1 INTRODUCTION

This report examines the pressure relief for the JLab Q2-Q3 Quadrupoles nitrogen cooled radiation screen. The report lists the heat flux for a Loss of Vacuum to air, defines the geometry and the resulting calculated vent flow rates. The report then summarises the vent flow rate, the vent pipe pressure drop and the capacity of the relief devices.

The report also considers fault conditions of a Loss of Vacuum to helium or the failure of a cryogen supply pipe.

Reference	JLab Q2-Q3 Relief 225_1 Screen.xls JLab Q2-Q3 Relief 226_1 N2 Vent Pipe RV.xls JLab Q2-Q3 Relief 227_1 N2 RV.xls JLab Q2-Q3 Relief 229_1 N2 Vent Pipe BD.xls
Attachments	JLab Q2-Q3 Relief 225_1 Screen.pdf JLab Q2-Q3 Relief 226_1 N2 Vent Pipe RV.pdf JLab Q2-Q3 Relief 227_1 N2 RV.pdf JLab Q2-Q3 Relief 229_1 N2 Vent Pipe BD.pdf
Geometry documents	317111-JLA-CCR.exe cryo pipes design.docx Scans14714.pdf Drg No 67145-00514 Sheet 1 of 1 Scans15050.pdf Drg No 67145-00513 Sheet 1 of 1

Rev	Date	Description
2	12 Jul 2013	Corrections to Section 8 Conclusions and additional explanation in Section 7.1 LOV to Helium

2 ASSUMPTIONS

2.1 HEAT FLUX IN FAULT CONDITIONS

In the calculations estimates are made for the heat flux to a liquid nitrogen cooled surface. Reference is made to the following:

- “Cryogenic Systems, Second Edition”, Randell F Barron, Oxford University Press, ISBN 0-19-503567-4.
- The heat flux listed in the JLab report “Safety Analysis of SHMS HB, Q1, Q2/3 and Dipole Magnets”, Eric Sun, 18 May 2009.
- Estimates of the heat transfer by air by natural convection to a vertical surface.

The heat fluxes according to these three sources are listed below.

Barron in Cryogenic Systems presents a graph which is shown below for the effective thermal conductivity of superinsulation as a function of pressure.

