5.2 Cryogenic Safety

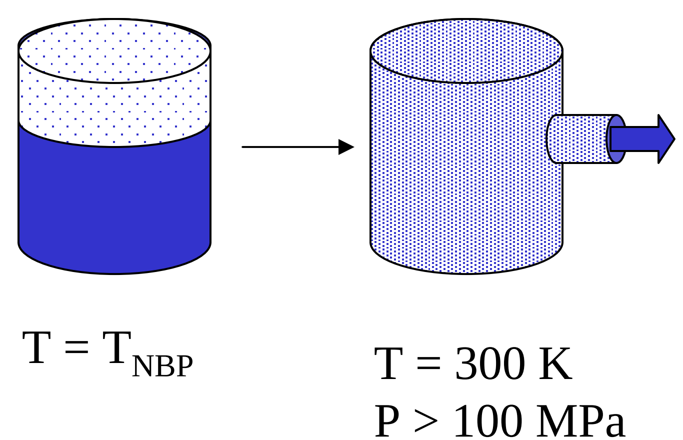
Main issues that must be considered in the design of a safe cryogenic system

1. Potential for over pressure leading to container rupture
2. Possibility of asphyxiation due to displacement of air
3. Danger of low temperature exposure to personnel
4. Fire hazard (H_2, O_2, CH_4)

Over pressure leading to container rupture

	$\rho(T_{NBP})$, kg/m^3	P(300K, ρ_{NBP}), MPa	V (300K, 1 atm)/V_{liq}
He	125	192	700
H_2	70	115	788
N_2	800	183	646

- The equivalent pressure of liquid density gas at room temperature is sufficiently high to burst any container.
- Containers must have pressure relief devices to prevent overpressure
- The size of the relief devise depends on requirements for safety



Designing a pressure vessel

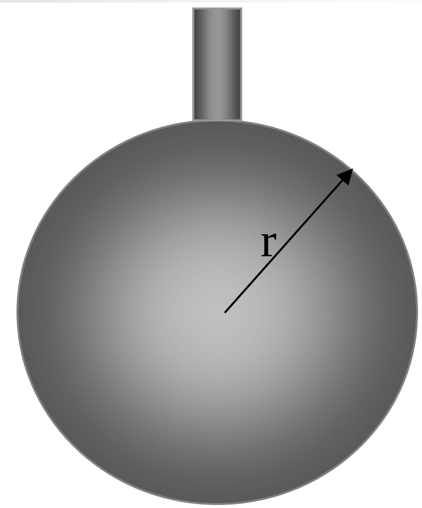
- Typically all cryogenic vessels are designed according to ASME code (or similar), which has particular requirements for design stresses.
  - A rough "rule-of-thumb" is that the maximum stress should not exceed 2/3 σ_y of the material. Thus, complex structural designs require significant stress analysis (FEA) to determine requirements.
  - Strictly, the ASME code requires that the material be tested at operating conditions (low temperature) to determine properties. This is required for ASME code stamping.
  - ASME code has many requirements about vessel penetrations
- Determining the stress state of a cryogenic vessel
  - Assumptions about peak pressure. Thermal excursions can lead to large pressure swings
  - Must consider the effect of thermal contraction
- Typical approach: analyze the system to death then pressure test ($P > P_{design}$) before operation

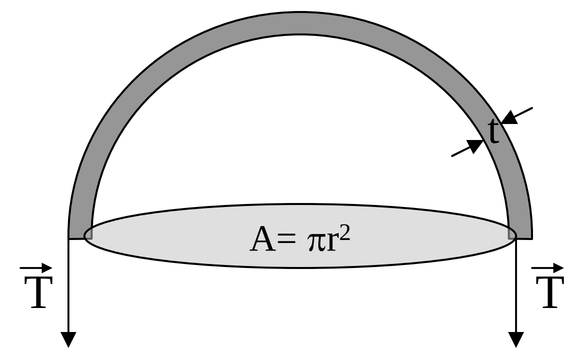
Cryogenic pressure vessel

- Consider a spherical vessel made from 2024-T4 Al. Calculate how thick the wall needs to be to meet ASME code (2/3 σ_y).
  - Design pressure = 0.5 MPa
  - Operating temp = 4.2 K
- 2024-T4 Al:

  σ_y(4 K) = 520 MPa
- t = 0.5 MPa x 1 m/1.33 x 520 MPa

  = 0.07 mm!!
- Under ideal conditions, wall can be very thin.





