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CLRC

The IRIS Graphite Analyser Cooling System
Volume One - Design Report

J J P Balchin

May 1996

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The IRIS Graphite Analyser Cooling System.

Volume One - Design Report

A design feasibility study prepared by:

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12 th March 1996.

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1.0 Summary:

This design report describes a new Cryogenic Cooling system for the IRIS Graphite Analyser on the ISIS Spallation Neutron Source. The report includes a brief description of the design requirements, the concept behind the cooling system, provision for an increase in the area covered by the analyser using a mixed array of the original Le Carbonne and new Atomgraph Pyrolitic Graphite crystals, design calculations supporting the new proposed design and Medusa CAD 3-D views showing the current design status.

2.0 Introduction:

The requirements of the new graphite analyser cooling system are:

1. To cool the Graphite Analyser Crystals to 5 Kelvin or below.

2. To increase the area covered by Crystals both Longitudinally & Latitudinally.

The IRIS instrument graphite analyser is located within a vacuum vessel some 36.5 m from the liquid hydrogen moderator on the ISIS pulsed neutron source. The cylindrical vessel, 2.0 m in diameter & 0.6 m in height currently contains two crystal analyser banks, muscovite mica & Pyrolitic graphite, arranged in inverted geometry close to back scattering. Each analyser material consists of a spherical surface reflecting scattered neutrons to an array of scintillation detectors below the sample position. The precise crystalline structure of each analyser material provide peak neutron reflection intensities (Bragg angle scattering) for particular neutron energies from different atomic planes. Use of a series of beam choppers to select different energies allows the instrument to measure d-spacings for a range of materials with different instrument resolution.

At present the graphite analyser is cooled to 25 Kelvin using a 2-stage gaseous Helium closed cycle refrigeration system circulating through a pipe brazed to the rear of the analyser mounting plate. The Helium refrigerator & cooling head, liquid Nitrogen feed pipework & storage vessel adjacent to the main vacuum vessel are linked to it via insulated pipework. Operation at this temperature reduces the background neutron scattering caused by an effect known as Thermal Diffuse Scattering (TDS). This effect is caused by neutron interactions with phonons within the graphite. Measurements conducted on the IRIS instrument suggest that reducing the analyser temperature produces a proportional reduction in TDS. An improvement in instrument signal background up to a factor of four is achievable by a four fold reduction in Thermal Diffuse Scattering. Cooling the graphite to 5 Kelvin using liquid Helium is expected to improve the instrument signal background from 1250:1 to 5000:1. Further reductions in TDS may be achievable by reducing temperatures still further by pumping on the Helium reservoir (this is not covered in the original design brief but may be incorporated at a later date).

In order to achieve this temperature a cryostat design is required which will fit within the IRIS vacuum vessel. This will consist of a liquid Helium reservoir surrounded by a radiation heat shield cooled to liquid Nitrogen temperature, 77 Kelvin. The current cooling installation will be retained & plumbed in to the new arrangement to provide pre-cooling and standby cooling during instrument operation. The graphite analyser crystals, together with Cadmium shielding plates will be secured to the surface of the Helium reservoir to provide good heat transfer characteristics and the required back scattering geometry.

In parallel with the installation of the cryostat the design incorporates an increase in graphite analyser coverage. Latitude angles are increased by 5.4° for low & high angle scattering, together with an increase in the solid angle subtended by the analyser in the longitudinal axis from 4.2° to 11.2°.(Subject to modifications to the collimation / beryllium filter assembly). The design mixes the original Le Carbonne & new Atomgraph crystals to give a uniform resolution function.

3.0 New Tile Geometry.

The current graphite analyser comprises 1344 x 2.0 mm Graphite Crystals mounted using a gold pin arrangement to form a nearly spherical surface. These are mounted on a solid machined aluminium mounting plate.

A further 2498 x 1.0 mm Graphite Crystals are available to extend analyser coverage. The new crystals distribution should be uniformly distributed in chequer board arrangement with current crystals to provide a uniform resolution function over the complete arc of the graphite analyser. The crystal arrangement has been chosen to match the ratio of 2.0 & 1.0 mm crystals available.

The instrument geometry requires an offset in precise back scattering to accommodate the detector assembly. In order to reduce time of flight defocusing caused by variation in flight path lengths the front crystal surface follows the surface of a volume of revolution formed by rotating an ellipse about a centre line. This is translated & inclined such that the principal foci are co-incident with the sample point, and with the focus of the detector array geometry. (It is not concentric with the vacuum vessel). This geometry introduces a variation in the Bragg wavelength as the analyser height is increased beyond 'near' back scattering.

The selection of where additional crystals should be placed within the analyser array is determined by the present dimensions & location of the vacuum vessel, current collimation & detector bank. This is shown in the figure : ' New Tile Geometry 7a.' A maximum of 11 rows of crystals can be added to the analyser array. A range of additional analyser crystal locations exist between the following limits :

a) Highest acceptable position of analyser bank:-

Add 6 Crystal rows above current position.
Add 5 Crystal rows below current position.

(Neutron beam from top analyser row just intersects top of detector bank).

b) Lowest acceptable position:-

Add 1 Crystal row above current position.
Add 10 Crystal rows below current position.

(Neutron beam from sample position just avoids incidence with top of detector bank).

The Proposed position of new rows :-

Add 3 Crystal Rows above current position.
Add 7 Crystal Rows below current position.
(Neutron beam from analyser is centred about its current incident position on the detector bank).

