CRYO AB

Thermal calculation

Project: RHEA

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RAS LAFFAN HELIUM 2
RECOVERY PROJECT (HeRU)

325-T001A/B/C/D
Liquid Helium Storage
Thermal calculation

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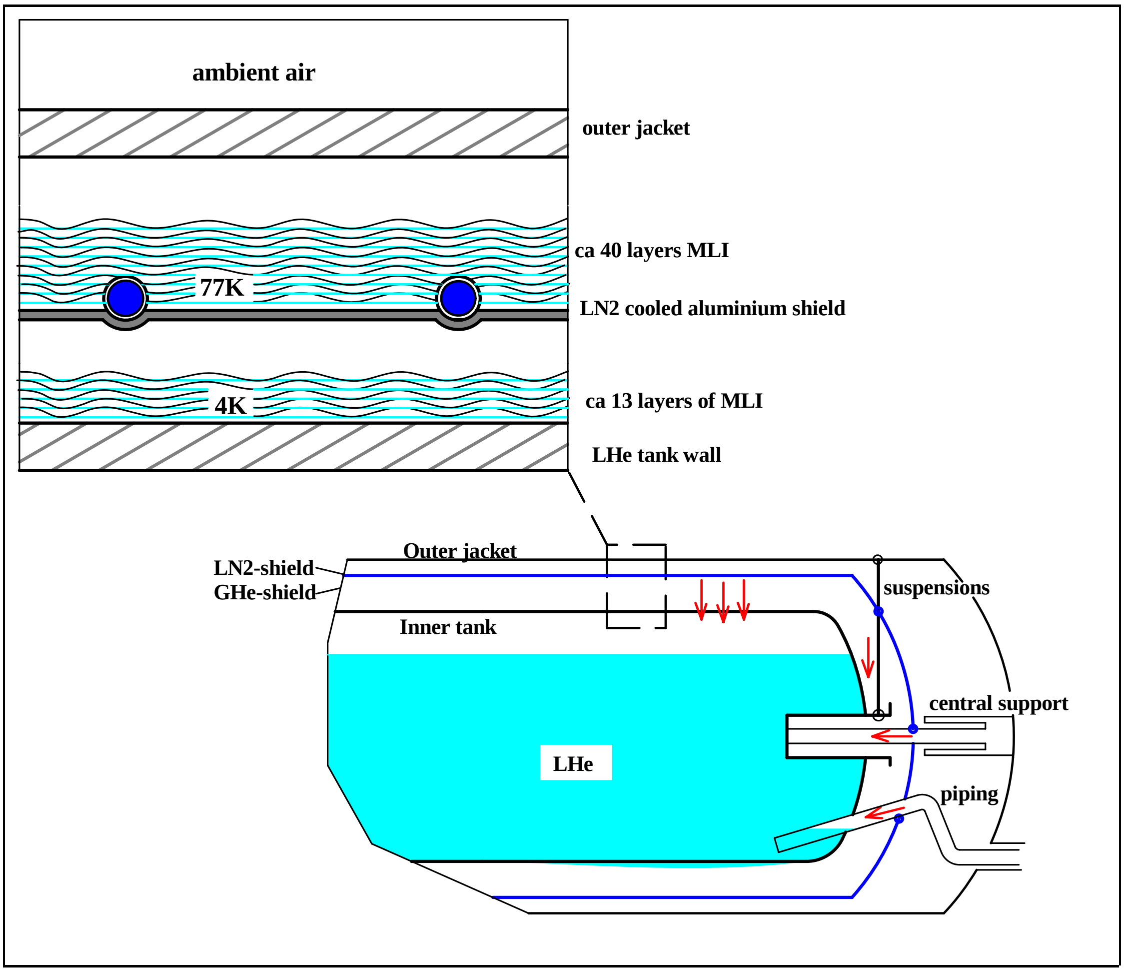
Heat Leak in Helium storage tanks for liquid Helium storage tanks in Quatar

Estimated heat leak to helium content and LN2 consumption for cooling during normal operation

1. Insulation system

In order to reduce the heat input to helium content, the temperature difference betwen ambient and liquid helium (4K) is reduced by an intermediate cooling shield at aproximately 80 K. This is achieved by letting liquid nitrogen cool the shield by continuous flow inside the coils attached to the shield. Liquid nitrogen will constantly be supplied from an external tank at a pressure near to atmospheric. The nitrogen shield, which is selfsupporting, encloses the inner tank completely.
It will be Multi Layer Insulated in order to reduce the heat leak from outer jacket. Evaporated N2 gas will be released to ambient by a phase-separator.

Additionally, heat is transfered to helium tank through piping, suspensions and supporting elements by solid conduction. All supporting elements and piping are thermaly short-circuited to LN2 temperatures before leaving the vacuum space out to ambient. All piping leaving the helium tank will also be provided with a thermal trap which estabilishes thermal stratification of the gas phase and hence prevents dangerous gas convection.