Force balance: $2\pi r t T = p\pi r^2$

$t = pr/2T$, where $T = 2/3\ \sigma_y$

Sealed Vessel Pressurization

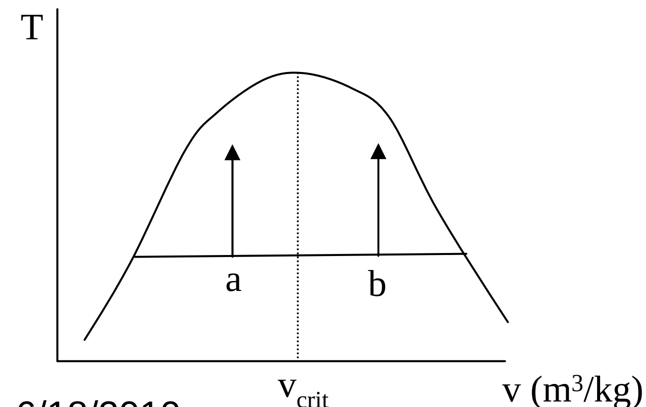
- Internal energy, U(J), increases with time due to heat leak into cryogenic space

$$U(t) = U_o + \int q(t)\,dt$$

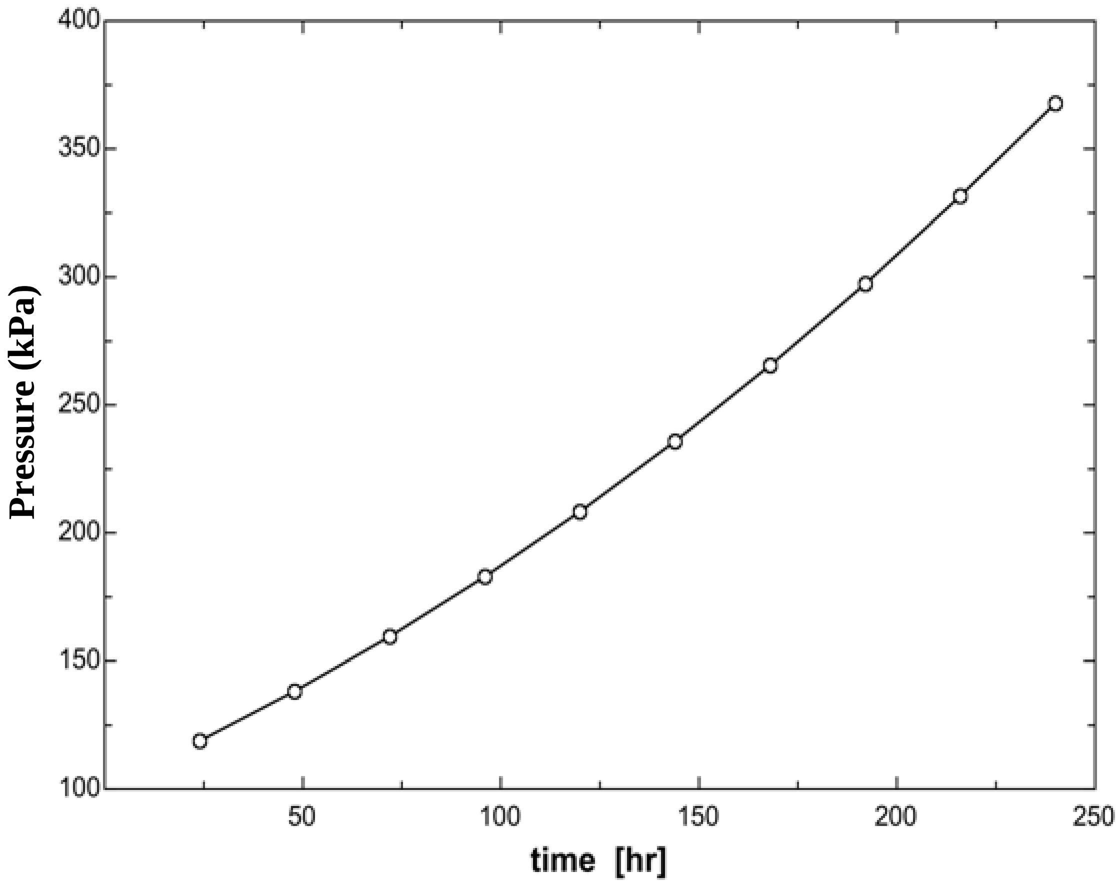
- With k_{eff} ~ 4×10^{-5} W/m-K for MLI insulation:

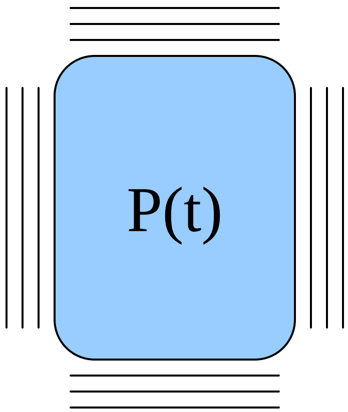
$$q(t) = Ak_{eff}\frac{T_{amb} - T(t)}{w_{MLI}}$$

- While $P < P_{crit}$, the fraction of liquid (or vapor) will increase or decrease depending on the initial overall specific volume (constant) as compared to v_{crit}.
  - Path (a) will exhibit an increase in liquid fraction until the vapor dome is reached
  - Path (b) will exhibit an decrease in liquid fraction



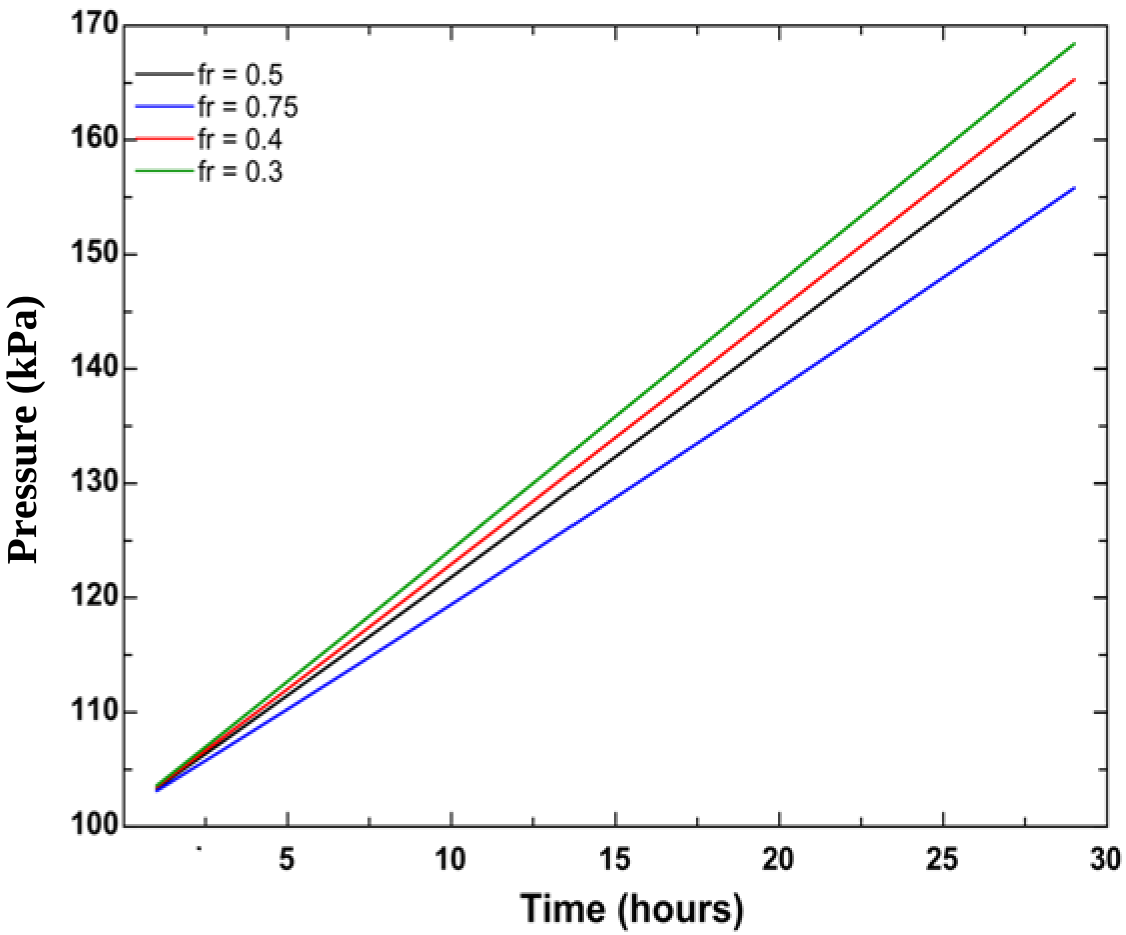
Example: LN_2

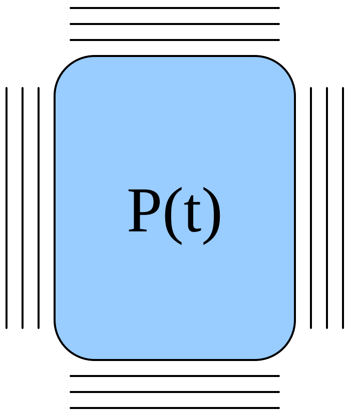




- 200 liter dewar
- Unity aspect ratio cylinder
- 5 cm blanket of MLI (k_{eff} = 4 x 10^{-5} W/m-K)
- $T_{ambient}$ = 300 K
- Fr_{liq} = 0.9 ($v > v_{crit}$)