Ten rows of crystals are added to the present analyser array, the remaining crystals are used to add a further 16 longitudinal

Crystal Columns (8 at each end of the analyser bank) to give a further 5.4° of both low & high angle scattering range.

This location allows clearance between the top of the analyser bank & the vacuum vessel lid to incorporate the new cooling system. The ends of the analyser mount are close to the beam entry & exit guides requiring the LN_2 radiation shields to fully enclose the Helium reservoir to reduce radiation losses.

4.0 Cadmium Tile Retaining Assembly.

The new design has to satisfy four requirements for retaining the graphite crystals :

1. To support a distributed array of 1.0 mm & 2.0 mm Graphite Crystals in good thermal contact with the Helium Reservoir.

2. To provide neutron absorption behind the graphite crystals eliminating stray scatter.

3. To reduce the quantity of drilled holes in the analyser mounting plate simplifying assembly (& reducing fabrication costs).

4. To permit crystal removal, addition and reconfiguration at a later date.

In order to achieve this a new retaining method is proposed.

4.1 Design Maxim:

The current fixing method permits dis-assembly of crystals from the mounting plate and insertion of cadmium sheet directly behind crystal without requirement for hydrogenous / organic adhesives. It also permits fine tuning of crystal distribution and surface profile to match analyser geometry to detectors. This feature will be important when the Microcontrole mechanical support is moved below the analyser since rotational & vertical degrees of freedom will be lost.

Although the gold pin method is already proven in service it requires expensive machining for each crystal mount (1 hole per crystal plus an additional row of holes), each of which has to be drilled perpendicular to the surface to a depth of 10 mm to allow insertion of the plugs securing the pins. In addition to its cost, it requires a relatively deep & massive plate to drill in to. In order to mix the 1.0 & 2.0 mm depth crystals spacers would be required to ensure the 1.0 mm crystals are securely gripped.

The new method attempts to build the analyser in a modular form, similar to that employed in the mica analyser, using a Aluminium foil / Graphite Crystal / Cadmium shielding sandwich which may be secured to a thin wall cryogen vessel. The 2.0 mm depth crystals should be fitted 'flush' with the 1.0 mm crystals using a pressed Cadmium sheet. Each sheet will form a module of up to 80 tiles which can be removed independently of other modules. The Cadmium sheet will be formed to the nearly spherical profile to ensure conformal thermal contact with the reservoir (which will also be machined to this spherical profile).

The current design proposal involves a punched cadmium sheet containing 10 mm square pockets. Flow of the cadmium between the pockets will form raised edges proud of the crystal front face. This sheet will be formed to a conformal shape with the front reservoir face. Once the crystal has been inserted the raised corners of the pockets will be pressed to retain the crystals in position. This reduces the quantity of drilled holes and thread inserts to 4 x the number of modules used. Each module will be screwed to the reservoir at its top & bottom to support the load. The thermal contact between the reservoir & modules may be enhanced by applying a filled cryogenic adhesive (such as Stycast) behind the Cadmium plate without affecting the background noise. This will also mitigate the effect of differential thermal contraction of the copper & cadmium. (Tests have shown that use of an epoxy adhesive to secure the graphite directly raises the background level by 20%).

This method requires prototyping to evaluate the maximum module size which can be supported by the foil.

5.0 Liquid Helium & Nitrogen Reservoirs & Feeds.

Reservoir shroud arrangement comprises a liquid Helium reservoir supporting the analyser array enclosed within a liquid Nitrogen shield based upon the current installation.

The front face of the Helium reservoir is machined from Copper to give the required analyser profile. The rear, sides &

internal bracing of the reservoir, together with the liquid Nitrogen shroud is fabricated from Copper sheet. The shroud incorporates an Aluminium foil window & Cadmium shielding to eliminate scattering from the analyser supports & IRIS vacuum vessel back to the detector bank.

Helium gas supplied from the existing CCR can be supplied at 10 K to the reservoir surface via a separate cooling loop (for pre-cooling) or to the radiation shield from the 25 K cold head (to reduce Helium boil-off rate during operation. The radiation shield also provides a surface for cryo-pumping the vacuum during vessel evacuation.

Outside the confines of the vacuum vessel transfer lines incorporate a return gas and vacuum shroud to reduce cryogen evaporation during transfer. Pressure relief valves & a bursting disc permit rapid release of cryogen in event of warm-up due to the loss of vacuum.

Ideally reservoir isolator control valves should be located as close as possible to the vacuum vessel to minimise reservoir filled volume & radiative surfaces. The design places these in locations just below the IRIS platform floor level to allow the valves to be operated from the platform without using up floor space.

Super conducting Platinum wire level & Rhodium-Iron resistor temperature sensors are incorporated on the helium reservoir at opposite end to reservoir feeds to control reservoir re-filling & monitor analyser temperature.

The space within the liquid nitrogen shroud will be evacuated separately to protect the IRIS instrument from sudden & rapid He boil-off when the main vacuum is lost. The design if the shroud is undergoing modification to form a sealed volume with a vacuum feed. Other modifications to the supply pipework (to thermally anchor feeds to the intermediate shield temperature & incorporate remotely operated solenoid valves) & cooling loops (to provide optional cooling of the shroud using the coldest 10 K gaseous Helium cold head) are under consideration .