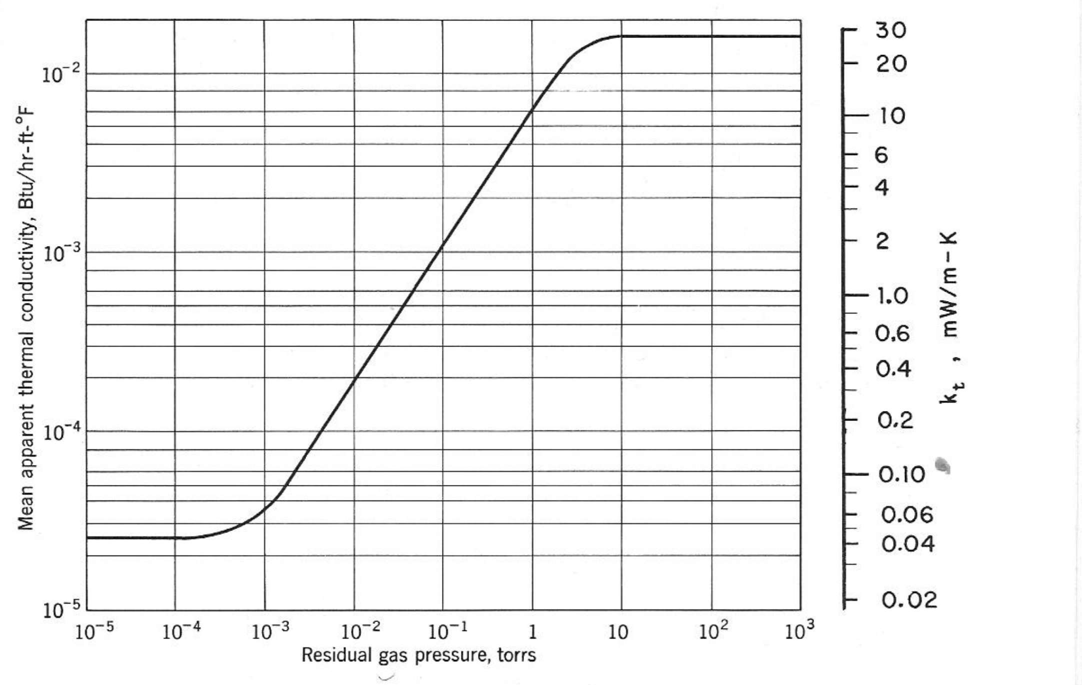

Fig. 7.15. Variation of mean apparent thermal conductivity with residual gas pressure for a typical multilayer insulation. The insulation layer-density is 24 layers/cm (60 layers/in.), and the boundary temperatures are 300 K (540°R) and 90.5 K (163°R).

At atmospheric pressure the effective thermal conductivity is 30 mW / m.K and operating across a temperature range from 20°C which is 293 K to 95 K the heat flux is 640 W / m² or 0.064 W / cm².

The value used in the JLab report “Safety Analysis of SHMS HB, Q1, Q2/3 and Dipole Magnets” a heat flux of 2 000 W / m² or 0.20 W / cm² is used.

The heat transfer by natural convection on a vertical surface is estimated in order to make a comparison. It is accepted that this is approximate given the large temperature difference, questionable validity over the temperature range the orientation of the surfaces and reduction in heat flux caused by superinsulation.

	Fluid	Air	
	Hot temperature	293	K
	Cold temperature	95	K
	Bulk temperature	195	K
	Temperature difference	200	K
Fluid Properties	Density	1.814	kg / m³
	Specific heat capacity	1.007	kJ / kg.K
	Thermal conductivity	0.0178	W / m.K
	Viscosity	1.308E-5	kg / m.s
	Buoyancy	0.0052	
	Prandtl Number	0.7404	
	Characteristic dimension	1.00	m
	Grasshof Number	7.02 E +06	
	Rayleigh Number	5.20 E +06	
	Nusselt Number	24.5	
	Heat flux	1600	W / m²
	Heat flux	0.160	W / cm²

With a characteristic dimension of 0.20 m then the heat flux is 1 800 W / cm².

These data points for a Loss of vacuum are summarised below.

Heat flux through superinsulation	0.064	W / cm²			
JLab Report	0.20	W / cm²			
Natural convection	0.16	W / cm	at	1.0	m
	0.18	W / cm²	at	0.2	m

Comparing these results, the analysis will use a heat flux of 0.20 W / cm² to a liquid nitrogen cooled surface wrapped in superinsulation under a Loss of Vacuum and considers this an appropriate but conservative figure.

2.2 CRYOGEN THERMOPHYSICAL PROPERTIES

The thermosphysical properties of the cryogens are evaluated using the NIST RefProps program Database 23, Version 9. This will evaluate the properties as a function of the statepoint of a fluid. Notably it will calculate the compressibility factor of nitrogen at close to the saturation conditions.

3 PARAMETERS

3.1 SURFACE AREAS

The surface areas of the radiation screen and whether the surface is wetted with liquid nitrogen or conduction cooled are listed below

Magnet Radiation Screen	Outer cylinder	9.51	m²	Wetted
	Inner cylinder	4.61	m²	Wetted
	Front end piece	1.09	m²	Conduction cooled
	Rear end piece – vertical	1.09	m²	Conduction cooled
Chimney	Screen	1.03	m²	Conduction cooled
CCR	Reservoir cylinder	1.48	m²	Wetted
	Screen cylindrical extension	0.39	m²	Conduction cooled
	Screen top plate	0.51	m²	Conduction cooled
	Screen bottom plate	0.51	m²	Conduction cooled
	TOTAL	20.22	m²	
	TOTAL – Wetted Surfaces	15.61	m²	
	TOTAL – Conduction Cooled Surfaces	4.62	m²	

(Surfaces which lie inside a radiation screen, for example the nitrogen pipes in the chimney are not listed because it is judged that any gas impacting on these surfaces in a fault condition will be close to the screen temperature and therefore will not add significantly to the heat load.)