2. Heat Leak to Helium tank

2.1 Properties

2.1.1 Surface areas

A , surface area of inner tank $A_{IT} := 181\text{m}^2$

A_{ShN2} , surface area of LN2 cooling shield $A_{ShN2} := 200\text{m}^2$

2.1.2 Temperatures

T_a , ambient/outer jacket temperature $T_a \equiv 321\text{K}$

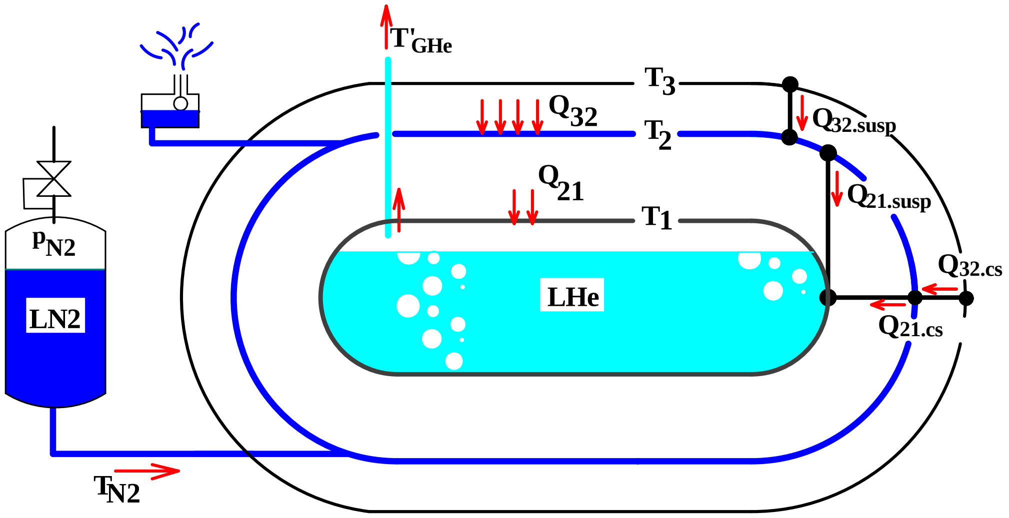
T_{LHe} , temperature of liquid helium in tank $T_{LHe} \equiv 4.22\text{K}$ => $p_{He} = 1.011\text{bara}$ "cold"

T_{N2} , temperature of incoming liquid nitrogen $T_{N2} \equiv 81\cdot\text{K}$ => $p_{N2}(T_{N2}) = 1.526\text{bara}$ "cold"

2.1.3 Vacuum pressure

p_v , vacuum pressure during operation (measured at T_a) $p_v := 1\cdot 10^{-5}\cdot\text{mbar}$ $p_v = 7.5006 \times 10^{-3}\text{mtorr}$

2.1.4 Notations



2.2 Heat transfered from cooling shield

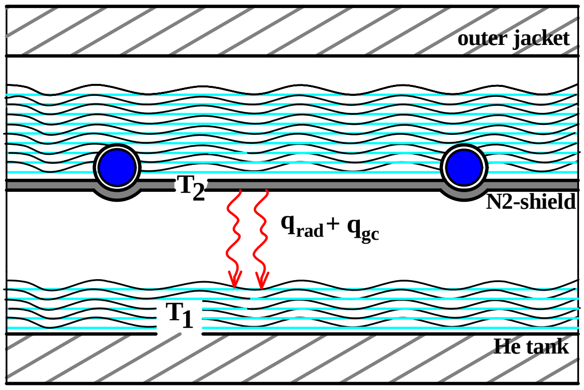
2.2.1 General

As can be seen from the sketches below, there are 2 annular gaps, one betwen N2-shield and helium tank, and the other one betwen outer jacket and N2-shield. These two gaps will *only* transfer heat by radiation and free molecular conduction. If the vacuum pressure can be kept sufficiently low, preferably $< 10^{-5}$ mbar, the molecular conduction can be reduced to a minimum.

Heat transfer by molecular gas conduction is determined by well known relation, deduced from kinetic theory of gases. According to this relation the heat transfer is direct propotional to the vacuum pressure and the temperature difference between ambient temperature T_a and the temperature T of the colder surface under consideration. The vacuum pressure shall be measured at the jacket and at ambient temperature $T_{a.}$

2.2.2 Heat transfer rate from N2-shield to He-tank (2 => 1)

As a conservative approach, the MLI on the helium tank is concidered not to have any thermal resistance. This means that the temperature of MLI is equal to the liquid helium temperature of inner tank.
The shield tamperature will vary and attain a maximum in between the cooling coils, see chapter 3.5



ΔT_{Sh}, maximum temperature difference in shield $\quad \Delta T_{Sh} := 2.0K$

T_2, nitrogen shield temperature $\quad T_2 := T_{N2} + \frac{3}{4} \cdot \Delta T_{Sh} \quad T_2 = 82.5\,K$

T_1, temp. of He-tank for calculation purposes $\quad T_1 := T_{LHe} \quad T_1 = 4.22\,K$

ε_2, emissivity of N2-shield (aluminium) $\quad \varepsilon_2 := 0.040$

ε_1, emissivity of outermost foil $\quad \varepsilon_1 := 0.015$

$Q_{21.rad}$, heat transfer rate by radiation $\quad Q_{21.rad} := \sigma \cdot \frac{1}{\frac{1}{\varepsilon_2} + \frac{1}{\varepsilon_1} - 1} \cdot A_{ShN2} \cdot \left(T_2^{\,4} - T_1^{\,4}\right) \quad Q_{21.rad} = 5.79\,W$

M, molar weight for He $\quad M := 4.0$

R, universal gas constant $\quad R = 8314 \frac{J}{kg \cdot K}$

κ, isentropic coefficient for Helium gas $\quad \kappa := 1.66$

α, accomodation coefficient for He at a wall temperature T $\quad \alpha(T) := 1 - 0.290 \cdot \ln\left(\frac{T}{4.2K}\right)^{0.70}$

α, accomodation coefficient for He at $T_2 = 82.5K$ $\quad \alpha_2 := \alpha(T_2) \quad \alpha_2 = 0.38$

α, accomodation coefficient for He at $T_1 = 4.22K$ $\quad \alpha_1 := \alpha(T_1) \quad \alpha_1 = 0.99$

