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RELIEF VALVE DESIGN RESULTING FROM CRYOGENIC LINE RUPTURE

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INTRODUCTION

Sizing the cryostat pressure relief valves are of vital importance to ensure that the cryostat (vacuum vessel) does not exceed the operating design pressure regardless of cause. Sizing of the cryostat relief valves will depend on the maximum creditable release of cryogens into the cryostat.

Cryogenic line failure can be defined as any break or rupture in a cryogenic line that will allow cryogenic fluid to spill into the vacua of the SSC beam tube and or vessel.

The cryogenic concerns must be addressed such that accelerator control and safety systems can be properly sized and designed. The safety of personnel and proper operation of equipment and cryogenic systems are of most importance as the control systems are designed to manage failures of any kind, safely.

The following families of cryogenic line failures are discussed: (See Fig. 1.0)

a) A hole in the beam tube that allows supercritical 4.15 K helium from line 1 to spill into the beam tube.

b) A damaged helium line that allows: supercritical 4.15 K helium from line 1, or 4.5 K helium from line 2 to spill into the vacuum vessel.

c) A damaged helium line that allows: 4.15 K gas from line 3, or 20 K gas from line 4 to spill into the vacuum vessel.

d) A damaged liquid nitrogen line that allows 80 K nitrogen from line 5 to spill into the vacuum vessel.

e) A damaged vacuum vessel that has a hole in its wall that allows air to vent the half cell.

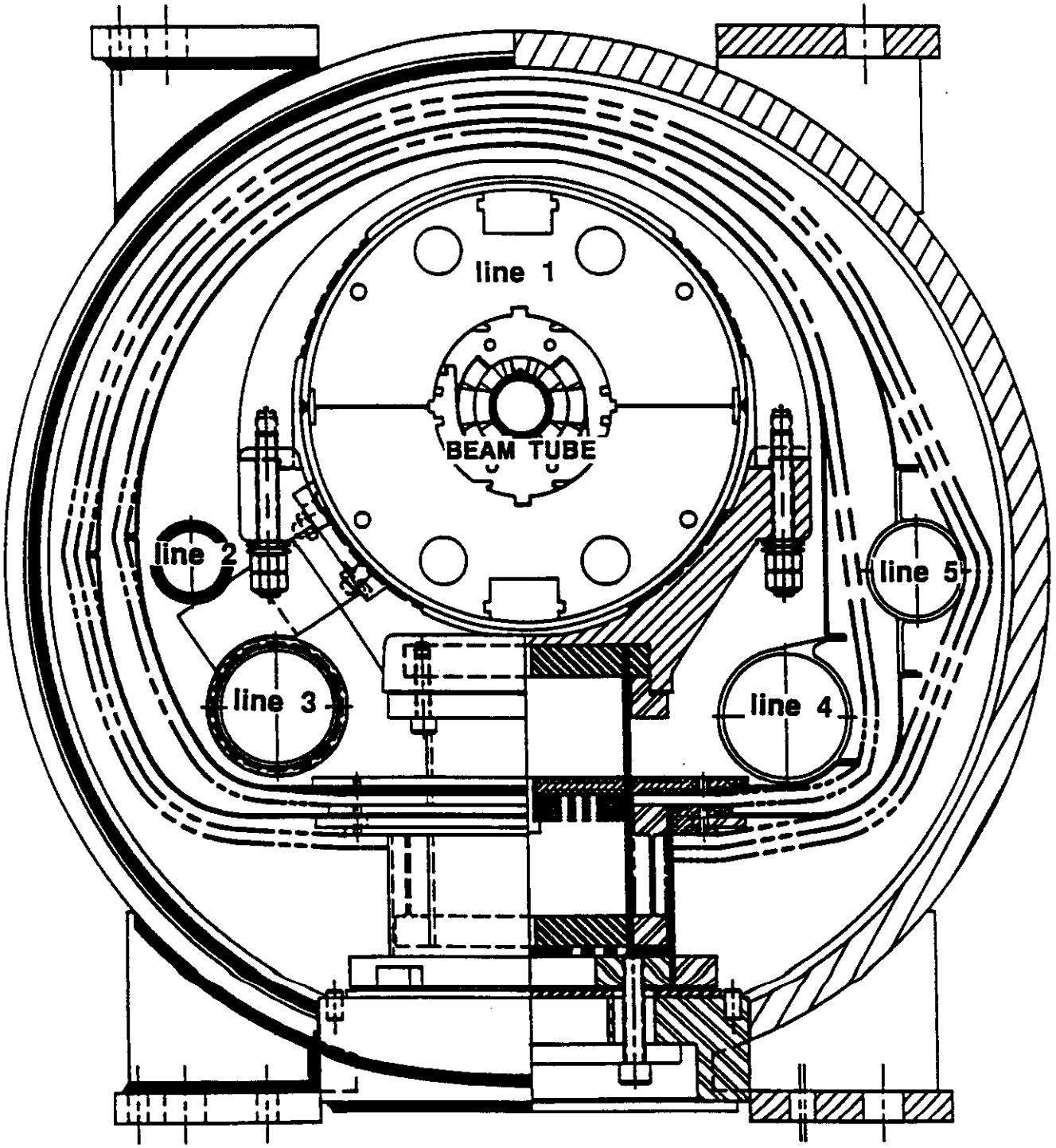


Fig. 1.0 Cryogenic line and beam tube identification

4. VACUUM VESSEL PRESSURE RELIEF VALVE

The following discussion outlines the sizing of the pressure relief ports for the volume contained within the half cell. The spool piece and magnet vacuum vessels must have pressure relief and vacuum evacuation ports.

It is desired that the maximum pressurization of the vacuum vessel be limited to 0.25 MPa. The spool piece will have pressure relief valves attached to the pressure relief ports. These valves will be located one on each side of the vacuum barrier.

