N_2, H_2, CH_4
- Clean positive displacement pumps
    - nEXO-style magnetically-coupled piston pump

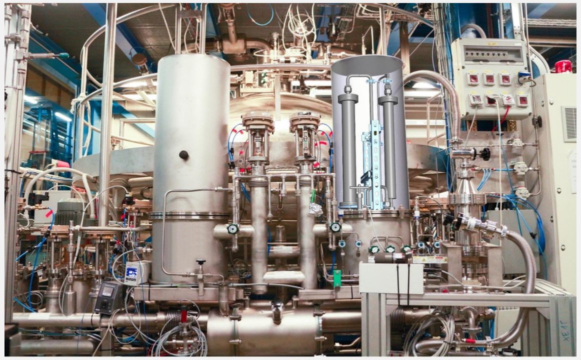
Purify in liquid phase

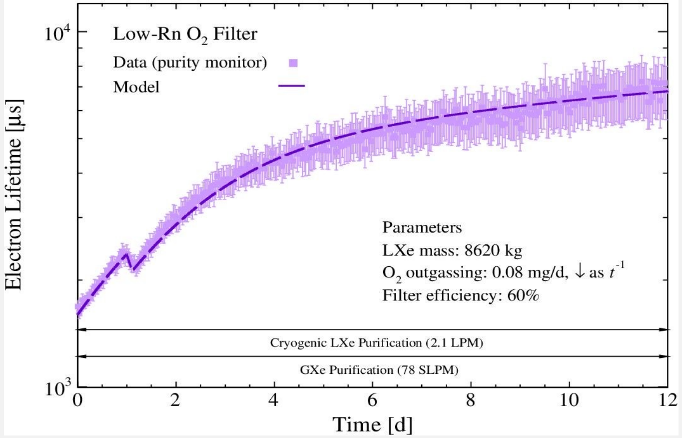
- Used in a number of liquid noble gas experiments for circulation/purification system
    - ICARUS, MEG, ProtoDUNE, XENONnT
- Barber-Nichols BNCP-32C-000
    - High-purity fluid compatibility
        - Hermetically sealed pump with magnetic shaft coupling
        - Stainless steel construction (except impeller, bearings)
    - Low heat influx
        - Thin-walled shaft/housing
          Anti-convection baffles
    - Vacuum housing / removable rotating assembly
        - High-speed motor with VFD
        - Wide performance range



Purify in liquid phase

- Liquid purification
  - Very high mass flow rates (>1 kg/s) and cleanliness achievable with specialized commercial products
  - Cryogenic liquid flows through a filter vessel filled with sorbent(s)
  - High performance sorbents exist but typically have high Rn emanation rate
  - Low-background experiments need sorbents with high O_2 sorption speed per unit Rn emanation rate
  - ≈7 ms electron lifetime with 6 kg/min in XENONnT