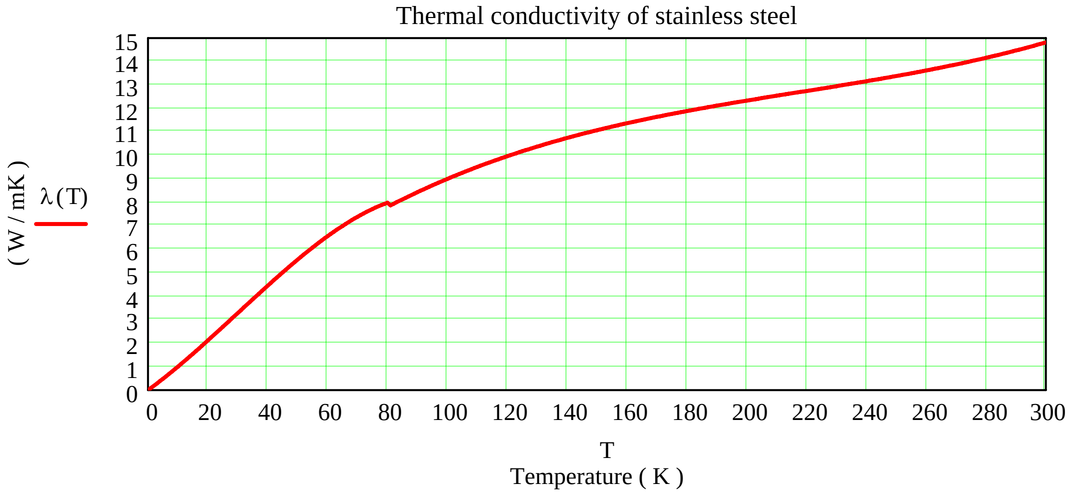
α_{21}, accomodation coefficient for He betwen T_2 and T_1 $\quad \alpha_{21} := \frac{\alpha_1 \cdot \alpha_2}{\alpha_2 + \alpha_1 \cdot (1 - \alpha_2)} \quad \alpha_{21} = 0.377$

$Q_{21.gc}$, free molecular gas conduction $\quad Q_{21.gc} := \alpha_{21} \cdot \frac{\kappa + 1}{\kappa - 1} \cdot \sqrt{\frac{R}{8 \cdot \pi}} \cdot \frac{p_v}{\sqrt{M \cdot T_a}} \cdot A_{ShN2} \cdot (T_2 - T_1) \quad Q_{21.gc} = 12.1\,W$

Q_{21}, heat transfer rate from N2-shield to He-tank $\quad Q_{21} := Q_{21.rad} + Q_{21.gc} \quad \boxed{Q_{21} = 17.9\,W}$

2.3 Conduction through Suspensions & Support elements

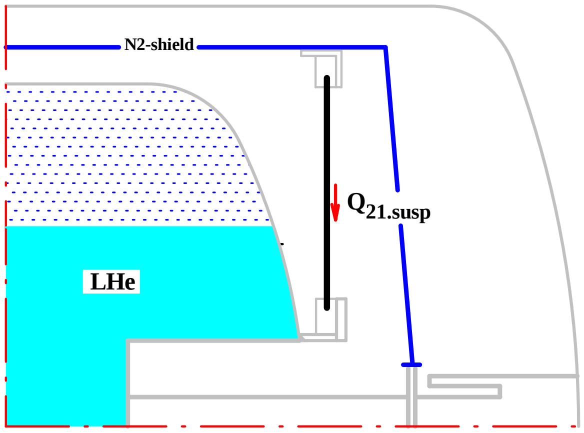
2.3.1 Thermal conductivity of stainless steel



The heat will be transfered by solid conduction in stainless steel, and depending on the boundary temperatures, the thermal conductivity, and hence the resistance, will vary considerably. The thermal resistance of an element is defined as; $R = \frac{L}{\lambda_m \cdot A}$,where the mean thermal conductivity λ_m is evaluated from; $\frac{1}{(T_1 - T_0)} \cdot \int_{T_0}^{T_1} \lambda(T)\, dT$

2.3.3 Heat conduction through suspension plates

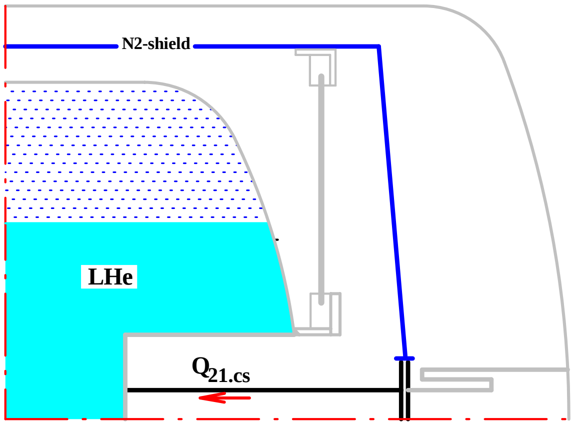
The suspension plates is asumed to be adequately insulated, but to include any imperfections the actual lengths will be reduced by 10%. Furthemore, to include any unfavourable effects of higher temperature gradients at the attachment point between suspensions and the the ring stiffener , a temprature increase of 5K will be included.



T_1, temperature of He-tank	$T_1 := T_{LHe}$	$T_1 = 4.22\,K$
T_2, temperature at the connection to N2-shield	$T_2 := T_{N2} + 5K$	$T_2 = 86\,K$
λ_{20}, mean thermal conductivity	$\lambda_{20} := \lambda_m\left(\frac{T_1}{K}, \frac{T_2}{K}\right)$	$\lambda_{20} = 4.8\,\frac{W}{m \cdot K}$
A, section area of suspension plate	$A := 6.0mm \cdot 80mm$	$A = 480\,mm^2$
n, number of suspension plates	$n := 2 \cdot 4$	
L, free length of suspension plate	$L := 1000mm$	
$Q_{21.susp}$, heat input through suspension plates	$Q_{21.susp} := \frac{\lambda_{20}}{0.9 \cdot L} \cdot n \cdot A \cdot (T_2 - T_1)$	$\boxed{Q_{21.susp} = 1.67\,W}$

2.3.4 Heat conduction through Central support

For conservative reasons, the thermal resistance of the flange connection is not included. The support tube is asumed to be adequately insulated, but to include any imperfections the actual length is reduced by 10%. Furthemore, as the flange connection communicates with ambient temperature through the outer central support (dashed line in the figure below), it will increase the temperature in the flange. To include this, a temperature increase of 10K will be added at nitrogen side.



