SAFETY AND FAULT MODES

The magnet system and the LHe storage dewar would have a common vacuum system. It is recommended to put an 8" diameter rupture disk in the LHe compartment at the power chimney and a 4" one on the cryostat of the LHe storage dewar. This arrangement would safely accommodate a 600 KW heat influx level, on the assumption that the total amount of liquid helium in the system is $\sim$ 4000 L. The calculations attached in the appendix take into account fault modes like sudden loss of vacuum, various forms of quenches, rapid charging and discharging.

APPENDIX: SAFETY AND FAULT MODE

1. OBJECTIVE

To determine the LHe system rupture disk requirements

2. ASSUMPTIONS

(a) The 2000 ℓ LHe storage dewar is assumed to have a common vacuum with the magnet.

(b) There exists a cooldown line 3/4" in diameter (3½" OD vacuum jacket) feeding liquid helium from storage dewar to magnet and a pressure equalization line of 1" in diameter (4" OD vacuum jacket).

3. CALCULATIONS

What are the causes of heat? What are their magnitude?

(a) Sudden loss of vacuum

(b) Various forms of quenches:

(1) low liquid level

(2) a typical quench

(c) charging loss

(d) Discharging loss

(a) Assuming that a system of 12 layers NRC-2 500 Å and 3M Aluminum tape on both the 78K and 4.2K surfaces is used for insulation between the radiation shield and the cryostat, we can arrive at a heat transfer coefficient per unit area due to air condensation upon a loss of vacuum. From "Technology of Liquid Helium", NBS Monograph 111 (1968), p. 270 and the Chicago Cyclotron Magnet Safety Review (1981) FNAL; expect

$$\frac{\dot{q}}{A} \approx 0.47 \text{ W/cm}^2$$

LHe temperature surface area for the cryostat

$$\sim \left[2\pi \left(\frac{63 + 60}{1}\right) \times 200 + 2\pi \left(\frac{63 + 60}{2}\right) \times 3 \times 2\right]$$

$$\times (2.54)^2 \text{ cm}^2$$

$$\sim 1.012 \times 10^6 \text{ cm}^2$$

∴ External energy input rate into the helium compartment upon a sudden loss of vacuum

$$= 1.012 \times 10^6 \times 0.47$$

$$= \underline{475.7 \text{ kW}}$$

Next, if we include the cooldown line of the 2000 ℓ dewar into a single common vacuum, additional surface area for heat transfer amounts to

$$\frac{\pi(1)(22)(12) + \pi(3/4)(42)(12)}{144} + \pi(2)^2 \times 2 + 2\pi(2)(6)$$

$$= 5.76 \text{ ft}^2 + 8.25 \text{ ft}^2 + 75.4 \text{ ft}^2$$

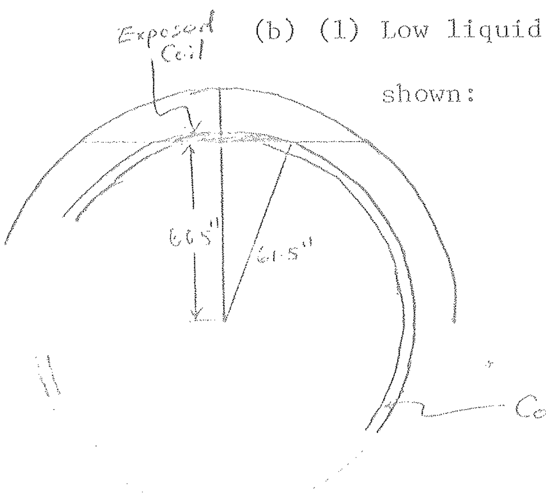
$$= 89.4 \text{ ft}^2 \text{ (or } 8.31 \times 10^4 \text{ cm}^2\text{)}$$

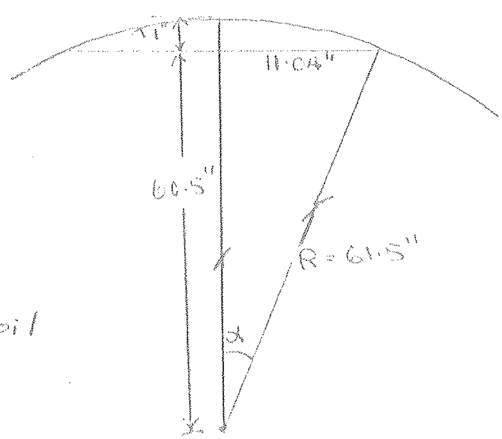
Total ext. energy input rate into the helium compartment upon a sudden loss of vacuum = $(8.31 \times 10^4 + 1.012 \times 10^6) \times 0.47$

= <u>514.7 kW</u>

It is a < 10% effect; hence use a common vacuum for both the storage dewar and magnet cryostat.