3.2 PRESSURES

The helium vessel will be protected by a relief valve and a burst disc. The set pressures and the venting pressures are listed below.

Relief Valve	Set pressure	4.0	atm gauge
		4.05	bar G
	Over pressure	10%	
	Vent pressure	4.46	bar G
		5.47	bar A
Burst Disc	Set pressure	5.0	atm gauge
		5.07	bar G
	Vent pressure	5.07	bar G
		6.08	bar A

4 ANALYSIS

The method of analysis is as follows:

1. The heat flux and the associated areas are consolidated to calculate a total heat load.
2. The gas evaporation flow rate is calculated for nitrogen boiling at 4.46 bar G.
3. The vent flow rate is calculated from the evaporation rate by making an allowance for the ullage.
4. The pressure drop and the temperature rise in the pipe from the CCR to the relief valve are calculated.
5. The pressure drop in an example pipe downstream of the relief valve is calculated.
6. The flow capacity of the relief valve is calculated for the over pressure and the outlet pressure.
7. The flow capacity of the burst disc is calculated.

5 RESULTS

5.1.1 Vent Flow Rate – Loss of Vacuum

The detailed results of the analysis are presented are summarised below.

	Heat flux on Loss of Vacuum	0.20	W / cm²
	Wetted surface area	15.61	m²
	Heating to helium on quench	31.21	kW
	Vent pressure	5.47	bar A
Nitrogen	Latent heat	171.1	kJ / kg
	Liquid density	717.4	kg / m³
	Vapour density	22.54	kg / m³
	Ullage	0.969	
	Evaporation rate	0.1824	kg / s
	Vent flow rate	0.1767	kg / s
		636	kg / hr

Based on the estimated inventory the vent period is approximately 6 minutes.

6 RELIEF CAPACITY

The capacity of a relief valve, the burst disc and the pressure drop along the vent pipe are evaluated. The geometry of the vent pipe is taken from the drawings 67145-00514 and 67145-00513 Rev A which have been submitted as documents Sans14714.pdf and Scans15050.pdf. A heat flux of 2 000 W / m² is used on all sections of the pipe.

6.1 RELIEF VALVE

The relief valve for the quench condition uses the same model as proposed in the JLab report "safety_analysis_Dec_2010.pdf".

For the initial flow capacity calculation a pressure at the outlet of the relief valve of 0.50 bar G is used. This pressure is low enough so that the back pressure correction factor, K_b, is unity. The detailed results are listed in "JLab Q2-Q3 Relief 227_1 N2 RV.pdf" and are summarised below.

	Manufacturer	Flow Safe Inc			
	Type	F84 Series			
	Part number	F84-8 0.75" by 1.00" F			
	Orifice diameter	0.261	in²		
A	Orifice area	168	mm²	1.838 in²	
K_d	Nozzle coefficient of discharge	0.975			
	Derated coefficient of discharge	0.878			
	Set pressure	4.05	bar G	4.00	atm
	Fully open pressure	5.472	bar A	79.4	psi A
Gas conditions	Fluid	Nitrogen			
M	Molar mass	28.014	kg / kgmol		
P_1	Upstream valve inlet pressure	5.472	bar A	79.4	psi A
P_2	Downstream valve outlet pressure	1.513	bar A	21.9	psi A
T	Temperature	96	K	174	R
k	Isentropic expansion coefficient	1.382			
Z	Compressibility factor Z	0.8664			
	Density	22.05	kg / m³	1.377 lb / ft³	
C	Pressure ratio factor	354			
K_b	Back pressure correction factor	1.000			
W	Relieving capacity	1260	kg / hr	2780	lb / hr

It is noted that the Flow Safe Inc sizing method derates the coefficient of discharge which is 0.975 by a factor 0.90 to a value of 0.878 and this has been used in the calculations above.