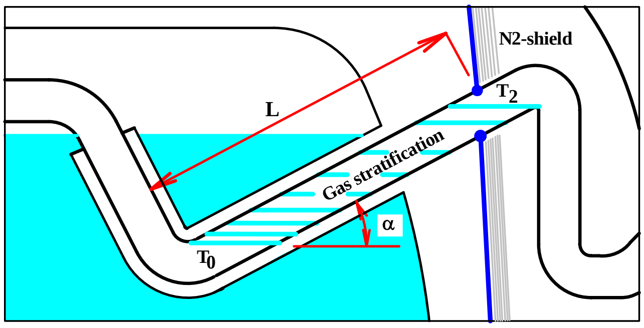
T_1, temperature of He-tank	$T_1 := T_{LHe}$	$T_1 = 4.22\,K$
T_2, temperature at the connection to N2-flange	$T_2 := T_{N2} + 10K$	$T_2 = 91\,K$
λ_{20}, mean thermal conductivity	$\lambda_{21} := \lambda_m\left(\frac{T_1}{K}, \frac{T_2}{K}\right)$	$\lambda_{21} = 5.0\,\frac{W}{m\cdot K}$
D, tube diameter	$D := 114.3mm$	
t, tube thickness	$t := 3.0mm$	
A, section area	$A := \frac{\pi}{4}\cdot\left[D^2 - (D - 2\cdot t)^2\right]$	$A = 1049\,mm^2$
L, actual length	$L := 1150mm$	$L = 1150\,mm$
$Q_{20.supp}$, heat input through central support	$Q_{21.cs} := \frac{\lambda_{21}}{0.9\cdot L}\cdot A\cdot(T_2 - T_1)$	$\boxed{Q_{21.cs} = 0.44\,W}$

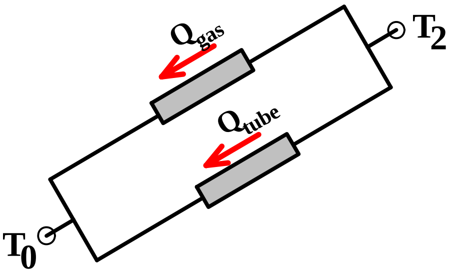
2.4 Heat conduction through Piping

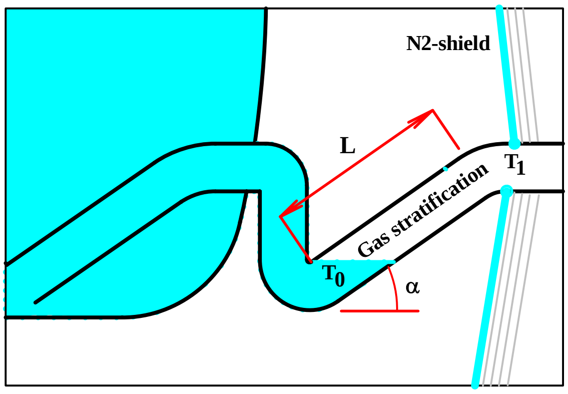
2.4.1 Thermal bridge to N2 temperatures

All pipes from Lhe tank will be thermaly circuited to LN2 temperatures before leaving the vacuum space out to ambient. The gain is smaller temperature difference and enhanced thermal resistance in stainelss steel tubing. The heat transfered to He content will then be reduced by a factor of 10 compared to a tube end-to-end temperature of 4K - 310 K. Considering the *gas relief pipe*, a thermal gas trap is provided inside LHe tank, see figure below. The purpose is to establish thermal stratification of the gas phase and hence allowing only pure gas conduction. But as the thermal conductivity of the gas is much more poore than for stainless steel pipe, the heat will mainly be transported in pipe wall. The 2 pipes fore liquid withdrawal and liquid fill, has the thermal traps outside LHe tank, see next figure.

Due to pipe inclinations, the gas and temperature layers will be spread over a larger area in pipe and thus reducing the effective length of the thermal trap.







Following formula has been applied in determining the heat input to He-tank content from the pipe trap:

-Heat conduction in the stratified He-gas: $Q_g = \frac{\lambda_g}{L_e} \cdot A_d \cdot \left(T_2 - T_1\right)$

-Heat conduction in stainless steel tube: $Q_{ss} = \frac{\lambda_{ss}}{L_e} \cdot A_t \cdot \left(T_2 - T_1\right)$

T_1 , pipe temperature in LHe content	$T_1 := T_{LHe}$	$T_1 = 4.22\,K$
T_2 , pipe temperature at the highest point	$T_2 := T_{N2} + 10K$	$T_2 = 91\,K$
λ_g , thermal conductivity of gasous He at mean temperature	$\lambda_g := \lambda_{He}\left(\frac{T_1 + T_2}{2}\right)$	$\lambda_g = 0.0441\,\frac{W}{m \cdot K}$
λ_{ss} , mean thermal conductivity of stainless steel	$\lambda_{ss} := \lambda_m\left(\frac{T_1}{K}, \frac{T_2}{K}\right)$	$\lambda_{ss} = 4.99\,\frac{W}{m \cdot K}$

The effective length due to tube inclination is determined from; $L_e = 0.9 \cdot \left(L - l_r\right) \;\; = 0.9 \cdot \left(L - \frac{d}{\tan(\alpha)}\right)$, where the reduction factor 0.9 is accounting for any unfavourable radiation exchange with outer environment.

