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, defines the geometry and the resulting calculated vent flow rates. The report then summarises the vent flow rate, the chimney pipe pressure drop, the vent pipe from the CCR pressure drop and the capacity of the relief devices.

Reference	JLab Q2-Q3 Relief 204_2 LOV + Quench No Protection.xls
	JLab Q2-Q3 Relief 204_2 Quench No Protection.xls
	JLab Q2-Q3 Relief 204_2 Quench Protected.xls
	JLab Q2-Q3 Relief 206_2 He RV.xls
	JLab Dipole Relief 207_1 He Z.xls
	JLab Q2-Q3 Relief 235_1 Chimney Drg 318711-JLA-001-001 - Quench No Protection.xls
	JLab Q2-Q3 Relief 236_1 He Vent Pipe RV.pdf
	JLab Q2-Q3 Relief 237_1 He Vent Pipe Downstream of RV.xls
	JLab Q2-Q3 Relief 238_1 Chimney Drg 318711- JLA-001-001 - LOV & Quench No Protection.xls
	JLab Q2-Q3 Relief 239_1 He Vent Pipe BD.xls
	rep SJQ3(1) Quench SHMS Quad.pdf
	Cv of SHMA Check Valve_v2.pdf
	CFD 821 JLab NRV
	CFD 821 JLab NRV Wa
Attachments	JLab Q2-Q3 Relief 204_2 LOV + Quench No Protection.pdf
	JLab Q2-Q3 Relief 204_2 Quench No Protection.pdf
	JLab Q2-Q3 Relief 204_2 Quench Protected.pdf
	JLab Q2-Q3 Relief 206_2 He RV.pdf
	JLab Dipole Relief 207_1 He Z.pdf
	JLab Q2-Q3 Relief 235_1 Chimney Drg 318711-JLA-001-001 - Quench No Protection.pdf
	JLab Q2-Q3 Relief 236_1 He Vent Pipe RV.pdf
	JLab Q2-Q3 Relief 237_1 He Vent Pipe Downstream of RV.pdf
	JLab Q2-Q3 Relief 238_1 Chimney Drg 318711-JLA-001-001 - LOV & Quench No Protection.pdf
	JLab Q2-Q3 Relief 239_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
	318711-JLA-001-001-detail of Helium chimney-revB.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
	318711-JLA-0200-section Rev A.PDF

Rev	Date	Description
3	5 Oct 2016	Reference document added; Text changes.
2	2 Oct 2016	Analysis for chimney pressure drop; Heat flux modified to include temperature effects.

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

“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 bare metal surface.

	Surface facing helium	Bare metal	
	Other surface	Bare metal	
	Condition	Loss of Vacuum to Air (LOV to Air) Magnet quench	
	Reference heat flux	3.8	W / cm²
Reference temperatures	Metal	63	K (freezing temperature of air)
	Helium	4.5	K
Comparison	Lehmann & Zahn	3.8	W / cm²
	Harrison	3.1	W / cm²

The following value is used as a reference the heat flux to helium from a metal surface covered in superinsulation.

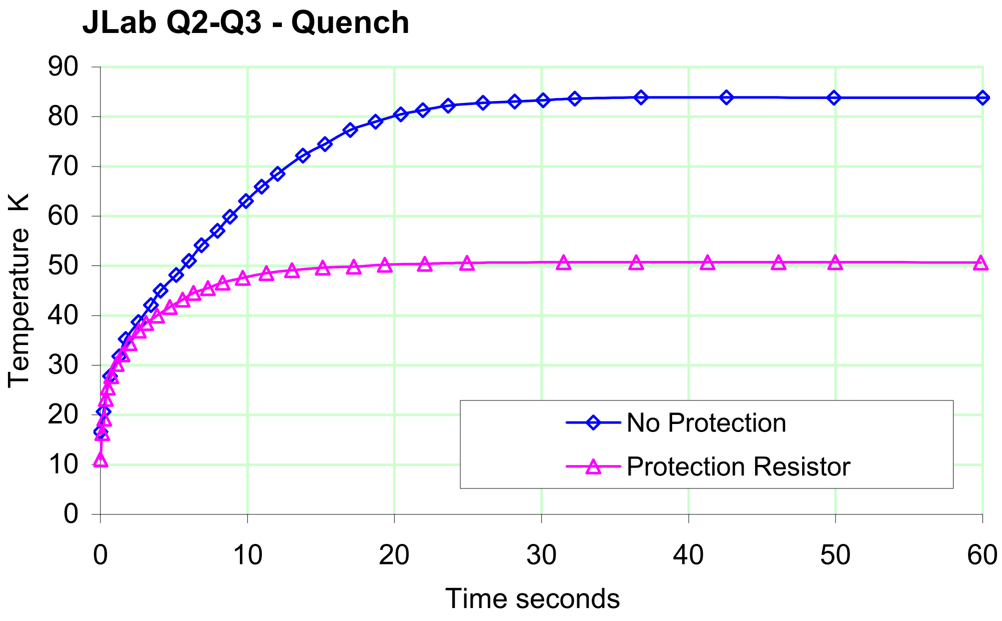
	Surface facing helium	Bare metal	
	Other surface	Superinsulation or Cryolite	
	Condition	Loss of Vacuum to Air (LOV to Air)	
	Heat flux	0.7	W / cm²
Reference temperatures	Metal	63	K (freezing temperature of air)
	Helium	4.5	K
Comparison	Lehmann & Zahn	0.6	W / cm² (Superinsulation)
	Harrison	0.44	W / 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.

