1 INTRODUCTION

This report examines the pressure relief for the JLab Q2-Q3 helium vessel. The report lists the heat flux for a quench and a loss of vacuum and 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.

Reference	JLab Q2-Q3 Relief 204_1 LOV + Quench No Protection.xls JLab Q2-Q3 Relief 204_1 Quench No Protection.xls JLab Q2-Q3 Relief 204_1 Quench Protection.xls JLab Q2-Q3 Relief 206_1 He RV.xls JLab Dipole Relief 207_1 He Z.xls JLab Q2-Q3 Relief 210_1 He Vent Pipe RV.xls JLab Q2-Q3 Relief 211_1 He Vent Pipe BD.xls
Attachments	JLab Q2-Q3 Relief 204_1 LOV + Quench No Protection.pdf JLab Q2-Q3 Relief 204_1 Quench No Protection.pdf JLab Q2-Q3 Relief 204_1 Quench Protection.pdf JLab Q2-Q3 Relief 206_1 He RV.pdf JLab Dipole Relief 207_1 He Z.pdf JLab Q2-Q3 Relief 210_1 He Vent Pipe RV.pdf JLab Q2-Q3 Relief 211_1 He Vent Pipe BD.pdf
Geometry documents	317111-JLA-CCR.exe 67125-E-00002-Q2-Q3 Assy sh2.pdf 67125-E-00004-Q2-Q3 He Chamber Assy sh2.pdf 67125-E-00008-Q2-Q3 Cold Mass sh1.pdf 318711-JLA-704-001-revA.PDF 318711-JLA-703-001-revA.PDF 318711-JLA-001-001-revA.PDF Scans14875.pdf Drg No 67145-00504 Rev A Sheet 1 of 1 Scans15049.pdf Drg No 67145-00503 Rev B Sheet 1 of 1

Rev	Date	Description

2 ASSUMPTIONS

2.1 HEAT FLUX IN FAULT CONDITIONS

In the calculations estimates are made for the heat flux to liquid helium which typically is supercritical. Reference is made to two papers and the JLab report.

"Safety Aspects for LHe Cryostats and LHe Transport Containers", W Lehmann, G Zahn, Proc. of the Int. Cryog. Eng. Conf., 7 (1978).

"Loss of Vacuum Experiments on a Superfluid Helium Vessel", Stephen M Harrison, 2001, http://www.scientificmagnetics.co.uk/pdf/technical-publications/Loss-of-vacuum-experiments-on-superfluid-helium-vessel.pdf

The value from the JLab report "Safety Analysis of SHMS HB, Q1, Q2/3 and Dipole Magnets", Eric Sun, 18 May 2009

The following values are used for the heat flux to helium from a surface.

	Surface facing helium	Bare metal	
	Other surface	Bare metal	
	Condition	Loss of Vacuum to Air (LOV to Air) Magnet quench	
	Heat flux	3.8	W / cm²
Comparison	Lehmann & Zahn	3.8	W / cm²
	Harrison	3.1	W / cm²
Maximum temperatures:			
	- LOV to Air	63	K
	- Unprotected quench	160	K*
	- Protected quench	83	K*