Pipe system under consideration	Outside diameter D (mm)	wall thickness t (mm)	actual length L (mm)	tube inclination α (deg)	Effective length L_e (mm)	Heat transfer rate Q_t (W)	Q_g (W)	Q_{pipe} (W)
Liquid fill	60,3	2,0	700	35	552	0,287	0,017	**0,304**
Liquid withdrawal	42,4	1,6	700	35	575	0,154	0,008	**0,162**
Gas relief pipe	114,3	2,6	1150	30	857	0,461	0,042	**0,502**
								0,968

2.5 Total Heat leak and Boil-off

2.5.1 Total heat leak to He-tank -Summary

Q_{LHe} , expected heat leak to inner tank content: $Q_{LHe} := Q_{21} + Q_{21.susp} + Q_{21.cs} + Q_{21.pipes}$ $\boxed{Q_{LHe} = 20.93\ W}$

Source/element	*number*	Q_i *(W)*	Q_i / Q_{tot} *(%)*
Suspension bars from **N2**-shield	4 x2	**1,67**	8,0
Axial support piping (DN100)	1	**0,44**	2,1
Pipe DN100	1	0,30	1,5
Pipe DN50	1	0,16	0,8
Pipe DN32	1	0,50	2,4
Total		**0,97**	4,6
Radiation from N2-shield		5,79	27,7
Molecular gas-conduction from N2-shield		12,06	57,6
Total		**17,85**	85,3
Total		**20,93**	100,0

2.5.2 Expected boil-off rate per day

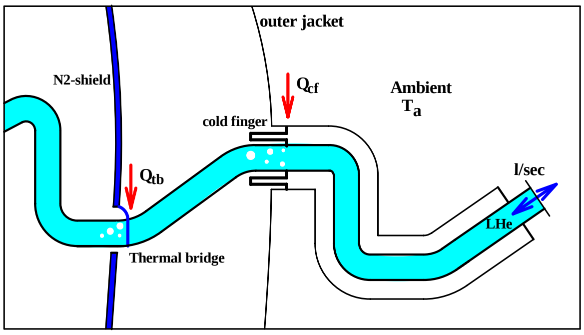
Δh , latent heat of vaporization at $T_{LHe} = 4.2K$ $\Delta h = 20401 \frac{J}{kg}$

m_{GHe} , expected boil-off of LHe per 24 hour $m_{GHe} := \frac{Q_{LHe}}{\Delta h}$ $\boxed{m_{GHe} = 88.6 \frac{kg}{24hr}}$

The boil-off rate of liquid helium per day will be then:

$$\frac{m_{GHe}}{V \cdot \rho_{LHe}} = \frac{m_{GHe}}{121 \cdot \left(m^3\right) \cdot 125 \cdot \left(\frac{kg}{m^3}\right)} = 0.586 \frac{\%}{day}$$

2.6 Heat leak to LHe filled pipe (during filling or withdrawal)



Following formulas have been applied when computing the maximum heat input through the cold finger and the thermal bridge from N2-shield:

-Heat conduction through cold finger: $$Q_{cf} = \frac{\lambda_{ss}}{L_{cf}} \cdot A_{cf} \cdot \left(T_{amb} - T_{LHe}\right)$$

-Heat conduction through thermal bridge: $$Q_{tb} = \frac{\lambda_{Al}}{L_{tb}} \cdot A_{tb} \cdot \left(T_{N2} - T_{LHe}\right)$$

T_{LHe} , pipe/LHe temperature $T_{LHe} = 4.22\,K$

T_{N2} , N2 shield temperature $T_{N2} = 81\,K$

T_{amb} , ambient temperature $T_a = 321\,K$

λ_{Al}, thermal conductivity of the thermal bridge (aluminium) $$\lambda_{Al} := \lambda_{5083}\left(\frac{T_{N2} + T_{LHe}}{2}\right) \qquad \lambda_{Al} = 32.6\,\frac{W}{m \cdot K}$$

λ_{ss} , thermal conductivity for cold finger material (stainless steel) $$\lambda_{ss} := \lambda_m\left(\frac{T_a}{K}, \frac{T_{LHe}}{K}\right) \qquad \lambda_{ss} = 10.32\,\frac{W}{m \cdot K}$$

Pipe DN	cold Finger					Thermal bridge					Total
	A_{cf}	L_{cf}	λ_{ss}	ΔT	Q_{cf}	A_{tb}	L_{tb}	λ_{tb}	ΔT	Q_{tb}	Q
	mm2	*mm*	*W/mK*	*K*	*W*	*mm2*	*mm*	*W/mK*	*K*	*W*	*W*
32	164,9	140	10,3	317	**3,8**	80,0	200	32,6	76,8	**1,0**	**4,9**
50	164,9	140	10,4	317	**3,9**	120,0	200	32,6	76,8	**1,5**	**5,4**
100	417,6	380	10,4	317	**3,6**	230,0	200	32,6	76,8	**2,9**	**6,5**

2.7 Heat leak through pipes when excluding thermal bridges to N2 shield (during Holding mode)

At customer request an estimation of the heat leaks to helium tank through piping is carried out when excluding the thermal bridges to LN2 shield. With direct referens to section 2.4.1 and changing the warmer boundary temperature of pipe from 80 K to 321 K then the heat leaks can be determined as below. First table gives a conservative estimate since we are neglecting the extra inclined pipe lengths with gas stratification before running to jacket/ambient. In the second table all pipe inclinations providing a thermal/gas trap are included. All vertical pipe section where dangerous gas convection can take place are excluded since they do not provide any thermal resistance

Following formula has been applied in determining the heat input to He-tank content from the pipe trap:

-Heat conduction in the stratified He-gas: $$Q_g = \frac{\lambda_g}{L_e} \cdot A_d \cdot \left(T_2 - T_1\right)$$

-Heat conduction in stainless steel tube: $$Q_{ss} = \frac{\lambda_{ss}}{L_e} \cdot A_t \cdot \left(T_2 - T_1\right)$$

T_1 , pipe temperature in LHe content $T_1 := T_{LHe}$ $T_1 = 4.22\,K$

T_2, pipe temperature at the highest point $T_2 := T_a$ $T_2 = 321\,K$

λ_g , thermal conductivity of gasous He at mean temperature $\lambda_g := \lambda_{He}\left(\frac{T_1 + T_2}{2}\right)$ $\lambda_g = 0.1031\,\frac{W}{m \cdot K}$

λ_{ss} , mean thermal conductivity of stainless steel $\lambda_{ss} := \lambda_m\left(\frac{T_1}{K}, \frac{T_2}{K}\right)$ $\lambda_{ss} = 10.32\,\frac{W}{m \cdot K}$

The effective length due to tube inclination is determined from; $L_e = 0.9 \cdot (L - l_r) = 0.9 \cdot \left(L - \frac{d}{\tan(\alpha)}\right)$, where the reduction factor 0.9 is accounting for any unfavourable radiation exchange with outer environment.