The calculations for the pressure drop for the vent pipe to the relief valve are summarised below. The detailed results are listed in "JLab Q2-Q3 Relief 226_1 N2 Vent Pipe RV.pdf" and are summarised below.

Pipe inside diameter					
	– Internal to the CCR	34.80	mm		
	- Relief Tree	26.64	mm		
Inlet	Pressure	5.472	bar A		
	Temperature	96	K		
	Vent flow rate	636	kg / hr		
	Density	22.22	kg / m³		
	Viscosity	7.00 E-6	kg / m.s		
Sudden Contraction					
	Upstream diameter	Large			
	Loss coefficient	0.464			
	Pressure drop			3.6	mbar
Pipe Loss	Reynolds Number	0.92 E 6			
	Friction factor	0.0102			
	Unit pressure drop	2.29	mbar per m		
	Length	0.575	m		
	Pressure drop			1.3	mbar
Sudden Contraction					
	Upstream diameter	34.80	mm		
	Downstream diameter	26.64	mm		
	Loss coefficient	0.123			
	Pressure drop			2.83	mbar
Pipe Loss	Reynolds Number	1.20 E 6			
	Friction factor	0.0096			
	Unit pressure drop	8.19	mbar per m		
	Length	0.476	m		
	Pressure drop			3.9	mbar
Tee along Run					
	Loss coefficient	0.46			
	Pressure drop			10.5	mbar
Pipe Loss	Unit pressure drop	8.26	mbar per m		
	Length	0.126	m		
	Pressure drop			1.0	mbar
Tee as Elbow Entering Run					
	Loss coefficient	1.38			
	Pressure drop			31.8	mbar
Pipe Loss	Unit pressure drop	8.33	mbar per m		
	Length	0.075	m		
	Pressure drop			0.6	mbar

Elbow (long radius)	Loss coefficient	0.69			
	Pressure drop			16.0	mbar
Reducer	Upstream diameter	26.64	mm		
	Downstream diameter	20.93	mm		
	Length	0.051	m		
	Loss coefficient	0.05			
	Pressure drop			1.1	mbar
Pipe Loss	Unit pressure drop	26.4	mbar per m		
	Length	0.038	m		
	Pressure drop			1.0	mbar
Total Pressure Drop				74	mbar

The velocity and Mach Number in the pipe rises from 8.4 m / s and 0.05 at the inlet to 24 m / s and 0.13 at the connection to the relief valve.

With a heat flux of 2 000 W / m², the calculated temperature rise due to heating is offset by the temperature drop due to the expansion process. The net temperature rise along the vent pipe is 1.2 K.

The design pressure of the radiation careen is 6 atm which is 6.08 bar. The Loss of Vacuum condition is calculated assuming that there is atmospheric pressure in the vacuum space and therefore the absolute pressure in the radiation screen could rise to 7.09 bar A which, relative to the pressure of 1.01 bar A does not exceed the design pressure. However it is conceivable that the fault condition is a partial Loss of Vacuum which creates a high heat flux but at a pressure in the vacuum space which is below atmospheric pressure. Therefore a conservative design assessment would assume a heat flux as calculated and a maximum permissible pressure in the screen of 6.08 bar A. This can be tolerated as follows:

Relief valve			
	Fully open vent pressure	5.47	bar A
	Pipework back pressure	0.07	bar
	Radiation screen pressure	5.54	bar A

This pressure is less than the design pressure of 6.08 bar A even if the pressure in the vacuum space has remained close to a vacuum. Therefore the design is satisfactory.

The maximum back pressure downstream of the relief which does not reduce the flow capacity of the relief is 1.8 bar G. The pressure drop of the elbow and the sharp edge expansion is calculated as 0.12 bar G which is less than the maximum and therefore acceptable.

The conclusion of this analysis is that the Flow safe Inc valve F84-8 0.75" by 1.00" F with a set pressure of 4.00 atm / 4.05 bar G will have a flow capacity of 1 260 kg / hr when the cryostat internal pressure is 5.69 bar A. This is sufficient to vent the flow rate generated by a Loss of Vacuum which is 640 kg / hr.