6.0 Equipment Support Structure.

The Microcontrole support structure is to be moved directly below Graphite Analyser bank in a central position to provide translational adjustment from a fixed datum. This simplifies the Cadmium shielding requirements.

A new convoluted tube support provides vertical height adjustment & attitude adjustment for installation purposes. This maximises the support length with minimal support cross sectional area. The increased analyser height means that there is insufficient space to retain Vertical & Rotational adjustment Microcontrole stages. The mass of the new design exceeds the maximum load supportable solely by the vertical stage (principally due to the Cadmium shielding).

Two new outrigger supports incorporating a convoluted tube support will be positioned at current support positions. Vertical height and attitude adjustment of each support is achieved using a single M 20 thread for coarse adjustment & four M 4 set screws for fine adjustment. The outrigger supports may be locked in place after attitude & translational adjustments have been made using a shim/lock nut arrangement.

The vertical supports use a convoluted thin walled seamless Stainless Steel tube for long conduction heat path and small cross section area. The new design uses a five tube nested arrangement to make the optimal use of available space. PTFE insulators reduce conduction from the analyser reservoir to the liquid Nitrogen radiation shield & down the support structure.

7.0 Control System Requirements.

Detailed specification of the control system has yet to be finalised but is expected to include the following.

1. Monitoring of analyser bank temperature along its length.

2. Monitoring of cryogen reservoir level & analyser temperature during cool-down & operation.

3. Monitoring reservoir & feed line pressures and provide automatic pressure relief and reservoir recharge during operation.

4. Incorporation of external pressure relief devices along closed sections of transfer/feed lines, reservoirs & exhaust lines, evacuating to atmosphere. Non-return valves are required to prevent moisture ingress from exhaust & back streaming from reservoirs to cryogen feeds & storage vessels.

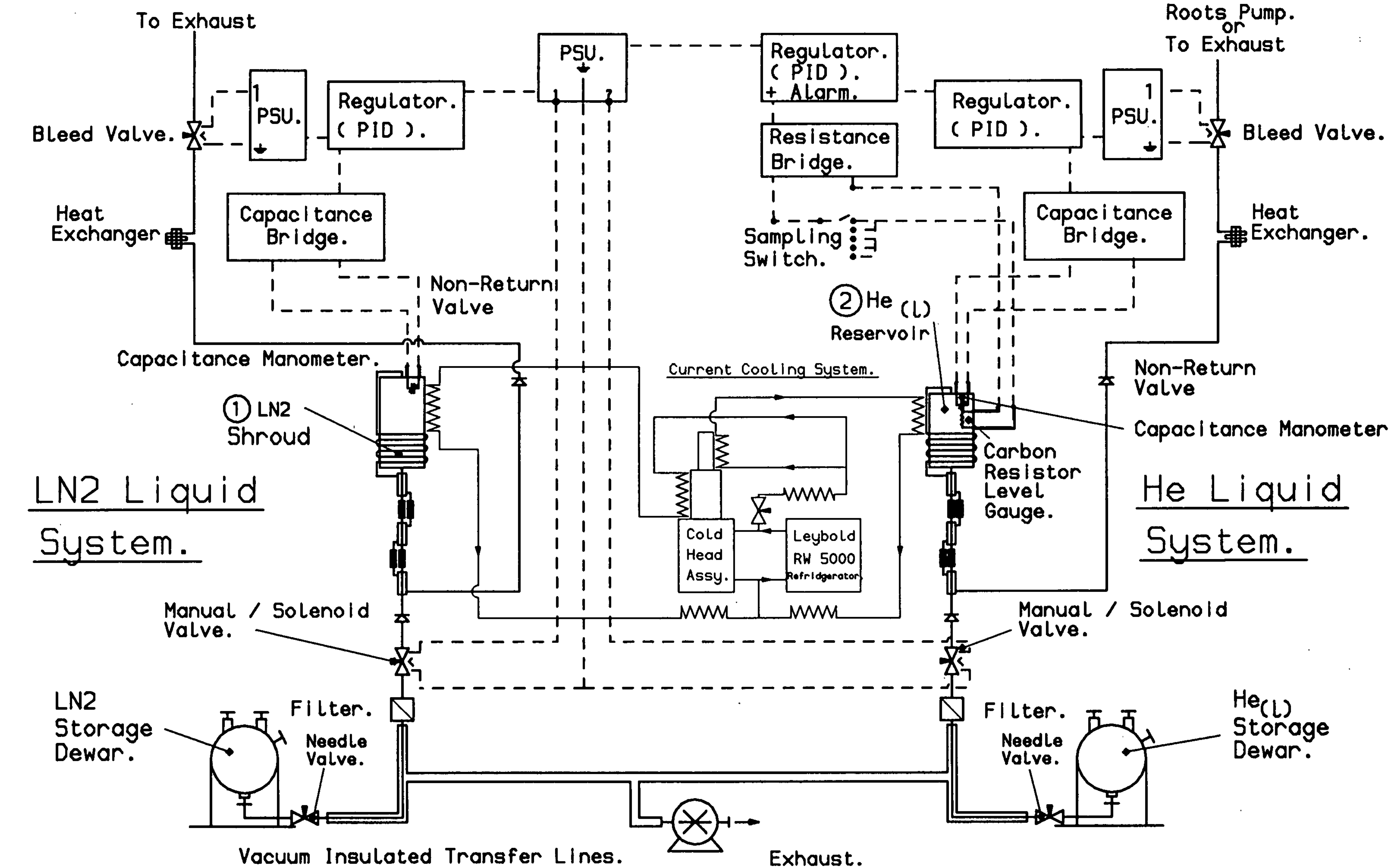
5. Possibly incorporate filters to eliminate particulate ingress (NB. this may reduce cool down rate due to the high surface area, conduction path to pipe wall & throttling/expansion effect boiling off liquid cryogen due to pressure drop across filter).

