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CCI Report 806-1A

SPILLAGE OF 80K SHIELD LINE CONTENTS INTO THE TUNNEL OF THE SSC

Submitted By

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I. SUMMARY

The report describes the events following a postulated major break in the vacuum wall of the cryostat. It is assumed that the line, containing the 80K shield cooling fluid, also breaks. After the break, the liquid nitrogen or helium from the 80K shield line flows freely from the rupture in the pipe. To be conservative, it has been assumed that the pipe break has the flow area of the pipe itself, immediately after the break occurs.

II. INTRODUCTION

The SSC magnet system contains a large inventory of cryogenic liquids and gases. Closest to the vacuum retaining wall of the cryostat is the 80K shield line. This line is filled with single phase liquid nitrogen under moderately high pressure of 6-10 ata. The temperature of this liquid may be varied from a range of 80-88K to one of 70-78K. The results of a major break in the line are quite different for the two cases.

A major break in the 80K shield line may occur in one of two ways. The first one occurs when it is postulated that an external source in the tunnel manages to penetrate first through the vacuum retaining wall of the cryostat and then breaks the 80K shield line. To be conservative it is postulated that the line break results in a clean cut of the line with exit flow area of the same cross-section as the line itself.

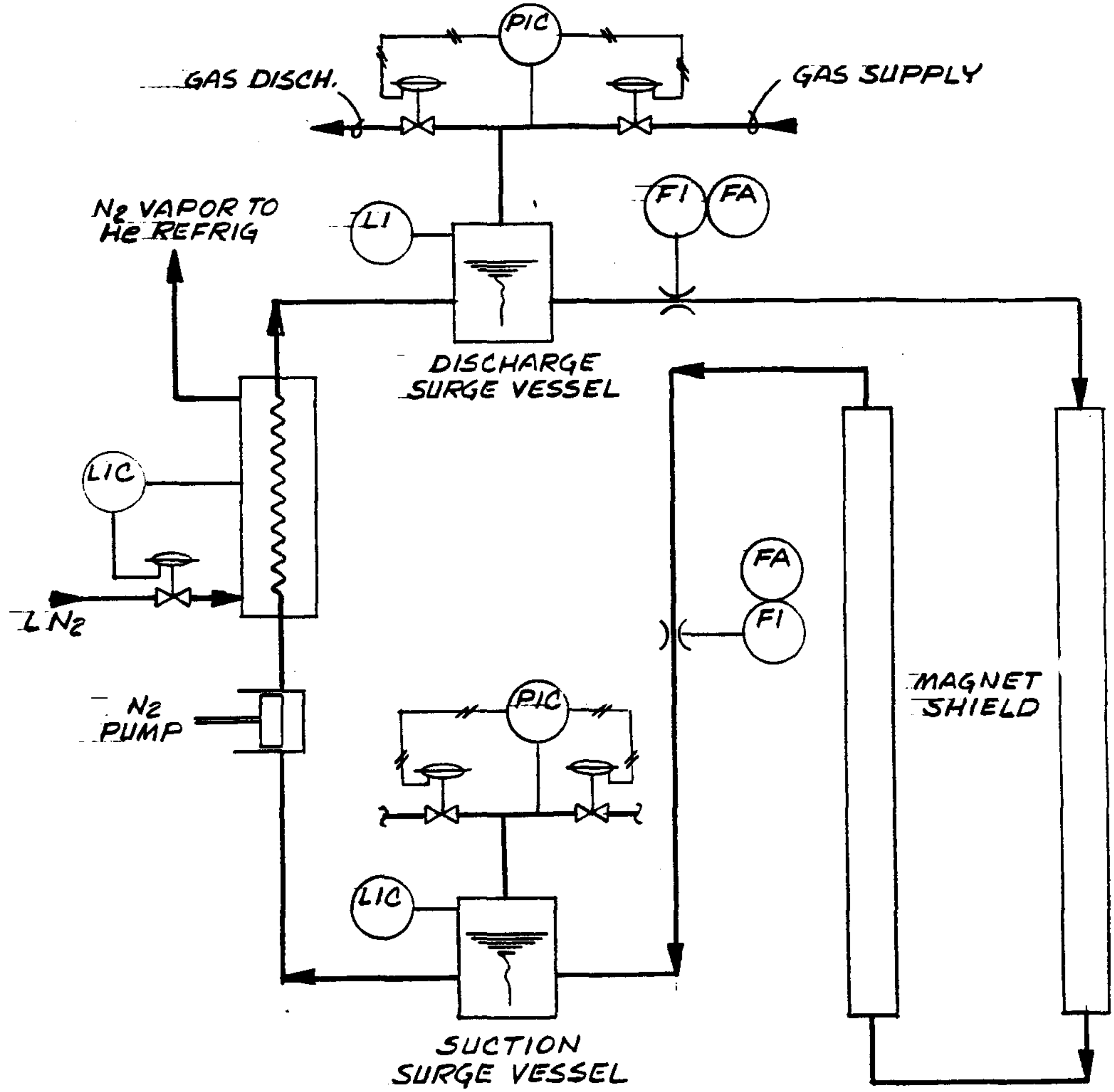
The second failure occurs when operator error will result in a "U" section being only partially removed from the two (2) bayonets of the spoolpiece, located at the one km intervals.

The final design of the one km interval spoolpieces has not been worked out. The CDG report scenario for the removal from operation of a one km long magnet section (for repair) assumes, that bayonets at each end of the one km long section allow re-routing of cryogenic fluids. This approach provides the possibility of a major leak to happen.

In order to describe the events following the break, certain assumptions about the operation and design of the 80K shield cooling system have been made. Figure 1 shows the flow system of the 80K shield system, which contains these assumptions.

The 80K shield cooling may also be provided by flowing helium gas at moderately high pressure (8-10 ata) through the shield line. Failure scenarios are the same as for the liquid nitrogen filled line.

The report describes the events following a line break, when the line contains cold high pressure helium gas.



FLOWSYSTEM OF MAGNET 80°K COOLED SHIELD SYSTEM

FIGURE - 1

III. DETECTION OF A LEAK IN THE LIQUID NITROGEN SHIELD SYSTEM.

1) At the location of the break pressure will decay to atmospheric plus a velocity head of the escaping liquid. The pressure may be somewhat lower, if the liquid escapes into the vacuum space of the magnets.

2) Pressure in the surge vessels upstream and downstream of the pump will remain constant until a signal is received, that pressure needs to be reduced.

3) Two flow measurements will be made. One of these is in the line from discharge surge vessel to the magnet shield; the other is in the line from magnet shield to suction surge vessel. A line break will have an immediate effect on the measurement. After steady state conditions have been reached, alarms will be activated. In case of a break, these alarms will indicate decreasing flowrate from the magnet shield to the suction surge vessel, and increasing flowrate from discharge surge vessel to magnet shield.

   Flowrate to the suction surge vessel will decrease rapidly, because the column of liquid moving between line break and surge vessel will be subjected to a negative pressure of the order of a few atmospheres. For instance, if the break occurs at a distance of 3 km from the suction surge vessel, a negative pressure differential of 3 ata will reduce flowrate to zero velocity in approximately seven seconds.

4) Pressure measurements at one km intervals will provide secondary information about any loss of liquid nitrogen from the magnet shield between discharge and suction surge vessels. In case of a leak, rate of pressure decay will vary from spoolpiece to spoolpiece. This information may then be used to pinpoint the location of the leak.

5) Level measurement in the surge vessels will provide secondary information. The combined levels in suction and discharge vessel will drop by at least the rate of liquid loss from the system. The loss of liquid from the line system may be greater than that of the surge vessels, if pressure decay occurs to a level, where boiling in the shield system is initiated. Decay of the level in the suction surge vessel will be faster than that of the discharge vessel, as long as the liquid pump is operating at the steady state flowrate.