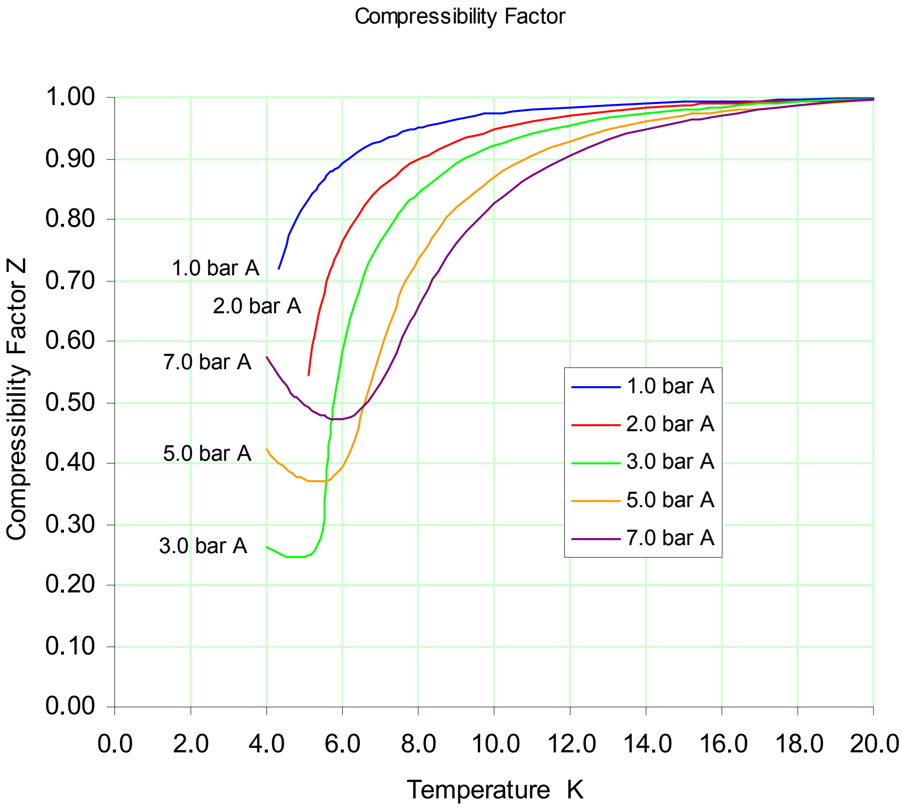
	Surface facing helium	Bare metal	
	Other surface	Superinsulation or Cryolite	
	Condition	Loss of Vacuum to Air (LOV to Air)	
	Heat flux	0.7	W / cm²
Comparison	Lehmann & Zahn	0.6	W / cm² (Superinsulation)
	Harrison	0.44	W / cm² (Cryolite)
	JLab report	0.7	W / cm²
	Maximum temperature	63	K

It is assumed that the JLab report heat flux applies to a surface which has multi-layer superinsulation.

* The maximum temperatures for the "Unprotected quench" and the "Protected quench" use the values from the Dipole quench analysis. These will be updated on completion of this work.

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 thermosphysical properties as a function of the statepoint of a fluid. Notably it will calculate the compressibility factor helium at low temperatures which is illustrated in the chart below. This parameter is used in the calculation of the relief valve capacity: typically at a temperature of 6.5 K and 4.5 bar A the compressibility factor Z is 0.51 which will increase the capacity of a relief valve by about 40% compared to the more conservative approximation of Z = 1. This correction is used for all the calculations of fluid density etc.



3 PARAMETERS

3.1 SURFACE AREAS

Wetted surface in contact with liquid helium

Helium Vessel for Magnet	Outer cylinder	8.27	m²		
	Inner cylinder – straight length	4.49	m²		
	End pieces	1.79	m²		
	TOTAL Magnet Assembly			14.54	m²
Helium Chimney Pipe	Feed pipe	0.05	m²		
	Feed pipe manifold – Magnet assembly	0.08	m²		
	Return pipes – all three	0.51	m²		
	TOTAL Chimney Pipes			0.65	m²
CCR	Reservoir top	0.24	m²		
	Reservoir base	0.24	m²		
	Reservoir cylinder	0.20	m²		
	Pipes	0.30	m²		
	TOTAL CCR			0.98	m²
Magnet Assembly	Coil inner surface	2.71	m²		
	Outer cylinder	7.38	m²		
	Inner cylinder – excluding coil surface	1.70	m²		
	End piece	0.74	m²		
	End piece	0.74	m²		
	TOTAL Magnet coil inner surface			2.71	m²
	TOTAL Magnet Assembly – less coil inner			10.56	m²

