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HELIUM VENTING INTO THE ACCELERATOR TUNNEL

PREPARED UNDER FERMILAB SUBCONTRACT NO. 92690
BY CRYOGENIC CONSULTANTS, INC.
ALLENTOWN, PA.

FOR

FERMI NATIONAL ACCELERATOR LABORATORY
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INTRODUCTION

The notes in this report address themselves to the potential problems associated with release of helium from the doubler magnet system into the tunnel. The calculations made are not exact, but approach the problem as a first order evaluation. They are probably accurate enough to indicate the general progression of events, assuming failure modes as represented by Cases I through IV. Before calculating (estimating) the effects from each case, some general notes cover the events of a single magnet quench and release of helium gas in the tunnel.

SUMMARY

It appears that thorough mixing of helium and air in the tunnel may be anticipated, because of the large amount of energy present in the high velocity relief valve vents. The thorough mixing will result in massive fogging, in spite of the low dewpoint normally maintained in the tunnel. The fog should clear in a few minutes because of the large amount of heat present in the magnet iron and structure of the tunnel.

Case I represents the worst case. This case assumes quenching of all 40 magnets in a 800 ft long string of magnets. A quench of this type will result in a short duration high

velocity stream of gas flowing away from the magnet string into the tunnel. The velocity may be high enough to knock people over and carry loose objects over a short distance.

It is anticipated that the atmosphere in the afflicted section of the tunnel will contain a sufficient percentage of oxygen to sustain life. It is possible that some pockets may exist, in which the oxygen concentration is too low for long term safe occupancy. The temperature of the mixture will not be extremely low. Temperatures in the range of 10-25°F are anticipated. Chill factor will be high especially during the first 5-10 sec.

The tunnel vent system will not participate significantly in the venting of the gas, because impedance of the tunnel cross section is very low relative to that of the vent system. The gas will first spread through the tunnel and then venting to the atmosphere will take place. Uniform quenching of all of the energy doubler magnets in the tunnel has not been considered. If this is a real case, calculations need to be made to determine the pressure rise in the tunnel as a function of time.