6. Needle valve control will be required to adjust cryogen flow. Heater coils will be required around the valve to prevent frosting & seizure. Stepper Motor control or Pneumatic piston can be used for accurate metering depending upon services available, valve supplier & RF interference. (e.g. Nupro valves currently used can be controlled Pneumatically, Edwards PVEK bellows valves can be solenoid operated, Oxford Instruments can supply Stepper Motor controlled needle valves).

7. Provision of a port & pump on $He_{(l)}$ exhaust line for forced cooling by evacuating vapour - uneconomic for He consumption for a large volume reservoir. A continuously operating ^4He refrigeration stage design would require an additional shroud stage between the inner He reservoir & outer LN_2 reservoir - the He pumped volume would be identical.

These requirements can be achieved easily using proprietary control equipment such as the Oxford Instruments ITC Temperature controllers & ILM Cryogenic level meters which can be used with a range of temperature & level sensors. Initially a simple manual control system will be required to minimise cost.

Figure 1. Control System - Schematic Block Diagram.



Appendix. - Calculations.

Based upon current arrangement:

Appendix A. Cool Down Rate:

Consider the Aluminium mounting block in total vacuum cooled to 4.2 Kelvin by liquid Helium & Liquid Nitrogen Shroud.

Cooling Power of He(l) is equal to:

(i) Enthalpy of He(l)* + (ii) Latent Heat of Vaporisation of He(l) + (iii) Enthalpy of He(g) - (iv) Conduction along Al plate supports - (v) Radiation from Vessel surroundings to Al plate.

* Only applies at base temperature of 4 Kelvin.

Assuming no pumping takes place on the He reservoir then we can neglect term (i) by assuming the liquid Helium vaporises instantaneously.

Assuming perfect thermal insulation, nil heat conduction down supports & all gaseous He enthalpy used to cool Aluminium we may neglect terms (iv) & (v), therefore:

$$Q'_{Al} = Q'_{Evap/He} + Q'_{Enthalpy/He}$$

where Q' represents rate of heat transfer (J/s or Watts).

or

$$m_{Al}cp_{Al}T' = 20.9\ m'_{He} + m'_{He}cp_{He}(\ 300 - 4.2\ )$$

Latent heat of vaporisation for $^4He(l)$ = 20.9 kJ/kg
For given T' (cool-down rate), can calculate best & worst case mass flow rate of Helium liquid (m'_{He}).

(I) Worst Case :- $m_{Al}cp_{Al}T' = 20.9\ m'_{He\#}$

(no re-circulation of He (g))

(II) Best Case:-

$$m_{Al}cp_{Al}T' = 20.9\ m'_{He} + m'_{He}cp_{He}(\ 300 - 4.2\ )$$

(all He(g) enthalpy transferred to Al block)

For ^{4}He over a temperature change of 300 to 4.2 Kelvin

$$m'_{He} Cp_{He} (300 - 4.2) = 1541.83\, m'_{He} \quad \text{kJ/s or kW.}$$

The current Al mass to be cooled is 9.748 kg.

Cp_{Al} at given temperatures may be sourced from data books.

Hence by specifying a given cool-down rate T' we may calculate the mass flow rate of He(l) required to cool the Al block under ideal conditions. Plotting this against temperature (or time) allows us to calculate approximately the total quantity of Helium used.

Table A.1 - Cool Down from Ambient to 4.2 Kelvin in 24 Hours.

Temp of Aluminium Plate (°K)	cpAl J/kg /°K	Cooling Power Required (kW)	BEST CASE m'He (kg/s) from (II) x 10^{-6}	WORST CASE m'He (kg/s) from (I) x 10^{-6}	Time from initial cool down. (seconds)
300	902.0	0.03007	19.2444	1438.94	0
280	896.0	0.02987	19.1164	1429.37	5 848
260	869.0	0.02897	18.5404	1386.30	11 695
240	849.0	0.02831	18.1137	1354.39	17 543
220	826.0	0.02754	17.6229	1317.70	23 391
200	797.0	0.02657	17.0042	1271.44	29 239
180	760.0	0.02534	16.2148	1212.41	35 086
160	713.0	0.02377	15.2121	1137.43	40 934
140	654.0	0.02181	13.9532	1043.31	46 781
120	580.0	0.01934	12.3745	925.26	52 629
100	481.0	0.01604	10.2623	767.33	58 477
80	357.0	0.01190	7.6167	569.51	64 325
60	214.0	0.00714	4.5658	341.39	70 173
40	77.5	0.00258	1.6535	123.63	76 020
20	8.9	0.00030	0.1899	14.198	81 868
4.5	0.3	0.000010	0.0064	0.479	86 400

Table A.2 - Cool Down from Ambient to 4.2 Kelvin in 48 Hours.