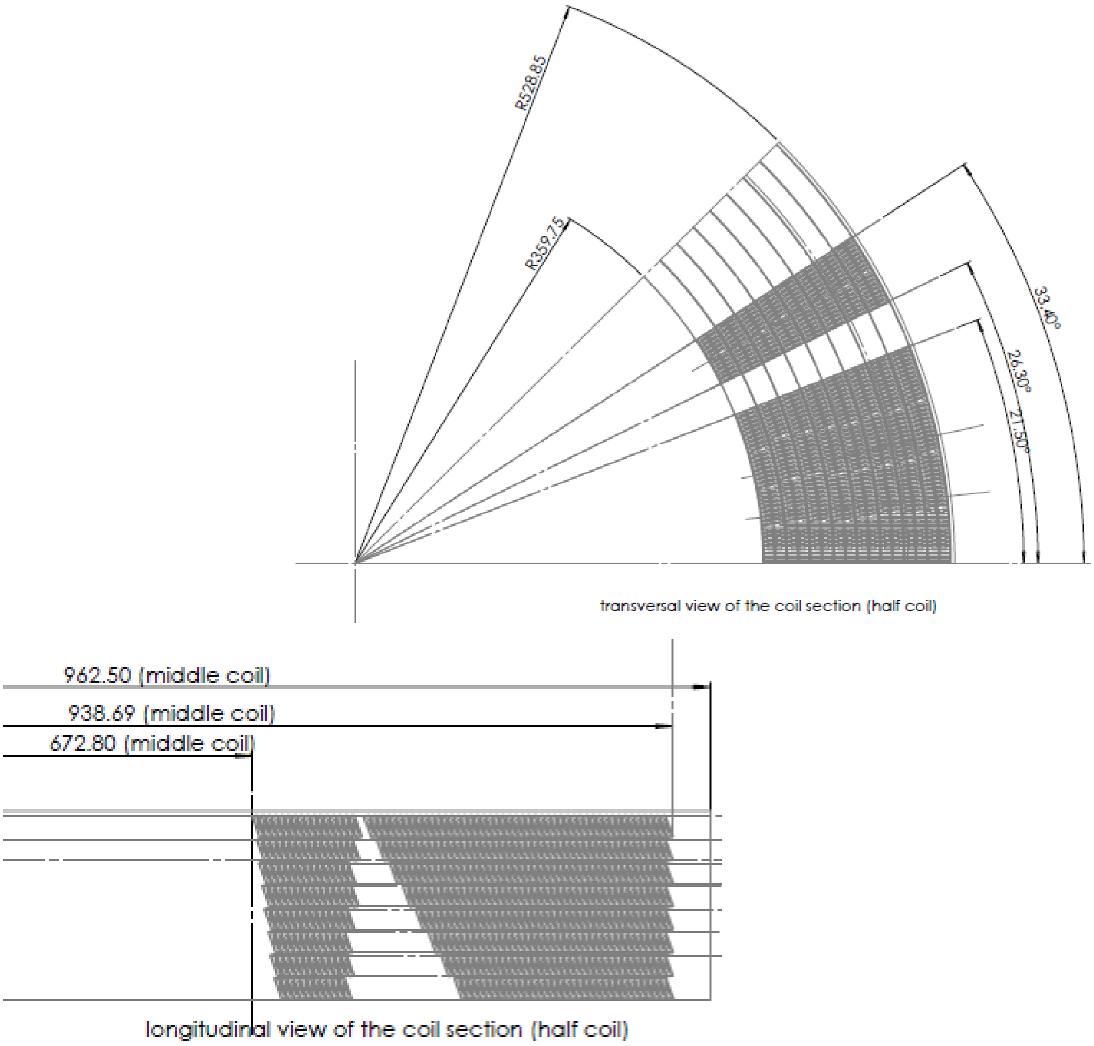
The heat flux to helium is scaled in proportion to the temperature difference compared to the difference of the reference temperatures. In the case of a Loss of

Vacuum it is assumed that the inside metal surface instantly rises to the freezing temperature of air, for which the freezing temperature of nitrogen at 63 K has been used.

In the case of a quench, reference has been made to the report by Martin Wilson “rep SJQ3(1) Quench SHMS Quad.pdf”. The temperature rise with time is used in the vent analysis program to define the temperature of the magnet surface. The chart for the temperature rises are illustrated below for a quench with a protection resistor and for a quench having no protection.



The heated surface area for a quench is taken as the winding surface on the inside diameter of the magnet assembly: the outer diameters of the winding are covered by the collars etc. The diagram below shows the cross section of the quadrupole assembly and illustrates qualitatively the proportion of the inside diameter where the helium is in contact with the superconductor winding, the shaded sections are the superconductor.