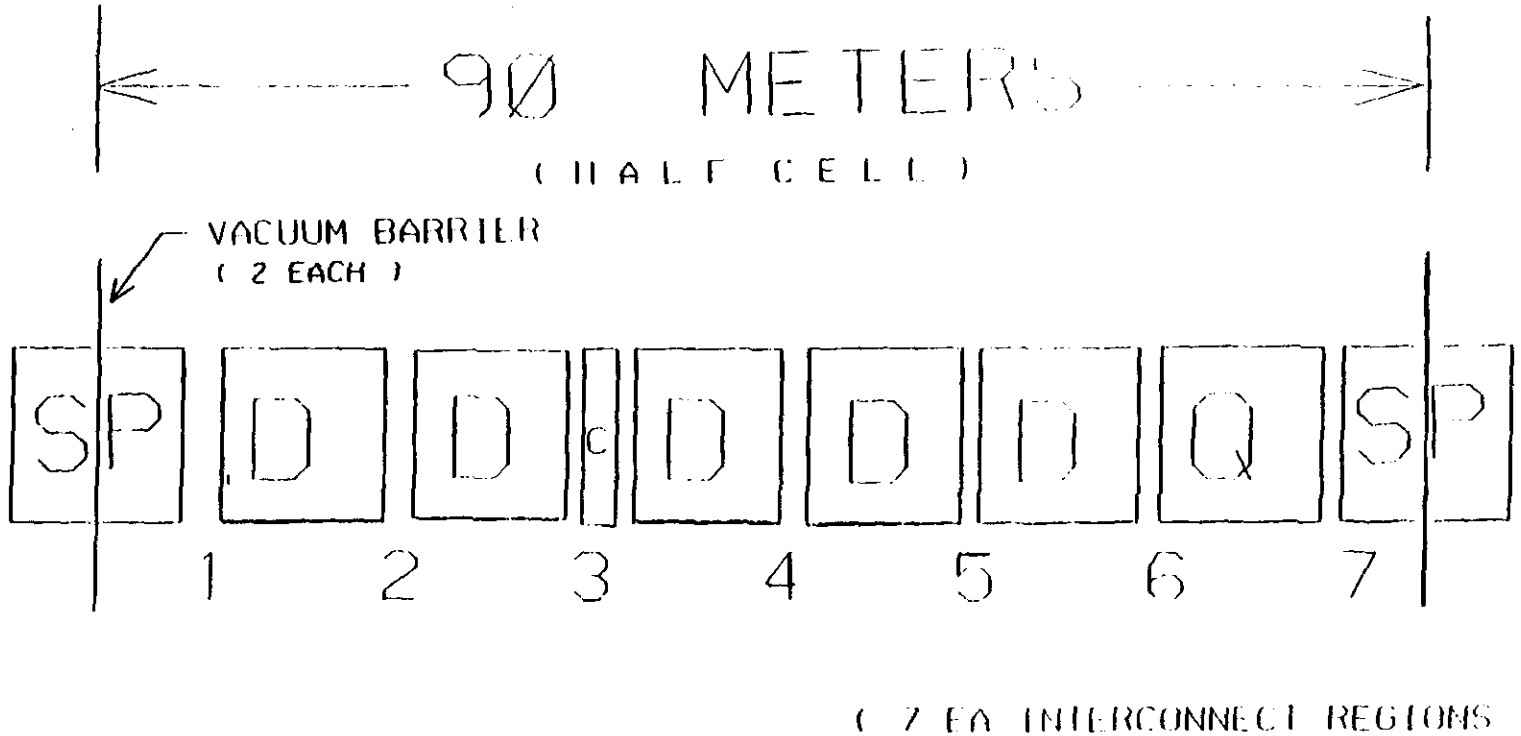
The half cell configuration is depicted in Fig. 2.0. The volumes contained by all cryogenic lines that are routed through the half cell and the volumes contained by the 20 K, and 80 K shields are defined as follows:

line 1 (supercritical helium)	5.518 cu meters/half cell
line 2 (single phase return)	0.142 cu meters/half cell
line 3 (4 K gas return)	0.507 cu meters/half cell
line 4 (20 K shield)	0.41 cu meters/half cell
line 5 (80 K shield)	0.285 cu meters/half cell
20 K shield zone	5.837 cu meters/half cell
80 K shield zone	4.64 cu meters/half cell
300 K zone	8.96 cu meters/half cell

Line 1 is the largest volume of supercritical helium and it will be pressurized to 0.4 MPa. Line 5 is the largest volume of liquid nitrogen and it will be pressurized to 0.5 MPa. These pressurized cryogenic lines were investigated to determine the maximum size of relief valves required to limit the half cell pressurization to 0.25 MPa.

Line 1 can be isolated only within a section. From a previous investigation at the Fermi Laboratory, the volume of supercritical helium contained in line 1 of the half cell was noted to be 0.624 cubic meters. The helium mass at 0.4 MPa and 4.15 K is 1044 kg/section. The helium mass at 0.25 MPa and 4.15 K is 1005.8 kg/section. The amount of spilled helium is the difference between these two values and that value is 38.2 kg/section.

Line 1 helium that spills into the vacuum vessel will be contained within the vacuum vessel. The mass capacity of the vacuum vessel is 46.4 kg/section at 0.25 MPa. This mass capacity of the vacuum vessel will accommodate a helium spill (for short periods of time as long as the heat transfer may be neglected) of 46.4 kg/section at 0.25 MPa without pressure relief.