It appears reasonable to detect larger leaks of the order of a few liters per second within 5-10 seconds after the leak occurs. When primary information is obtained from flow measurements, secondary information will be used to verify that a leak is occurring. This secondary information will be:

a) Pressure profile of a 8 km long line section will be measured and compared to the steady state profile.

b) Level measurements will be made for both surge vessels.

c) Valve positions of gas valves, which either add or remove vapor from the surge vessels, will be observed and compared to the steady state position of these valves.

IV. DISCHARGE OF LIQUID NITROGEN FROM A LINE BREAK

Figure 2 shows a pressure profile of a 8.2 km long shield line under steady state conditions. At the entrance to the line pressure has been chosen at 8 ata; at the suction surge vessel pressure will be of the order of 5.5 ata. Figure 2 also shows the boiling point pressure of the liquid as a function of distance travelled. There are two lines. One of the lines represents liquid entering the line at 80K and leaving at 88K. The other line shows liquid entering at 70K and leaving at 80K.

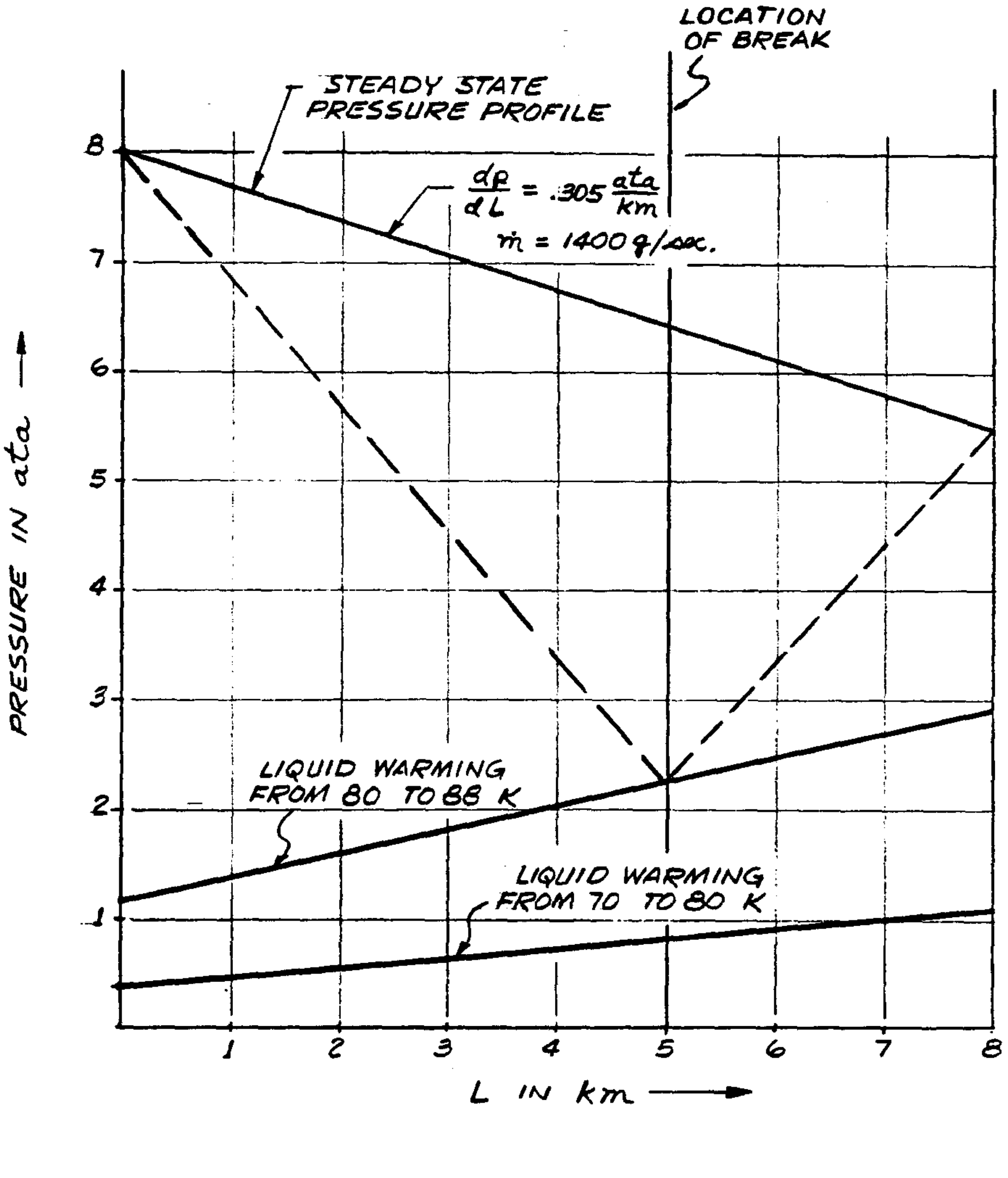
It is postulated that a break occurs at a distance of 5 km from the inlet to the shield line. The system will behave differently depending on whether the temperature of the liquid in the line is between 80 and 88K or between 70 and 78K.

First we will examine the behavior of the system filled with liquid of a temperature between 80 and 88K.

At the break, pressure will decrease to the local boiling point pressure of 2.25 ata. As soon as this pressure is reached boiling of liquid will start. Volume expansion of the boiling liquid nitrogen is large. A pressure reduction from 35 to 30 psia will yield a volume of 2.5 times of the original volume of the liquid. Therefore, pressure decay below the original boiling point value is slow. Figure 3 shows the relative volume of the fluid as a function of pressure during the boiling process.

The figure shows that only 40% of the original mass remains in the line when pressure drops to 2.094 ata from the starting pressure of 2.38 ata. For consideration of early events in the tunnel at the break, it may be assumed that the pressure in the line at the break will be that of the local boiling point. Pressure in the shield line, at points some distance removed from the break, will not immediately drop to the boiling point, because surge vessel pressures will not decay immediately. The dotted lines of Figure 2 represent the new pressure distribution in the bulk of the lines, after the break occurs. Only in the immediate vicinity of the break will pressure drop below the boiling point.

The mass flowrate out of the line is determined by the velocity head at the exit of the pipe. Over a distance of less than 10 meters from the break, frictional pressure drop is small relative to the exit velocity head. This can be shown as follows. At a velocity of 2,000 cm/sec, velocity head is 1.6 ata for liquid escaping from the hole. At the steady state velocity of 55 cm/sec in the shield line, frictional pressure drop is .3 ata per km. An increase of velocity to 2,000 cm/sec yields a pressure drop of $(2000/55)^{1.8} \times .3 = 193$ ata per km. A length of one meter then has a pressure drop of .193 ata for all liquid flow. Also, mass flowrate at the exit of the pipe will be proportional to $(\rho)^{.5}$ With the above, it is possible to indicate the maximum exit velocity at the break.



PRESSURE PROFILE OF 8.2 KM OF LIQUID NITROGEN COOLED 80 K SHIELD

FIGURE - 2

At time zero, maximum velocity and mass flowrate is determined from the available velocity head. If this is 1.38 ata, then maximum velocity is 1852 cm/sec, and maximum mass flowrate is 58.9 liters per second. This flowrate decreases very rapidly, as shown below.

Consider the first meter of liquid at the break. Mass in the line is 2,532 grams. Accelerating force available is 1.38 atm. Acceleration is then 16,895 cm/sec^2. To eject one meter of liquid (2,532 grams), distance travelled is one meter. Time for the liquid to move 1 meter is then .1055 second. Total liquid spilled in .1055 second is then 2,532 grams (3,165 liters). Rate is then 30.0 liters per second. Velocity at the exit of the pipe (at the break) becomes 1,840 cm/sec. At time zero, this represents a mass flowrate of 46,574 grams per second.