Temp of Aluminium Plate (°K)	cpAl J/kg /°K	Cooling Power Required (kW)	BEST CASE m'He (kg/s) from (II) x 10^{-6}	WORST CASE m'He (kg/s) from (I) x 10^{-6}	Time from initial cool down. (seconds)
300	902.0	0.01505	9.6320	720.2	0
280	896.0	0.01495	9.5679	715.41	11 695
260	869.0	0.01450	9.2796	693.85	23 390
240	849.0	0.01417	9.0660	677.88	35 086
220	826.0	0.01378	8.8204	659.52	46 781
200	797.0	0.01330	8.5107	636.36	58 477
180	760.0	0.01268	8.1156	606.82	70 172
160	713.0	0.01190	7.6137	569.29	81 868
140	654.0	0.01091	6.9837	522.19	93 563
120	580.0	0.00968	6.1935	463.10	105 258
100	481.0	0.00803	5.1363	384.05	116 954
80	357.0	0.00596	3.8122	285.05	128 649
60	214.0	0.00357	2.2852	170.87	140 345
40	77.5	0.00129	0.8276	61.88	152 040
20	8.9	0.00015	0.0950	7.106	163 736
4.5	0.3	0.000005	0.0032	0.239	172 800

Figure 2. Graph of Helium mass flow rate (kg/s) v. Temperature (Kelvin) during analyser cool-down period of 24 hours..

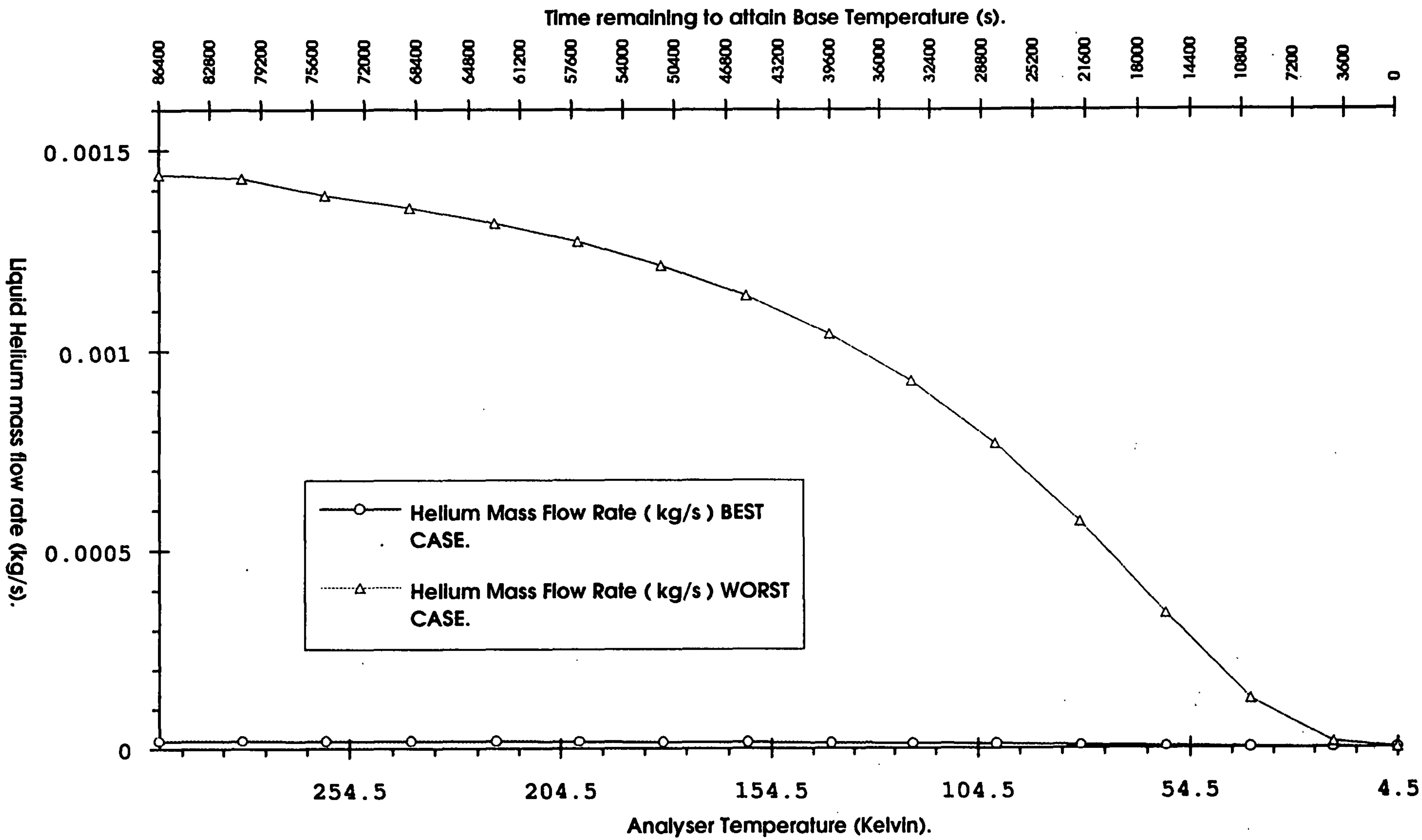
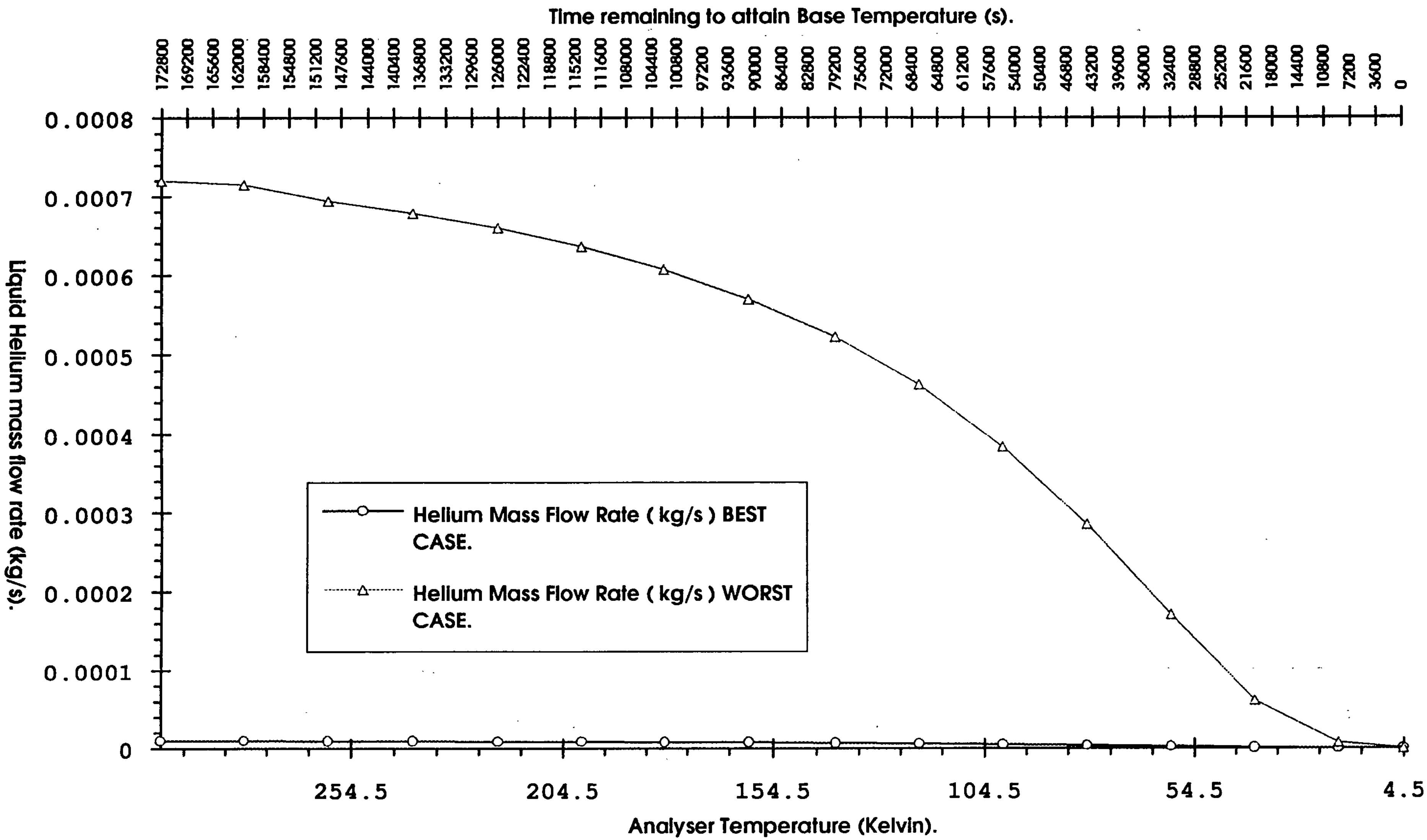