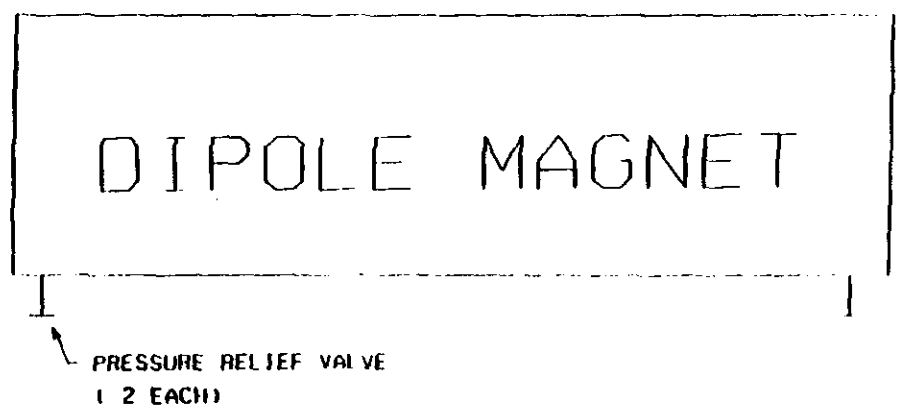


Fig. 2.0 Half cell with vacuum barriers, spool pieces and magnet cryostat

Heat transfer is the source of energy that will cause the vacuum vessel to pressurize. The port diameters were calculated to be:

d = 8.56 mm for helium fluid spilling from line 1 to the 20 K shield only

d = 11.74 mm for helium fluid spilling from line 1 to the 20 K and 80 K shields

d = 31.45 mm for helium fluid spilling from line 1 to the 20 K, 80 K shields and the 300 K vacuum vessel wall

The diameters were calculated from the conditions of isentropic flow, 0.25 MPa vacuum vessel pressure, and helium escaping the vacuum vessel through a port at Mach 1 velocity.

If the rupture of the nitrogen line were to occur during machine operation, the nitrogen would freeze within the 20 K shield. If the rupture were to occur during initial cool down of the rings, the vacuum vessel pressure would exceed 0.25 MPa. The port diameter for a nitrogen spill from line 5 to the 300 K vacuum vessel wall was calculated to be 30.18 mm.

A ruptured line 1 is the most critical failure mode and thus sizing information for the pressure relief valves is based on the complete rupture of line 1.

B. MECHANISMS OF LINE FAILURES

A hole in the beam tube may result from magnet quenching. Because of the intense heating due to the quench and the 0.4 MPa pressure differential of supercritical helium contained in line 1 opposing the vacuum in the beam tube, it is possible for the beam tube wall to rupture.

The mechanical and thermal designs of the SSC storage rings minimize stresses during normal operation of the collider; however, fatigue due to thermal cycling of bellows and other joints may cause cryogenic line failures.

There are 49 flexible connections (bellows) per half cell. A half cell is 90 meters in length. A section is defined as a part of a string that may be cryogenically isolated. According to the current design, the section is 1080 meters in length and contains six cells. A string is defined as four sections in series for a length of 4320 meters. There are 588 flexible connections of assorted sizes per the 1080 meter section. The most predictable place to have a cryogenic line failure or rupture is in the area of the bellows; however, the analysis remain valid for any possible rupture.

A puncture in the vacuum vessel may be caused by any accidental force exerted on the exterior of the vessel.

C. PHYSICAL AND GEOMETRIC DATA

The nominal pressure in the vacuum vessel is 1.33E-04 Pa (1.0E-06 Torr).

* The high operating limit: 1.33E-02 Pa
* The high alarm limit: 1.33E-01 Pa

An unacceptable rate of change of pressure must be instrumented to sound an alarm. A sharp and substantial increase in the vacuum vessel pressure will require emergency switching off of the cryogenics and the accelerator section.

Geometric and physical parameters of each cryogenic line are listed as follows:

NOTE: The following numbers in the table are correct for the previous B-version of the 40 mm magnet design.

	line 1 magnet string flow	line 2 single phase return	line 3 4 K gas return	line 4 20 K shield	line 5 80 K shield
Fluid	He	He	He(gas)	He(gas)	N2
Max Pressure (MPa)	0.4	0.3	0.1	0.4	0.5
Pipe diameter I.D. (mm)	-	44.9	84.7	76.2	63.5
Volume per half cell (cu meters)	0.625	0.144	0.507	0.410	0.285
Volume per section (cu meters)	7.5	1.714	6.08	4.925	3.42
Mass of fluid per section (kg)	1058	235	103	48.3	2700
Volume of fluid after warming to 300 K and 1 atmosphere (cu meters)	6510	1446	634	297	2411
Length of tunnel with diameter of 3.66 meter occupied by gas of 1 atmosphere and 300 K (meter)	619	138	60	28	229

Geometric and physical parameters of the vacuum vessel are listed as follows:

Diameter of the cold mass	- 279.4 mm
Average diameter of the 20 K shield	- 419.1 mm
Average diameter of the 80 K shield	- 495.3 mm

Net volume per half cell between the 4 K cold mass and the 20 K shield - 5.837 cubic meters

Net volume per half cell between the 20 K shield and the 80 K shield - 4.64 cubic meters

Net volume per half cell between the 80 K shield and the 300 K vacuum vessel wall - 8.96 cubic meters

D. DISCUSSION

1.0 Flow of helium into the beam tube

A quench may cause a hole in the beam tube. Helium entering a sudden hole in the beam tube is assumed to be isentropic. The initial quality of the expanding helium is in the range of 0.1% to 0.2%. The expanding of helium into the beam tube will initiate a pressure wave that travels in both directions from the damaged section of the beam tube with a velocity at the speed of sound (approximately 200 meters/sec).

Vacuum in the beam tube is monitored by ion pumps located at 180 meter intervals. The beam tube isolation valves are located every 1080 meters. The ion pumps operate with an upper pressure limit of 1.0E-03 Pa before being automatically switched off by the current limiting ion pump controllers.

A 1 mm diameter hole has been calculated to cause an initial flow of 100 gm/sec of helium fluid into the beam tube. This mass flow rate will result in a rapid increase in beam tube pressure. The average pressure in an isolated beam tube after a leak of 100 gm of helium will be approximately 0.6357 Pa.