Purify from radioactive impurities

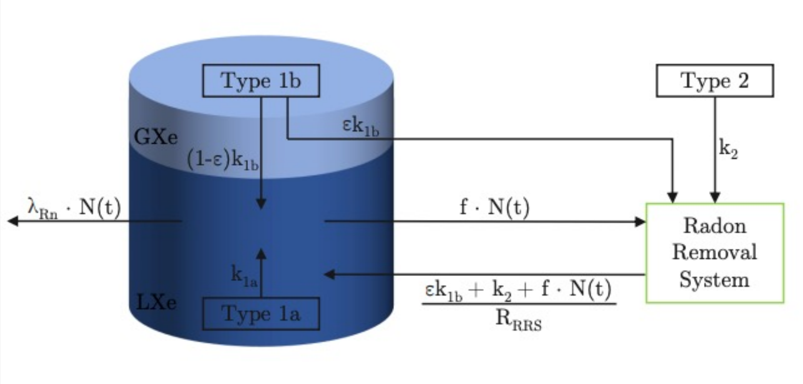
Remove ^{85}Kr and ^{222}Rn

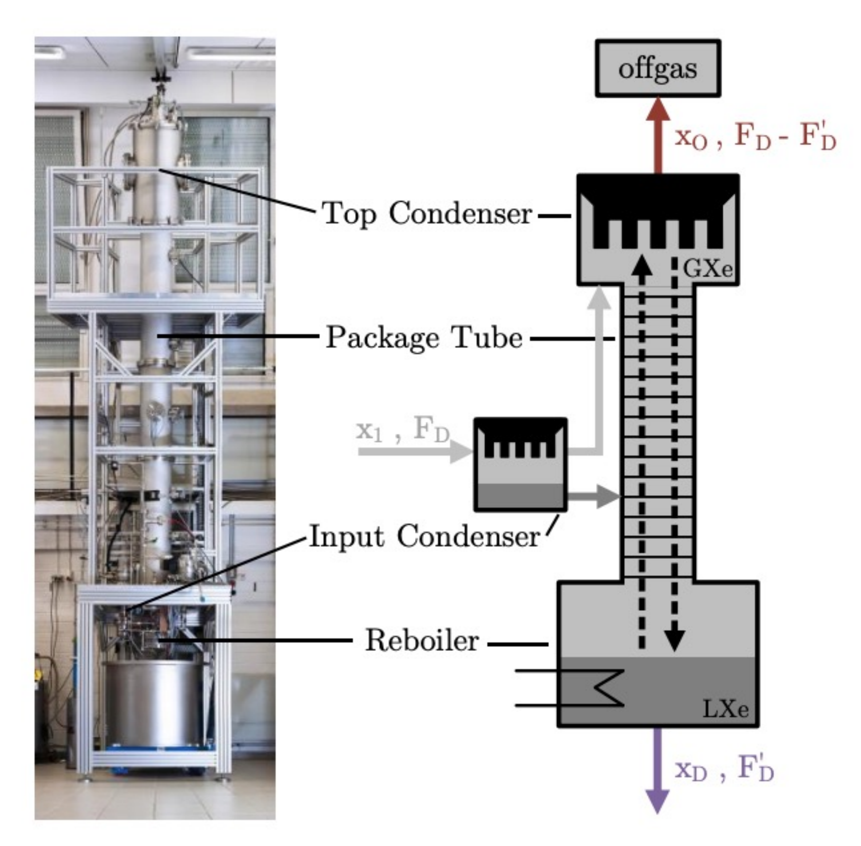
For ^{222}Rn can use:

- charcoal (LZ)
- distillation (XENONnT)

For ^{85}Kr can use:

- Gas chromatography
- Distillation





Typical operations

Outline of the section:

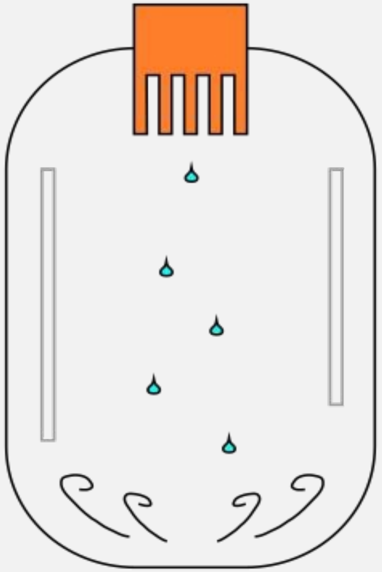
- Evacuation
- Cool down
- Filling
- Stable operation and continuous purification during data taking
- Recuperation
- Warm-up

Evacuation

- Main purpose is the reduction of the quantity of impurities mixed with the cryogenic fluid
- Often performed with turbomolecular pumps and dry backing pumps
- Not always possible (e.g. very large cryostats that cannot withstand external pressure)
  - Use dilution to reduce the quantity of impurities
- Vacuum level requirement often dictated by impurities continuously released
- Example: 1 ms electron lifetime in a 10t LXe detector (≈3500 L)
  - At equilibrium, electron lifetime $\approx V/(\Lambda \cdot \tau)$, where Λ is impurity desorption rate, τ purification time constant
  - Assume $\tau = 1$ d, then directly $\Lambda < 3.5\ \mu s^{-1} \cdot L/d \approx 0.63$ mg O_2/d
  - Assume a factor 100 between cold and room temperature O_2 desorption rate
  - Estimate the minimum vacuum level requirement given vacuum pumping speed
  - For example, with a 20 L/s effective pumping speed, then p $O_2 < 3.5x10$^-5 mbar