The exit velocity is reached in the pipe at a distance L from the break in

$$t = .1054\ L \text{ seconds,}$$

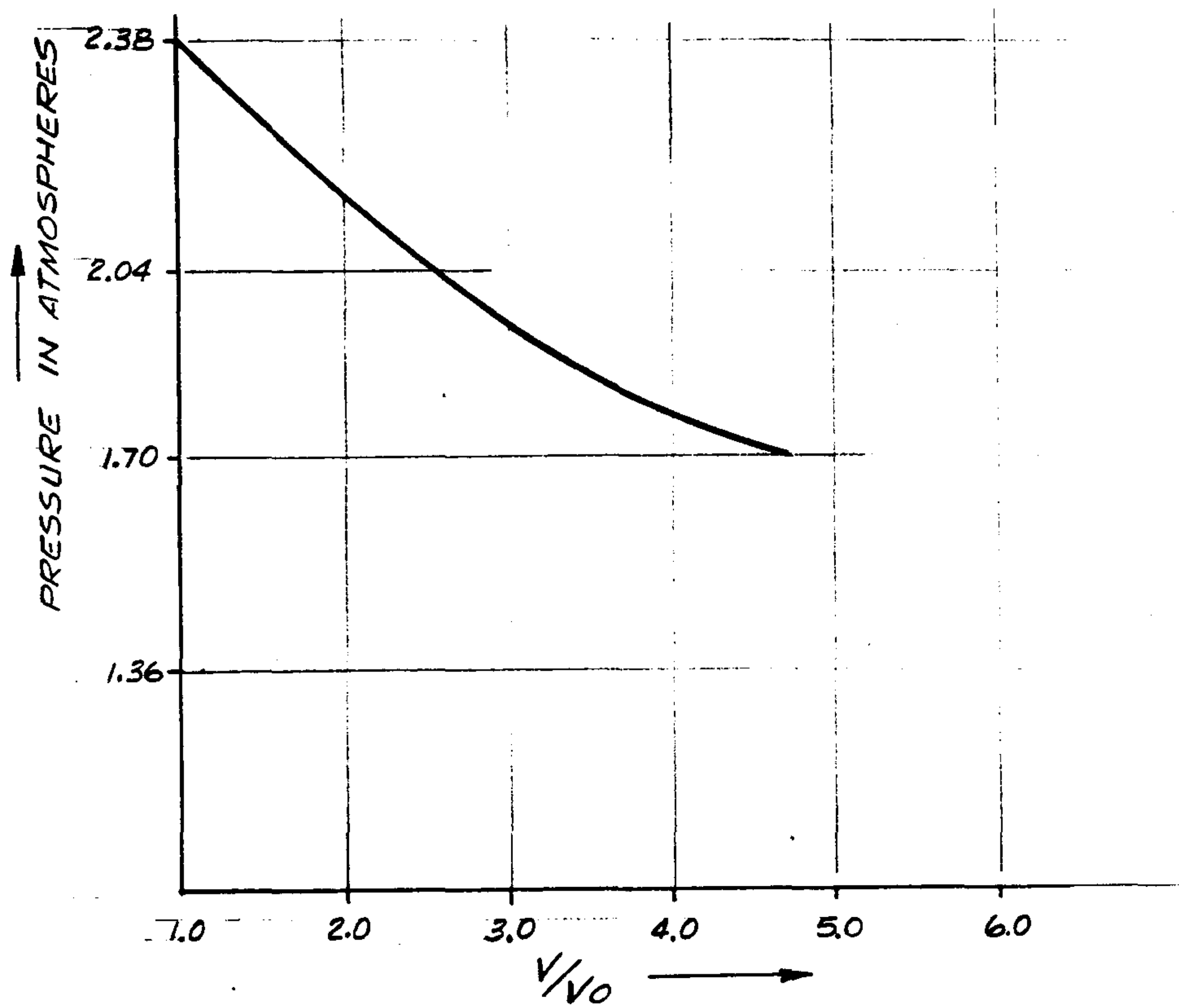
where L is expressed in meters. Pressure drop in the line at the break increases by .15 ata/meter at a velocity of 1,840 cm/sec. This number is based on all liquid flow and does not take into consideration, that boiling in the line is initiated as soon as pressure drop occurs.

Combining Figure 3 with the above yields Table I. This table is based on a constant exit velocity of 1,840 cm/sec at the break, and a pressure drop of .15 atm per meter of pipe length, independent of local quality.

TABLE I

PARAMETERS AT EXIT OF PIPE DURING A SPILL

L (meters)	0	1	2	3	4
a (cm/sec^2)	∞	16917	8459	5639	4230
t (sec)	0	.1054	.211	.3162	.421
Vt (cm/sec)	1860	1860	1860	1860	1860
Δp_L (atm)	0	.15	.30	.45	.60
Δp_{exit} (atm) g	1.38	1.23	1.08	.93	.782
$\left(\frac{G}{\rho}\right)^2 \times 10^{-6}$ $\frac{\text{dynes}}{\text{cm}^2}$	2.76	2.46	2.16	1.86	1.56
ρ (g/cc)	.8	.533	.346	.246	.196
$\frac{dm}{dt}$ (g/sec)	47074	36229	27352	21402	17271
V_{exit} (cm/sec)	1860	2148	2498	2750	2785



RELATIVE FLUID VOLUME AS A FUNCTION
OF PRESSURE DURING THE BOILING PROCESS

FIGURE - 3

Figure 4 shows the accumulated spill rate from half of the break as a function of time, based on the numbers of Table I.

It should be understood that Figure 4 flowrates are based on the existence of an unrestricted opening of the full diameter of the liquid nitrogen shield line.

The previous discussion of the initial spill rate from a break is valid for both sides of the break since conditions in the pipe are not much different in the first 20-30 meters of pipe and are not immediately affected by the conditions at great distances from the break.

Developing events, after the break has occurred, depend on the action taken in the system. The liquid nitrogen pump, moving liquid into the discharge surge vessel, should be stopped immediately. Also, vapor in the surge vessels should be vented, in order to lower the driving force moving liquid to the break. Rate of pressure decay in the surge vessels is a function of valve size and mass of vapor to be removed.

