1 INTRODUCTION

This report examines the pressure relief for the JLab Dipole 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 Dipole Relief 204_1 LOV + Quench No Protection.xls
	JLab Dipole Relief 204_1 Quench No Protection.xls
	JLab Dipole Relief 204_1 Quench Protection.xls
	JLab Dipole Relief 206_1 He RV.xls
	JLab Dipole Relief 207_1 He Z.xls
	JLab Dipole Relief 210_2 He Vent Pipe RV.xls
	JLab Dipole Relief 211_2 He Vent Pipe BD.xls
Attachments	JLab Dipole Relief 204_1 LOV + Quench No Protection.pdf
	JLab Dipole Relief 204_1 Quench No Protection.pdf
	JLab Dipole Relief 204_1 Quench Protection.pdf
	JLab Dipole Relief 207_1 He Z.pdf
	JLab Dipole Relief 210_2 He Vent Pipe RV.pdf
	JLab Dipole Relief 211_2 He Vent Pipe BD.pdf
Geometry documents	317111-JLA-201-001-FULL.exe
	317111-JLA-703-001.exe
	317111-JLA-CCR.exe
	317111-JLA-001-001.exe
	317111-JLA-301-001.exe
	317111-JLA-701-001.exe
	317111-JLA-702-001.exe
	Scans14705.pdf Drg No 67145-00501 Sheet 1 of 1
	Scans15047.pdf Drg No 67145-00500 Sheet 1 of 1

Rev	Date	Description
2	16 Mar 2013	Updated geometry for the vent pipes.

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.

"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

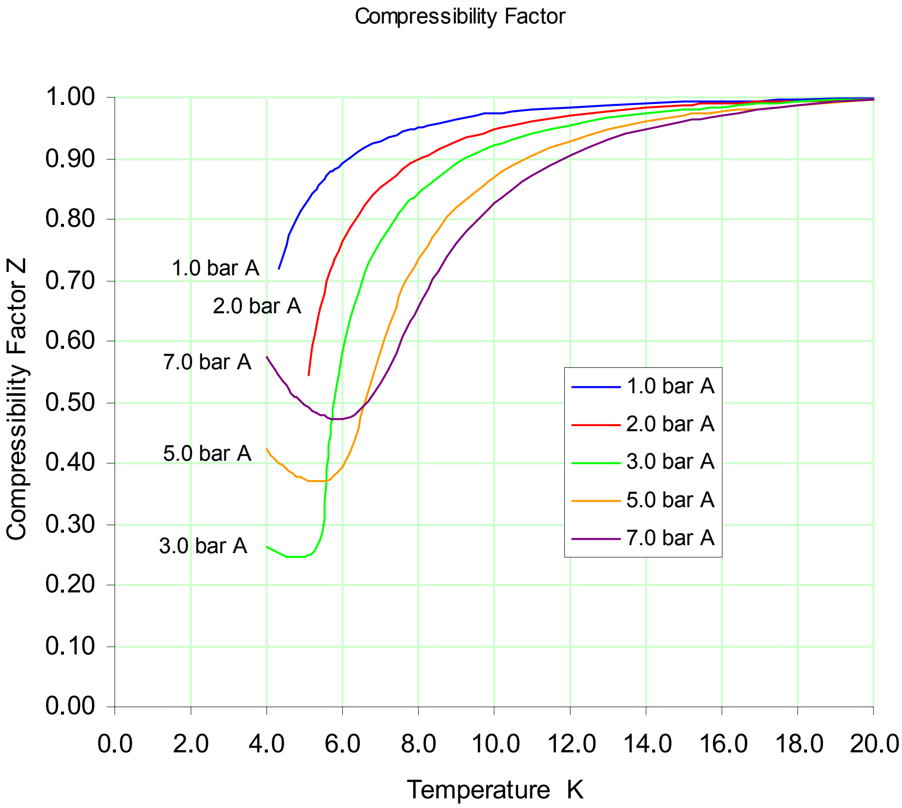
The following values are used for the heat flux to helium from a surface.

	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.