An unacceptable rate of change that exceeds the operating vacuum limit will allow the central control system to close the isolation beam valves. The beam tube isolation valves have relatively slow closing times (2 to 6 seconds). Ten seconds will elapse before the most adjacent beam tube valves will close. The pressure wave will travel 2000 meters in ten seconds from the rupture and the pressure wave will be in two directions. Because of the long closing times of the beam tube valves, at least three sections in each direction from the rupture will require beam tube valve closures.

After beam tube isolation, resulting from the closing valves, the supercritical helium will continue to flow into the beam tube until the pressure in the damaged section is equal to the pressure in line 1. The beam tube isolation valves are not able to withstand a pressure differential of 0.4 MPa and the helium will leak into the adjacent sections because the beam tube valves will not seat against such a high pressure differential. To decrease further degradation of the vacuum in the beam tube, the moment failure in the beam tube vacuum is detected, it will be necessary to depressurize line 1. The depressurization of line 1 will take approximately one hour.

2.0 Flow of liquid cryogens into the vacuum vessel

A cryogenic line is damaged. The damage initially has not been detected by instrumentation. The cryogenic fluid is spilling into the vacuum vessel and the pressure in the vacuum vessel increases.

The pressure in the vacuum vessel will exceed the alarm limits after a certain time delay. The control system identifies the location of the vacuum failure or the half cell of the cryogenic pressure decrease.

If the rate of change of the pressure in the vacuum vessel is greater than the alarm limit, then emergency shutdown of the sector cryogenics is required. If the rate of change is very small, then it is possible for a vacuum pump to be installed locally to the specific half cell and continue normal operation of the storage ring.

After detection and identification of the damaged section, isolation from the other sections must be conduced by closing beam tube valves, cryogenic valves, and bypassing the section via the cryogenic U-tubes on each side of the damaged section enabling the continuation of cryogenic cooling to the other sections in the string.

If the damaged cryogenic line has not been identified, an immediate response to aid in system protection will be to stop the cryogenics pumps of line 1, line 4, and line 5 then initiate depressurization of line 1, line 2, and line 4 in the string and also the parallel string. The final pressure may be as low as 0.15 MPa in each of these lines and the process will take one or more hours. An amount of 300 kg of helium must be evacuated in order to decrease the pressure in line 1 from 0.4 MPa to 0.15 MPa

Because the cryogenics plants are located at different elevations along the ring, depressurization of the cryogenic lines will result in different final pressure values along the string. Depending upon the location of the damaged section, it will be necessary to initiate depressurization of line 5 in both rings to aid in system protection. Automatic isolation may take up to 1 second. Manual isolation will take hours. Restart of the cryogenic pumps that supply cryogens to the adjacent sections will be required as soon as the isolation of the damaged section is accomplished. Restart is necessary to minimize warmup of the other sections. Disconnecting line 4 or line 5 will effect both collider rings.

Large cryogenic spills into the vacuum vessel will cause the pressure to rise quickly. The vacuum vessel relief valves will open and release fluid through the valves to the tunnel or a return header. The remaining pressure in the vacuum vessel will depend on the designed value of the pressure relief valves. The current design allows for a maximum vacuum vessel pressure of 0.25 MPa.

The heat transfer to the damaged half cell increases due to the loss of the vacuum insulation. The heat transfer to the isolated section is unchanged (excluding the damaged half cell) for relatively short times as long as there are no external interventions i.e., warmup or fluid evacuation from the section.

Additional fluid is forced from the broken line to the vacuum vessel as a result of heat transfer.

The pressure in the other lines will increase steadily at a rate depending on the heat transfer. The maximum time to release the pressure in these lines before additional damage occurs must be calculated. Without automatic or manual intervention, the pressure in these lines will increase until the relief valves in the specific lines open.

3.0 Flow of gaseous cryogens into the vacuum vessel

Escaping helium gas from line 3 will spoil the vacuum of the vacuum vessel and increase the heat transfer to the cryostat. Line 3 is the 4 K vapor return line that will have a helium vapor pressure of 0.09 MPa.

Escaping helium gas from line 4 will expand into the vacuum vessel at a faster rate for a comparable rupture in line 3 because of the higher pressure.

Shut down and isolation of each ring will be required as the helium return lines will effect the operation of both rings. The escaping vapor with time will pressurize the vacuum vessel. Automatic intervention will be required to detect and safely shut down the storage rings.

Fig. 3.0 identifies the initial volume of a line 3 or a line 4 rupture.

4.0 Line 5, the nitrogen line

Any escaping nitrogen will expand into the vacuum vessel. However, the operating temperatures of the helium lines will instantaneouly freeze any released nitrogen to the helium lines or the 20 K helium shield.

If the spill is small, the pressure in the vacuum vessel will not change quickly. A larger spill will cause an increase in heat transfer to the vacuum vessel and without safety controls or automatic intervention, nitrogen gas will pressurize the vessel.