Figure 3. Graph of Helium mass flow rate (kg/s) v. Temperature (Kelvin) during analyser cool-down period of 48 hours.



Integrating the area beneath each graph we obtain, for a worst case scenario, a total $He_{(l)}$ consumption during cool-down of approx. 75 kg or 600 litres.

In order to reduce $He_{(l)}$ consumption during cool-down we should:-

a) Attempt to re-circulate Helium vapour around the Support Block to use as much vapour enthalpy as possible.

b) Pre-cool the support block, first using liquid nitrogen to 77 Kelvin via the radiation shield & then to 25 Kelvin using the current Helium gas closed cycle refrigerator.

c) Attempt to reduce the temperature gradient across the support structure to the vacuum vessel by using a moderate cooling rate. This will help to reduce conduction & radiation to the Helium reservoir.

Appendix B. Continuous Operation.

We may assume that there is a steady boil off rate of He(l) due to:-

a) Conduction from the Vacuum Vessel along the support structure to the He reservoir.

b) Radiation from the Vacuum Vessel via the intermediate LN2 shroud to the He reservoir.

a) Consider the current 3 stage convoluted tube support.

This has 6 component sections:-

i) a support plate 1,
ii) a thick welded section 2,
iii) a tube welded section 3,
iv) & vi) 2 nested tubes, 4 & 6, with
v) an intermediate tube welded joining section 5.

each with lengths l_1, l_2 l_3, l_4, l_5, & l_6 and cross sectional areas of A_1, A_2 A_3 A_4 A_5 & A_6.

$$Q'_{Support} = - A_1/\, l_1 \int_{T1}^{T2} k\, dT = - A_2/\, l_2 \int_{T2}^{T3} k\, dT = - A_3/\, l_3 \int_{T3}^{T4} k\, dT$$
$$= - A_4/\, l_4 \int_{T4}^{T5} k\, dT = - A_5/\, l_5 \int_{T5}^{T6} k\, dT = - A_6/\, l_6 \int_{T6}^{T7} k\, dT.$$

(Where T_1 , T_2 , T_3 , T_4 , T_5 , T_6 & T_7 are the intermediate temperatures at the coldest ends of sections 1, 2, 3, 4, 5 & 6 respectively).