3.2 HELIUM INVENTORY

	Magnet vessel	129	litres
	Helium feed pipe	0.4	litres
	Return pipes – all three	7.7	litres
	CCR – working volume	92	litres
	CCR – vapour contents	28	litres
Totals	Working volume	229	litres
	Liquid helium inventory	201	litres
	Vapour helium inventory	28	litres

Rev	Date	Description

3.3 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
	Over pressure	10%	
	Vent pressure	5.57	bar G
		6.58	bar A

3.4 VENT PIPE INTERNAL TO THE CCR

Internal to the CCR the vent pipe is 4.00" nb Schedule 10 and contains a non-return valve. The pressure drop for the vent pipe will be modeled using the following geometry.

Sharp edge entry						
Pipe	Length	127	mm	Diameter	108.2	mm
Non return valve	Kv	200	(Estimate)			
Pipe	Length	576.1	mm	Diameter	108.2	mm

The flow coefficient for the non-return valve should be confirmed by JLab.

The geometry and the insulation of the pipe downstream of the flange to the relief devices and the vent path downstream of the vent devices is defined in the drawings Scans14875.pdf which is Drg No 67145-00504 Rev A Sheet 1 of 1 and Scans15049.pdf which is Drg No 67145-00503 Rev B Sheet 1 of 1.

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 analysis is made for time increments for which the energy increment is calculated.
3. Initially there is no volume expansion and the helium properties are evaluated for a constant volume and increasing internal energy until the vent pressure is reached.
4. Once venting has started the helium properties are calculated for a constant pressure and increasing enthalpy. This results in an increasing specific volume. Therefore the vent quantity is calculated as the increment over the working volume of the cryostat. Combined with the time increment this corresponds to a vent flow rate.

This method produces an analysis of the pressure build and venting process over time for the cryostat.

The method of analysis produces results which are consistent with the techniques detailed by the Compressed Gas Association design code CGA S-1.2 1995. This document presents a parameter for supercritical gas which is the enthalpy absorbed for a volume increase and the maximum vent flow rate occurs when this parameter is a minimum. The evaluation of this parameter is not included in this report.

The vent flow rate is then used to select the relief devices which have sufficient capacity.

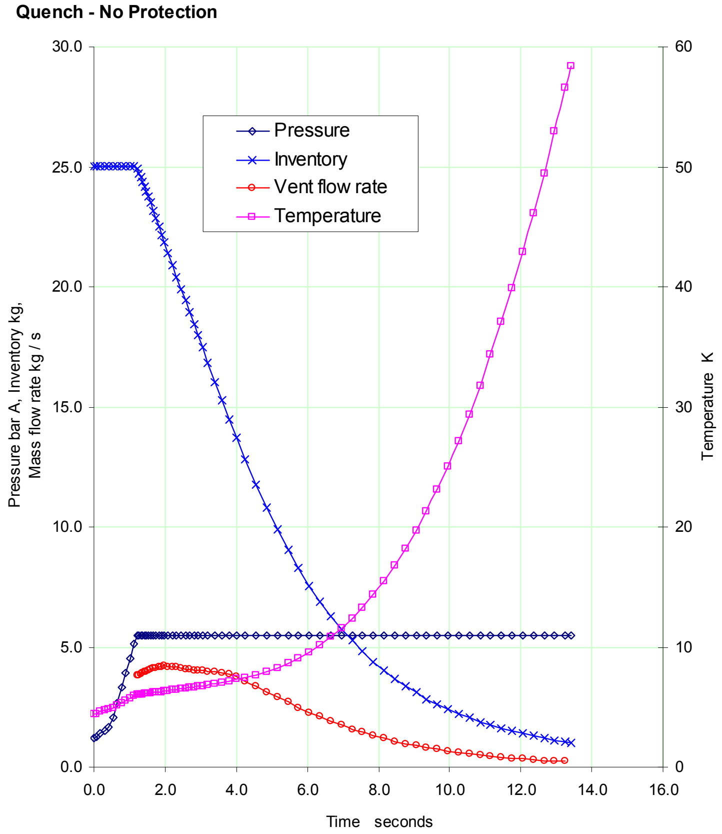
5 RESULTS

5.1.1 Quench – No Protection

The detailed results of the analysis are presented in the attached “JLab Q2-Q3 Relief 204_1 Quench No Protection.pdf” and are summarised below.