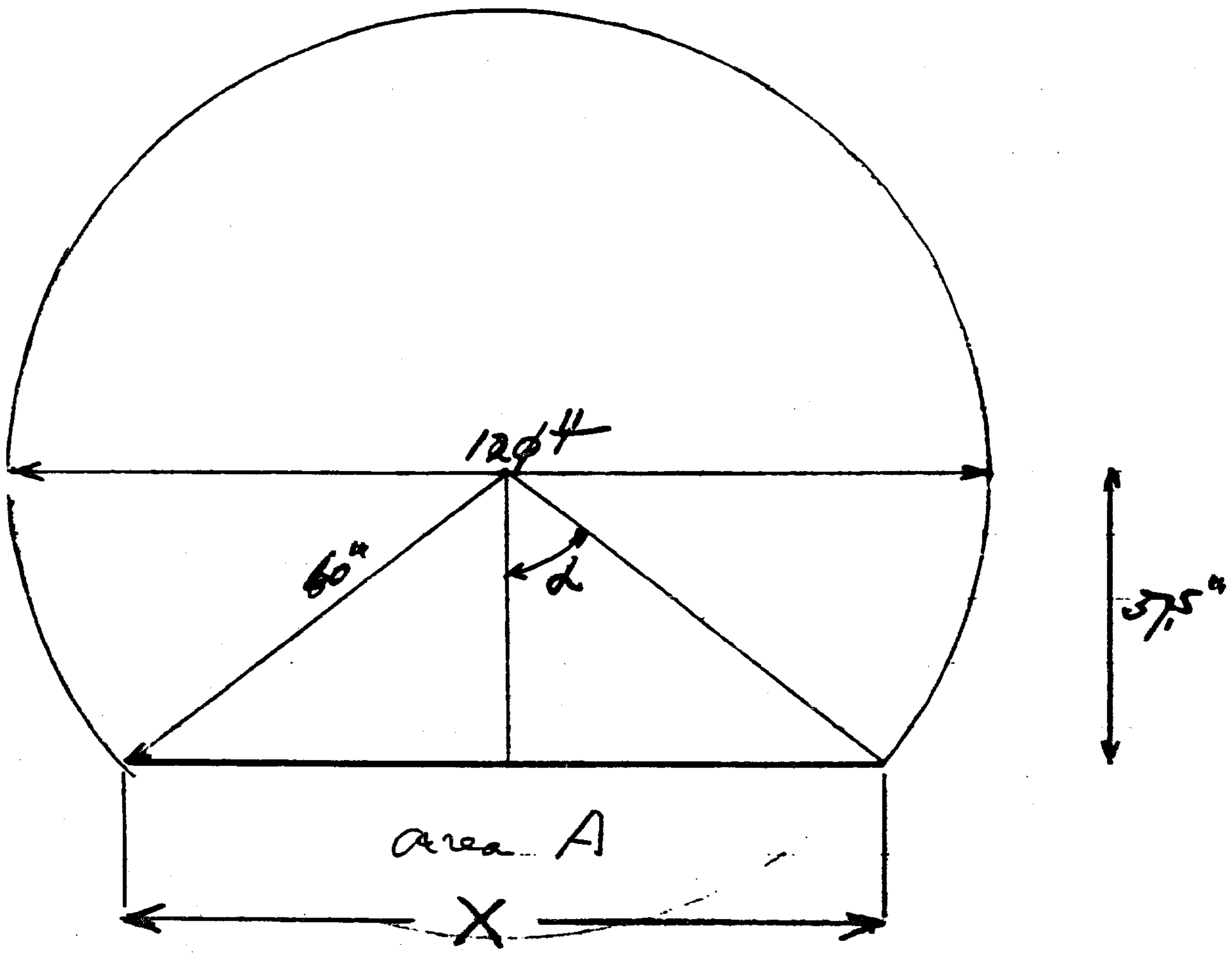
RECOMMENDATIONS

1. Provide some breathing apparatus at 40 ft intervals. This apparatus could be a 1 in. pipe extending from the service buildings with bleed points at 40 ft spacings.

2. Instruct personnel in the use of this apparatus.
3. Do not install a collection header for the helium.

GENERAL

Tunnel Volume:



$$(1/2\ X)^2 + 37.5^2 = 60^2$$

$$1/2\ X = \sqrt{3600 - 1406.25} = 46.837 \text{ in.}$$

$$X = 93.674 = 7 \text{ ft, } 9\text{-}11/16 \text{ in.}$$

$$= 7.806 \text{ ft}$$

$$tg\,\alpha = 1.249 \qquad \alpha = 51.32°$$

$$\text{Area } A = \frac{102.64}{360} \times 100 \times 1/4\pi - \frac{37.5 \times 46.837}{144} = 10.19 \text{ ft}^2$$

Area of tunnel is: $100 \times 1/4\pi - 10.19 = 68.35 \text{ ft}^2$

One ft of tunnel contains 68.35 cft of air at 70°F.

$$\frac{68.35}{379} = .180 \text{ M of gas}$$

Oxygen Content = .18 x .20 x 32 = 1.152 lb

Nitrogen Content = .18 x .8 x 28 = 4.032 lb

Surface area of tunnel per ft length is:

$$\pi \times 10 \left(1 - \frac{102.64}{360}\right) + 7.8 = 22.46 + 7.8 = 30.26 \text{ ft}^2$$

Volume of magnets plus iron is: $2.8 + 1.0 = 3.8 \text{ ft}^3$ per ft

This reduces air contents of tunnel to:

$$\frac{64.55}{68.35} \times 100 = 94.4\%$$

O_2 = 1.088 lb)
per ft of tunnel
N_2 = 3.806 lb)

Surface area of tunnel and structures is increased to:

$30.26 + 10.6 = 40.86 \text{ ft}^2$ per ft of tunnel length

ASSUMPTIONS

1. Relief valves dump helium into the tunnel.
2. Vacuum system relief systems dump helium into the tunnel.
3. Tunnel relief system consists of 30 in. I.D. pipes located at 800 ft intervals. Length of pipe is approximately 20 ft. Pipes vent to the atmosphere.
4. Doubler magnets are located below the conventional magnets. Vents from relief valves may be placed at any elevation. Selection to be based on conclusions of report.

5. Cooling of a string of magnets is by flow in series through 400 ft of magnet to a J-T valve. Two-phase flow returns to the service building through a small diameter shell on the outside of the magnet vessel.
6. Inventory in the single-phase system of the dipole magnet is 20 liters, when at steady state. Inventory of two-phase system is negligible relative to that of the single-phase system.
7. Tunnel atmosphere is at 90°F and has a relative humidity of 25%. Dewpoint is then 50°F and water vapor pressure is 9 mm Hg.