Maximum possible heat leak

Pipe system under consideration	Outside diameter D (mm)	wall thickness t (mm)	actual[1] length L (mm)	tube inclination α (deg)	Effective length L_e (mm)	Heat transfer rate		
						Q_t (W)	Q_g (W)	Q_{pipe} (W)
Liquid fill	60,3	2,0	700	35	552	2,167	0,147	**2,31**
Liquid withdrawal	42,4	1,6	700	35	575	1,165	0,068	**1,23**
Gas relief pipe	114,3	2,6	1150	30	857	3,480	0,356	**3,84**
								7,38

[1] accounting only the first pipe inclination (thermal trap) nearest tank

Minimum possible heat leak

Pipe system under consideration	Outside diameter D (mm)	wall thickness t (mm)	actual[1] length L (mm)	tube inclination α (deg)	Effective length L_e (mm)	Heat transfer rate		
						Q_t (W)	Q_g (W)	Q_{pipe} (W)
Liquid fill	60,3	2,0	1400	35	1182	1,012	0,069	**1,08**
Liquid withdrawal	42,4	1,6	1400	35	1205	0,556	0,033	**0,59**
Gas relief pipe	114,3	2,6	2000	30	1622	1,838	0,188	**2,03**
								3,70

[1] accounting all pipe inclinations where gas startification can occure

An importante **note** must be emphasized; since the pipes are not longer anchored to an intermediate temperature in this design (80 K) one must considere that the risk of **Thermo acustic oscillations** (TAO'S) in pipes is much higher now. If TAO'S occure it could pump in appreciable amounts of heat to helium tank, much higher than above calculated.

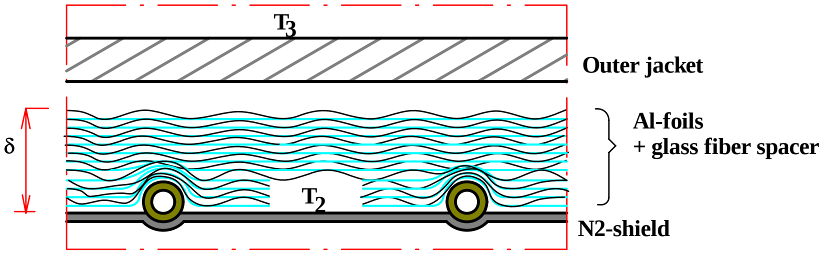
3. Liquid Nitrogen consumption

3.1 Heat transfer through MLI

3.1.1 General

The MLI insulation on LN2 shield consists of aluminium foils, seperated with a spacer of glass fibre, allowing only conduction through discrete contact spots. There exists basically 3 heat transfer modes, which will be considered in the following calculation; radiation, free molecular conduction (of air) and solid conduction in spacer material. At low vacuum pressures, below 10^{-5} mbar, heat transfer will mainly take place by radiation and solid conduction.

Measurements have shown a heat flux rate of 0,42 W/m^2 for 40 layers of properly installed MLI with no penetrations.



3.1.2 Boundary temperatures

T_2, N2-shield temperature:	$T_2 := T_{N2}$	$T_2 = 81\,\mathrm{K}$
T_3, temperature of outer jacket:	$T_3 := T_a$	$T_3 = 321\,\mathrm{K}$

3.1.3 Properties

A_{ShN2}, surface area of N2-shield		$A_{ShN2} = 200\,\mathrm{m}^2$
δ, thickness MLI insulation	$\delta := 51\mathrm{mm}$	
N_s, number of layers of MLI	$n_s := 40\mathrm{layers}$	
h_s, thermal conductance for the spacer material	$h_s := 0.050\,\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}}\cdot\mathrm{layer}$	
t_s, layer thickness	$t_s := \frac{\delta}{n_s}$	$t_s = 1.3\,\frac{\mathrm{cm}}{10\mathrm{layers}}$
ε_s, emissivity for Al-foils:	$\varepsilon := 0.030$	
α, overall accommodation coefficient for free molecular conduction of air between; $T_2 = 81\mathrm{K}$ and $T_3 = 321\mathrm{K}$	$\alpha := 0.9$	
M, molar weight for air	$M := 28.96$	
R, universal gas constant		$R = 8314\,\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}}$
κ, isentropic coefficient for air	$\kappa := 1.40$	

3.1.4 Heat transfer to N2-shield through MLI

Q_{rad}, radiation betwen long coaxial cylinders	$Q_{rad} := \sigma\cdot\frac{\varepsilon}{2\cdot(n_s+1)}\cdot A_{ShN2}\cdot\left(T_3^{\,4} - T_2^{\,4}\right)$	$Q_{rad} = 43.9\,\mathrm{W}$
Q_{gc}, molecular gas conduction of air	$Q_{gc} := \alpha\cdot\frac{\kappa+1}{\kappa-1}\cdot\sqrt{\frac{R}{8\cdot\pi}}\cdot\frac{p_v}{\sqrt{M\cdot T_a}}\cdot A_{ShN2}\cdot(T_3 - T_2)$	$Q_{gc} = 48.9\,\mathrm{W}$
Q_{sc}, solid conduction in spacer material	$Q_{sc} := \frac{h_s}{n_s}\cdot A_{ShN2}\cdot(T_3 - T_2)$	$Q_{sc} = 60.0\,\mathrm{W}$
$Q_{32.MLI}$, total heat input to N2-shield from ambient/jacket	$Q_{32} := Q_{rad} + Q_{gc} + Q_{sc}$	$\boxed{Q_{32} = 152.8\,\mathrm{W}}$