We may assume under steady state conditions that T_1 = 4.2 Kelvin and T_7 = 300 Kelvin (ambient temperature).

Since in the Cryogenic region thermal conductivity k is non-linear we require an iterative calculation to calculate the intermediate temperatures, and equate the resultant Q'.

either

i) Assume intermediate temperatures.

ii) Calculate $- A / l \int_{Tc}^{Th} k\, dT.$

iii) Re-try until $- A / l \int_{Tc}^{Th} k\, dT$ equate for sections 1 to 6.

or

i) Assume a Q'.

ii) Calculate $-A / l \int_{Tc}^{Th} k\, dT$.

iii) Work out intermediate temperatures.

We shall use the second method since boundary condition temperatures are known.

Using the cross section area $A_6 = 3.070845 \times 10^{-5}\ m^2$ & assuming this is constant for the support length, & a total length $l_{total} = l_1+l_2+l_3+l_4+l_5+l_6 = 0.208998$ m we require $\int_{Tc}^{Th} k\, dT$ for stainless steel where T_h= 300 Kelvin & T_c= 4.2 Kelvin.
These integrals may be obtained from tabulated data & = 3060 W/m for the stated boundary temperatures.

Hence $-A_6 / l_{total} \int_{Tc}^{Th} k\, dT = 0.44961$ W for each convoluted tube support.

The following values apply for the current tube support.

$A_1 =$	180.11	mm^2	$l_1 =$	42.57	mm
$A_2 =$	258.67	mm^2	$l_2 =$	2.0	mm
$A_3 =$	81.96	mm^2	$l_3 =$	8.0	mm
$A_4 =$	28.09	mm^2	$l_4 =$	118.82	mm
$A_5 =$	716.28	mm^2	$l_5 =$	1.498	mm
$A_6 =$	30.69	mm^2	$l_6 =$	79.601	mm

$$Q'_{Support} = -A_1 / l_1 \int_{T1}^{T2} k\, dT = -A_2 / l_2 \int_{T2}^{T3} k\, dT = -A_3 / l_3 \int_{T3}^{T4} k\, dT$$
$$= -A_4 / l_4 \int_{T4}^{T5} k\, dT = -A_5 / l_5 \int_{T5}^{T6} k\, dT = -A_6 / l_6 \int_{T6}^{T7} k\, dT.$$