Maximum surface temperature	160	K		
Heat flux on quench	3.8	W / cm²		
Magnet assembly surface area	2.71	m²		
Heating to helium on quench	103	kW		
Maximum energy released	9.9	MJ		
Vent pressure	5.47	bar A		
Time to initiate venting	1.2	seconds		
Time to reach maximum flow rate	2.0	seconds		
Maximum calculated flow rate	4.20	kg / s at	6.31	K
	15140	kg / hr		
Energy absorbed by helium at max. flow	0.20	MJ		
Time to reduce inventory by 90%	9.7	seconds		
Energy absorbed by helium	0.96	MJ		

JLab Quadrupole



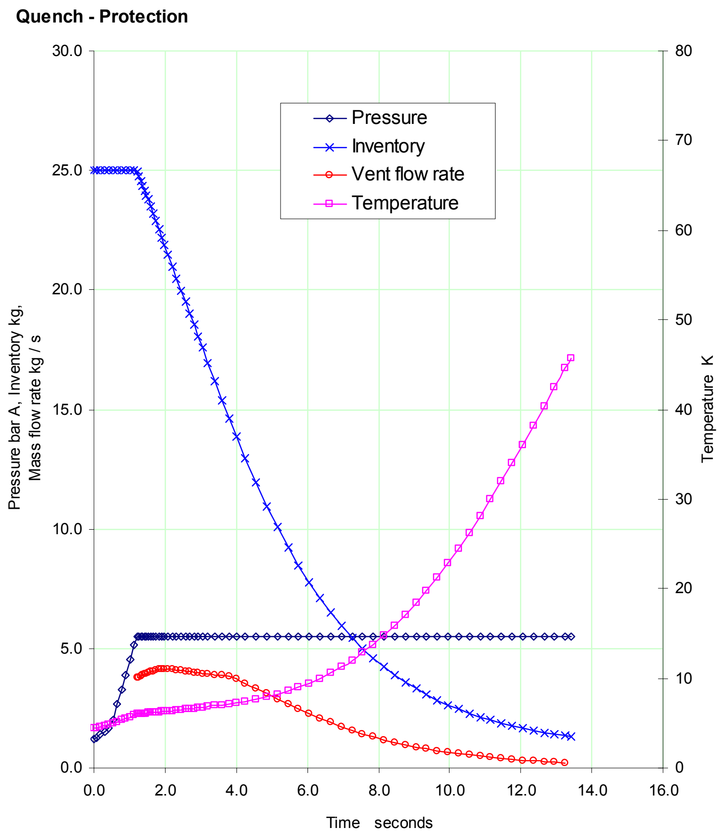
Rev	Date	Description

5.1.2 Quench – Protection

The detailed results of the analysis are presented in the attached "JLab Q2-Q3 Relief 204_1 Quench Protection.pdf" and are summarised below.

Maximum surface temperature	83	K		
Heat flux on quench	3.8	W / cm²		
Magnet assembly surface area	2.71	m²		
Heating to helium on quench	103	kW		
Maximum energy released	9.9	MJ		
Vent pressure	5.47	bar A		
Time to initiate venting	0.9	seconds		
Time to reach maximum flow rate	1.2	seconds		
Maximum calculated flow rate	4.15	kg / s at	6.30	K
	15000	kg / hr		
Energy absorbed by helium at max. flow	0.20	MJ		
Time to reduce inventory by 90%	10.0	seconds		
Energy absorbed by helium	0.95	MJ		