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 and this is expanded in the next section 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 where the compressibility factor Z is 0.51 which will increase the capacity of a relief valve by about 40% compared to the more 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	15.65	m²		
	Inner cylinder – straight length	7.95	m²		
	End pieces	2.17	m²		
	TOTAL Magnet Assembly			25.76	m²
Helium Chimney Pipe	Feed pipe	0.41	m²		
	Feed pipe manifold – Magnet assembly	0.12	m²		
	Return pipes – all three	3.00	m²		
	TOTAL Chimney Pipes			3.53	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	4.37	m²		
	Outer cylinder	14.36	m²		
	Inner cylinder – excluding coil surface	3.46	m²		
	End piece	0.96	m²		
	End piece	0.96	m²		
	TOTAL Magnet coil inner surface			4.37	m²
	TOTAL Magnet Assembly – less coil inner			19.74	m²

3.2 HELIUM INVENTORY

	Magnet vessel	145	litres
	Helium feed pipe	4	litres
	Return pipes – all three	58	litres
	CCR – working volume	92	litres
	CCR – vapour contents	28	litres
Totals	Working volume	299	litres
	Liquid helium inventory	271	litres
	Vapour helium inventory	28	litres

Rev	Date	Description
2	16 Mar 2013	Updated geometry for the vent pipes.

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 should be confirmed by JLab.

Rev	Date	Description
2	16 Mar 2013	Updated geometry for the vent pipes.

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 Dipole Relief 204_1 Quench Protection.pdf" and are summarised below.

Maximum surface temperature	160	K
Heat flux on quench	3.8	W / cm²
Magnet assembly surface area	4.37	m²
Heating to helium on quench	166	kW
Maximum energy released	16	MJ
Vent pressure	5.47	bar A
Time to initiate venting	0.9	seconds
Time to reach maximum flow rate	2.3	seconds
Maximum calculated flow rate	6.70	kg / s
	24100	kg / hr
Energy absorbed by helium at max. flow	0.38	MJ
Time to reduce inventory by 90%	7.9	seconds
Energy absorbed by helium	1.28	MJ

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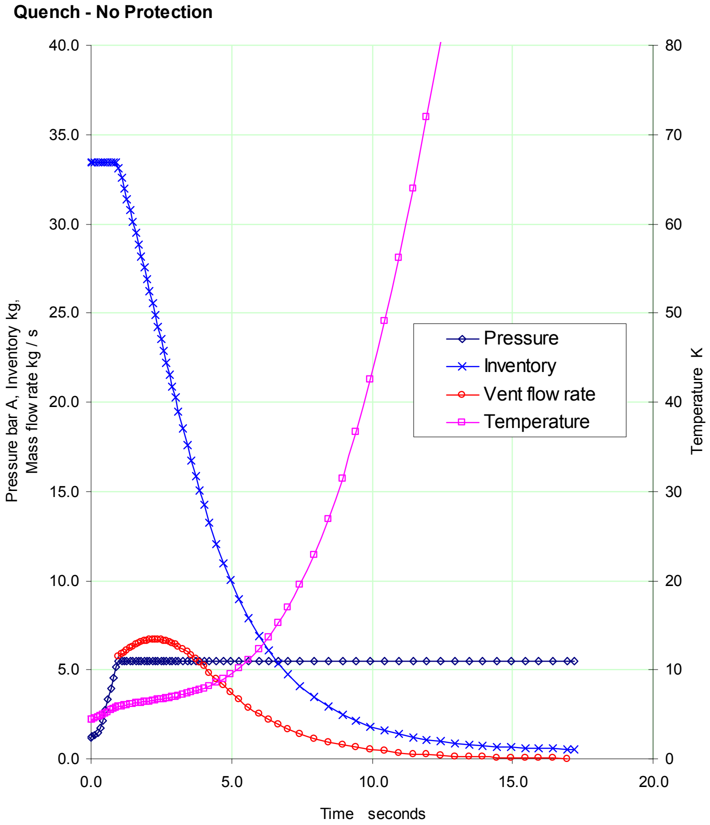
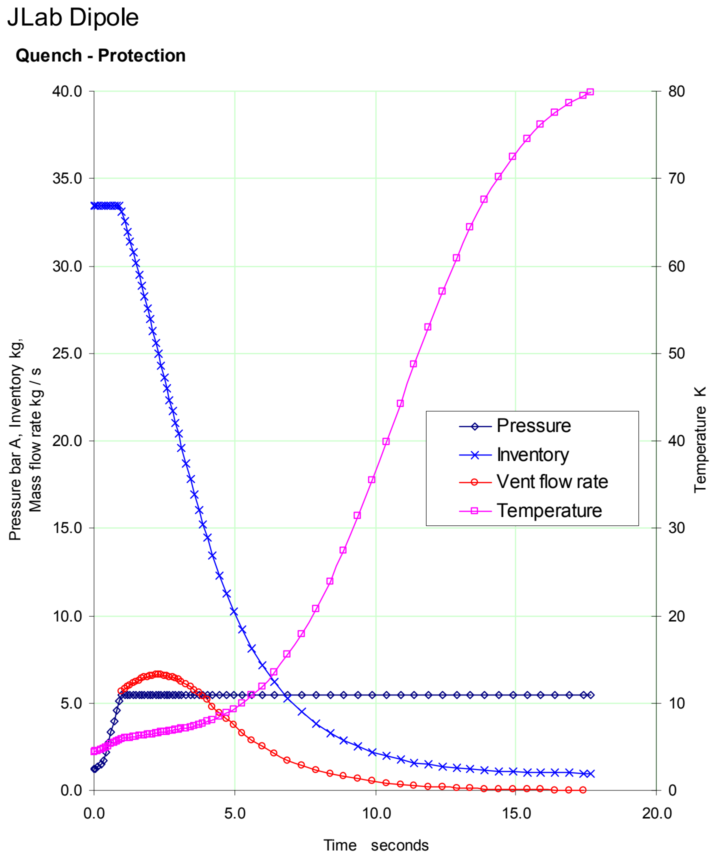