CALCULATIONS

Consider a quench of a single magnet. Assume that 80% of the liquid (16 liters) will be ejected in 5 sec (to be verified by B-12 tests). Rate of helium injection into the tunnel is then $\frac{16 \times 125}{5} = 400$ g/sec.

Assume that the temperature of this helium (average over 5 sec) is 10°K. Then conditions of this helium at entry in the tunnel are as follows:

$P = 1.0$ atm

$T = 10°K$

$H = 65$ J/gr

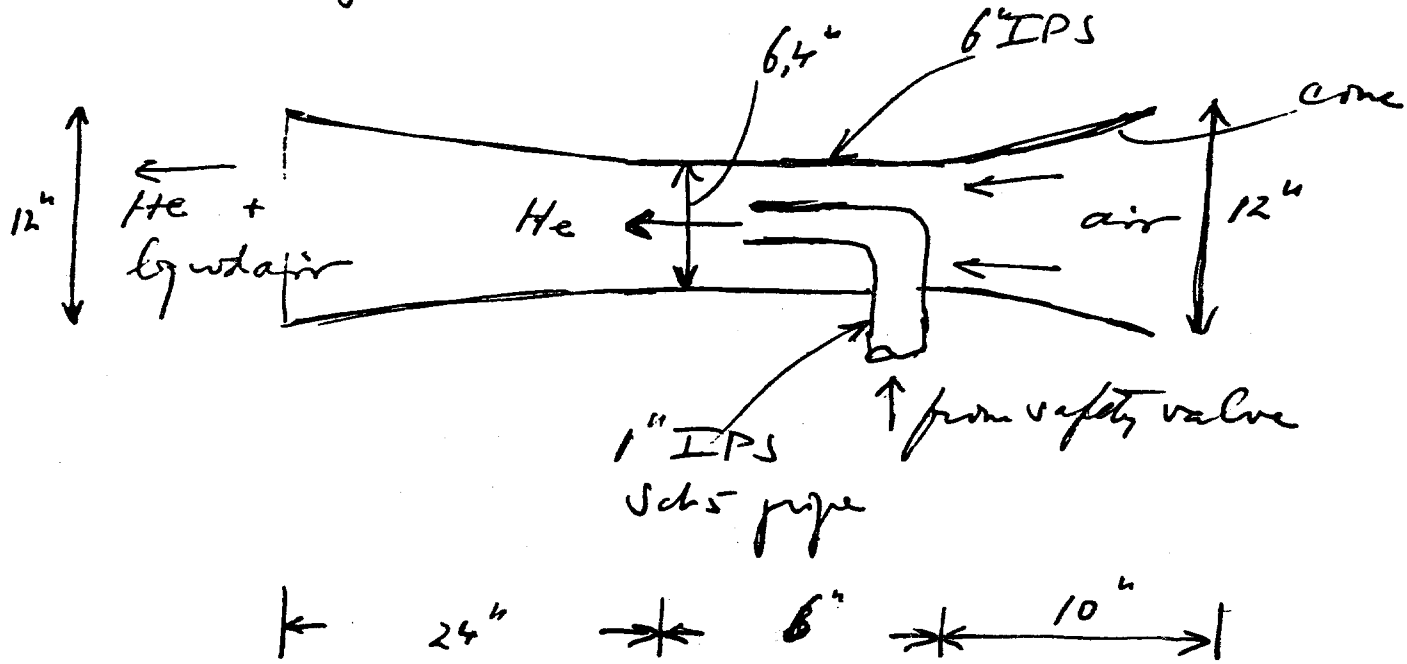
$V_s = 199.1$ cc/gr

$S = 13.64$ J/gr °K

By mixing with a small amount of air, we can liquefy the air. Consider the mixing process by means of a crude ejector system. Figure 1 shows the arrangement.

Fig 1

He ejector from safety valve of magnet



Dimensions of the device are rough. It is not necessary to adhere to these exactly and different configurations are possible. How much air can we pump with the helium stream?