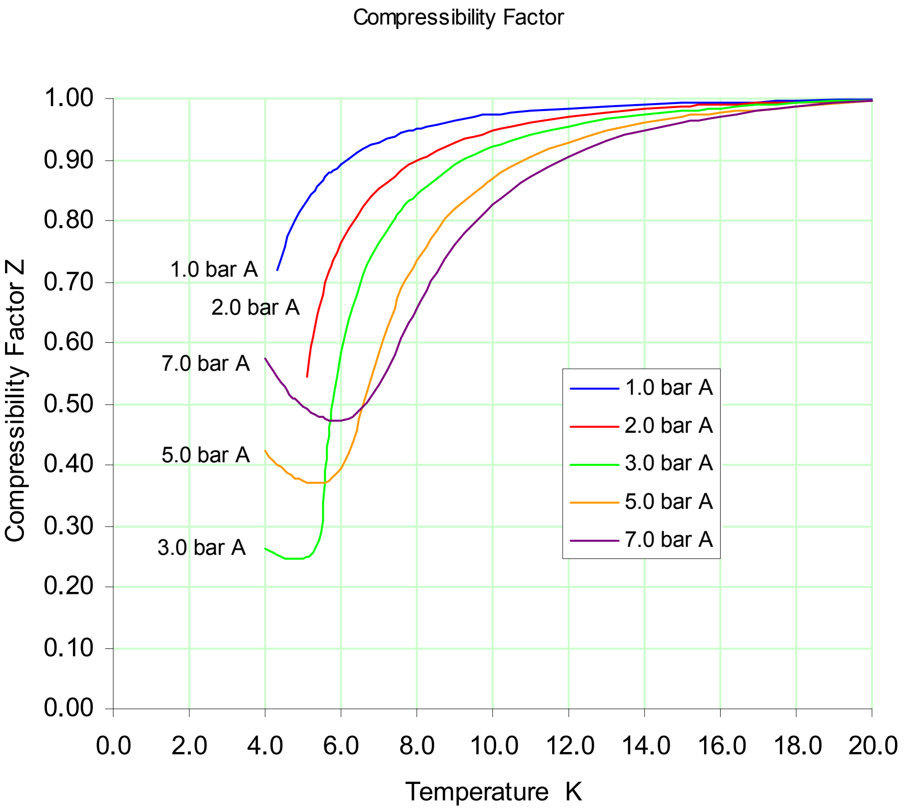
318711-JLA-0200-section Rev A.PDF

The perimeter wetted by the superconductor is 21.50° plus 26.30° less 33.40° which is a total of 28.6° out of 45.0°. As a simplification the wetted surface area is taken as 64% of the inside diameter over an average length of the winding of 1.88 m.

This is conservative since the quench will originate in one zone and then propagate. Therefore the wetted area will be less than this.

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	0.15	m²		
	Feed pipe manifold – Magnet assembly	0	m²		
	Return pipes – all three	0.83	m²		
	TOTAL Chimney Pipes			0.97	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	1.0	litres
	Return pipes – all three	14.6	litres
	CCR – working volume	92	litres
	CCR – vapour contents	28	litres
Totals	Working volume	237	litres
	Liquid helium inventory	209	litres
	Vapour helium inventory	28	litres

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 CHIMNEY VENT PIPE

The geometry of the two Chimney pipes carrying the current leads and the single Chimney pipe carrying the instrumentation is defined in the drawing “318711-JLA-001-001-detail of Helium chimney-revB.PDF”.

3.5 VENT PIPE INTERNAL TO THE CCR

The vent pipe of the CCR is 4.00” nb Schedule 10 and contains a non-return valve. The pressure drop for the vent pipe will be modelled as follows:

Sharp edge entry						
Pipe	Length	127	mm	Diameter	108.2	mm
Non return valve	Kv[*]	270	(Estimate)			
Pipe	Length	576.1	mm	Diameter	108.2	mm

The valve flow coefficient for the non-return valve has been evaluated by JLab report “Cv of SHMA Check Valve_v2.pdf” and also by Sigmaphi. The results summarised below.

JLab	Air	Cv = 366	Kv = 317	$x_T = 0.3$
JLab	Air	Cv = 311	Kv = 269	$x_T = 0.6$
JLab	Air	Cv = 299	Kv = 259	$x_T = 0.84$
JLab	Air	Cv = 294	Kv = 254	$x_T = 1.0$
JLab	Water	Cv = 228	Kv = 197	17.9 kg / s
JLab	Water	Cv = 228	Kv = 197	13.6 kg / s
Sigmaphi	Helium	Cv = 337	Kv = 291	17.9 kg / s, 6.92 K
Sigmaphi	Water	Cv = 328	Kv = 284	17.9 kg / s

For this analysis a value of a Kv of 250 will be used. This discounts the Kv values evaluated by JLab for water.

It is assumed that there is no back pressure downstream of the relief valve or the burst disc.

---

[*] In this report valve flow coefficient values for Kv are in units equivalent to m^3 / hr and bar.

4 ANALYSIS

The method of analysis is as follows:

1. The heat flux is scaled for the temperature difference 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 as a function of 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 evaluate the pressure drop along the chimney, from the CCR and across the relief devices in order to confirm that the available pressure is adequate to move the required vent flow rate.

The variations from the previous issue number 1 of this report are listed below.

a) In the earlier report the heat flux was constant. In this version the heat flux is scaled in proportion to the temperature difference.

b) In the earlier report the heat load for the Loss of Vacuum condition was overstated by adding a heat load for the outside diameter of the magnet assembly. The error has been corrected for this version of the report.