Rev	Date	Description
2	16 Mar 2013	Updated geometry for the vent pipes.

5.1.2 Quench – Protection

The detailed results of the analysis are presented in the attached "JLab Dipole 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	4.37	m²
Heating to helium on quench	166	kW
Maximum energy released	16	MJ
Vent pressure	5.47	bar A
Time to initiate venting	0.9	seconds
Time to reach maximum flow rate	2.3	seconds
Maximum calculated flow rate	6.61	kg / s
	23800	kg / hr
Energy absorbed by helium at max. flow	0.37	MJ
Time to reduce inventory by 90%	7.9	seconds
Energy absorbed by helium	1.23	MJ



Rev	Date	Description
2	16 Mar 2013	Updated geometry for the vent pipes.

5.1.3 Loss of Vacuum to Air and Quench

The detailed results of the analysis are presented in the attached "JLab Dipole 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	4.37	19.75	30.28	m²
Heating to helium on quench	166	138	212	kW
Total heating to helium	516	kW		
Maximum energy released	16	MJ		
Vent pressure	6.59	bar A		
Time to initiate venting	0.36	seconds		
Time to reach maximum flow rate	0.8	seconds		
Maximum calculated flow rate	17.90	kg / s		
	64400	kg / hr		
Energy absorbed by helium at max. flow	0.40	MJ		
Time to reduce inventory by 90%	3.3	seconds		
Energy absorbed by helium	1.48	MJ		

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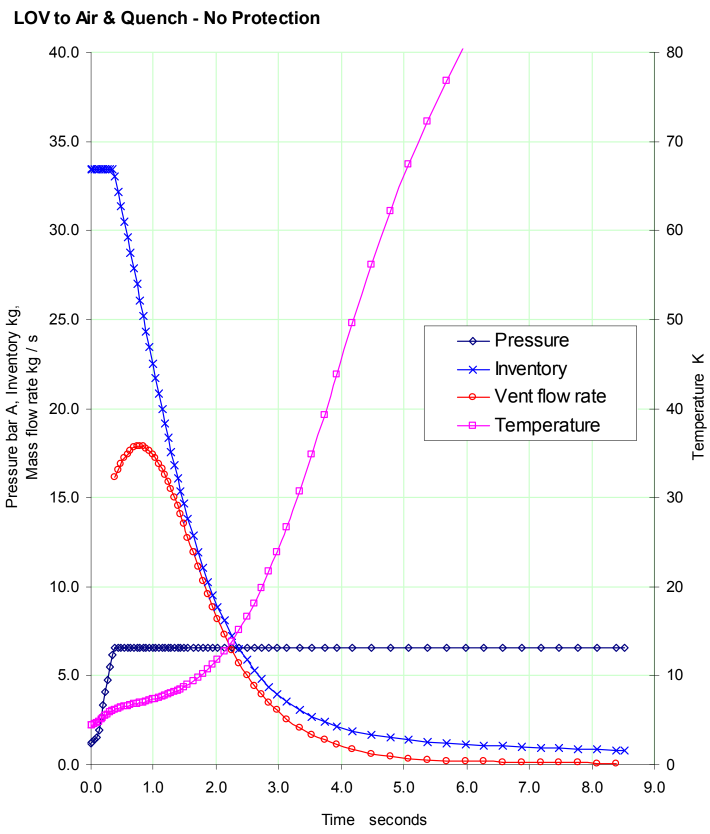

Rev	Date	Description
2	16 Mar 2013	Updated geometry for the vent pipes.