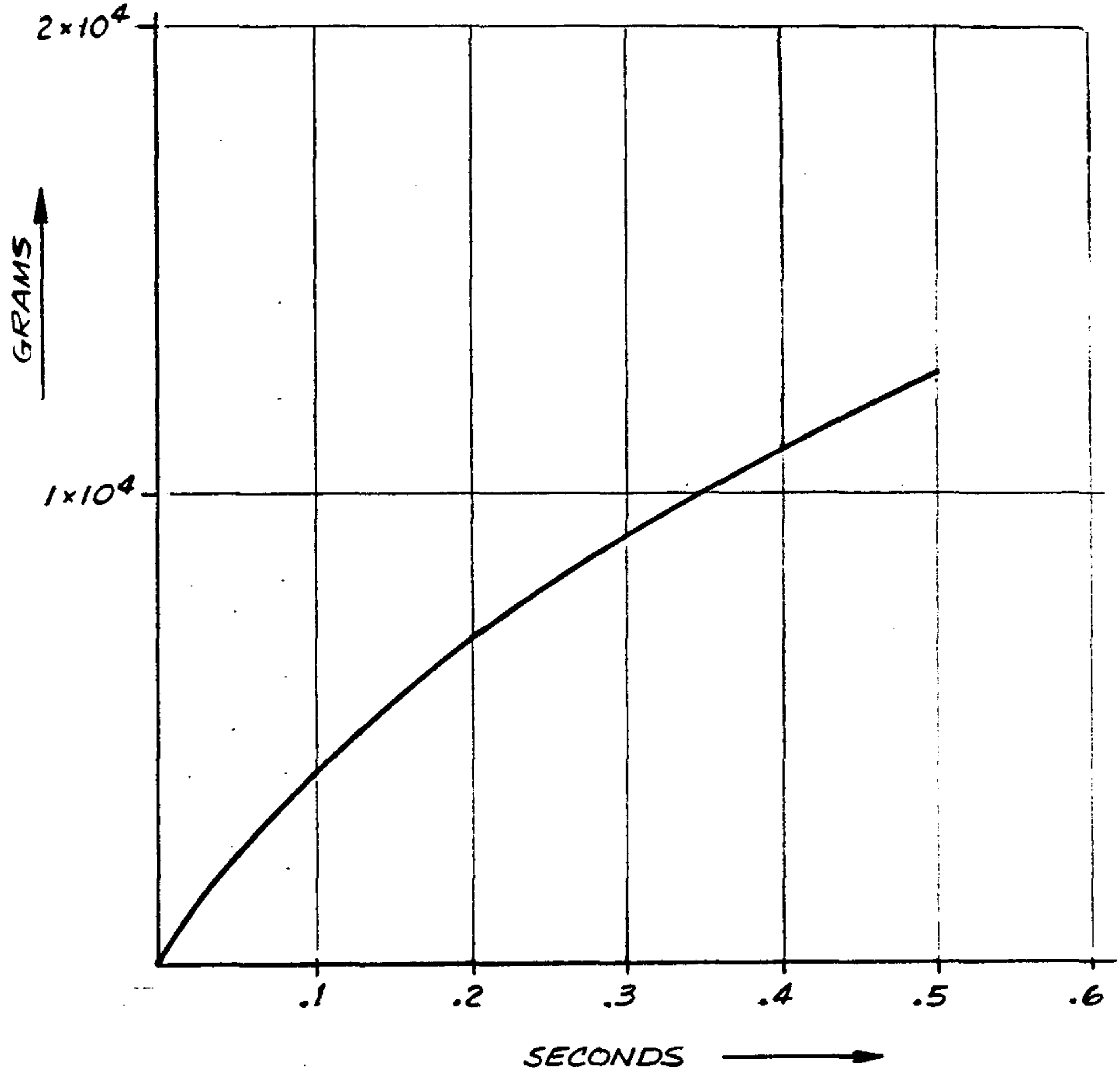
Careful attention to these matters will make it possible, to remove pressure from the system within a minute after the break occurs.

The addition of check valves in the shield system at one km intervals will prevent backflow and thereby reduce the total flow of liquid nitrogen through the break into the tunnel.

BEHAVIOR OF SYSTEM WHEN OPERATED WITH LIQUID OF A TEMPERATURE BETWEEN 70 AND 78K.

When a break in the line occurs, pressure at the break will reduce to atmospheric pressure plus a velocity head. Boiling will not occur in the line, since vapor pressure is below atmospheric. The pressure wave caused by the sudden depressurization at the break will move away from the break at a speed of approximately 1,000 meters/sec. Pressure will decay locally to one atmosphere plus an exit velocity head based on the existing velocity of 55 cm/sec plus pressure drop commensurate with the steady state flowrate in the pipe.

Only in the surge vessels will the pressure remain at the steady state pressure, until the gas is bled off.



ACCUMULATED SPILL RATE FROM HALF
OF THE LINE BREAK

FIGURE - 4

In first instance then, flowrate out of the break of the pipe will be 1,400 grams per second from the upstream pipe section and zero from the downstream section. In the downstream section, velocity will decay to zero and then reverse unless gas pressure has been removed from the suction surge vessel. With gas pressure in the surge vessels, the mass of liquid in the surge vessels and pipes will be accelerated towards the break in the pipe. If pressure is not removed, ultimate velocities will be determined by the pressure differential between surge vessel and break. These will be 127.8 and 132.8 cm/sec at a break point 5 km from the discharge surge vessel. Total flowrate out of the break is then 7.93 liters per second.

Time to accelerate the mass in the pipe is of the order of 5-10 seconds, assuming that the pressure over the liquid in the surge vessels remains constant during the period of acceleration.

EFFECT OF NORMAL HEAT LEAK ON SPILLAGE RATE.

After the break has occurred, approximately all of the liquid in the line located in the section with destroyed vacuum, will find its way into this vacuum space. After this, heat leak has no immediate effect on the spill rate until pressure in the surge vessels of the liquid nitrogen pump has been removed.

After this pressure has been removed, the events will depend on the thermal condition of the liquid in the line. If the liquid is superheated, local vapor volume generation will vary from .8 to .4 cc per Joule for 80 and 88K respectively. At a heat leak of 2.5W per meter (net), vapor volume generation is 2 to 1 cc per meter per second. With pressure removed from the surge vessel, there will be 4 escape points for the liquid and only half of the line will push liquid into the break. At an average volume generation of 1.5 cc per second per meter, flowrate from vapor displacement of liquid would be of the order of 6 liter per second. This is small relative to the postulated rate of 25 liters per second shortly after the break occurs.

When the line is filled with subcooled liquid, there will not be any vapor generation in the tunnel from the thermal heat leak of the shield. Table III of SSC-N-388 shows the heat capacity of the liquid nitrogen cooled shield. Approximately one hour is required to warm shield plus liquid by 1 K. If the warmest part of the shield vents to the surge vessel of the liquid nitrogen pump, effect of heat leak on the flowrate through the break will be zero for at least an hour of time.

V. EVENTS IN THE TUNNEL AFTER A VACUUM BREAK AND A LIQUID NITROGEN LINE BREAK HAVE OCCURRED.

The vacuum break will act as a vacuum pump, until the pressure in the vacuum space equals atmospheric. The velocity in the vacuum break will be sonic until the pressure in the vacuum space has reached approximately .5 ata.

Since 100 meters of vacuum is destroyed, cryopumping by 100 meters of cold magnet mass will occur. Immediately following the vacuum break, no mass will spill into the tunnel.

CCI Report 593-106 addresses itself to the event of a vacuum break and liquid nitrogen line break. The report points out that freezing of only 60 liters of liquid nitrogen is required to warm the 20K shield to 60K and 250 liters to warm all of the magnets (105 meters) to 50K. It is of interest to compare the flowrates through the break in the outer vacuum wall and the break in the liquid nitrogen line. The flowrate through the vacuum wall initially will be at a rate of 20-25 g/cm^2 (sonic velocity at roughly .5 ata and ambient temperature). A hole of 30 cm^2 then will pass some 600 g/sec of air. This flowrate is considerably less than the flowrate possible from the broken liquid nitrogen pipe, assuming a complete clean break.

It may be assumed that immediately after a vacuum break occurs, none of the liquid nitrogen will spill in the tunnel, but will remain in the vacuum space and will warm up 100 meters of magnet and 20K shield. At least 300 liters (24,000 grams) will be needed to allow the pressure in the vacuum space of the magnets to rise to atmospheric pressure.

An average spill rate of 25 L/sec from the nitrogen line over 12 seconds will remain in the vacuum space and this much time is at least available before liquid nitrogen starts spilling into the tunnel.

If, on the other hand, subcooled liquid nitrogen is used in the shield line, leakage rate is only of the order of 8 liters per second and some 30-40 seconds will pass by before any liquid nitrogen starts flowing into the tunnel.

Once the vacuum space has been filled with air and liquid nitrogen, liquid nitrogen will start spilling into the tunnel. From the foregoing we may assume the rates to be of the order of 25 liters or 8 liters per second. The first number is based on extrapolation of Figure 3, the second number is based on operating the shield line with liquid nitrogen between 70K and 78K.

It has also been assumed that the break in the liquid nitrogen line provides the full area of 31.6 cm^2 for spilling liquid. This is a very conservative assumption and probably not realistic.

In the tunnel, spilled liquid nitrogen will vaporize as a result of:

a) temperature of the spilled liquid.

b) thermal contact between liquid nitrogen and environment.