JLab Quadrupole



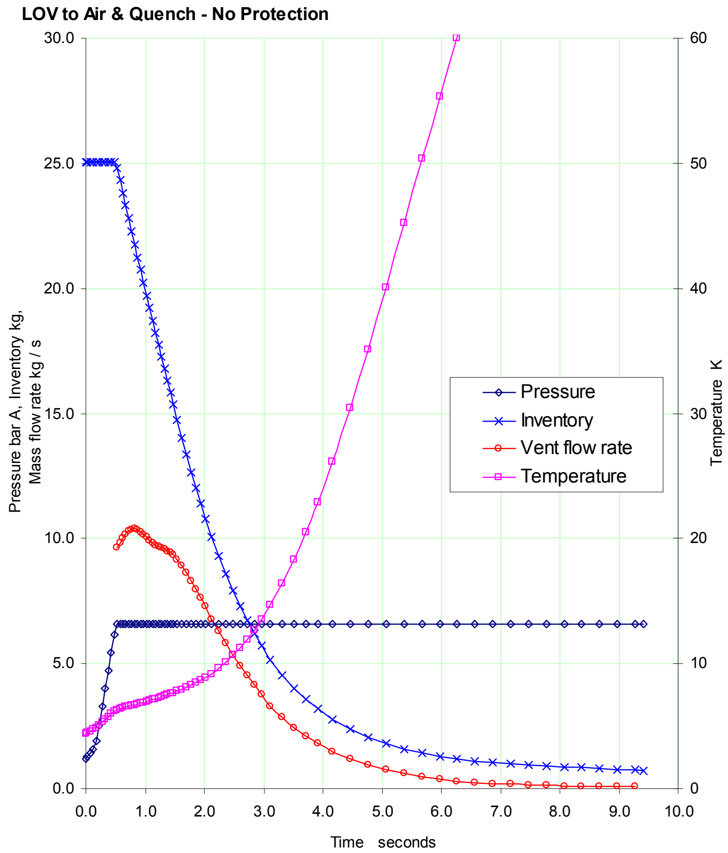
Rev	Date	Description

5.1.3 Loss of Vacuum to Air and Quench

The detailed results of the analysis are presented in the attached “JLab Q2-Q3 Relief 204_1 LOV + Quench No Protection.pdf” and are summarised below.

Maximum surface temperature	160	77	63	K
Heat flux on quench	3.8	0.70	0.70	W / cm²
Magnet assembly surface area	2.71	10.56	16.17	m²
Heating to helium on quench	113	74	103	kW
Total heating to helium	290	kW		
Maximum energy released	9.9	MJ		
Vent pressure	6.59	bar A		
Time to initiate venting	0.50	seconds		
Time to reach maximum flow rate	0.8	seconds		
Maximum calculated flow rate & temperature	10.37	kg / s at	6.71	K
	37350	kg / hr		
Energy absorbed by helium at max. flow	0.24	MJ		
Time to reduce inventory by 90%	4.2	seconds		
Energy absorbed by helium	1.11	MJ		

JLab Quadrupole



Rev Date Description

5.2 SUMMARY OF THE VENT FLOW RATES

The results for the maximum vent flow rate are summarised in the table below.

	Vent Pressure bar A	Vent Flow Rate kg / hr	Temperature K
Quench – Protection	5.47	15 000	6.30
Quench – No Protection	5.47	15 140	6.31
LOV to Air + Quench No Protection	6.59	37 350	6.71

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 67145-00503 Rev B and 67145-00504 Rev A which have been submitted as documents Scans15049.pdf and Scans14875.pdf. The vertical rise of the pipe is vacuum insulated and a conservative heat flux of 7 000 W / m² is used. The remaining sections of pipe are un-insulated and a heat flux 33 000 W / m² is used. The non-return valve has been analysed by a Computational Fluid Dynamics software package. The evaluated valve Kv value is between 296 and 286 (units as a function of bar and m³ / hr). A Kv value of 270 has been used in the analysis.

6.1 RELIEF VALVE

The relief valve for the quench condition uses the same valve 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.