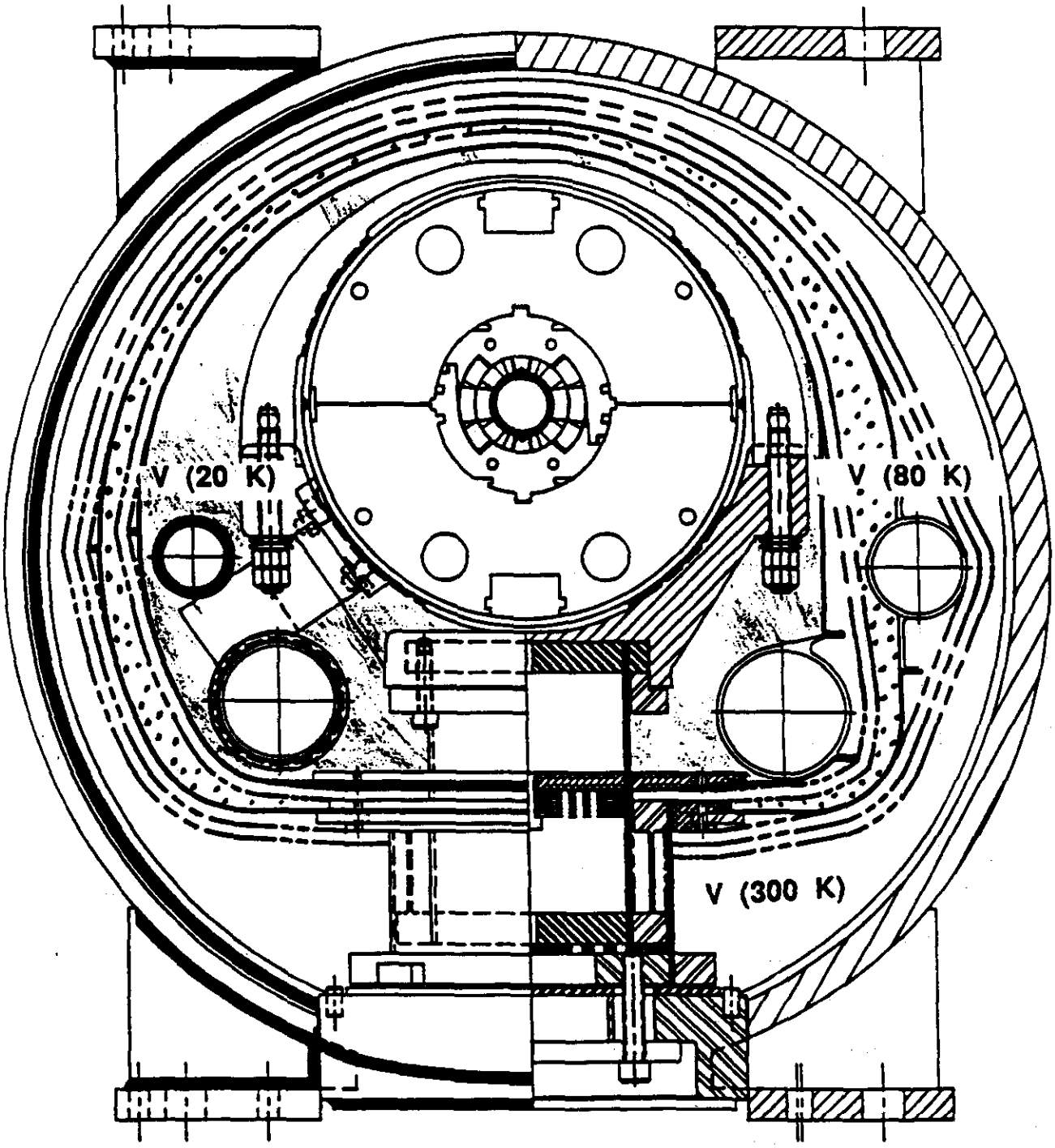


Fig. 3.0 Volume identification of temperature zones

The detection of a small nitrogen spill in the vacuum vessel may result from the following:

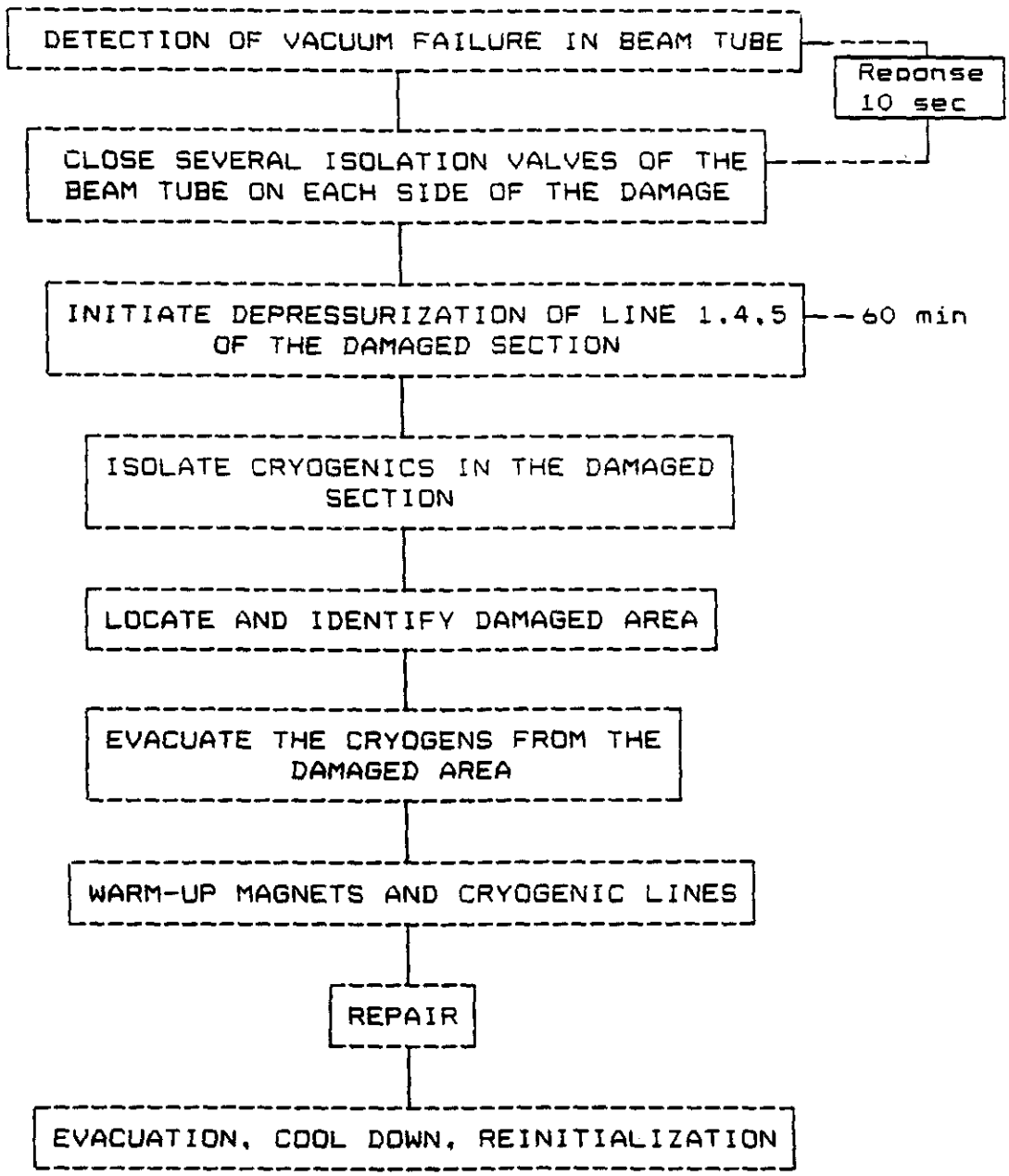
A pressure drop in the LN line
Increase in the LN temperature change along the section
Increase in the pressure in the vacuum vessel