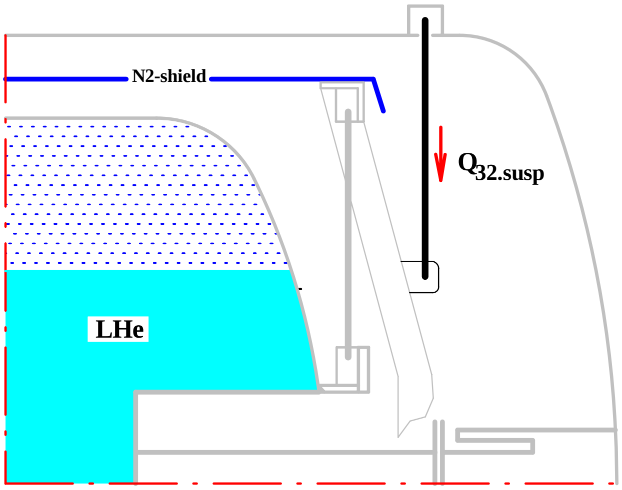
from ambient/jacket

3.2 Heat conduction through Suspension & Support elements

In order to make a conservative estimate of the heat input from suspension, the thermal resistance of additional links or attachments are not included. The rods is asumed to be adequately insulated, but to include any imperfections the actual lengths will be reduced by 10%

3.2.1 Heat conduction in suspension plates

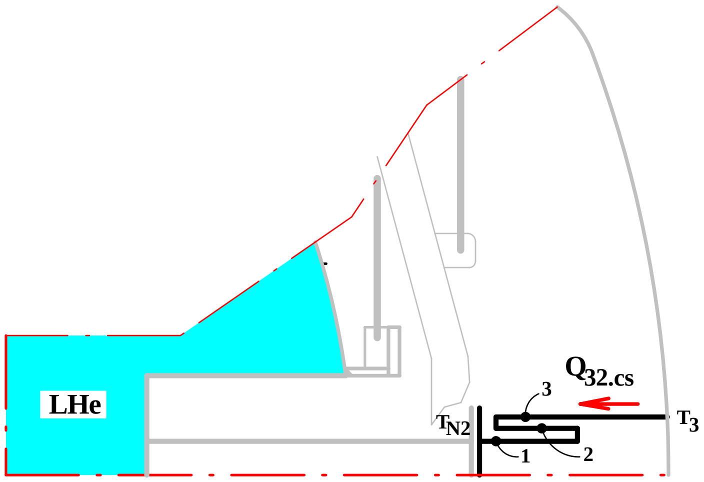
The suspension is asumed to be adequately insulated, but to include any imperfections the actual lengths will be reduced by 10%. Furthemore, to include any temperature variations in the ring stiffener for N2-shield, a temprature increase of 5K will be added locally at the suspension attachment.



T_2, temperature of N2-shield	$T_2 := T_{N2}$	$T_2 = 81\,K$
T_3, temperature of vacuum jacket	$T_3 := T_a$	$T_3 = 321\,K$
λ_{20}, mean thermal conductivity	$\lambda_{32} := \lambda_m\left(\frac{T_2}{K}, \frac{T_3}{K}\right)$	$\lambda_{32} = 12.2\,\frac{W}{m\cdot K}$
A, section area of a susp. plate	$A := 6.0mm\cdot 100mm$	$A = 600\,mm^2$
n_l, number of lateral suspensions	$n_l := 2\cdot 2$	
L_l, length of lateral suspensions	$L_l := 1100mm$	
n_v, number of vertical suspensions	$n_v := 2\cdot 2$	
L_v, length of vertical suspensions	$L_v := 1300mm$	
L_m, mean length of suspensions	$L_m := \frac{n_l\cdot L_l + n_v\cdot L_v}{n_l + n_v}$	$L_m = 1200\,mm$
$Q_{32.susp}$, heat input through suspension plates	$Q_{32.susp} := \frac{\lambda_{32}}{0.9\cdot L_m}\cdot(n_l + n_v)\cdot A\cdot(T_3 - T_2)$	$\boxed{Q_{32.susp} = 13.0\,W}$

3.2.2 Heat conduction through outer central support

The support is asumed to be adequately insulated, but to include any imperfections the actual length is reduced by 10%.



T_2 , temperature of N2-shield $\quad T_2 := T_{N2} \quad T_2 = 81\,K$

T_3 , temperature of vacuum jacket $\quad T_3 := T_a \quad T_3 = 321\,K$

1			2			3		
D *mm*	t *mm*	L *mm*	D *mm*	t *mm*	L *mm*	D *mm*	t *mm*	L *mm*
800,0	3,0	700	830,0	3,0	700	880,0	3,0	650

As the the 3 tubes are coupled in serie following relation is valid:

$$Q_{32.cs} = \frac{T_3 - T_2}{R_1 + R_2 + R_3} \text{ ,where}$$

R_i = thermal resistance for each tube = $\dfrac{L_i}{A_i \cdot \lambda_i}$

λ_i = mean thermal conductivity evaluated between the inlet and outlet temperatures T´ and T´´ of each tube