(b) (1) Low liquid level, assume exposure of the top of the coil as shown:





Volume of coil that is normal $= \frac{R^2}{2}\left[2\alpha - \sin 2\alpha\right] \times 200 \text{ in}^3$

$$\cos\alpha = \frac{60.5}{61.5} \rightarrow \alpha = 10.35^\circ \text{ (or 0.18 radian)}$$

$$\sin 2\alpha = 0.353$$

$$2\alpha = 0.1805 \times 2 = 0.361$$

Equivalent length of conductor that is normal per turn

$$= (0.361 - 0.353) \left(\frac{61.5}{2}\right)^2 \times \frac{1}{1}$$

$$= 15 \text{ inches.}$$

No. of turns

$$= 3 \times 200 = 600 \text{ turns.}$$

Resistance of normal zone

$$= \rho \frac{\ell}{A}$$

$$= \frac{2.67 \times 10^{-6}}{770} \Omega \times 600 \times 15 \times 2.54 \times \frac{1}{2[1 \times 0.36 - 0.47 \times 0.18]}$$

$$= 3.468 \times 10^{-9} \times (2.286 \times 10^{4}) \times \frac{1}{0.5508}$$

$$= 1.439 \times 10^{-4} \, \Omega$$

Operating current

$$= 10{,}000 \text{ A}$$

Instantaneous power generated

$$= (10{,}000)^2 (1.439 \times 10^{-4})$$

$$= \underline{14.39 \text{ kW}}$$

(2) A Typical Quench

Requires a quench run to determine the exact number.

A pool boiling magnet is not supposed to be able to quench when fully immersed in liquid.

(c) Charging Loss } ≈ 50W

(d) Discharging Loss } ≈ 10KW

based on CDF Engineering Design Report #1

We therefore will size the rupture disk for a 600 KW power generation level.

Assume that we have 1000 ℓ of LHe in the magnet, 350 ℓ in the vent tubes and 2000 ℓ in the storage dewar; use a number of 4000 ℓ LHe in the system for calculation.

Heat of vaporization of liquid helium (going from 4.2K liquid to 4.2K vapor)

= 8.72 BTU/lb.

= 2533.7 J/ℓℓ

= 20.27 J/gm

600 KW input energy ⟹ LHe boil-off rate of $\frac{600 \times 10^3}{2533.7}$ ℓ/s

= 236.8 ℓ/s

⟹ $236.8 \times \frac{7.798}{1.04}$

∿ 1775.6 liters/sec helium gas

= 62.8 cfs at 4.2 and 1 atm. helium gas

Choose burst disks to be set at 12.5 psig

$$\Rightarrow \text{He gas escape rate} \approx 62.8 \times \left(\frac{14.7}{14.7 + 12.5}\right)$$

$$= 33.9 \text{ cfs at } 12.5 \text{ psig.}$$

Helium gas flow rate at STP conditions

$$Q_{sa} = \frac{236.8 \times \left(\frac{7.798}{0.01114}\right)}{28.3} \text{ scfs}$$

$$= 5857.2 \text{ scfs}$$

$$= \underline{3.51 \times 10^5 \text{ scfm}}$$

Using the rupture disk sizing formula supplied by the chosen rupture disk manufacturer, Fike Metal Products Corporation,

for gaseous,

$$A_g = \frac{Q_{sa}}{11.4\ P_R} \sqrt{\frac{460 + T}{520}} \sqrt{\frac{m}{29}} \qquad (1)$$

for liquid

$$A_\ell = \frac{144\ Q_{AVG}}{0.62\ \sqrt{2gh}} \qquad (2)$$

We are using the A_g case for sizing the rupture disk, but in actual situation, the required area is somewhere between A_g and A_ℓ. So there is some safety factor built into the design already when we are using the A_g formula for design.

where

A_g = required flow area (in^2) for gas

A_ℓ = required flow area (ft^2) for liquid

Q_{sa} = flow (scfm)

m = molecular weight of gas

T = temperature of flowing media at disc rupture pressure (^oF)