	Manufacturer	Anderson Greenwood			
	Type	Pilot operated relief valve			
	Part number	25905J34 / S			
	Orifice diameter	32.5	mm		
A	Orifice area	830.3	mm²	1.838 in²	
K_d	Nozzle coefficient of discharge	0.975			
	Set pressure	4.05	bar G	4.00	atm
	Fully open pressure	5.472	bar A	79.4	psi A
Gas conditions	Fluid	Helium			
M	Molar mass	4.003	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	6.31	K	11.4	R
k	Isentropic expansion coefficient	4.367			
Z	Compressibility factor Z	0.4390			
	Density	95.09	kg / m³	5.936 lb / ft³	
C	Pressure ratio factor	494.3			
K_b	Back pressure correction factor	1.000			
K_c	Combination correction factor	1.000			
W	Relieving capacity	20000	kg / hr	44100	lb / hr

The pressure relief valve for the Dipole has to handle a larger flow rate and the specified valve is 25905K34 / S having a larger orifice of 1 186 mm². This valve has a marginally lower set pressure of 3.80 atm / 3.85 bar G to compensate for the back pressure in the Dipole relief path and the calculated capacity is 27 100 kg / hr. Although larger than necessary it may be desirable to use this valve to reduce the spares inventory.

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 210_1 He Vent Pipe RV.pdf” and are summarised below.

	Pipe inside diameter	108.2	mm internal to the CCR		
		82.8	mm external to the CCR		
Inlet	Pressure	5.472	bar A		
	Temperature	6.31	K		
	Vent flow rate	15140	kg / hr		
	Density	95.12	kg / m³		
	Viscosity	2.86 E-6	kg / m.s		
Internal to the CCR Sudden Contraction					
	Upstream diameter	Large			
	Loss coefficient	0.464			
	Pressure drop			5.1	mbar
Pipe Loss	Reynolds Number	1.73 E 7			
	Friction factor	0.00490			
	Unit pressure drop	0.50	mbar per m		
	Length	0.127	m		
	Pressure drop			0.1	mbar
Non-Return Valve	Valve Kv	270			
	Pressure drop			33.2	mbar
Pipe Loss	Unit pressure drop	0.50	mbar per m		
	Length	0.576	m		
	Pressure drop			0.3	mbar
External to the CCR Sudden Contraction					
	Upstream diameter	108.2	mm		
	Downstream diameter	82.8	mm		
	Loss coefficient	0.123			
	Pressure drop			4.1	mbar
Pipe Loss	Reynolds Number	2.29 E 7			
	Friction factor	0.00457			
	Unit pressure drop	1.81	mbar per m		
	Length	0.08	m		
	Pressure drop			0.1	mbar

Pipe Loss	Unit pressure drop	1.83	mbar per m		
	Length	0.80	m		
	Pressure drop			1.5	mbar
Tee as Elbow Entering Run					
	Loss coefficient	1.08			
	Pressure drop			36.3	mbar
Pipe Loss	Unit pressure drop	1.86	mbar per m		
	Length	0.08	m		
	Pressure drop			0.1	mbar
Tee as Elbow Entering Run					
	Loss coefficient	1.08			
	Pressure drop			36.7	mbar
Pipe Loss	Unit pressure drop	1.91	mbar per m		
	Length	0.09	m		
	Pressure drop			0.2	mbar
Total Pressure Drop				118	mbar

The velocity and Mach Number in the pipe rises from 4.8 m / s and 0.03 at the inlet to 8.9 m / s and 0.06 at the connection to the relief valve.

With a heat flux of 7 000 W / m² on the sections with superinsulation and 33 000 W / m² on the sections without superinsulation, the calculated temperature rise due to heating is 0.1 K.

The pressure drop on the feed pipe to the relief valve is approximately 118 mbar which is only 3.0% of the set pressure of the valve. At this low value, the capacity relief valve has not been re-evaluated for the lower set pressure.