For short times and small spills, the pressure in the vacuum vessel may remain within the operating vacuum limits. This will make the spill difficult to detect. For longer times or larger spills, the damage may be identified by pressure and temperature changes in line 5 and the formation of ice on the external surfaces of the vacuum vessel.

5.0 A hole in the 300 K shield

A break or hole in the vacuum vessel may be caused by any accidental force exerted on the external vessel. If air leaks into the vacuum vessel, depending on the size of the leak, the vessel vacuum will be vented to atmospheric pressure and the cryogenic fluid requirements will increase. Ice will form in the area of the leak and the pressure in the vessel will rise.

5.0 ACTION TREE



APPENDIX A

INITIAL SPILL

CALCULATIONS. HEAT TRANSFER

A.1 INITIAL SPILL

A ruptured line will allow cryogens to spill into the vacuum vessel. The pressure values and fluid changes are evaluated with initial spills that are instantaneous and allow depressurization of the string before valve isolation.

Line 1:

volume per string	= 30 cu meters
initial pressure	= 0.4 MPa
initial mass	= 4180 kg
initial temperature	= 4.15 K
initial density (line)	= 0.1392 g/cc
final density (line)	= 0.1341 g/cc
residual mass	= 4026 kg
spilled fluid	= 154 kg

Note: The change in temperature of the residual mass is neglected

Line 2:

volume per string	= 6.856 cu meters
initial pressure	= 0.35 MPa
initial mass	= 923 kg
initial temperature	= 4.35 K
initial density (line)	= 0.1347 g/cc
final pressure	= 0.25 MPa
final density (line)	= 0.1306 g/cc
residual mass	= 895 kg
spilled fluid	= 28 kg

Line 3:

volume per string	= 24.32 cu meters
initial pressure	= 0.09 MPa
initial mass	= 359 kg
initial temperature	= 4.15 K
initial density (line)	= 0.0148 g/cc
final pressure	= 0.082 MPa
residual mass	= 320 kg
spilled fluid	= 39 kg

Note: The nominal pressure in this line is 0.09 MPa. Given the present evaluation, if the line is damaged then the final pressure in the line 3 and the vacuum vessel are equal.

Line 4:	volume per string	= 19.9 cu meters
	initial pressure	= 0.45 MPa
	initial mass	= 206.96 kg
	initial temperature	= 20 K
	initial density (line)	= 0.0104 g/cc
	final pressure	= 0.25 MPa
	final density (line)	= 0.006118 g/cc
	residual mass	= 121.748 kg
	spilled fluid	= 85 kg
Line 5:	volume	= 0.285 cu meter/90 meters
	per section	= 3.42 cu meter
	per sector	= 13.68 cu meter
	initial pressure	= 0.5 MPa
	initial mass	= 226.32 kg/90 meters
	per section	= 2715.85 kg
	per string	= 10863 kg
	initial temperature	= 20 K
	initial density (line)	= 794.11 kg/cu meter
	final pressure	= 0.25 MPa

Note: Nitrogen is in the 80 K zone at a pressure of 0.25 MPa. A part of this nitrogen is warmed to 300 K and fills the 300 K zone. The moment vacuum vessel is pressurized to 0.25 MPa, the pressure relief valve will open.

ume that the initial spill occurs instantaneously and the pressure the damaged line and cryostat are balanced. Also assume that the perature of the fluid of each layer is equal to the temperature of heat shield.

culate the amount of fluid required in the cryostat in order for cryostat to be pressurized to 0.25 MPa.

ote: Calculate the mass of helium, given the three heat shields.

$$M_{total} = M_{20K} + M_{80K} + M_{300K}$$

$$M_{total} = V_{20K}\,\rho_{20K} + V_{80K}\,\rho_{80K} + V_{300K}\,\rho_{300K}$$

$$M_{total} = (5.839\ 0.006118) + (4.64\ 0.001518) + (8.93\ 0.000406)$$

$$M_{total} = 46.4 \text{ kg/section}$$

ompare: The amount of spilled helium is the difference of the helium mass contained in line 1 at 0.4 MPa as compared to the amount in line 1 at 0.25 MPa. (1044 - 1005.8 = 38.2 kg/section)

The heat shields capacity is 46.4 kg/section.

Since 46.4 kg is greater than 38.2 kg, this will mean that any sum that is less than 46.4 kg will not cause the cryostat to pressurize above 0.25 MPa. At least this will be true initially, disregarding any resulting heating of the spilled fluid due to heat transfer...

Mass sums greater than 46.4 kg will cause the cryostat to be pressurized above 0.25 MPa instantaneously.

By modeling steady state heat transfer through the vacuum vessel per unit length and assuming heat conduction through cylindrical fluid layers, the following approximation can be made:

$$\frac{q}{L} = 210 \quad \text{watt/meter}$$

Q(half cell) = 210 x 90 = 18,900 watts/half cell

Warmed fluid will be forced from the inner layers to the outer layers. The fluid within the 300 K layer will flow out via the pressure relief valve.