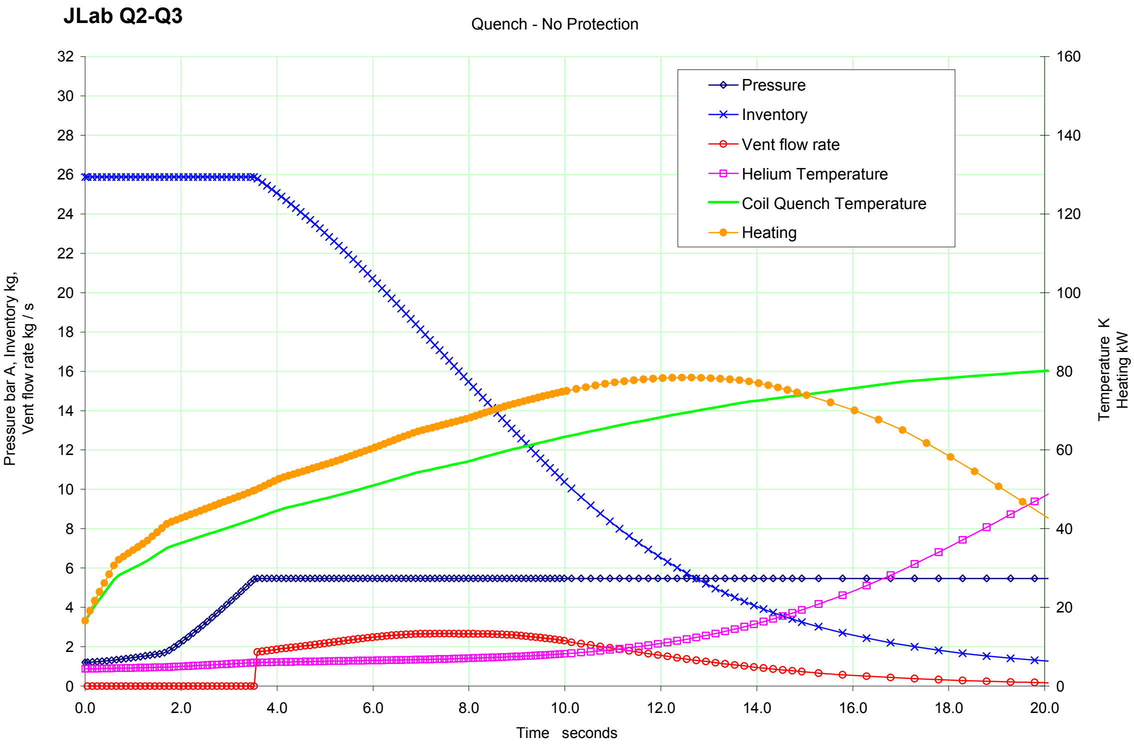
c) Analysis of the pressure drop in the chimney has been included in this version of the report.

5 RESULTS

5.1.1 Quench – No Protection

The detailed results of the analysis are presented in the attached “JLab Q2-Q3 Relief 204_2 Quench - No Protection.pdf” and are summarised below.

Reference temperature	80	K		
Reference heat flux	3.8	W / cm²		
Heated surface area	2.71	m²		
Maximum heating	78	kW		
Maximum energy released	9.9	MJ		
Vent pressure	5.47	bar A		
Time to initiate venting	3.54	seconds		
Time to reach maximum flow rate	7.49	seconds		
Maximum calculated flow rate	2.66	kg / s at	6.89	K
	9590	kg / hr		
Energy absorbed by helium at max. flow	0.37	MJ		
Time to reduce inventory by 90%	15.8	seconds		
Energy absorbed by helium	0.99	MJ		