The maximum back pressure downstream of the relief valve which does not reduce the flow capacity of the relief is 0.74 bar G. The pressure drop of the elbow and the sharp edge expansion is calculated as 0.19 bar G which is less than the maximum and therefore acceptable.

Confirmation is required from the designers of the non-return valve flow capacity Kv value. With this proviso, the following valves can be selected:

~ The Anderson Greenwood valve 25905J34 / S with a set pressure of 4.00 atm / 4.05 bar G will have a flow capacity of 20 000 kg / hr

~ For compatibility with the Dipole, the Anderson Greenwood valve 25905K34 / S with a set pressure of 3.80 atm / 3.85 bar G will have a flow capacity of 27 100 kg / hr when the cryostat internal pressure is 5.42 bar A.

As a conditional conclusion, until the flow capacity of the non-return valve is confirmed, either valve is sufficient to vent the flow rate generated by a quench with no protection which is 15 140 kg / hr through the relief valve.

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 detailed results are listed in "JLab Q2-Q3 Relief 211_1 He Vent Pipe BD.pdf"

	Pipe inside diameter	108.2	mm internal to the CCR		
		82.8	mm external to the CCR		
Inlet Conditions	Pressure	6.583	bar A		
	Temperature	6.71	K		
	Vent flow rate	37350	kg / hr		
	Density	94.97	kg / m³		
	Viscosity	2.96 E-6	kg / m.s		
Internal to the CCR Sudden Contraction					
	Upstream diameter	Large			
	Loss coefficient	0.464			
	Pressure drop			31.1	mbar
Pipe Loss	Reynolds Number	4.13 E 7			
	Friction factor	0.00394			
	Unit pressure drop	2.45	mbar per m		
	Length	0.127	m		
	Pressure drop			0.3	mbar
Non-Return Valve	Valve Kv	270			
	Pressure drop			202	mbar
Pipe Loss	Unit pressure drop	2.48	mbar per m		
	Length	0.576	m		
	Pressure drop			1.4	mbar
External to the CCR Sudden Contraction					
	Upstream diameter	108.2	mm		
	Downstream diameter	82.8	mm		
	Loss coefficient	0.123			
	Pressure drop			24.8	mbar
Pipe Loss	Reynolds Number	5.49 E 7			
	Friction factor	0.00367			
	Unit pressure drop	8.89	mbar per m		
	Length	0.08	m		
	Pressure drop			0.7	mbar
Pipe Loss	Unit pressure drop	8.93	mbar per m		
	Length	0.80	m		
	Pressure drop			7.1	mbar

Tee as Elbow	Loss coefficient	1.08			
	Pressure drop			219.0	mbar
Pipe Loss	Unit pressure drop	9.11	mbar per m		
	Length	0.08	m		
	Pressure drop			0.7	mbar
Tee as Run	Loss coefficient	0.36			
	Pressure drop			74.6	mbar
Pipe Loss	Unit pressure drop	9.24	mbar per m		
	Length	0.05	m		
	Pressure drop			0.5	mbar
Elbow (long radius)	Loss coefficient	0.29			
	Pressure drop			61.0	mbar
Pipe Loss	Unit pressure drop	9.35	mbar per m		
	Length	0.10	m		
	Pressure drop			1.0	mbar
Burst Disc	Manufacturer	FIKE			
	Type	3.00" AXIUS Low Pressure			
	MNFA	7.39	in² (manufacturer's date)		
		4768	mm²		
	Effective orifice diameter	77.9	mm		
	KR	0.45	(manufacturer's date)		
	Helium density	86.83	kg / m³		
	Pressure drop			122.7	mbar
Sudden Expansion					
	Downstream diameter	Large			
	Pressure drop			219.5	mbar
Total Pressure Drop				967	mbar

The velocity and Mach Number in the pipe rises from 12 m / s and 0.07 at the inlet to 23 m / s and 0.14 at the outlet.

With a heat flux of 7 000 W / m² on the sections with superinsulation and 33 000 W / m² on the sections without superinsulation, the calculated temperature rise due to heating is offset by the temperature drop due to the expansion process and there is no net temperature rise.