Energy of helium is in velocity at the exit of the pipe. This velocity is:

$$\frac{199.1 \times 400}{(1.185)^2 \times .785 \times 6.45} = 11{,}201 \text{ cm/sec}$$

The velocity head associated with this is approximately:

$$1/2 \rho v^2 = \frac{1}{2 \times 199} \times (11201)^2 \times 10^{-6} = .315 \text{ atm}$$

Consider the available energy for pumping that we get from isentropic expansion of the helium gas from 1.4 atm to 1 atm:

$P = 1.4$ atm

$T = 11.5$

$H = 72.4$

$S = 13.64$

Net available work is: $\Delta H \times M = (72.4 - 65) \times 400 = 3{,}000$ J/sec

We would like to draw in sufficient air to bring the helium temperature up to 80°K. Rate of heat transfer from helium to air is then:

$400 \times (430 - 65) = 146{,}000$ W

To liquefy 1 gr of N_2 requires approximately 430 joules. Minimum flow of N_2 (or air) is then 340 g/sec. Volume of this air is:

$340 \times 850 = 289{,}000$ cc/sec

To pull this in through a 12 in. diameter hole requires a velocity of: $\frac{289000}{730} = 400$ cm/sec

At the entry to the 6.4 in. diameter section the velocity is 1,450 cm/sec. This represents a velocity head of .00125 atm. To compress air from 1 to 1.01 atm requires work as follows:

$$W = 1 \times .25 \times 520\ (1.01 - 1) =$$

$$= 137 \text{ Btu/lb}$$

$$= .86 \text{ joules/gr}$$

To compress 340 g/sec requires 292 joules/sec.

If the ejector works with an efficiency of 10%, we can pull in the right amount of air to warm the helium and liquefy the air. The rate of heat transfer in the jet is then:

$400 \times (430 - 65) = 146{,}000$ W and the helium gas exits at a temperature of some 80°K.

The exit velocity (hole diameter = 12 in.) of the warm helium is of the order of:

$$\frac{400 \times 1643}{930 \times .785} = 900 \text{ cm/sec}$$

(20 mph)

The air entrained in the helium is liquefied and the volume flow rate is $\frac{340}{1} \times 1.25 = 425$ cc/sec

This is insignificant!

How much volume has been added to the tunnel in warming up the helium to 80°K and liquefying the air. New volume (he) is:

$$2000 \text{ g} \times 1643 = 3.286 \times 10^6 \text{ cc}$$

$$= 115.7 \text{ cft}$$

Volume removed is:

$$1700 \times 850 = 1.45 \times 10^6 \text{ cc} = 50.9 \text{ cft}$$

To remain at 1 atm of pressure it is necessary to remove 65 cft from 20 ft of tunnel or:

$$\frac{65}{20 \times 64.5} \times 100 = 5\%$$

Water Condensation

The tunnel has a dewpoint of 50°F and the water vapor pressure is 9 mm Hg. At the mixture temperature of 80°K all of the water vapor has been removed, condensed and frozen. To remove and cool requires roughly 1200 Btu per lb of water. 1700 gr of air contains 12 gr of water. To condense and freeze requires:

$$1200 \times 1055 \times \frac{12}{454} = 34{,}000 \text{ joules}$$

This represents less than 10% of the cold available in the helium vented from the magnet and does not affect the previous calculations. However, it is obvious that the mixture of helium, air and liquid, air contains many small particles of water. It may be that a large part of these particles will be part of the liquid air.

At the exit of the mixer and liquefier, the helium and liquid air enter the tunnel volume. From this point on there is mixing of warm air and cold helium. The final temperature of the mixture is a function of the amount of air participation in the mixing process.

A first assumption may be that all of the remaining air in the tunnel participates. What is the end condition?

Consider first of all that in the first few seconds of the process the liquefied air remains liquid. Available for mixing with the helium is then:

$$20 \times 64.5 - 51 = 1{,}240 \text{ scft}$$
$$= 41{,}400 \text{ gr}$$

Also, consider that in the first few seconds heat transfer between wall of the tunnel and cold gas is insignificantly small compared to the large rate of heat transfer represented by the mixing process. The final temperature of the mixture is determined from the following equation (assuming the condensation of 60% of the water vapor):

$$450000 + 41400 \times 1.04\ (305 - T_F) = 2000 \times 5.2 \times (T_F - 80)$$

$$T_F = 269°K = 24°F$$

The new volume of this mixture at 1 atm is:

$$41400 \times 787 + 2000 \times 5515 = 43.6 \times 10^6 \text{ cc}$$
$$= 1535 \text{ cft}$$

Tunnel volume per 20 ft length is approximately 1290 cft. It is necessary to vent 245 cft of gas from the 20 ft section of tunnel in order to maintain atmospheric pressure.

Consider pressure drop and heat transfer between tunnel wall and gas for a flow rate of 200 cft in 5 sec.