Example LHe



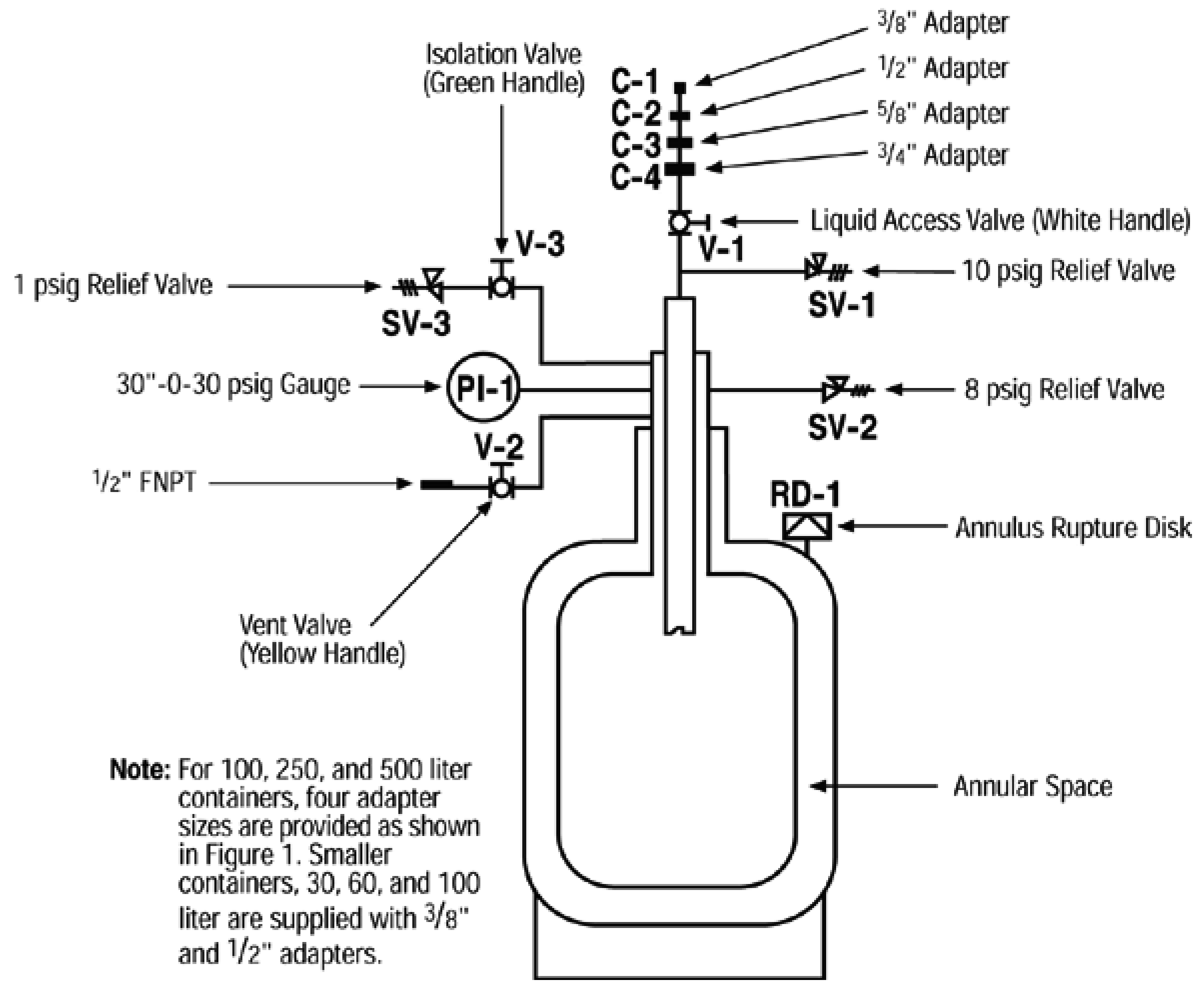


- 200 liter dewar
- Unity aspect ratio cylinder
- 5 cm blanket of MLI ($k_{eff} = 4 \times 10^{-5}$ W/m-K)
- $T_{ambient}$ = 300 K

System venting

- Any time there is a closed vessel containing a cryogen, it is essential to provide over pressure relief.