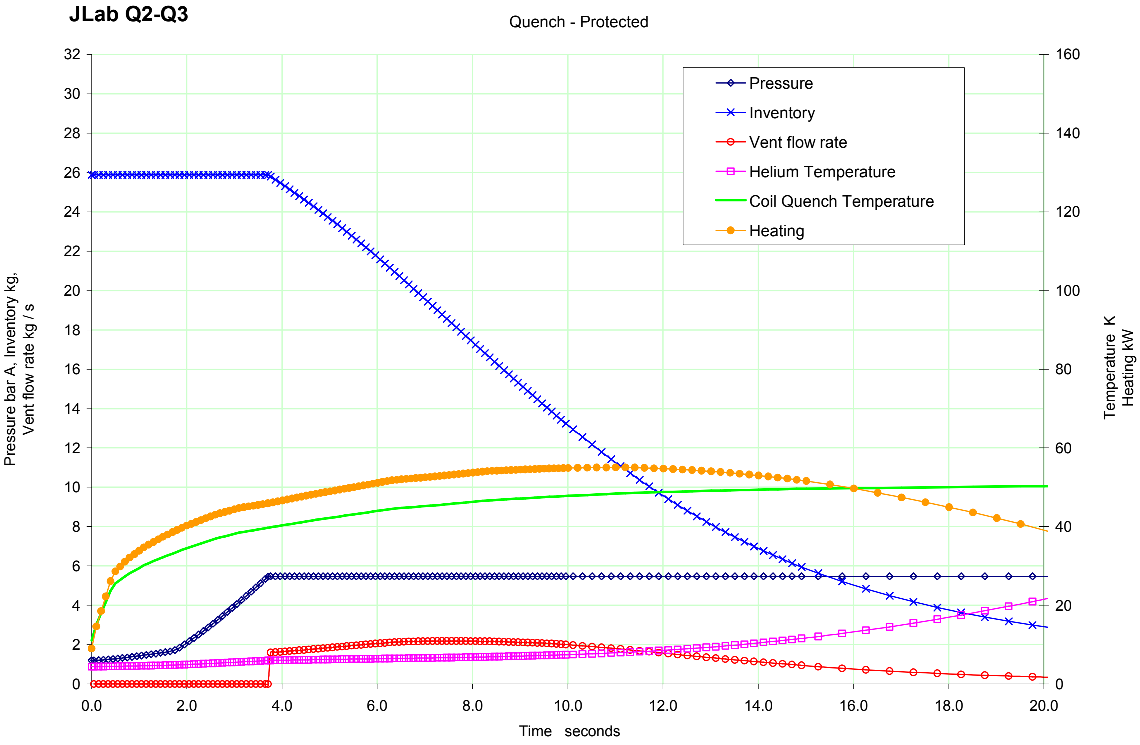


Rev	Date	Description
3	5 Oct 2016	Reference document added; Text changes.
2	2 Oct 2016	Analysis for chimney pressure drop; Heat flux modified to include temperature effects.

5.1.2 Quench – Protection

The detailed results of the analysis are presented in the attached "JLab Q2-Q3 Relief 204_2 Quench Protected.pdf" and are summarised below.

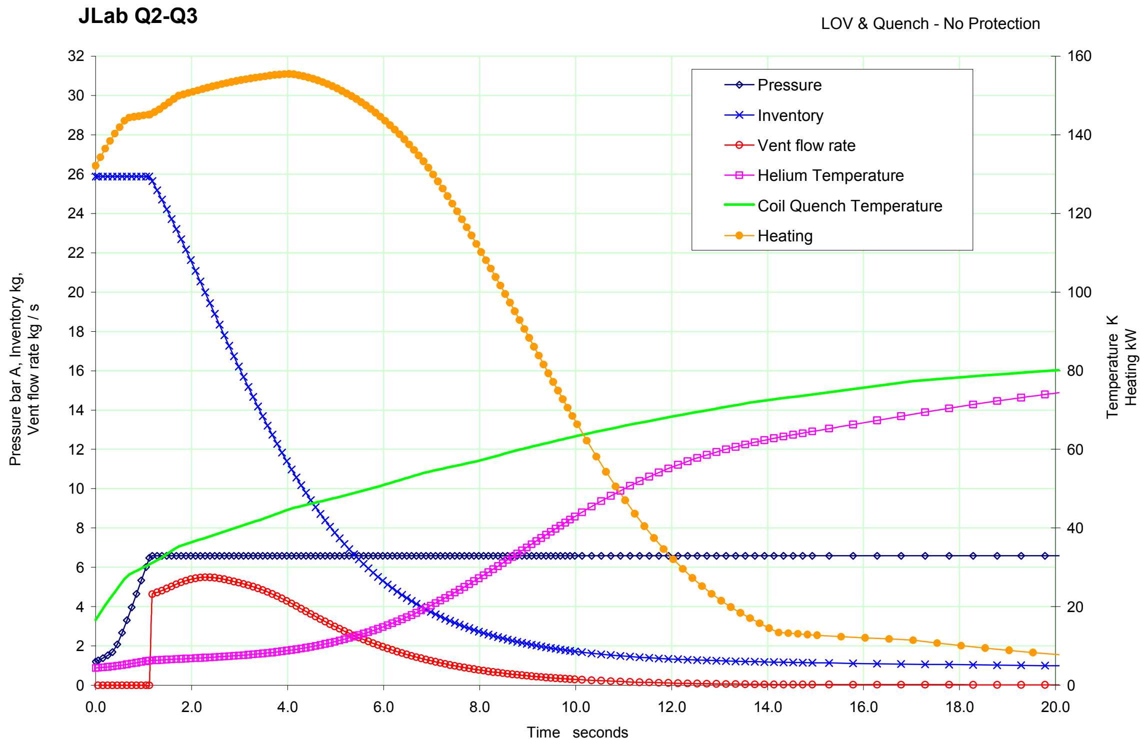
Reference temperature	80	K		
Reference heat flux	3.8	W / cm²		
Heated surface area	2.71	m²		
Maximum heating	55	kW		
Maximum energy released	2.2	MJ		
Vent pressure	5.47	bar A		
Time to initiate venting	3.71	seconds		
Time to reach maximum flow rate	7.46	seconds		
Maximum calculated flow rate	2.19	kg / s at	6.70	K
	7870	kg / hr		
Energy absorbed by helium at max. flow	0.32	MJ		
Time to reduce inventory by 90%	20.5	seconds		
Energy absorbed by helium	0.98	MJ		



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_2 LOV + Quench No Protection.pdf” and are summarised below.