The vaporization under a) is instantaneous and does not require thermal contact with the environment. the location of the break determines the instantaneous rate of vaporization. Figure 1 shows the temperature profile of the liquid nitrogen versus length traversed. From this we find the instantaneous rate of vaporization to be

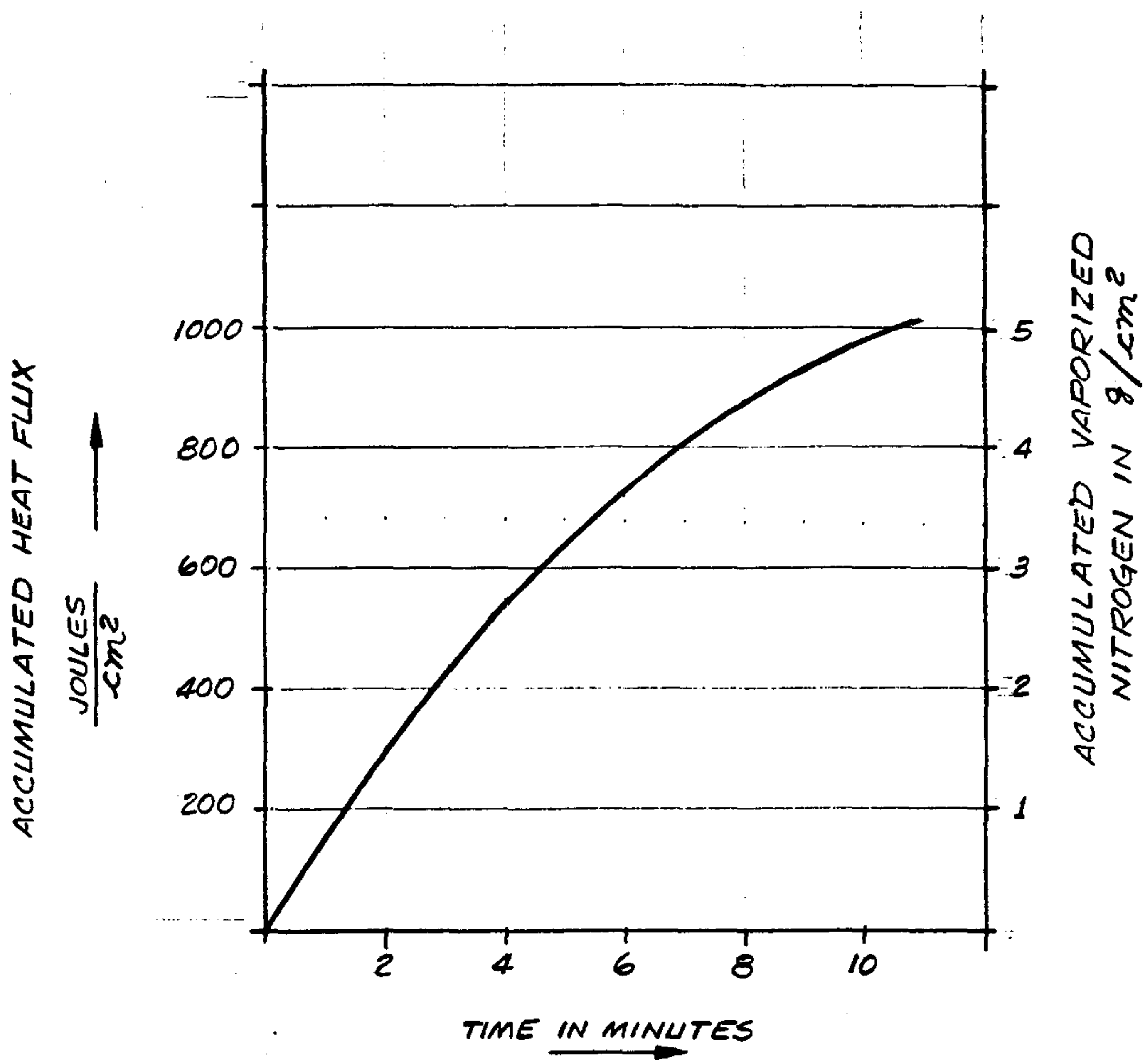
$$.11 \frac{L}{L_{total}} \times \text{spill rate}$$

When liquid temperature is between 70K and 78K, instantaneous evaporation rate is zero.

Vaporization of liquid nitrogen from thermal contact with the environment is primarily from contact with the floor of the tunnel. Figure 2 shows that the volume of a liquid droplet increases by a large factor for a relatively small fraction of the droplet vaporized. The vapor will surround the droplet and will insulate it from further vaporization, while the droplet traverses the air of the tunnel under the influence of gravity. The same is true for droplets of subcooled liquid falling to the floor. In fact, air surrounding the droplet will be cooled and partly condensed in bringing the droplet to a temperature of 78K.

Once the droplet reaches the floor, rate of vaporization will be determined by the thermal diffusivity of the concrete floor and the total surface area wetted. Figure 5 shows the cumulative heat transfer from a slab of concrete with an initial surface temperature of ambient.

Figure 5 allows us to make an estimate of the instantaneous rate of vapor generation by the concrete floor. An assumption needs to be made about the total floor area participating in the vaporization process. This participating floor area is large, when superheated liquid is spilled, because of the high exit velocity from the broken pipe. With a horizontal velocity of 2,000 cm/sec at an elevation of 60 cm above the floor, roughly .3-.4 seconds are required for the liquid droplets to reach the floor. Horizontal distance travelled is then of the order of 6-8 meters.



ACCUMULATED HEATFLUX BY LIQUID NITROGEN FROM A CONCRETE FLOOR

FIGURE - 5

If we assume that the floor slopes to a drain, we may expect a wetted concrete floor area of a length of 8 meters by a width of 2 meters. Maximum wetted floor area is then 160,000 cm^2. This area will generate vapor at a rate of 112,000 grams in the first 60 seconds of spill. Average rate is then 1,867 g/sec or roughly 2-1/3 liters/sec of liquid equivalent. Since spill rate is at least an order of magnitude higher, when spilling superheated liquid, liquid will start to accumulate on the floor and will start to spread over a larger floor area, unless a drainage system is provided. It will be assumed that a drain will be provided, through which liquid nitrogen will be directed to a storage vessel, made of a material with low thermal diffusivity and low heat capacity.

When the spilled liquid is from a line system operating at 70-78K, instantaneous rate of vaporization from the floor of the tunnel is the same per cm^2 of floor area. However, because of a low liquid ejection velocity wetted area of the tunnel is small. Instantaneous rate of vaporization from the flow is then less than 1,000 g/sec.

In summary, we find the rates of instantaneous vapor generation from the spill to be 3,300 and 1,000 g/sec for superheated and subcooled liquid respectively. The high rate occurs 12 seconds, and the low rate some 40 seconds after the break occurs.

The tunnel ventilation system is capable of providing fresh air at a rate of 4,200 grams/sec. We can assume, that this system goes into operation, immediately after a massive vacuum failure has been detected. Mixing of ventilation air with the vaporized nitrogen then produces a gas with 11 and 16% oxygen concentration for superheated and subcooled liquid nitrogen respectively. The mixing of ventilation air and cold nitrogen vapor also produces a gas of 201 and 257K respectively for superheated and subcooled liquid nitrogen.

The speed at which the cold gas travels down the tunnel is approximately that of the ventilation air moving through the tunnel. Because of the large difference in density of the warm ventilation air relative to that of the cold nitrogen vapor, the lower elevation of the tunnel will have a lower than average oxygen concentration and a colder than average temperature.

VI. TEMPORARY STORAGE VESSEL FOR SPILLED LIQUID NITROGEN.

Requirements are:

1) Vessel will hold 3,000 liters of liquid nitrogen.

2) Vapor space above 3,000 liters can be zero.

3) Loss rate from vessel is less than 500 liters per hour. This includes cooldown of the wetted wall of the vessel.