- A redundant system (i.e. two relief valves set at different pressures is good practice

Liquid Helium Container Design Features



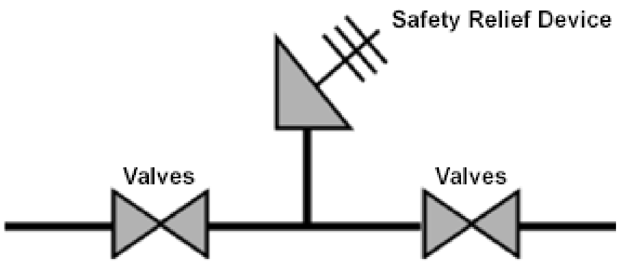
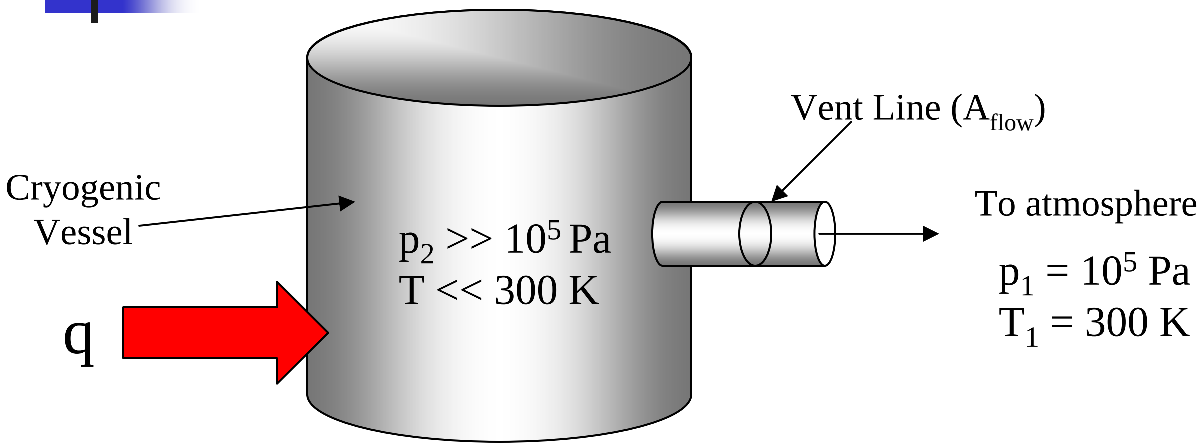


Fig. 1 Potential for trapping liquid between valves.