Reference temperature	80	63		K
Reference heat flux	3.8	0.70		W / cm²
Heated surface area	2.71	16.50		m²
Maximum heating	155	kW		
Maximum quench energy released	9.9	MJ		
Vent pressure	6.59	bar A		
Time to initiate venting	1.13	seconds		
Time to reach maximum flow rate	2.28	seconds		
Maximum calculated flow rate & temperature	5.49	kg / s at	7.03	K
	19780	kg / hr		
Energy absorbed by helium at max. flow	0.33	MJ		
Time to reduce inventory by 90%	8.1	seconds		
Energy absorbed by helium	1.17	MJ		



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 – Protected	5.47	7 870	6.70
Quench – No Protection	5.47	9 590	6.89
LOV to Air + Quench No Protection	6.59	19 780	7.03

6 RELIEF VALVE CAPACITY: QUENCH - NO PROTECTION

The capacity of the relief valve, the pressure drop along the chimney from the magnet assembly to the CCR and the pressure drop from the CCR to the relief valve are evaluated.

The geometry of the two Chimney pipes carrying the current leads and the single Chimney pipe carrying the instrumentation is defined in the drawing “318711-JLA-001-001-detail of Helium chimney-revB.PDF”.

The geometry of the vent pipe from the CCR is taken from the drawings 67145-00504 Rev A and 67145-00503 Rev B which have been submitted as documents Scans14875.pdf and Scans15049.pdf. The vertical rise of the pipe is vacuum insulated. Under the quench conditions, when the vacuum insulation remains intact, the heat flux on these sections of pipe is negligible compared to the quench heat load. The un-insulated sections of pipe which are exposed to atmosphere are given a heat flux 38 000 W / m².

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. The details of the calculations are listed in “JLab Q2-Q3 Relief 206_2 He RV.pdf”.

	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	6.89	K	12.40	R
k	Isentropic expansion coefficient	4.367			
Z	Compressibility factor Z	0.5400			
	Density	70.80	kg / m³	4.420	lb / ft³
C	Pressure ratio factor	446.0			
K_b	Back pressure correction factor	1.000			
K_c	Combination correction factor	1.000			
W	Relieving capacity	15570	kg / hr	34300	lb / hr

The vent flow rate from an unprotected quench is 9 590 kg / hr which is 62% of the full flow capacity of the valve at 15 570 kg / 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 21 880 kg / hr. Although larger than necessary it may be desirable to use this valve to reduce the spares inventory.

6.2 CHIMNEY: MAGNET TO CCR

The pressure drop for the three pipes of the Chimney assembly is evaluated in the design spreadsheet “JLab Q2-Q3 Relief 235_1 Chimney 318711-JLA-001-001 – Quench No Protection.xls” using the geometry illustrated in the drawing “318711-JLA-001-001-detail of Helium chimney-revB.PDF”.

A summary of the calculation method of the design spreadsheet is listed below:

1. The vent flow rate is defined by the analysis for Quench – No Protection.
2. The pressure drop due to friction losses, section changes, pipe fittings and hydrostatic pressure is calculated. The section changes include the restriction at each clamp for the superconductor and the instrumentation. The pipe flow area makes an allowance for the area obstructed by the instrumentation and the superconductor.
3. The change in pressure and temperature as calculated in one node are used to adjust the properties for the subsequent node along the length of the flow path of the Chimney.
4. A convergence routine adjusts the flow rate in the three Chimney pipes so that the pressure drop along the length of each Chimney is equal.

The summary results are included as the attachment “JLab Q2-Q3 Relief 235_1 Chimney 318711-JLA-001-001 – Quench No Protection.pdf”. (Compared to the vent process from the CCR described in the next section, the details of the analysis are too extensive to be listed in the report and should be obtained from the attachment.)

The results show that with an inlet pressure and temperature of 5.50 bar A and 6.89 K, the outlet pressure and temperature at the CCR helium reservoir are

5.47 bar A and 6.88 K. (The temperature becomes colder since the gas conditions are below the Joule-Thomson Inversion temperature and the gas is expanding.)

A summary of the parameters is listed below.

		Instrumentation Chimney	Superconductor Chimney	Total	
	Number	1	2	3	
	Mass flow rate	2 817	6 777	9 594	kg / hr
Pressure Drop	- Friction losses	1.3	1.0		mbar
	- Section change	10.0	11.8		mbar
	- Fittings	10.2	8.6		mbar
	- Hydrostatic	8.7	8.7		mbar
Total Pressure drop		30.1	30.1	30	mbar

6.3 VENT PIPE CCR TO ATMOSPHERE

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 236_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	5.473	bar A		
	Temperature	6.88	K		
	Vent flow rate	9594	kg / hr		
	Density	71.18	kg / m³		
	Viscosity	2.58 E-6	kg / m.s		
Internal to the CCR Sudden Contraction					
	Upstream diameter	Large			
	Loss coefficient	0.464			
	Pressure drop			2.7	mbar
Pipe Loss	Reynolds Number	1.21 E 7			
	Friction factor	0.0053			
	Unit pressure drop	0.29	mbar per m		
	Length	0.127	m		
	Pressure drop			0.04	mbar
Non-Return Valve	Valve Kv	250			
	Pressure drop			21.3	mbar
Pipe Loss	Unit pressure drop	0.29	mbar per m		
	Length	0.576	m		
	Pressure drop			0.2	mbar