6.2 Burst Disc

The calculations for the pressure drop for the vent pipe and the burst disc are summarised below. At each node the pressure and the temperature is calculated and the corresponding helium gas properties. The analysis is completed for FIKE 1.00" AXIUS burst disc. The detailed results are listed in "JLab Q2-Q3 Relief 229_1 N2 Vent Pipe BD.pdf" with a burst pressure of 5.0 atm which is 5.07 bar G.

Pipe inside diameter					
	- Internal to the CCR	34.80	mm		
	- Relief Tree	26.64	mm		
Inlet Conditions	Pressure	6.08	bar A		
	Temperature	97.0	K		
	Vent flow rate	636	kg / hr		
	Density	24.78	kg / m³		
	Viscosity	7.11 E-6	kg / m.s		
Sudden Contraction					
	Upstream diameter	Large			
	Loss coefficient	0.464			
	Pressure drop			3.2	mbar
Pipe Loss	Reynolds Number	0.91 E 6			
	Friction factor	0.0102			
	Unit pressure drop	2.06	mbar per m		
	Length	0.575	m		
	Pressure drop			1.2	mbar
Sudden Contraction					
	Upstream diameter	34.80	mm		
	Downstream diameter	26.64	mm		
	Loss coefficient	0.123			
	Pressure drop			2.5	mbar
Pipe Loss	Reynolds Number	1.18 E 6			
	Friction factor	0.0096			
	Unit pressure drop	7.35	mbar per m		
	Length	0.476	m		
	Pressure drop			3.5	mbar
Tee along Run					
	Loss coefficient	0.46			
	Pressure drop			9.4	mbar
Pipe Loss	Unit pressure drop	7.43	mbar per m		
	Length	0.126	m		
	Pressure drop			0.9	mbar

Tee along Run					
	Loss coefficient	0.46			
	Pressure drop			9.5	mbar
Pipe Loss	Unit pressure drop	7.46	mbar per m		
	Length	0.094	m		
	Pressure drop			0.7	mbar
Burst Disc	Manufacturer	FIKE			
	Type	AXIUS Low Pressure			
	MNFA	0.864	in^2 (manufacturer's date)		
		557	mm^2		
	Effective orifice diameter	26.6	mm		
	KR	0.45	(manufacturer's date)		
	Nitrogen density	24.20	kg / m^3		
	Pressure drop			9.3	mbar
Pipe Loss	Unit pressure drop	7.62	mbar per m		
	Length	0.115	m		
	Pressure drop			0.8	mbar
Elbow (short radius)	Loss coefficient	0.46			
	Pressure drop			9.7	mbar
Sudden Expansion					
	Downstream diameter	Large			
	Pressure drop			21.2	mbar
Total Pressure Drop				72	mbar

The velocity and Mach Number in the pipe rises from 7 m / s and 0.04 at the inlet to 13 m / s and 0.07 at the outlet.

With a heat flux of 2 000 W / m², the calculated temperature rise due to heating is 2.2 K.

The analysis is repeated to find the limiting flow rate for the burst disc vent path. It is estimated that the flow rate can rise by a factor of 7.1 to a value of 4 530 kg / hr with an inlet at the CCR of 6.08 bar A and the exhaust venting to atmosphere. This is equal to the design pressure and less than the test pressure by 1.01 bar.

The heat flux is calculated assuming that the Loss of Vacuum condition causes a pressure rise in the vacuum space of 1.0 bar A. The analysis is conservative because no allowance has been made to reduce the stress pressure of the radiation screen by this pressure.

Even with these conservative fault conditions the vent path with a burst disc offers protection by at least a factor of four on the vent flow rate.

7 OTHER FAULT CONDITIONS

7.1 LOV TO HELIUM

The Loss of Vacuum may be caused by a leak of helium gas. An estimate of the heat flux by natural convection is presented below. This assumes that the warm surface is at ambient which is 290 K and the cold surface is at the temperature of the radiation screen which is a nominal 80 K. The gap between the radiation screen and the helium vessel is taken as the characteristic dimension and is a nominal 100 mm.