Calculate the mass flow rate given the value of Q for the half cell:

$$Q = m \left[h_{300K} - h_{20K} \right]$$

$$Q = m \, (1573 - 117.1)$$

$$m = \frac{18900}{1573 - 117.1} = 13 \quad \text{gm/sec}$$

Volume flow rate per second

$$\frac{Vol}{sec} = \frac{m}{\rho} = \frac{13}{0.000406} = 32019.7 \quad cc/sec$$

Volumetric flow rate of helium at 0.25 MPa and 300 K is equal to:

Vol/sec = 32 liters/sec

Given Sonic Flow conditions of helium exiting the vacuum vessel, calculate the required vacuum vessel valve area, and port diameter.

Utilize Isentropic flow of a perfect gas:

$$\frac{w}{A_{max}} = \sqrt{\left[\frac{k}{R}\right] \cdot \left[\frac{2}{k+1}\right]^{\left[\frac{k+1}{k-1}\right]}} \; \frac{P_0}{\sqrt{T_0}}$$

$$w = A_{max} \; 225.68 \qquad \text{note: } w = 0.013 \text{ Kg/sec}$$

$$A_{max} = 5.76 \cdot 10^{-5} \; \text{meters}^2$$

And, D, for a circular cross section is 8.56 mm

Therefore, use D = 10.0 mm.

And the diameters:

$D_{I} = 8.56$ mm

$D_{II} = 11.74$ mm

$D_{III} = 31.45$ mm

en a rupture in Line 1 and helium in contact with each heat
eld, the relief valve diameters have been calculated as
ted with vacuum vessel internal pressure of 0.25 MPa:

1) He spill, Line 1 to 20 K shield only: D = 8.56 mm
2) He spill, Line 1 to 20 K and 80 K shields: D = 11.74 mm
3) He spill, Line 1 to 20 K, 80 K and 300 K D = 31.45 mm

as been found that a liquid nitrogen spill during cool down
ation would require a port diameter of D = 30.18 mm.

these results, there must be placed a vacuum vessel relief valve
diameter of, say 31.75 mm on each side of the vacuum barrier.
relief valve per half cell is sufficient per the calculations.

reasons of safety and redundancy, other relief valves are required.

efore, each half cell (90 meters) volume can be vented via 8 vacuum
ief valves. The spool piece shall contain two relief valves located
on each side of the vacuum barrier. And the magnet vacuum vessels
ll contain at least one relief valve.

APPENDIX B

ACTION DIAGRAMS

3.1 FLOW OF HELIUM INTO THE BEAM TUBE

The beam tube vacuum is monitored at a rate of 1 Hertz

The pressure in the beam tube is measured by distributed ion pumps located every 180 meters. The response time of the ion pumps to change in pressure is instantaneous. The ion pumps are switched off at pressures greater than 0.001 Pa. There is no pressure indication for the beam tube for pressures greater than 0.001 Pa.

Adjacent ion pumps to the damaged area will detect any change in pressure resulting from a hole in the beam tube. The control system detects the alarm condition at least 1 second later.