The pressure on the outlet of the burst disc is calculated for a gas expansion from a sharp edge. The drawing shows a top plate which is 1¼" above the exit flange of the burst disc holder. On the basis of a visual examination it is recommended that this gap be increased.

Confirmation is required from the designers of the non-return valve flow capacity (Kv value). As a conditional conclusion, until the flow capacity of the non-return valve is confirmed, the total pressure drop from the reservoir to the downstream side of the burst disc is 0.97 bar at the required vent flow rate of 37 350 kg / hr. Since the internal pressure is 5.57 bar G there is sufficient capacity to vent through the burst disc the gas generated during a Loss of Vacuum to Air and an unprotected quench.

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 the temperature of liquid nitrogen cooled radiation screen which is 80 K and the cold surface is cooled by liquid helium and is at 5 K.

The gap between the radiation screen and the helium vessel is taken as the characteristic dimension.

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

	Helium gas pressure	1000	mbar
	Hot temperature	80	K
	Cold temperature	5	K
	Mid temperature	43	K
Helium properties	Density	1.130	kg / m³
	Specific heat capacity	5.231	kJ / kg.K
	Thermal conductivity	0.0420	W / m.K
	Viscosity	5.75E-6	kg / m.s
	Buoyancy	0.0235	K^{-1}
	Prandtl Number	0.7121	
	Grasshof Number	3.25E+7	
	Rayleigh Number	2.31E+7	
	Nusselt Number	35.4	(Parallel vertical plates)
	Heat Transfer Coefficient	40.7	W / m².K
	Heat flux	3060	W / m²
		0.31	W / cm²

The calculated heat flux is approximate and is less than half the design heat flux due to a Loss of Vacuum to Air which is 0.7 W / cm². The heat flux will be reduced by several factors on account of the superinsulation on the helium vessel. Therefore the Loss of Vacuum to Helium is a less severe condition than the Loss of Vacuum to Air and does not need to be analysed separately.

7.2 UNCONSTRAINED PIPE FLOW

The maximum supply pressure in the helium pipes is 2.5 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 MAWP of the helium vessel.

8 CONCLUSIONS

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

The vent flow rates have been evaluated as follows.

	Vent Pressure bar A	Vent Flow Rate kg / hr	Temperature K
Quench – Protection	5.47	15 000	6.30
Quench – No Protection	5.47	15 140	6.31
LOV to Air + Quench No Protection	6.59	37 350	6.71

The vent capacity has been evaluated as follows:

Relief Valve

	Conditions at the maximum flow rate	
Flow rate	15140	kg / hr
Pressure in the CCR reservoir	5.47	bar A
Temperature of the helium	6.3	K
Vent pipe pressure drop		less than 2% of the set pressure
Pressure at valve inlet – Fully open	4.46	bar G
Relief valve set pressure	4.05	bar G
	4.00	atm
Valve Manufacturer	Anderson Greenwood POPRV	
Valve Type	25905J34 / S	

For standardization with the Dipole the larger Anderson Greenwood 25905K34 / S relief valve could be selected.

Burst Disc

	Conditions at the maximum flow rate	
Flow rate	37350	kg / hr
Pressure in the CCR reservoir	6.58	bar A
Temperature of the helium	6.7	K
Burst disc manufacturer	FIKE	
Burst disc type	AXIUS Low Pressure	
Nominal size	3	in
MNFA	7.79	in^2
Vent pipe pressure drop	0.97	bar A

The Loss of Vacuum to Helium will generate a vent flow rate which is less than the Loss of Vacuum to Air.

The supply pressure of the helium is less than the MAWP of the helium vessel and the set pressure

Conditional on the flow capacity of the Non-Return valve in the CCR being confirmed as having a capacity greater or equal to a Kv of 270 (m^3 / hr), then the relief valve, the burst disc and the vent geometry described in this report have adequate relief capacity for the fault conditions described in this report.