External to the CCR Sudden Contraction					
	Upstream diameter	108.2	mm		
	Downstream diameter	82.8	mm		
	Loss coefficient	0.12			
	Pressure drop			2.1	mbar
Pipe Loss	Reynolds Number	1.59 E 7			
	Friction factor	0.0050			
	Unit pressure drop	1.04	mbar per m		
	Length	0.08	m		
	Pressure drop			0.1	mbar
Pipe Loss	Unit pressure drop	1.06	mbar per m		
	Length	0.72	m		
	Pressure drop			0.8	mbar
Tee as Elbow Entering Run					
	Unit pressure drop	1.06	mbar per m		
	Length	0.17	m		
	Pressure drop			0.2	mbar
	Loss coefficient	1.02			
	Pressure drop			17.8	mbar
Pipe Loss	Unit pressure drop	1.09	mbar per m		
	Length	0.05	m		
	Pressure drop			0.1	mbar
Tee as Elbow Entering Run					
	Unit pressure drop	1.09	mbar per m		
	Length	0.17	m		
	Pressure drop			0.2	mbar
	Loss coefficient	1.02			
	Pressure drop			18.5	mbar
Pipe Loss	Unit pressure drop	1.13	mbar per m		
	Length	0.09	m		
	Pressure drop			0.1	mbar
Total Pressure Drop				64	mbar

The velocity and Mach Number in the pipe rises from 4.1 m / s and 0.03 at the inlet to 7.6 m / s and 0.05 at the connection to the relief valve.

With a heat flux of 33 000 W / m² on the pipe sections without superinsulation, the calculated temperature rise due to heating is 0.2 K.

The total pressure drop on the pipework upstream of the relief valve is therefore 30 mbar for the chimney and 64 mbar for the pipe from the CCR which is a total of 94 mbar and therefore 2.3% of the set pressure. Since this is less than the 3% of the set pressure it is acceptable.

The maximum back pressure downstream of the relief valve which does not reduce the flow capacity of the relief is 0.96 bar G. The pressure drop of the elbow and the sharp edge expansion is calculated as 0.06 bar G which is less than the maximum and therefore acceptable (“JLab Q2-Q3 Relief 237_1 He Vent Pipe Downstream of RV.pdf”). If additional pipework is added downstream of the relief valve then the pressure drop should be evaluated to ensure that it does not rise to the point where the back pressure will reduce the vent capacity of the relief valve.

The Anderson Greenwood valve 25905K34 / S with a set pressure of 4.00 atm / 4.05 bar G will have sufficient flow capacity to pass the vent flow rate of 13 910 kg / hr which results from a quench with no protection.

7 BURST DISC CAPACITY: LOV & QUENCH – NO PROTECTION

The capacity of the burst disc and the pressure drop along the chimney from the magnet assembly to the CCR and from the CCR to the relief valve are evaluated.

As in the previous section, the geometry of the three chimney pipes carrying the current leads and the single Chimney pipe carrying the instrumentation is defined in the drawing “318711-JLA-001-001-detail of Helium chimney-revB.PDF”.

Similarly from the previous section, the geometry of the vent pipe from the CCR is taken from the drawings 67145-00504 Rev A and 67145-00503 Rev B which have been submitted as documents Scans14875.pdf and Scans15049.pdf. The vertical rise of the pipe is vacuum insulated. Under the conditions of a Loss of Vacuum a heat flux of 7 000 W / m² is applied to the sections of pipe which are part of the vacuum insulation. The un-insulated sections of pipe which are exposed to atmosphere are given a heat flux 38 000 W / m².

7.1 CHIMNEY: MAGNET ASSEMBLY TO CCR

The pressure drop for the three pipes of the chimney assembly is evaluated in the design spreadsheet “JLab Q2-Q3 Relief 238_1 Chimney Drg 318711-JLA-001-001 - LOV & Quench No Protection.xls” using the geometry illustrated in the drawing “318711-JLA-001-001-detail of Helium chimney-revB.PDF”.

The flow rate is reduced to exclude the flow rate generated in the CCR.

A summary of the calculation method of the design spreadsheet is listed below:

1. The vent flow rate is defined by the analysis for Loss of Vacuum with a quench having no protection. A proportion of the flow rate is generated by the heat load on the Chimneys and in theory this additional flow rate accumulates along the length of the Chimneys. The analysis is conservative by including this increment of flow rate at the inlet to the Chimneys. To avoid double counting the temperature rise, this heating is not included as a heat load on the wall of the Chimneys. The contribution to the flow rate by the heat load on the CCR is excluded.
2. The pressure drop due to friction losses, section changes, pipe fittings and hydrostatic pressure is calculated. The section changes include the restriction at each superconductor or instrumentation clamp. The pipe flow area makes an allowance for the area obstructed by the instrumentation and the superconductor.

3. The change in pressure and temperature as calculated in one node are used to adjust the properties for the subsequent node along the length of the flow path of the Chimney.
4. A convergence routine adjusts the flow rate in the three Chimney pipes so that the pressure drop along the length of each Chimney is equal.

The summary results are included as the attachment “JLab Q2-Q3 Relief 238_1 Chimney Drg 318711-JLA-001-001 - LOV & Quench No Protection.pdf”. (Compared to the vent process from the CCR described in the next section, the details of the analysis are too extensive to be listed in the report and should be obtained from the attachment.)

The results show that with an inlet pressure and temperature of 6.58 bar A and 7.03 K, the outlet pressure and temperature at the CCR helium reservoir are 6.50 bar A and 7.01 K. (The temperature drops since the gas conditions are below the Joule-Thomson Inversion temperature and the gas is expanding.)