4) Naturally occurring water in the tunnel will drain out of the vessel into the tunnel water drainage system.

DESIGN

1) Space available below floor is 18" maximum. Use a 16" OD pipe (Aluminum), with a liner of ID = 15". Insulation space between aluminum vessel and liner is of the order of 1/4 inch.

2) The liner is made of .008" stainless steel sheet, rolled, seal welded at the top, with two flat .008" thick flat plates at the ends. Then volume of vessel, for liquid storage, is: 34.7 liters/ft. Length required is 86.5 ft. Possibly provide 2 separate vessels, each 40-45 feet long.

3) Cooldown of the liner requires removal of 3.7 x 10^6 Joules (weight = 116 lbs.) In cooling vaporize ~ 23 liters of liquid nitrogen.

4) Provide stagnant gas in the layer between outer shell and line by means of either powder or rock wool, with communication between insulation space and liquid space.

Then $\int kdT = .038$ W/cm

Surface area ~ 325,000 cm^2

Thickness of insulation ~ .6 cm

Loss rate is then ~ 470 $\frac{\text{liters}}{\text{hour}}$

This loss rate is essentially proportional to the wetted surface area.

5) Drain from liquid volume to water drain. This drain needs to be small to keep liquid nitrogen from entering at a high rate. To be able to clean drain, it should be located directly below the tunnel floor drain. Make drain out of a 1/2" IPS pipe or equivalent.

6) Since there will be flow in of liquid and flow out of vapor at the same time, it probably will be best to provide two connections. The liquid can flow in through a relatively small diameter opening. It is necessary to accommodate a flowrate of 10-20 liters per second. A velocity of 25 cm/sec through the inlet pipe is permissible. This yields a diameter of roughly 12 inches.

   An opening of smaller size can be used as a vent. By locating the vent at the other end of the vessel, vaporized nitrogen can flow through a vent stack of 6 inch diameter will suffice.

   To prevent water from draining into the vent stack, the exit will be elevated somewhat above the floor of the tunnel.

VII. EXPERIMENTAL PROGRAM FOR A LIQUID NITROGEN SPILL.

Experimental verification of the numbers generated in the report is very desirable. The Protomain tunnel at Fermilab could possibly be used for this purpose. The tunnel is 200 feet long, and this length is sufficient.

The floor of the tunnel needs to be modified in the spill area to provide for:

a) A sloping section of 30 feet length to a liquid drain.

b) A 45 ft. long storage vessel of a design as described needs to be buried under the floor.

Liquid nitrogen may be supplied from an external storage vessel of a capacity of 3,000-6,000 gallons. This vessel could be a trailer, which could be supplied by a liquid supplier. Discharge of liquid into the tunnel will be accomplished through a 2.5 inch diameter pipe. The pipe is insulated and equipped with a flowmeter and a controlled discharge valve. Pressure, temperature and flowrate in the line will be monitored during the test. To cool and fill the line, gas and liquid will be bypassed outside the tunnel. The bypass will take off from the main line just upstream of the control valve.

A ventilation system as planned for the SSC tunnel will be provided.

INSTRUMENTATION

TEMPERATURE

Thermocouples will be used to measure temperature. Total number should be of the order of 30-40. At least 4 thermocouples should be located in a vertical array spanning the height of the tunnel.

FLOWRATES

A flowmeter in the liquid supply line will indicate flow. The valve located near the end of the line will be a pneumatic valve, controlled from outside the tunnel.

Air flow into the tunnel needs to be measured. This could be done independently from the actual test.

LIQUID ACCUMULATION

The buried storage vessel will be equipped with a differential level indicator, from which accumulated liquid in the reservoir can be calculated.

AIR SAMPLING

Oxygen analyzers should be located outside the tunnel, to prevent low temperature and water condensate effects. Tunnel air can be pumped out of the tunnel through a large number of parallel sample tubes. Solenoid valves between analyzers and tubes allow rearrangement of analysis from location to location. A total of 6-8 analyzers will be sufficient, provided the technique for pulling gas through the sample tubes is arranged properly.

THERMAL CONDITIONS OF THE SPILLED LIQUID

It will be easy to spill liquid of a temperature of 78K into the tunnel. This liquid may be generated in the supply tank by letting the tank vent freely to the atmosphere prior to the test. To superheat the liquid to a boiling point of 85.5K requires the addition of 17.1 Joules per gram or 13,700 Joules per liter. At a flowrate of 20 liters per second we need some 275.4kW of instantaneous heat.

It is therefore necessary to pre-condition the liquid in the trailer. Since a number of trailers come equipped with a liquid pump, it is possible to use this pump to increase the enthalpy of the liquid. The pump will discharge the liquid to a non-insulated line, connected to the vent of the trailer. The line will be equipped with a vent system, through which vapor may be discharged at a predetermined pressure. For instance, a vent pressure at 35 psig will yield a liquid temperature of 85.56K.

Subcooling of liquid is more difficult to obtain. To reduce temperature by 1K requires a subcooler, in which 1.2% of the liquid is vaporized and pumped away at a pressure of approximately 1-12 psia. Flowrate to the vacuum pump then will be of the order of 190-22 grams/sec (400 acfm) assuming that the gas has been warmed to 220K before it reaches the pump.

VIII. LEAKAGE OF HELIUM FROM: 80K SHIELD LINE WITH HELIUM GAS COOLING

It is possible to eliminate the nitrogen from the cooled shield lines by using helium gas. In that case, helium under pressure will be circulated by the refrigerator compressor. Typically, helium gas will enter the shield at a pressure of 10 ata and a temperature of 70K. The supercharging is necessary in order to keep pressure drops in the line at a reasonable value and reduce the amount of power required to drive the gas.

The following assumptions were made to calculate the mass and physical properties of the helium discharged from the rupture as a function of time:

1) Initial pressure = 10 ata, uniform throughout the pipe.

2) Initial temperature = 70K, uniform throughout the pipe.

3) Pipe size = 2.7 inches I.D.

4) Volume of pipe = 3.03×10^7 cc

5) Total pipe length = 8200 meters

6) Mass in pipe = 2.07×10^5 grams (456 lbs.)