Flow Area = 65 ft^2

Flow Rate = 15.3 lb/sec = 11,066 lb/hr

Then:

$$G = 171 \text{ lb/hr ft}^2$$

$$\rho = .064 \text{ lb/cft}$$

d_h = 6 ft

μ = .039 lb/ft hr (air @ 260°K)

Pr = .73

C_p = .297 Btu/lb °F (mixture)

Re = 27000

j = .0028

f = .0056

$$h = \frac{j\ C_p\ G}{Pr^{2/3}} = \frac{.0028 \times .297 \times 171}{.81} = .18 \text{ Btu/hr ft}^2\ °F$$

$$\frac{\Delta P}{L} = \frac{f\ G^2}{193 \times \rho \times d_h \times 12 \times (3600)^2} =$$

$$= \frac{.0056 \times (.048)^2}{193 \times .064 \times 72} = 1.4 \times 10^{-8} \text{ psig/ft}$$

Obviously, the tunnel itself does not restrict the flow of gas to the vent tubes. Also, the heat transfer coefficient between gas and wall is low and as a result the mixture will not warm up rapidly. Rate of heating of the gas, assuming a coefficient of .5 Btu/hr ft^2 °F, will be:

$$Q = .5 \times (305 - 269) \times 1.8 \times 41 \times 20 = 26{,}500 \text{ Btu/hr}$$

per 20 ft section of tunnel.

Gas starts warming at the rate of $\frac{26500}{95 \times .297}$ = 940°F/hr

Because of this heating, some additional volume needs to be vented. This amounts to 1.1 cft/sec or 25% of the rate calculated before. Obviously there is no problem with pressure drop in the tunnel.

Oxygen contents of the mixture.- After mixing we have:

2,000 g of He	=	500 gmoles
9,400 g of O_2	=	294 gmoles
31,900 g of N_2	=	1,140 gmoles
TOTAL:		1,934 gmoles

Concentrations and partial pressures are:

	Concentration	Partial Pressure
Helium	25.9%	3.70 Psia
Oxygen	15.2%	2.17 Psia
Nitrogen	58.9%	8.42 Psia

For breathing the minimum allowable partial pressure is 1.7 psia; for short periods of time (less than a few minutes) this level could be lowered to 1.4 psia.

Water Vapor Condensation

At 269°K the water vapor pressure is 3.4 mm Hg. This means that approximately 60% of the water vapor present in the tunnel condenses. The heat of vaporization is of the order of 1,000 Btu per lb and total water condensation in 20 ft of tunnel is .36 lb. This requires removal of 400 Btu's of heat. This number was assumed in determining the final temperature of the mixture.

To warm the mixture above the dewpoint of 50°F, heat is supplied from the tunnel wall and the iron of the magnets. Total amount of heat to be supplied is then:

$$43400 \times .297 \times (283 - 269) + 450000 = 630,000 \text{ joules}$$

Average rate is 25000 Btu/hr or $\frac{25000 \times 1055}{3600}$ = 7,326 J/sec.

Time required to clear the fog will be of the order of 90 sec. The various calculations and estimates made previously may be applied to different cases of energy doubler magnet failures.

CASE I

An 800 ft long string of magnets is quenched under full power. All stored energy is dumped into the magnets in .2 sec. Helium will vent from all relief systems. The rate of release will be a function of the vent system capability. However, we will assume that 16 liters of liquid per magnet or a total of 640 liters of liquid will enter the tunnel in 1 sec.

The tunnel vent system consists of air intakes and exhausts, alternating between service buildings. Intakes and exhausts are identical and gas may be blown out through both of them. Openings consist of a 36 in. diameter, 20 ft long shaft, turing above ground into an ell. The ell is covered by a flat plate with two 15 in. diameter holes. Exhaust fans are located in these holes at every other service building.

