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

- 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.

<table>
<thead>
<tr>
<th></th>
<th>(\rho(T_{\text{NBP}})), kg/m(^3)</th>
<th>(P(300K, \rho_{\text{NBP}})), MPa</th>
<th>(V(300K, 1\text{ atm})/V_{\text{liq}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>125</td>
<td>192</td>
<td>700</td>
</tr>
<tr>
<td>(H_2)</td>
<td>70</td>
<td>115</td>
<td>788</td>
</tr>
<tr>
<td>(N_2)</td>
<td>800</td>
<td>183</td>
<td>646</td>
</tr>
</tbody>
</table>

\[ T = T_{\text{NBP}} \]
\[ T = 300\text{ K} \]
\[ P > 100\text{ MPa} \]
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 \( \frac{2}{3} \sigma_y \) 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 \((P > P_{\text{design}})\) 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 $\sigma_y$).
  - Design pressure = 0.5 MPa
  - Operating temp = 4.2 K

- 2024-T4 Al:
  - $\sigma_y(4 \text{ K}) = 520 \text{ MPa}$
  - $t = 0.5 \text{ MPa} \times 1 \text{ m} / 1.33 \times 520 \text{ MPa} = 0.07 \text{ mm}!!$
  - Under ideal conditions, wall can be very thin.

Force balance: $2\pi rtT = p\pi r^2$
$t = pr/2T$, where $T = 2/3 \sigma_y$
Sealed Vessel Pressurization

- Internal energy, \( U(J) \), increases with time due to heat leak into cryogenic space
  \[
  U(t) = U_0 + \int q(t) dt
  \]

- With \( k_{\text{eff}} \sim 4 \times 10^{-5} \text{ W/m-K} \) for MLI insulation:
  \[
  q(t) = A k_{\text{eff}} \frac{T_{\text{amb}} - T(t)}{W_{\text{MLI}}}
  \]

- While \( P < P_{\text{crit}} \), the fraction of liquid (or vapor) will increase or decrease depending on the initial overall specific volume (constant) as compared to \( v_{\text{crit}} \).
  
  - Path (a) will exhibit an increase in liquid fraction until the vapor dome is reached
  - Path (b) will exhibit a decrease in liquid fraction
Example: LN$_2$

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

- 200 liter dewar
- Unity aspect ratio cylinder
- 5 cm blanket of MLI ($k_{eff} = 4 \times 10^{-5} \text{ W/m-K}$)
- $T_{ambient} = 300 \text{ K}$
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.
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)
  \[ c = \sqrt{\frac{\gamma RT}{M}} \approx 120 \text{ m/s for helium @ 4.2 K; } \gamma = \frac{C_p}{C_v} \]

- Mass flow rate through the vent, \( \dot{m}_{\text{flow}} \approx \rho A_{\text{flow}} c \)

- Flow rate is also determined by the rate of heat transfer to the vessel:
  \[
  \dot{m}_{\text{flow}} = \frac{q A_{\text{vessel}}}{h_{fg}} \quad \rightarrow \quad A_{\text{flow}} = \frac{q A_{\text{vessel}}}{\rho_{\text{vapor}} c h_{fg}} = \frac{q A_{\text{vessel}}}{\rho_{\text{vapor}} h_{fg}} \sqrt{\frac{M}{\gamma RT}}
  \]

- 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:**

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

“\( K \)” 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.
H₂ Flammability

- The use of moderate quantities of LH₂ requires special safety considerations
- Ignition temperature in Air:
  - $T(H₂) = 858 \text{ K}$
  - $T(CH₄) = 813 \text{ K}$
  - $T(\text{kerosene}) = 523 \text{ K}$
  - Low ignition energy makes hydrogen more flammable than kerosene
- Flammability limits
  - In Air: 4 to 75%
  - In pure $O₂$: 4 to 96%

FIGURE 3. Electric spark ignition energy requirements for methane-air and hydrogen-air mixtures as a function of composition.\textsuperscript{16}
Liquid nitrogen safety

- Danger from low temperature exposure (same with other cryogens)
- Asphyxiation
  - Normal air is 80% N₂/19% O₂/1% other
  - 15 to 19% O₂ causes impaired coordination
  - 12 to 15% O₂ Deep respiration, impaired coordination, perception
  - 10 to 12% O₂ lips turn blue, poor coordination
  - 8 to 10% O₂ Nausea, fainting, unconsciousness
  - 6 to 8% O₂ is fatal in about 8 minutes
  - 4 to 6% O₂ is fatal in less than 1 minute.
- Always use good ventilation when exposed to LN₂ 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