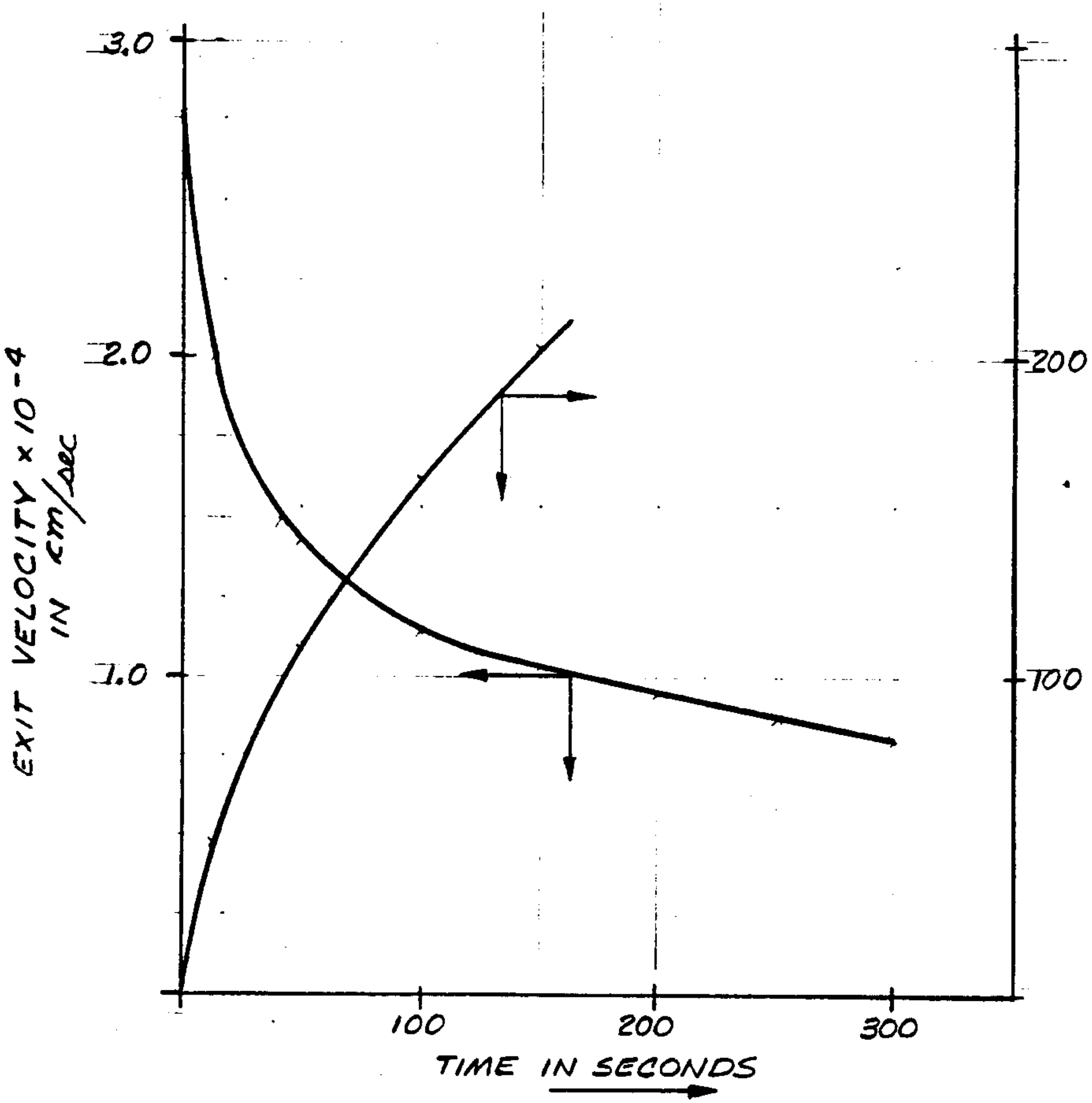
7) The rupture occurs at the midpoint, and helium gas is discharged from both halves at the same rate.

8) The helium gas expansion in the pipe following rupture is isenthalpic.

The last assumption is almost right, because of the high specific heat, large mass of the shield and large heat transfer coefficient in the shield line. Isentropic expansion of the helium in the line would result in a slower discharge of helium from the shield line.

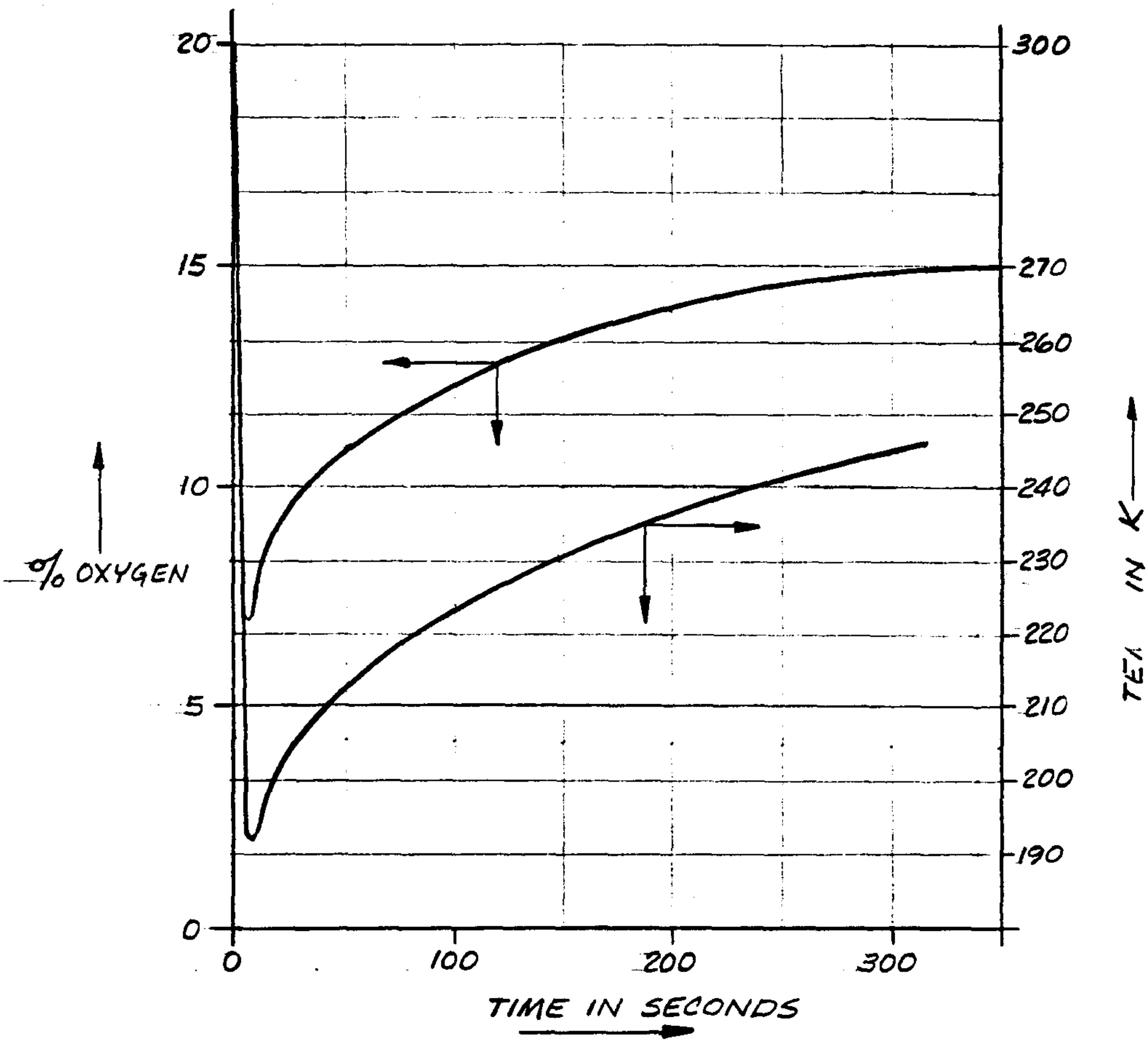
Figure 6 shows the decay of exit velocity at the break and total amount of helium vented as a function of time.

The vented helium mixes with the ventilation air in the tunnel. Complete mixing yields a low oxygen concentration and temperature of the mixture, which changes with time. Figure 7 shows the oxygen concentration and mixture temperature as a function of time, assuming an air flowrate of 4,200 grams per second.



EXIT VELOCITY AND TOTAL AMOUNT OF HELIUM VENTED

FIGURE - 6



OXYGEN CONCENTRATION AND MIXTURE TEMPERATURE AS A FUNCTION OF TIME

FIGURE - 7

Water vapor in the air will change Figure 7 somewhat. Temperature of the mixture will not be as cold and the tunnel in the mixing area will be filled with a dense fog, which will make visibility zero in the mixing area. Since the mixture will move at a velocity of approximately 1.5 foot per second, area of zero visibility may stretch over a length of some 100 meters downstream of the spill area.

DETECTION OF A BREAK IN THE SHIELD LINE

Pressure measurement along the shield line at one km intervals will provide the most direct and fastest indication, that something is wrong. These pressure measurements will be interlocked with the tunnel ventilation system.