P_R = Disc rupture pressure in psi absolute

Q_{AVG} = discharge in cfs

ρ = fluid density in lbm/cft

h = pressure head = $\frac{144\ P}{\rho}$

P = Disc rupture pressure in psig

g = $32.2\ ft/sec^2$

From Eq. (1)

$$A_g = \frac{3.51 \times 10^5}{11.4(12.5 + 14.7)} \sqrt{\frac{460 - 452.1}{520}} \sqrt{\frac{4}{29}}$$

$$= \underline{51.82\ in^2}$$

This is equivalent to one

$$2\sqrt{\frac{51.82}{\pi}} \text{ is } = 8.12'' \text{ in dia. rupture disk}$$

Rupture disks come in 4", 6", 8", 10" diameter ones. If we use an 8" one, neglecting pressure drop in the plumbings, at a 600 KW heat influx level, we'll have a gas volume increase rate of

$$\left[1 - \frac{50.27}{51.82}\right] \times 3.51 \times 10^5 \times \frac{0.01114}{1.04} \times \frac{14.7}{12.5 + 14.7}$$

= 60.8 cfm at 4.2 K and 12.5 psig rupture pressure

Additional pressure rise =

$$= \frac{4000\ \ell}{236.8\ \ell/s} \times \frac{60.8\ \text{cfm}}{60\ \text{s/m}} \times \frac{(12.5 + 14.7)\ \text{psi}}{\frac{4000}{28.3}\ \text{cf}}$$

= <u>3.29 psi.</u>

Looking at it from a different angle, an 8" diameter rupture disk can handle a heat flux of

$$\frac{50.27}{51.82} \times 600\ \text{KW} = \underline{582.1\ \text{KW}}$$

PRESSURE DROP IN THE VENT TUBES

The worst case would be the 2000 ℓ liquid helium has to go through the 3/4" pipe to reach the 8" rupture disk. In such a situation, the heat influx level = $8.31 \times 10^4 \times 0.47$ W

= 39 KW

Generated gaseous helium flow rate

$$= 33.9 \times \frac{39}{600}\ \text{cfs at 4.2 K and 12.5 psig}$$

= 2.2 cfs

Area of cross section for flow $= \frac{\pi(3/4)^2}{4} = 0.442\ \text{in}^2$

velocity of flow u $= \frac{2.2 \times 144}{0.442} = 716.7$ fps

$\ell = 40$ ft.

$d = 3/4'' = 0.0625$ ft

Reynold's number $R_e = \frac{\rho u d}{\mu}$

$= \frac{\text{density of 4.2K He gas x velocity of flow of gas x diameter}}{\text{viscosity of 4.2 K gas}}$

$= \frac{1.04 \times 716.7 \times 0.0625}{\frac{0.00309}{3600}}$

$= 5.43 \times 10^7$

$\frac{K}{d}$ = roughness factor

$= \frac{0.045 \times \frac{1}{25.4} \times \frac{1}{12}}{d}$ for steel

$= \frac{0.045 \times \frac{1}{25.4} \times \frac{1}{12}}{0.0625}$

$= 2.36 \times 10^{-3}$

f = friction factor {from Moody Chart p. 178, Mech. of Fluids (Massey)}

= 0.0035

h_f = head pressure $= \frac{4 f \ell}{d} \frac{u^2}{2g}$

$= \frac{4 \times 0.0035(40)(716.7)^2}{(0.0625)(2)(32.2)}$

= 71465.6 ft.

$\sim \frac{1.04 \times 71465.6}{144}$ psi

$\sim$ 516 psi.

Too high. The surface area available for heat transfer upon a loss of vacuum onto the dewar is only $\frac{1}{10}$ of that of the magnet cryostat, also since all quench activities start in the magnet, a relatively smaller rupture disk would be able to tackle any malfunction originating from the dewar area.

It is recommended to put a 4 inch rupture disk on the helium compartment of the LHe storage dewar (which can handle a power level of $\frac{4 \times 4}{8 \times 8} \times 600$ KW $\sim$ 150 KW safely).

4. CONCLUSION

1. It is therefore recommended to put an 8" diameter rupture disk in the LHe compartment at the power chimney and an 4" one on the cryostat of the LHe storage dewar.
2. A common vacuum for the LHe storage dewar and the magnet system should be OK.
3. The size of the rupture disk required (cf., calculation earlier on pressure rise) is independent of the size of the liquid helium compartment when it is full. The reason being that the rupture disks are sized for instantaneous situations.