Consider Figure 2. A mixture of helium and air will flow through interfaces A-A, B-B and C-C. The impedance of interface C-C is large, relative to those at A-A and B-B and flow rate through this interface may be ignored in first instance with regard to providing a meaningful relief function. Therefore, the tunnel will take up all of the helium gas and

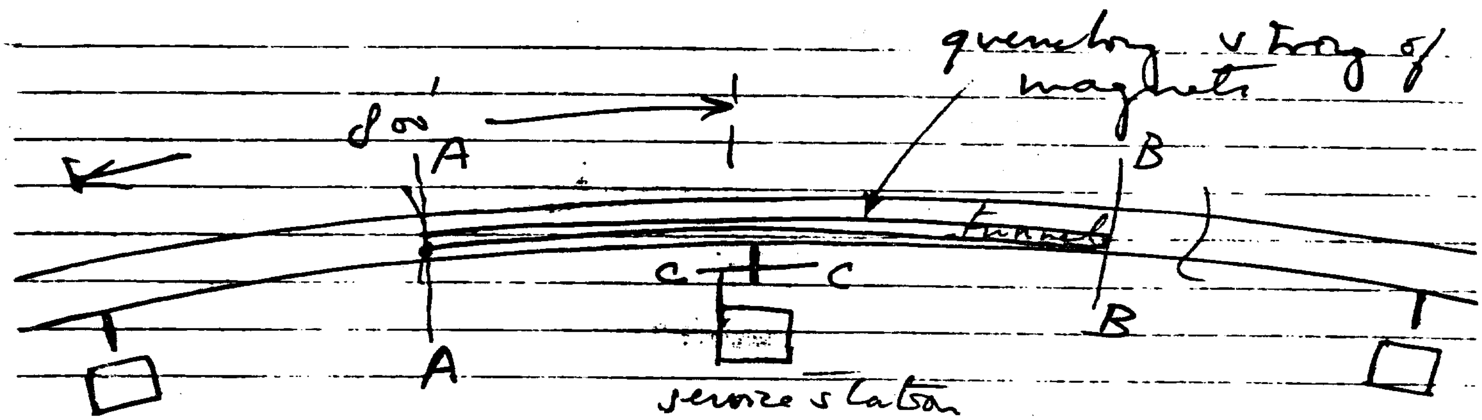


Figure 2

the mixture will push through the interfaces A-A and B-B.

Calculations have shown that the increase in volume required to maintain 1 atm pressure is as follows:

Step I Warming of helium to 80°K by condensation of air requires removal of 65 cft per dipole magnet.

Step II Mixing of 80°K helium and remaining air to reach a final temperature of 269°K requires removal of 245 cft of gas per dipole magnet.

Step III Warming of mixture requires removal of 1.1 cft per sec per dipole magnet.

Step IV Vaporization of liquefied air and warming to ambient temperature requires removal of 51 cft of mixture per dipole.

Steps III and IV take place at a rate which is at least one order of magnitude smaller than Steps I and II.

Maximum flow rate of mixture occurs at interfaces A-A and B-B. Total gas mixture to move through each is

$20 \times (245 + 65) = 6200$ cft of gas. At a density of .064 lb/cft mass flow is 397 lb per interface.

It is permissible to allow a slight increase in the pressure of The section of tunnel where the release occurs. At 1.1 atm this section will hold $.1 \times 800 \times 64.5 = 5160$ cft of gas extra. It appears that we may consider flowing the extra gas from the venting section into the rest of the tunnel over a period of at least 3 sec. Then:

Mass flow rate is: $\frac{397}{3} \times \frac{3600}{64} = 7450$ lb/hr ft^2

Velocity at interface = 32.3 ft/sec

To accelerate mixture to this velocity requires a pressure of .5 cm H_2O = ($.5 \times 10^{-4}$ atm). Apparently we do not need much pressure to accelerate. The pressure drop per ft length at the interfaces A-A and B-B is:

$$G = 7450 \text{ lb/hr ft}^2$$

$$d_h = 6 \text{ ft}$$

$$\mu = .039 \text{ lb/ft hr}$$

$$\rho = .064$$

$$Re = 1.0 \times 10^6$$

$$f = \frac{.046}{Re} = .003$$

$$\frac{\Delta P}{L} = \frac{.003 \times (2.08)^2}{193 \times 72 \times .064} = 1.5 \times 10^{-5} \text{ psig/ft}$$

Because of the low pressure drop, the mixture will be accelerated to a much higher velocity and it may be possible that the velocity at interfaces A-A and B-B reaches 80-100 ft/sec in 1 sec. After this it will decay to much lower velocities.