One could ask the question whether starting the tunnel ventilation system is the right thing to do. In the absence of air flow in the tunnel, mixing will occur initially; however, the mixed volume.of air and helium will be driven away from the spill area and occupy a length of tunnel on both sides of the spill. This area will grow to be a large area. For instance, in 50 seconds a total of 110 lbs. of helium has been discharged. The helium by itself will occupy a volume of some 2,500 cft (at 70K and 1 ata). Mixing with 2,400 cft of air (volume of 40 ft. of tunnel) will yield temperature and volume of 125K and 5,600 cft respectively. The oxygen concentration of the mixture will be approximately 3.75%.

This analysis shows that it probably is better to start extra tunnel ventilation immediately. This will increase the local oxygen concentration and temperature.

CONCLUSIONS AND RECOMMENDATIONS

1) The high pressure and large inventory of the shield system will result in a large mixing zone with low temperature and oxygen concentration. Both are lethal for anyone remaining in this mixing zone.

2) Providing ventilation at the projected rate of 4,200 g/sec will keep the upstream side of the spill area reasonable warm and high in oxygen concentration. The downstream side of the spill area will be lethal for a period of at least one minute. After the first minute, oxygen concentration will rise to 12-13% and temperatures are such that short exposure will not be harmful. However, in the path of the high velocity stream of helium conditions will remain lethal for a number of minutes.

3) In order to reduce the flowrate of the venting gas, check valves should be used in the shield line at intervals of one km or less.

IX. CONCLUSIONS

I) 80K SHIELD SYSTEM FILLED WITH LIQUID NITROGEN

There is a significant difference in the events following the break in the 80K shield line when warm (80-88K) or cold (70-78K) liquid nitrogen is used for shield cooling. A number of specific items are listed below for both cases.

Comparing the listed specifics shows, that the use of subcooled liquid nitrogen for 80K shield cooling can be considered safe, even in case of a large line break. The following section (recommendations) states specifically, what needs to be done during the design and construction of the system.

A. Liquid nitrogen shield line filled with subcooled liquid nitrogen (70<T<78K)

1) Liquid starts spilling into the tunnel some 40 seconds after the break occurs.

2) Spillrate into the tunnel is less than 8 liters (6,400 grams) per second, while pressure is maintained over the liquid in both suction and pump discharge surge vessels.

3) Spillrate into the tunnel is less than 2 liters per second (1,600 grams per second), after pressure in both surge vessels has been removed.

4) Instantaneous rates of vaporization from droplets falling to the floor is zero.

5) Instantaneous rate of vaporization from contact between liquid and concrete floor of the tunnel is less than 1,000 grams/sec.

6) Mixing with ventilation air in the tunnel is incomplete. This results in an oxygen concentration of more than 16% in the upper part of the tunnel.

7) Temperature of the mixture of ventilation air and nitrogen will be of the order of 0°F. Incomplete mixing will generate a higher temperature in the top half of the tunnel.

8) The reduced oxygen atmosphere will spread at the rate of air flow in the tunnel (roughly speed will be 50 cm/sec).

9) Fog formation will be primarily in the bottom half of the tunnel. The volume of fog will be bounded by the volume of reduced oxygen concentration gas.

B. Liquid nitrogen shield line filled with superheated nitrogen (80-88K).

1) Liquid starts spilling into the tunnel some 12 seconds after the break occurs.

2) Spill rate into the tunnel will be of the order of 25-30 liters per second (20,000-24,000 g/sec). This rate will not change materially when the pressure is removed from the surge vessels of the liquid nitrogen pump. The rate will slowly decrease with time.

3) Instantaneous rate of vaporization due to superheating of the liquid is roughly $.11 \frac{L}{L_{total}} \times$ spill rate

4) Because of relatively high velocity of liquid spilling from the break, a large floor area of tunnel is covered with boiling liquid. Instantaneous rate of vaporization from this is of the order of 1,800-2,000 grams per second.

5) Mixing of ventilation air and nitrogen vapor will be greater than in the case of subcooled liquid nitrogen. Oxygen percentage in a completely mixed gas will be of the order of 11%, when the break occurs at the 5 km spoolpiece.

6) Temperature of the mixture, assuming complete mixing, will be of the order of -90 to -100°F. Incomplete mixing will result in a lower temperature at floor level and a higher temperature in the upper part of the tunnel.

7) The mixed cold mass will move through the tunnel at a rate somewhat larger than the normal ventilation air velocity of 50 cm/sec.

8) Fog formation will occur in a larger volume and fog will, due to better mixing, fill the tunnel from top to bottom.

Comparison of A and B above shows that operation at 70-78K is very much safer in case a large break occurs.

It is improbable that a break as postulated can occur. Any rupture will be preceded by a deformation and flattening of the pipe or bellows in the area of the break. This will have a greater effect on the spill of warm liquid, since these events are more influenced by exit phenomena at the break.

Detection of a break and fast action after the break is detected will reduce the total amount of liquid spilled and reduce the detrimental effects of the break greatly. It appears, that this is easy to do.

The conceptual design report describes the use of "U" tubes at one km intervals for the purpose of warming up a one km long magnet section. It is not necessary to make these "U" tubes and their connecting bayonets of the same diameter as the shield line, because:

1) Energy to drive the liquid nitrogen pump is small,

2) Absolute pressure levels in the 80K shield line may be varied considerably within the range of system capability.

The smaller bayonets will reduce flowrates, in case of a failure during the removal of the "U" tubes.

2) <u>80K SHIELD FILLED WITH HELIUM GAS</u>

It is considered to be fundamentally safer to use helium gas for 80K shield cooling but the analysis in this report shows, that a large break will generate a large volume deficient in oxygen and low in temperature. Because of the high pressure in the line, needed for normal operation, mixing of helium and air in the area of the break will be vigorous. Demixing will only take place, after the supply of helium to the break is either exhausted or stopped by means of closing valves in the 80K shield system.

The high velocity of the escaping helium gas generates a dangerous area in the path of the gas. Temperatures will be very low and will cause serious harm to personnel in the flowpath of the gas.

X. RECOMMENDATIONS

1) It is recommended that serious consideration be given to the use of subcooled liquid nitrogen for 80K shield cooling. This requires vacuum pumps at each refrigerator station. These pumps need to pump nitrogen vapor from a pressure of approximately 5 psia to atmospheric pressure. Power consumption will be of the order of 400 KW for the total system. Some of this power will be returned because of lower heatleak to the 20K shield system. This in turn will allow the 20K shield system to operate at a lower flowrate, coupled with a lower pressure in the 20K shield system. this in turn will reduce the inventory of that system.

2) It is recommended that each 80K flow system be equipped with flowmeters and alarms in suction and discharge lines of the liquid nitrogen pump. These flowmeters will be interlocked with:

   a) Liquid nitrogen pump cut-off.

   b) Pressurization gas valves in order to rapidly reduce the pressure in the liquid nitrogen system.

3) It is recommended that each 80K shield system be equipped with pressure gauges at one km intervals. The information provided by these gauges will be used to back up the flowmeters of 2) above.

4) It is recommended that suction and surge vessels of the liquid nitrogen pump be equipped with level gauges. Information from these level gauges will be used to back up the flowmeters of 2) above.

5) It is recommended that maximum tunnel ventilation will be provided from information supplied under 2), 3), and 4) above.

6) Provide a volume for temporary storage of liquid nitrogen below the floor of the tunnel at one km intervals. These volumes need to be large enough to store 30 minutes worth of spillage. This will be of the order of 3,000 liters. The vessel needs to be equipped with a thin walled inner liner, with a nominal amount of insulation to reduce vaporization to less than 500 liters of liquid per hour.

7) Provide a sloping floor in the tunnel towards the drain to the temporary storage vessel.

8) In providing 6) and 7) above, provide for drainage of water from the potential spill area and the temporary liquid storage vessel.

9) It is recommended, that bayonets and vacuum jacketed "U" sections, when used at the one km interval spoolpieces, be made of a smaller diameter than the shield line.

10) It is recommended, that helium gas will not be used for 80K shield cooling.