Designing a vent port for helium cryostat



- Depending on the heat generation rate, the flow through vent line may be "choked" (i.e. limited by sound speed in venting gas)

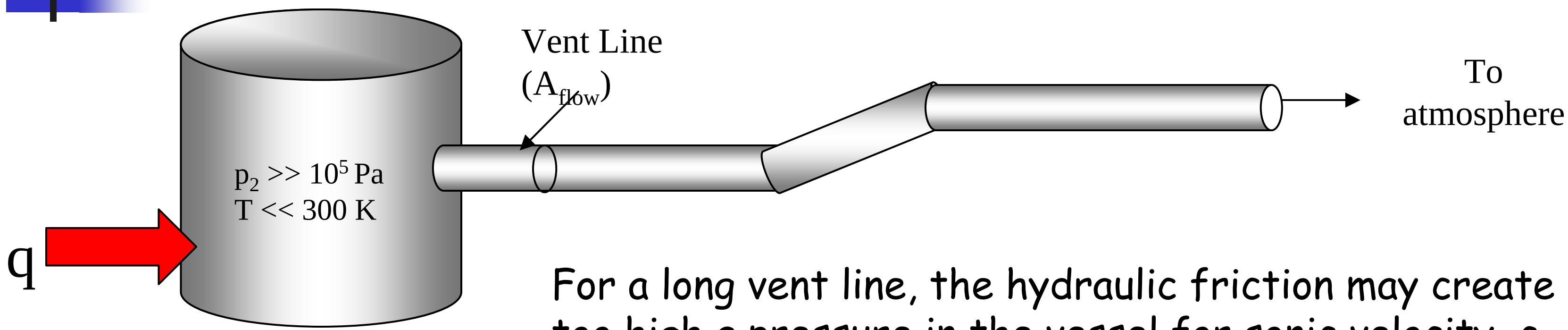
$$c = \sqrt{\frac{\gamma RT}{M}} \qquad \sim 120 \text{ m/s for helium @ 4.2 K; } \gamma = C_p/C_v$$

- Mass flow rate through the vent, $\dot{m}_{flow} \approx \rho A_{flow} c$
- Flow rate is also determined by the rate of heat transfer to the vessel

$$\dot{m}_{flow} = \frac{qA_{vessel}}{h_{fg}} \longrightarrow A_{flow} = \frac{qA_{vessel}}{\rho_{vapor} c h_{fg}} = \frac{qA_{vessel}}{\rho_{vapor} h_{fg}} \sqrt{\frac{M}{\gamma RT}}$$

- This is an upper limit since it does not tell us what the pressure is inside the vessel

Designing a vent port for helium cryostat



For a long vent line, the hydraulic friction may create too high a pressure in the vessel for sonic velocity, c. Therefore, u < c and can be calculated if one knows the friction factor or loss coefficient for the line.

- Friction limited mass flow:

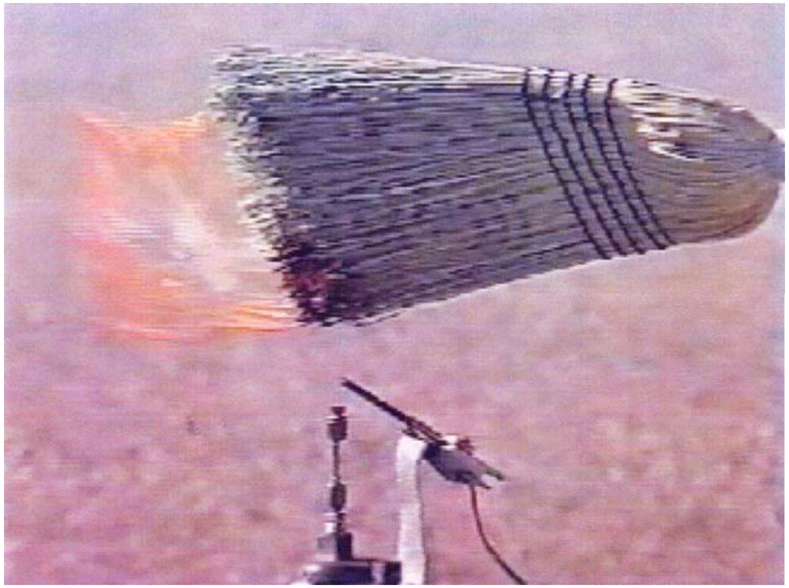
$$\dot{m} = A_{flow}\sqrt{\frac{2\rho\left(P_1 - P_2\right)}{K}} \quad \text{where} \quad \rho = \frac{1}{2}\left(\rho_1 + \rho_2\right)$$

"K" is the total loss coefficient including tube friction and losses in bends, elbows, and other discrete components

- Flow is compressible

LO_2 and LH_2 safety issues

- LO_2 and LH_2 are unique cryogenic fluids because of the potential for combustion
- LO_2 will augment any combustion process and can allow things to burn that are normally inert (metals, for example)
- LH_2 will burn in air producing an invisible flame



Condensation of O_2 enriched air

- Cold surfaces during transfer of LHe, LH_2 and even LN_2 can condense air.
- The "phase rule" indicates that the condensation will be enriched with LO_2.
- Numerous "inert" materials will burn in LO_2 (decreased ignition temperature)

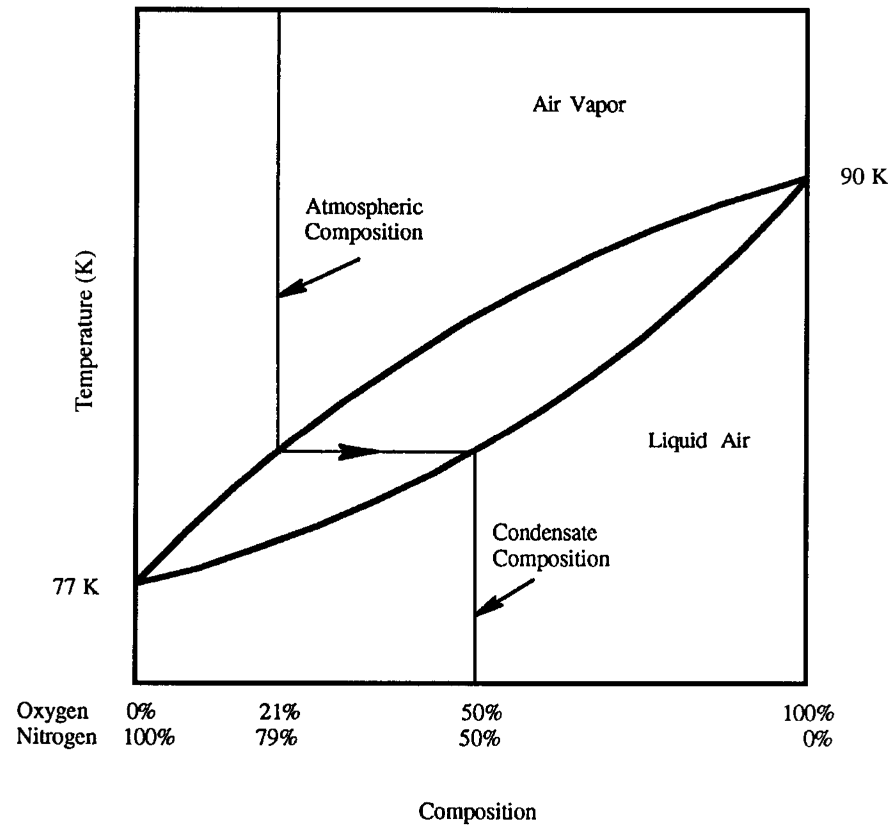


Figure 11-4 Oxygen–nitrogen phase diagram showing ambient and condensate compositions.