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	23 800	6.58
Quench – No Protection	5.47	24 100	6.59
LOV to Air + Quench No Protection	6.59	64 400	6.94

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 67145-00500 Rev A and 67145-00501 Rev - which have been submitted as documents Sans15047.pdf and Scans14705.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 type as proposed in the JLab report “safety_analysis_Dec_2010.pdf” but one size larger.

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	25905K34 / S			
	Orifice diameter	38.9	mm		
A	Orifice area	1186	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	6.59	K	11.7	R
k	Isentropic expansion coefficient	3.516			
Z	Compressibility factor Z	0.4807			
	Density	83.17	kg / m³	5.192	lb / ft³
C	Pressure ratio factor	468.9			
K_b	Back pressure correction factor	1.000			
K_c	Combination correction factor	1.000			
W	Relieving capacity	25340	kg / hr	55900	lb / hr

The valve in the same class having a smaller orifice of 830.3 mm² is the 25905J34 / S. The capacity of this valve is 17 740 kg / hr which is not adequate to handle the flow rate generated by a quench.

The calculations for the pressure drop for the vent pipe to the relief valve are summarised below. The detailed results are listed in "JLab Dipole Relief 210_2 He Vent Pipe RV.pdf" and are summarised below.

	Pipe inside diameter	108.2	mm		
Inlet	Pressure	5.472	bar A		
	Temperature	6.59	K		
	Vent flow rate	24100	kg / hr		
	Density	83.17	kg / m³		
	Viscosity	2.71 E-6	kg / m.s		
Sudden Contraction					
	Upstream diameter	Large			
	Loss coefficient	0.464			
	Pressure drop			14.8	mbar
Pipe Loss	Reynolds Number	2.91 E 7			
	Friction factor	0.00430			
	Unit pressure drop	1.27	mbar per m		
	Length	0.127	m		
	Pressure drop			0.2	mbar
Non-Return Valve	Valve Kv	270			
	Pressure drop			96.2	mbar
Pipe Loss	Unit pressure drop	1.29	mbar per m		
	Length	0.576	m		
	Pressure drop			0.7	mbar
Pipe Loss	Unit pressure drop	1.30	mbar per m		
	Length	0.09	m		
	Pressure drop			0.1	mbar
Pipe Loss	Unit pressure drop	1.30	mbar per m		
	Length	0.43	m		
	Pressure drop			0.6	mbar
Tee as Elbow Entering Run					
	Loss coefficient	1.02			
	Pressure drop			33.8	mbar

Pipe Loss	Unit pressure drop	1.33	mbar per m		
	Length	0.08	m		
	Pressure drop			0.1	mbar
Tee as Elbow Entering Run					
	Loss coefficient	1.02			
	Pressure drop			34.7	mbar
Pipe Loss	Unit pressure drop	1.36	mbar per m		
	Length	0.08	m		
	Pressure drop			0.1	mbar
Total Pressure Drop				181	mbar

The velocity and Mach Number in the pipe rises from 8.8 m / s and 0.06 at the inlet to 9.5 m / s and 0.67 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 offset by the temperature drop due to the expansion process. The net temperature rise along the vent pipe is 0.08 K.

When the relief valve capacity is re-evaluated with an inlet pressure which is lower by 0.181 bar (an inlet pressure of 4.277 bar A) then the flow capacity is calculated as 24 090 kg / hr. This is oversized by 1.2% for a quench with protection which generates a vent flow rate of 23 800 kg / hr and on size for a quench when there is no protection which generates a flow rate of 24 100 kg / hr. The set pressure of the relief valve should be set at 0.18 bar below the desired relieving pressure to allow for the vent pipe pressure drop. Therefore the set pressure should be set at 3.80 atm which is 3.85 bar G. When fully open the pressure at the valve inlet is 4.23 bar G. Including the pressure drop along the vent pipe the pressure in the cryostat is 4.41 bar G which is 5.42 bar G.