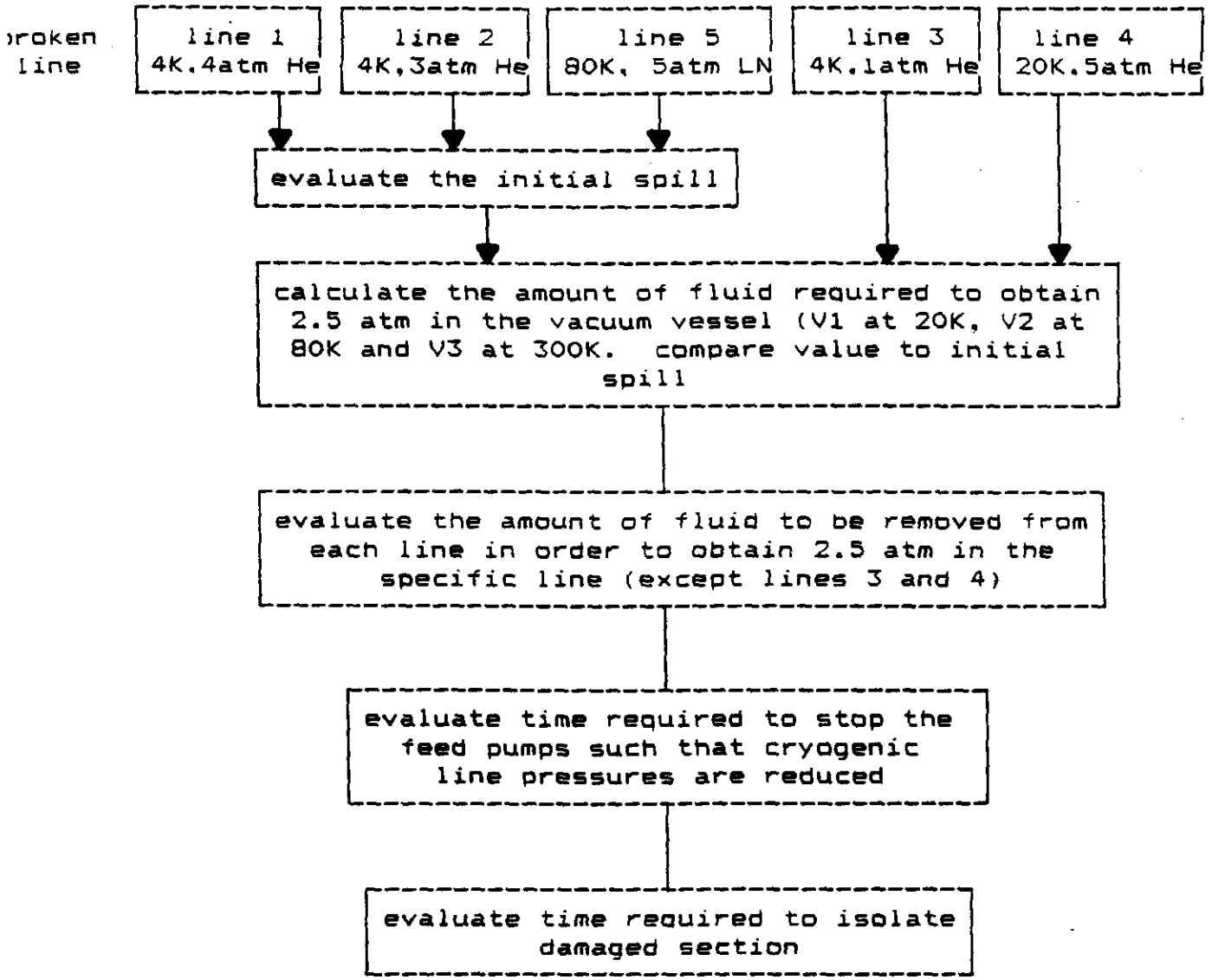
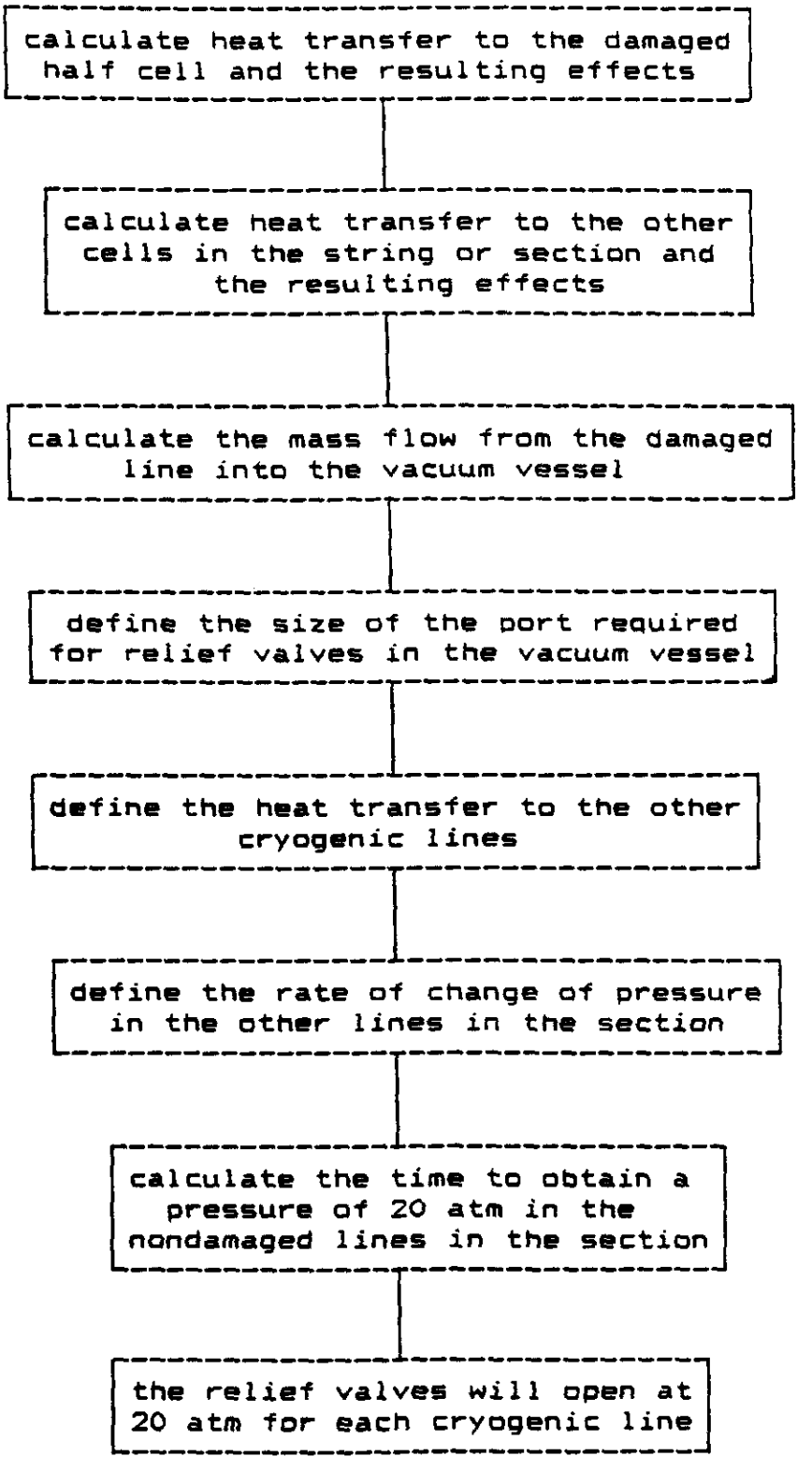
The immediation reaction is to close the beam tube isolation valves of the damaged section. Valve closing time is 2 to 6 seconds. Isolating the damaged section will take a minimum of 8 seconds. Given this amount of time and the speed of the pressure wave at 200 m/sec, the helium will expand through the length of 1600 meters in both directions from the damaged section. To stop the pressure wave and to minimize the affects on the remaining beam tube vacuum, there will be a requirement to close several isolation valves on both sides of the damaged section.

The damaged section will be known within a distance of 180 meters. The damaged section may be filled with 4K and 0.4 MPa helium. Adjacent sections will be isolated because of beam tube valve closures. The pressure will increase in the isolated sections.

The emergency response is to depressurize the cryogenic lines, close the cryogenic isolation valves of the damaged section, bypass the U-tubes, and operate the cryogenic system for the nondamaged sections.

Monitoring changes in vacuum, temperature, and pressure within the spool pieces and magnet cryostats, will aid in locating the damaged section.

.2 FLOW OF CRYOGEN INTO THE VACUUM VESSEL



B.2 (continued)... FLOW OF CRYOGEN