H_2 Flammability

- The use of moderate quantities of LH_2 requires special safety considerations
- Ignition temperature in Air:
  - $T(H_2) = 858$ K
  - $T(CH_4) = 813$ K
  - T(kerosene) = 523 K
  - Low ignition energy makes hydrogen more flammable than kerosene
- Flammability limits
  - In Air: 4 to 75%
  - In pure O_2: 4 to 96%

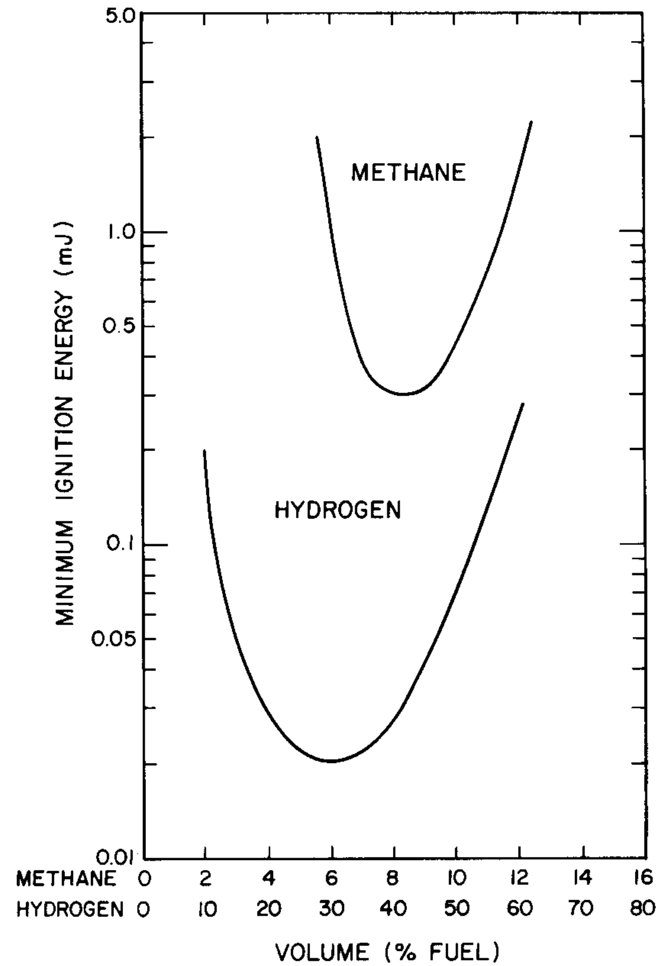


FIGURE 3. Electric spark ignition energy requirements for methane-air and hydrogen-air mixtures as a function of composition.[30]

Liquid nitrogen safety

- Danger from low temperature exposure (same with other cryogens)
- Asphyxiation
  - Normal air is 80% N_2/19% O_2/1% other
  - 15 to 19% O_2 causes impaired coordination
  - 12 to 15% O_2 Deep respiration, impaired coordination, perception
  - 10 to 12% O_2 lips turn blue, poor coordination
  - 8 to 10% O_2 Nausea, fainting, unconsciousness
  - 6 to 8% O_2 is fatal in about 8 minutes
  - 4 to 6% O_2 is fatal in less than 1 minute.
- Always use good ventilation when exposed to LN_2 in open container

Materials safety issues

- Embrittlement resulting from low temperatures
  - FCC materials better than BCC
  - Low temperature phase transitions
  - Many polymer based materials get brittle at low temperature (PVC)
- Hydrogen embrittlement
  - High strength steel, Ti and Ni alloys are bad
  - Al alloys, copper and austenitic steels (300 series) are good.
- It is important to avoid mechanical failure due to thermal contraction (Design issue)

Safety review of a cryogenic system

- Before a cryogenic system is built, the design should undergo a thorough safety review
- Safety system should be passive (not requiring a control system)
- Structural safety (mechanical properties)
- Fluid safety (over pressure)
- Electrical safety