The maximum back pressure downstream of the relief 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 0.17 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. As a conditional conclusion, until the flow capacity of the non-return valve is confirmed, the Anderson Greenwood valve 25905K34 / S with a set pressure of 3.80 atm / 3.85 bar G will have a flow capacity of 24 100 kg / hr when the cryostat internal pressure is 5.42 bar A. This is sufficient to vent the flow rate generated by a quench with no protection which is.24 100 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 detailed results are listed in "JLab Dipole Relief 211_2 He Vent Pipe BD.pdf"

	Pipe inside diameter	108.2	mm		
Inlet Conditions	Pressure	6.583	bar A		
	Temperature	6.94	K		
	Vent flow rate	64430	kg / hr		
	Density	87.39	kg / m³		
	Viscosity	2.86 E-6	kg / m.s		
Sudden Contraction					
	Upstream diameter	Large			
	Loss coefficient	0.464			
	Pressure drop			100.7	mbar
Pipe Loss	Unit pressure drop	6.89	mbar per m		
	Length	0.127	m		
	Pressure drop			0.9	mbar
Non-Return Valve	Valve Kv	270			
	Pressure drop			658	mbar
Pipe Loss	Unit pressure drop	7.25	mbar per m		
	Length	0.576	m		
	Pressure drop			4.2	mbar
Pipe Loss	Unit pressure drop	7.28	mbar per m		
	Length	0.09	m		
	Pressure drop			0.7	mbar
Pipe Loss	Unit pressure drop	7.29	mbar per m		
	Length	0.43	m		
	Pressure drop			3.2	mbar
Tee as Elbow					
	Loss coefficient	1.02			
	Pressure drop			239.7	mbar
Pipe Loss	Unit pressure drop	7.47	mbar per m		
	Length	0.08	m		
	Pressure drop			0.6	mbar
Tee as Run					
	Loss coefficient	0.34			
	Pressure drop			82.2	mbar

Pipe Loss	Unit pressure drop	7.58	mbar per m		
	Length	0.08	m		
	Pressure drop			0.6	mbar
Elbow (long radius)					
	Loss coefficient	0.27			
	Pressure drop			66.4	mbar
Pipe Loss	Unit pressure drop	7.69	mbar per m		
	Length	0.25	m		
	Pressure drop			1.9	mbar
Burst Disc	Manufacturer	FIKE			
	Type	AXIUS Low Pressure			
	MNFA	12.7	in² (manufacturer's date)		
		8194	mm²		
	Effective orifice diameter	102.8	mm		
	KR	0.45	(manufacturer's date)		
	Helium density	75.45	kg / m³		
	Pressure drop			142.3	mbar
Sudden Expansion					
	Downstream diameter	Large			
	Pressure drop			257.7	mbar
Total Pressure Drop				1559	mbar

The velocity and Mach Number in the pipe rises from 22 m / s and 0.14 at the inlet to 26 m / s and 0.18 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. The net temperature drop along the vent pipe is 0.3 K.

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 1.6 bar at the required vent flow rate of 64 430 kg / hr. Since the internal pressure is 5.7 bar G there is sufficient capacity to vent the gas during a Loss of Vacuum to Air and an unprotected quench.

Rev	Date	Description
2	16 Mar 2013	Updated geometry for the vent pipes.

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	23 800	6.58
Quench – No Protection	5.47	24 100	6.59
LOV to Air + Quench No Protection	6.59	64 400	6.94

The vent capacity has been evaluated as follows:

Relief Valve

	Conditions at the maximum flow rate	
Flow rate	24100	kg / hr
Pressure in the CCR reservoir	5.42	bar A
Temperature of the helium	6.6	K
Vent pipe pressure drop	0.18	bar
Pressure at valve inlet – Fully open	4.23	bar G
Relief valve set pressure	3.85	bar G
	3.80	atm
Valve Manufacturer	Anderson Greenwood POPRV	
Valve Type	25905K34 / S	

Burst Disc

	Conditions at the maximum flow rate	
Flow rate	64400	kg / hr
Pressure in the CCR reservoir	6.58	bar A
Temperature of the helium	6.9	K
Burst disc manufacturer	FIKE	
Burst disc type	AXIUS Low Pressure	
Nominal size	4	in
MNFA	12.7	in^2
Vent pipe pressure drop	2.16	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

These conclusions are provisional until the flow capacity of the non return valve in the CCR has been confirmed.

Rev	Date	Description
2	16 Mar 2013	Updated geometry for the vent pipes.