Heat transfer at interfaces A-A and B-B between wall and gas.- Assume a velocity of 60 ft/sec for a short period of time. Then:

$$G = 15000 \text{ lb/hr ft}^2$$

$$Re = 2 \times 10^6$$

$$j = .0013$$

$$h = \frac{.0013 \times .297 \times 15000}{.8} = 7 \text{ Btu/hr ft}^2 \text{ °F}$$

The high heat transfer coefficient does not change the rate of heating of the gas materially. The instantaneous rate is (per 20 ft length of tunnel):

$$Q = UA\,\Delta T = 7 \times 41 \times 20 \times 35 \times 1.80 =$$

$$= 361{,}620 \text{ Btu/hr} = 105{,}000 \text{ W}$$

Gas flow rate is 800 lb/sec or 363,200 g/sec

Then $\Delta H = .289$ J/gr

$$\Delta T = \frac{.289}{1.24} = .23\text{°K/sec}$$

The temperature of the wall of the tunnel changes. The thermal diffusivity of the material is low and for this reason it is assumed that only 1/8 in. depth participates in the heat transfer. Mass per 20 ft of tunnel is:

$$820 \times 1/8 \times 1/12 \times 120 = 1025 \text{ lb}$$

With C_p = .12 Btu/lb rate of temperature drop of the wall is .8°F/sec. This is approximately twice as fast as the increase of the gas temperature.

Decay of oxygen concentration.- Because of the relatively high velocities in the tunnel, mixing of the helium and air in the tunnel will be reasonably good. This is important, because complete and uniform mixing will result in a mixture with approximately 15% oxygen. Non-uniform mixing will result in pockets with less oxygen and it may be that personnel cannot stay very long in these areas. Because of the low density of the helium, venting at the high point of the tunnel is preferred in order to maintain oxygen concentrations of at least 15% near the floor of the tunnel.

Clearing of fog.- Lower areas of the tunnel will clear first, because of two effects:

a) The helium mixture has a lower density than air.
b) The magnet iron will remain warm, because of high thermal diffusivity and gas in the immediate area of the iron will warm first above the dewpoint.

Major problems of Case I.-

1. A short burst of high velocity gas mixture will occur at the ends of the strings of magnets. The velocity may be high enough to blow around loose articles, tools, etc, and may knock people down.
2. Visibility will be zero for a period of a few minutes throughout 800-1200 ft of tunnel at equal distance from the service building of the quenched circuit.

3. There may be pockets of low oxygen concentration.
4. A low temperature of 20-30°F will be generated. Warming will be relatively fast, but the chill factor at the ends of the magnet string will be large due to some velocity of the gas.

CASE II

A 100 ft long string of magnets is quenched under full power. All stored energy is dumped into the magnet in .2 sec.

This case is identical to that of Case I, with the following differences:

a) Only 100 ft of tunnel is affected.
b) The velocities through interfaces A-A and B-B of Figure 2 are approximately 10% of those of Case I.

Major problems of Case II are the following:

1. Visibility will be zero in a 100-150 ft long section of the tunnel.
2. There may be pockets of low oxygen concentration.
3. A low temperature of 20-30°F will be generated. The chill factor is not nearly as bad as in Case I, because of much lower velocities.

CASE III

A total rupture of the vacuum system to 1.2 atm of nitrogen occurs at one point. The following will happen:

a) Liquid and gaseous nitrogen will pour out of the hole into the vacuum space. Rate will be determined by the impedance in the nitrogen circuit and the area of the hole. For a short period of time the nitrogen flow will occur from two directions until the supply is exhausted in the section downstream of the break.

b) The nitrogen will cryopump on the helium surface of the magnet cryostat.

c) It will be assumed that the flow of nitrogen is one way and that all nitrogen molecules stick to the helium surface.

d) Velocity in the break to the vacuum system will be sonic. Sonic velocity of gas and liquid is quite different. We will assume that the sonic velocity of the gas will occur, for the following reasons:

   1. By volume, the bulk of flow through the hole will be gaseous ($>$99%).
   2. Liquid will be suspended as fine individual droplets in the gas stream.

Mass flow rate into the vacuum space will be velocity times area times density. For a 1/2 in. tube opening, a pressure of 10 psia in the hole, volume flow rate will be:

$$(1.27)^2 \times .785 \times 565 \times 30.5 = 21{,}820 \text{ cc/sec}$$

Density of gas will be:

$H = 100$ J/gr

$H_L = 23.4$ J/gr

$V_L = 1.22$ cc/gr

$H_V = 226.3$ J/gr

$V_V = 301.6$ cc/gr

Fraction liquid and vapor is:

$$100 = (X)\ (23.4) + (1 - X)\ (226.3)$$

$$X = .62$$

Specific volume of mixture is:

$$.62 \times 1.22 + .38 \times 301.6 = 115.4 \text{ cc/gr}$$

Density is .00867 g/cc

Mass flow rate into vacuum space is:

$$\frac{21820}{115.4} = 189 \text{ g/sec}$$

Heat transport to the helium system is then: $189\ \Delta H$ J/sec

ΔH is a function of the final temperature at which the N_2 sticks to the wall of the helium vessel and the initial enthalpy as a mixture of liquid and gas in the shield system. We will assume $\Delta H = 200$ J/gr. Heat transport is then of the order of 40 kW. This heat will be depositied in the area of the nitrogen leak primarily and it will be assumed that the 40 kW will be depositied in two adjacent magnets. The heat will mainly be added to the two-phase system through a surface area of approximately 40 ft^2. Heat flux is then 1 kW/ft^2. To transfer to the two-phase stream requires a ΔT of the order of 20-30°K between wall and gas. Temperature of the wall will be of the order of 30°K quickly. In first instance only the two-phase system will relieve. The single-phase system will quickly heat uniformly to the point where the magnets go normal. At that point, the energy in the magnetic field will be dumped partially in the two magnets closest to the break. Generally though, the energy added to the helium from the vacuum break is small compared to that from a quench.

Major problems of Case III.-

1. Loss of vacuum will result in loss of superconductivity of all magnets which are part of the system. Field energy will be dumped into the helium and venting may be as bad as Case I.

CASE IV

A rupture of the vacuum system to 1.2 atm of helium occurs at one point.

The mode of heat transportation into the magnet cryostats is thermal conduction and convection between shield and 4°K system. The vacuum system quickly fills to the pressure at which the vacuum system relieves. If the relief valve setting of the vacuum system is significantly below the pressure in the single-phase helium system direct venting into the tunnel will occur. Rate of venting is a function of the capacity of the relief system. Venting is continuous because high heat leak of the magnet system maintains high pressure in the cryostats.

The rate of heat transfer may be estimated as follows:

Shield to Cryostats.-

Thermal conductivity of the helium gas located in the vacuum space between shield and cryostat is of the order of 40×10^{-5} W/cm °K. If the shield temperature can be maintained at 70-80°K, flux will be per dipole:

$$Q = \frac{40 \times 10^{-5} \times 20000 \times 70}{.3} = 1{,}870 \text{ W}$$

At this rate of heating, the two-phase system will start relieving helium to the tunnel within 1 sec. The two-phase system will start venting somewhat later. The rate of internal energy increase of the single-phase system will be of the order of .75 W/gr, assuming an inventory of 20 liters of liquid per magnet. At this rate some 4 sec will elapse before the single-phase helium reaches a temperature of 5°K and a pressure of 2 atm. After the relief pressure setting of the single-phase system is reached venting will commence at a rate to accommodate the volume increase of the fluid in the single-phase system at constant pressure. The rate of vaporization is some 200 gr per sec (at 5.0°K and 2 atm) and the volume generated is at a rate of 13.5 x 200 = 2,700 cc/sec. This is the flow rate out of the relief system. The density of this fluid will change with time, but initially will be close to .1 g/cc (6.25 lb/cft). Rate of venting is then:

270 g/sec = .6 lb/sec per dipole

Since the total inventory of the single-phase system (per dipole) is of the order of 20 liters (5.5 lb) most of the single-phase helium will vent over a period of 10-15 sec.

Superconductivity will be lost more or less uniformly. Initially, the temperature of the helium will rise slowly from 4.6 to 5.0°K over 4 sec. After 4 sec at the onset of venting this temperature will be maintained until super-heating of the gas starts to occur. If the magnets will be superconductive at 5°K at full field, loss of superconductivity may be postponed for a few seconds after the single-phase system starts venting. It may be possible to remove some of the field energy before loss of superconductivity occurs.

The final result is the same in all cases. All of the helium will vent in the tunnel, but at a somewhat slower rate than calculated (estimated) in Case I.

Major problems of Case IV.-

1. Visibility will be zero for a period of a few minutes throughout 800-1200 ft of tunnel at equal distance from the service building of the quenched circuit.
2. There may be pockets of low oxygen concentration.
3. A low temperature of 20-30°F will be generated. Warming will be relatively fast, but the chill factor at the ends of the magnet string will be large due to some velocity of the gas.

It is anticipated that velocities in the tunnel will be somewhat less than those estimated for Case I and will not constitute a major problem.