Cool down

- Reduce the thermal gradients in inner detector components that could occur during filling
- Often the cryostat is the largest thermal mass, inner detector structures contribute less but are often fragile
- Maximum cool down rate is usually constrained by the most fragile component
- With careful design it is sometimes possible to simply cool down the inner structures and fill simultaneously
- Condensation/boiling heat transfer coefficients are much larger than those from natural convection
    - Very difficult to extract extract heat from cryostat using just cold gas
    - Arrangement to have condensation/evaporation cycle
    - Limit the condensation rate to limit the rate

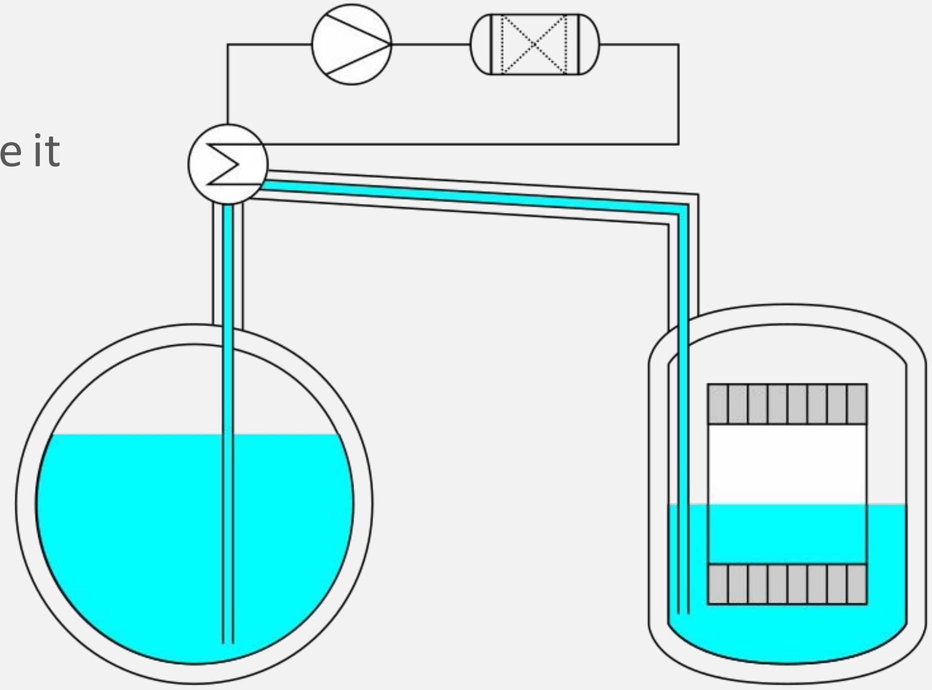


Filling

- Transfer of the cryogenic fluid from storage to the detector until nominal volume reached
- Very often performed in dynamic equilibrium at approximately constant pressure
    - With expensive cryogenic fluids, excess pressure cannot be vented
- Filling the detector in the gaseous phase
    - Filling speed might be limited by the available cooling power
    - Traditional gas-phase purification possible
- Filling the cryogenic liquid directly
    - Faster filling rates achievable even with limited cooling power
    - Cool down operation very likely a requirement
    - Use of heat exchangers make gas-phase purification also possible (XENON1T/nT)

Filling (example)

- XENON1T/nT: filling LXe in liquid phase
- Use of a two-phase heat exchanger make it possible to use a gas pump and a gas purifier



Stable operation and continuous purification

- State in which a detector spends most of its life
  - Acquiring data probably the reason the detector was built in the first place...
- Requirements on the cooling system of the detector
  - Maintain thermodynamic conditions as stable as possible
  - Extract heat constant flowing in to keep temperature, pressure, and liquid level constant
  - Equipment redundancy for continuous operation
    - Unexpected equipment failure
    - Maintenance
  - Resilience to loss of electrical power
- Continuous purification is most often required to reach required purity
  - Electronegative impurities in particular usually make continuous purification a requirement
  - Continuous removal of radioactive impurities (e.g. ^{222}Rn) can also be an important element
  - More details on this important topic discussed in the next section (purification techniques)

Recuperation

- Gradual transfer of the cryogenic liquid from the detector back to storage
- Multiple reasons why recuperation might be performed
  - Detector maintenance/upgrade is required
  - Severely limited access to laboratory is likely
  - Decommissioning of the experiment
- Gaseous phase recuperation
  - Limited by the heat that can be delivered to the liquid phase
  - Pressure reduction can be substantial if heat input is low
- Liquid phase recuperation
  - Very small decrease in pressure during recuperation

Warm-up