A summary of the parameters is listed below.

		Instrumentation Chimney	Superconductor Chimney	Total	
	Number	1	2	3	
	Mass flow rate	5 559	13 361	18 920	kg / hr
Pressure Drop	- Friction losses	3.7	3.0		mbar
	- Section change	32.9	39.0		mbar
	- Fittings	33.7	28.3		mbar
	- Hydrostatic	10.2	10.2		mbar
Total Pressure drop		80.4	80.4	80	mbar

7.2 VENT PIPE CCR TO ATMOSPHERE

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 239_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	6.50	bar A		
	Temperature	7.01	K		
	Vent flow rate	19780	kg / hr		
	Density	83.68	kg / m³		
	Viscosity	2.81 E-6	kg / m.s		

Internal to the CCR Sudden Contraction

Upstream diameter	Large		
Loss coefficient	0.464		
Pressure drop		9.9	mbar

Pipe Loss	Reynolds Number	2.30 E 7			
	Friction factor	0.00456			
	Unit pressure drop	0.90	mbar per m		
	Length	0.127	m		
	Pressure drop			0.1	mbar
Non-Return Valve	Valve Kv	250			
	Pressure drop			78	mbar
Pipe Loss	Unit pressure drop	0.91	mbar per m		
	Length	0.576	m		
	Pressure drop			0.5	mbar
External to the CCR Sudden Contraction					
	Upstream diameter	108.2	mm		
	Downstream diameter	82.8	mm		
	Loss coefficient	0.123			
	Pressure drop			7.8	mbar
Pipe Loss	Reynolds Number	3.03 E 7			
	Friction factor	0.00426			
	Unit pressure drop	3.27	mbar per m		
	Length	0.08	m		
	Pressure drop			0.3	mbar
Pipe Loss	Unit pressure drop	3.29	mbar per m		
	Length	0.72	m		
	Pressure drop			2.4	mbar
Tee as Elbow	Unit pressure drop	3.32	mbar per m		
	Length	0.17	m		
	Pressure drop			0.6	mbar
	Loss coefficient	1.02			
	Pressure drop			65.9	mbar
Pipe Loss	Unit pressure drop	3.37	mbar per m		
	Length	0.05	m		
	Pressure drop			0.2	mbar
Tee as Run	Unit pressure drop	3.38	mbar per m		
	Length	0.17	m		
	Pressure drop			0.6	mbar
	Loss coefficient	0.34			
	Pressure drop			22.5	mbar
Pipe Loss	Unit pressure drop	3.43	mbar per m		
	Length	0.05	m		
	Pressure drop			0.2	mbar

Elbow (LR)	Unit pressure drop	3.44	mbar per m		
	Length	0.11	m		
	Pressure drop			0.4	mbar
	Loss coefficient	0.27			
	Pressure drop			18.2	mbar
Pipe Loss	Unit pressure drop	3.47	mbar per m		
	Length	0.10	m		
	Pressure drop			0.3	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	76.06	kg / m³		
	Pressure drop			39.4	mbar
Sudden Expansion					
	Downstream diameter	Large			
	Pressure drop			68.7	mbar
Total Pressure Drop				298	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 0.09 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 (nominally 0.18 K) is partially offset by the temperature drop due to the expansion process so that the overall temperature rise is 0.11 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.

At the vent flow rate of 19 780 kg / hr for the Loss of Vacuum and an unprotected quench, the pressure drop from the magnet assembly to the CCR is 80 mbar and from the CCR to the downstream side of the burst disc is 298 mbar. Therefore the total pressure drop from the magnet assembly is 0.4 bar at the required vent flow rate. Since the internal pressure is 5.57 bar G there is sufficient capacity to vent the gas during a Loss of Vacuum to Air and a quench with no protection.

8 OTHER FAULT CONDITIONS

8.1 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 / m^3
	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 / m^2.K
	Heat flux	3060	W / m^2
		0.31	W / cm^2

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 / cm^2. 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.

8.2 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.

9 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	7 870	6.70
Quench – No Protection	5.47	9 590	6.89
LOV to Air + Quench No Protection	6.59	19 780	7.03

The vent capacity for the system defined by the geometry and operation in the referenced documents is summarised as follows:

The relief valve from Anderson Greenwood POPRV, type 25905J34 / S with a set pressure of 4.00 atm, which is 4.05 bar G, can handle the vent flow rate of 9 590 kg / hr at 6.9 K resulting from a Quench with No Protection. (The effect of the downstream pipework on the vent capacity of the relief valve is the responsibility of the Jefferson Laboratory.) For standardization with the Dipole the larger Anderson Greenwood 25905K34 / S relief valve could be selected.

The burst disc from FIKE, type AXIUS Low Pressure having a nominal size of 3.00 in, a MNFA of 7.79 in² and a set pressure of 5.00 atm, which is 5.07 bar A, can handle the vent flow rate of 19 780 kg / hr at 7.03 K resulting from a Loss of Vacuum to air plus a Quench with No Protection. (The effect on the vent capacity of any pipework or devices downstream of the burst disc is the responsibility of the Jefferson Laboratory.)

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

Rev	Date	Description
3	5 Oct 2016	Reference document added; Text changes.
2	2 Oct 2016	Analysis for chimney pressure drop; Heat flux modified to include temperature effects.