In the first place this analysis assumes that there is no insulating effect due the superinsulation.

	Helium gas pressure	1000	mbar
	Hot temperature	290	K
	Cold temperature	80	K
	Mid temperature	190	K
Helium properties	Density	0.2600	kg / m³
	Specific heat capacity	5.193	kJ / kg.K
	Thermal conductivity	0.1129	W / m.K
	Viscosity	1.45E-6	kg / m.s
	Buoyancy	0.0053	K^{-1}
	Prandtl Number	0.6672	
	Characteristic dimension	0.10	m
	Grasshof Number	3.61 E+7	
	Rayleigh Number	2.41 E+7	
	Nusselt Number	20.43	(Parallel vertical plates)
	Heat Transfer Coefficient	23.1	W / m².K
	Heat flux	4960	W / m²
		0.496	W / cm²

The same calculation repeated for air evaluates a heat flux of 0.22 W / cm².

This calculation is approximate given the simplification of the orientation of the heat transfer surfaces and the characteristic dimension. It does indicate that the heat flux may be 2.2 times higher which gives a flow rate of 1 400 kg / hr if the loss of vacuum is caused by a leak from helium. In the event of a failure of the helium containment, the leaking helium will be at a low temperature and would therefore cool the nitrogen radiation screen. Even if the heat transfer from ambient creates a high heat load on the radiation screen and a flow rate of 1 400 kg / hr, the previous section has shown that the burst disc has a flow capacity which is three times this vent flow rate.

7.2 UNCONSTRAINED PIPE FLOW

The supply pressure from the helium pipes is 2.5 atm and from the nitrogen pipes is 3 atm. This is less than the set pressure of the relief valve which is 4.0 atm. Therefore a fault condition of a valve failing open or a pipe rupturing inside the helium vessels will not cause the pressure to rise above the set pressure of the relief valve or the design pressure of the helium vessel.

8 CONCLUSIONS

The analysis and results of this report are summarized in this section.

The vent flow rates for the liquid nitrogen radiation screen have been evaluated as follows:

- A Loss of Vacuum to air will cause a vent flow rate of 640 kg /hr.
- A Loss of Vacuum to helium will cause a vent flow rate as high as 1 400 kg / hr.

The vent capacity of the relief devices have been evaluated as follows:

Relief Valve — Conditions at the vent flow rate

Flow rate	640	kg / hr
Pressure in the CCR reservoir	5.54	bar A
Temperature of the nitrogen	96	K
Vent pipe pressure drop	0.07	bar
Pressure at valve inlet – Fully open	4.46	bar G
Relief valve set pressure	4.05	bar G
	4.00	atm
Valve Manufacturer	Flow Safe Inc	
Valve Type	F84-8 0.75” by 1.00”F	

Burst Disc — Conditions at the maximum flow rate

Flow rate	4530	kg / hr
Pressure in the CCR reservoir	6.08	bar A
Temperature of the nitrogen	97	K
Burst disc manufacturer	FIKE	
Burst disc type	AXIUS Low Pressure	
Nominal size	1	in
MNFA	0.81	in^2
Vent pipe pressure drop	5.07	bar

The design pressure of the radiation screen is 6.0 atm and the test pressure is 7.0 atm.

The specified relief valve has adequate capacity to discharge the vent flow rate in the event of a Loss of Vacuum to air.

A Fike 1.00” Axius Low Pressure burst disc has sufficient capacity to vent the flow rate in the event of a loss of vacuum to helium.

The analysis is conservative for two reasons:

- It calculates the heat flux assuming that the pressure in the vacuum space has risen to 1.0 bar A but considers the stress pressure on the radiation as if the vacuum space is at 0 bar A;
- It considers only the design pressure of the radiation screen.

Therefore the liquid nitrogen cooled radiation screen has sufficient vent capacity at the design pressure to vent the nitrogen under the anticipated fault conditions.

Rev	Date	Description
2	12 Jul 2013	Corrections to Section 8 Conclusions and additional explanation in Section 7.1 LOV to Helium