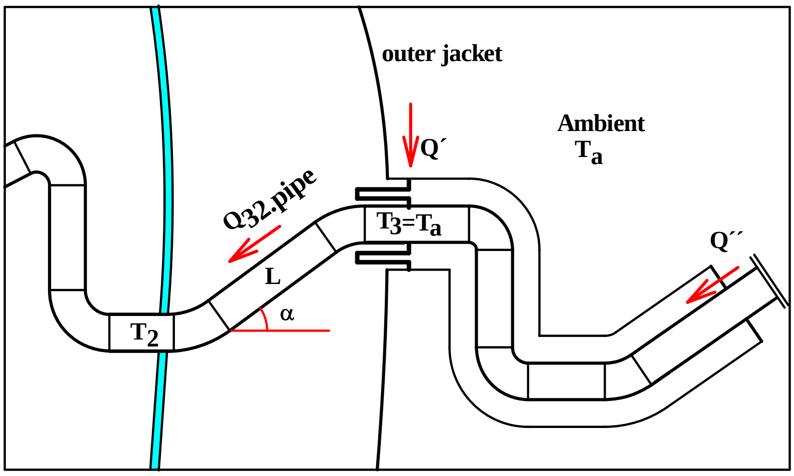
1			2			3		
T´ *K*	T´´ *K*	λ *W/mK*	T´ *K*	T´´ *K*	λ *W/mK*	T´ *K*	T´´ *K*	λ *W/mK*
81	182	10,3	182	261	12,8	261	321	14,6

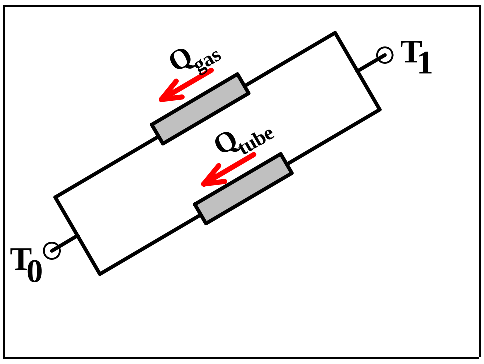
$Q_{32.cs}$, heat transfer rate through outer central support $\quad \boxed{Q_{32.cs} = 11.2\,W}$

3.3 Heat transfer through piping

3.3.1 Thermal connections to N2 temperatures

All pipes greater than DN 15 comming from He- tank will be thermally short-circuitted to N2 temperature before running out to ambient. The pipe has been tilted in order to create a thermal trap of stratified gas, allowing only pure gas conduction. Solid conduction along the pipe wall will then be the main heat transfer mode. The effective length of a tilted tube is set to ; $L_e = 0.9\cdot\left(L - l_r\right) = 0.9\cdot\left(L - \frac{d}{\tan(\alpha)}\right)$ where the reduction factor 0.9 is accounting for any unfavourable radiation exchange with outer environment. Furthermore, a conservative simplification is also made; the pipe temperature at nozzle connection/cold finger is set to equal the ambient temperature, neglecting all resistance in the cold finger and in the vacuum insulated piping outside jacket, see figure below.





Following formula has been applied in determining the heat input to He-tank content from the pipe trap:

-Heat conduction in the stratified He-gas: $Q_g = \frac{\lambda_g}{L_e}\cdot A_d\cdot\left(T_3 - T_2\right)$

-Heat conduction in stainless steel tube: $Q_{ss} = \frac{\lambda_{ss}}{L_e}\cdot A_t\cdot\left(T_3 - T_2\right)$

T_2, pipe temperature at N2 connection $T_2 := T_{N2}$ $T_2 = 81\,K$

T_3, pipe temperature at cold finger joint $T_3 := T_a$ $T_3 = 321\,K$

λ_g, thermal conductivity of gasous He at mean temperature $\lambda_g := \lambda_{He}\left(\frac{T_2 + T_3}{2}\right)$ $\lambda_g = 0.118\,\frac{W}{m\cdot K}$

λ_{ss}, mean thermal conductivity of stainless steel $\lambda_{ss} := \lambda_m\left(\frac{T_2}{K}, \frac{T_3}{K}\right)$ $\lambda_{ss} = 12.16\,\frac{W}{m\cdot K}$

Pipe system under consideration	Outside diameter D (mm)	wall thickness t (mm)	actual length L (mm)	tube inclination α (deg)	Effective length L_e (mm)	Heat transfer rate Q_t (W)	Q_g (W)	Q_{pipe} (W)
Liquid fill	60,3	2,0	1 000	17	722	1,479	0,097	**1,58**
Liquid withdrawl	42,4	1,6	1 100	17	865	0,691	0,039	**0,73**
Gas relief pipe	168,0	2,6	1 700	20	1114	3,536	0,528	**4,06**
								6,37

$Q_{32.pipe}$, heat input rate at pipe short-circuits $\boxed{Q_{32.pipes} = 6.37}$

3.4 Total heat leak & LN2 consumption rate

Q_{LN2} , net heat input to LN2

$$Q_{LN2} := Q_{32} + Q_{32.susp} + Q_{32.cs} \cdots + Q_{32.pipes} \cdot W - Q_{21} - Q_{21.susp} - Q_{21.cs} - Q_{21.pipes}$$

$$\boxed{Q_{LN2} = 162.3\ W}$$

▶

Source/element	number	Q_i (W)	Q_i / Q_{tot} (%)
Suspension bars	4 x2	***12,97***	1,0
Axial support piping (labyrinth)	1	***11,15***	6,9
Pipe DN100	1	*4,06*	2,5
Pipe DN50	1	*1,58*	1,0
Pipe DN32	1	*0,73*	0,5
Total		***6,37***	3,9
Radiation through MLI		*43,87*	27,0
Molecular gas-conduction through MLI		*48,90*	30,1
Solid conduction through MLI		*60,00*	37,0
Total		***152,77***	94,1
Total		**183,26**	112,9
Total heat leak from LN2 to LHe-tank		**-20,93**	12,9
Net heat absorbed by LN2		**162,33**	100,0

M_{LN2}, expected consumption of
LN2 for cooling purposes

$$M_{LN2} := \frac{Q_{LN2}}{200 \cdot 10^3 \left(\frac{J}{kg}\right)}$$

$$\boxed{M_{LN2} = 70.1\ \frac{kg}{24hr}}$$

▶ T-distribution in shield