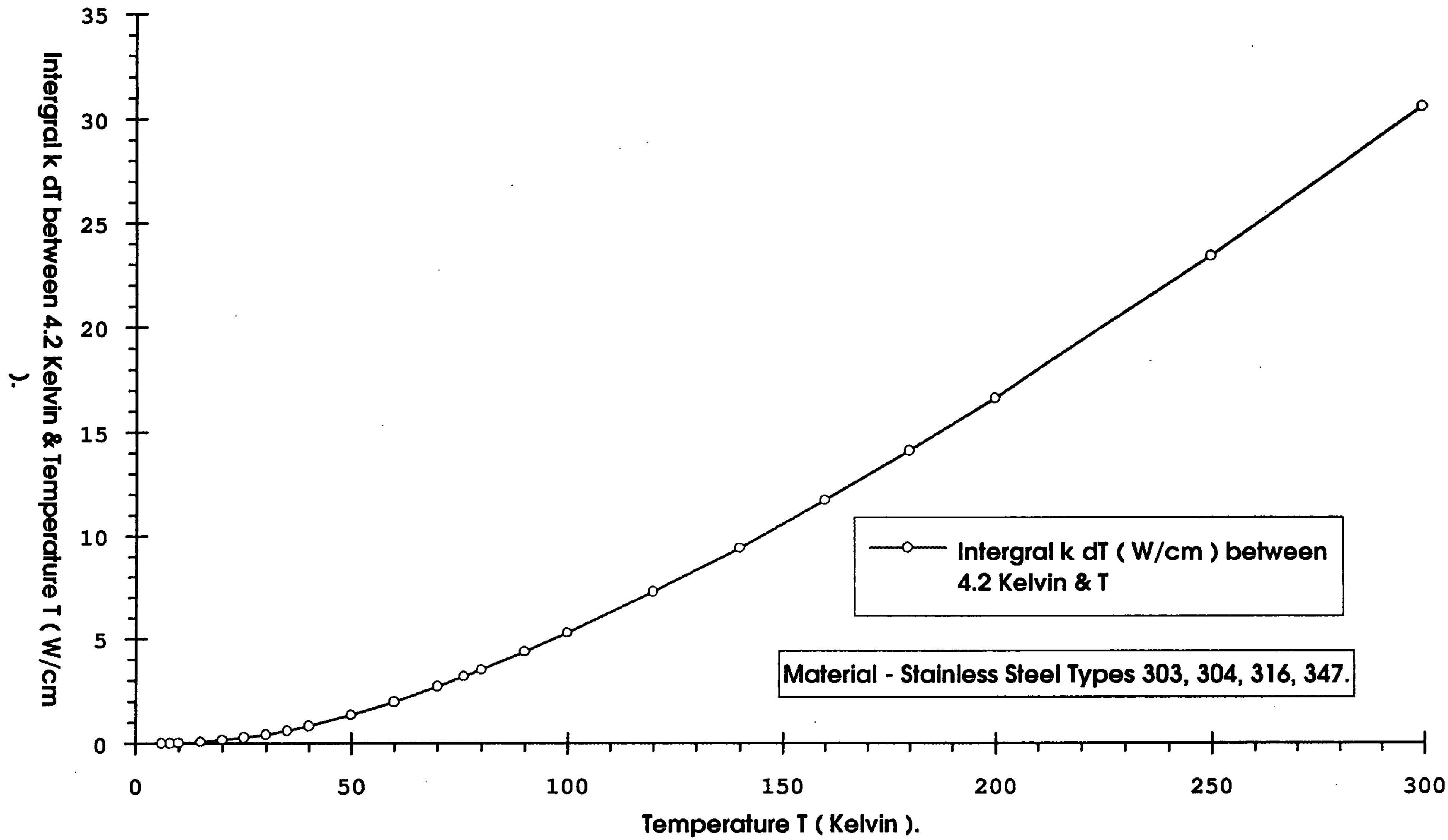
or

$$0.44961 = 4.23091 \times 10^{-3} \int_{T1}^{T2} k\, dT$$
$$= 4.23091 \times 10^{-3} \left[\int_{4.2}^{T2} k\, dT - \int_{4.2}^{T1} k\, dT \right].$$
$$= 4.23091 \times 10^{-3} \int_{4.2}^{T2} k\, dT \text{ (since } T_1 = 4.2\ ^\circ K).$$

$$\int_{4.2}^{T2} k\, dT = 1.062679187 \text{ W / cm}.$$

By plotting a graph of $\int_{4.2}^{T} k\, dT$ vs. temperature T for Stainless Steel we obtain $T_2 = 44.54\ ^\circ K$.

Figure 4. Graph of Intergral k dT (W/cm) between 4.2 Kelvin & T (Kelvin) for Stainless Steel.



similarly : $0.44961 = 0.129335 \int_{T2}^{T3} k\,dT$

=> $\int_{T2}^{T3} k\,dT = 3.476321181$ W/m. = 0.034763211 W/cm.

We may then use this to calculate

$\int_{4.2}^{T3} k\,dT = \int_{T2}^{T3} k\,dT + \int_{4.2}^{T2} k\,dT$ & obtain T_3 graphically.

Next : $0.44961 = 0.010245 \int_{T3}^{T4} k\,dT$

and : $\int_{4.2}^{T4} k\,dT = \int_{T3}^{T4} k\,dT + \int_{4.2}^{T3} k\,dT$; obtain T_4 graphically.

Using this procedure we may obtain T_5, T_6 & T_7. We can compare T_7 with the assumed value of 300 °K and use the error to re-iterate.

This yields the following results:-

Temperature (°K).	Assumed Boundary Conditions (°K)	First Iteration (°K)	Second Iteration (°K)	Third Iteration (°K)
T_1	4.2	4.2	4.2	4.2
T_2	-	44.54	43.76	43.59
T_3	-	45.20	44.40	44.22
T_4	-	52.96	52.02	51.81
T_5	-	229.08	223.27	221.99
T_6	-	229.15	223.33	222.05
T_7	300	312	302.67	300.79
% Error (T_7)		4.0 %	0.9 %	0.3 %
Q' down support.		0.4496 W	0.43232 W	0.42851 W

Conduction down current support design would be 0.429 Watts per support for 300 Kelvin & 4.2 Kelvin boundary conditions.

b) Radiative Heat Transfer.

Assume the He(l) reservoir within the LN2 shroud is representative of a cylinder within a cylinder.

Net exchange of Radiation is :

$$Q'/A_1 = \frac{\sigma (T_2^4 - T_1^4)}{(1/\varepsilon_1 + A_1/A_2 (1/\varepsilon_2 - 1)}$$

Where :

- Q' = Heat Transfer Rate (Watts).
- A_1 = Surface Area of Inner Cylinder cm^2.
- A_2 = Surface Area of Outer Cylinder cm^2.
- σ = Stefan Boltzman Constant (5.67×10^{-8} J/s m^2 $°K^4$).
- ε_1 = Emissivity of Inner Cylinder.
- ε_2 = Emissivity of Outer Cylinder.
- T_2 = Temperature of Outer Cylinder (Warm) °K.
- T_1 = Temperature of Inner Cylinder (Cold) °K.

For the proposed design :

- A_1 = 1.79952 m^2
- A_2 = 0.640345 + 0.74997 m^2 = 1.390315 m^2.
- ε_1 (Copper) = 0.03 (Commercially available - emeried
- ε_2 (Copper) = 0.03 with pits remaining).
- T_2 = 77.35 °K.
- T_1 = 4.2 °K

Q' (Radiative) = 0.0486 W (from LN2 to He(l) reservoir)

Total Heat transfer to He(l) reservoir = 3 (0.42851) + 0.0486 W
= 1.33413 W

In order to obtain the maximum duration between replenishment of He(l) reservoir we require:-

a) Minimum Heat transfer to reservoir:

=> i) Maximum length of convoluted tube support.
ii) Minimum Support cross-sectional area.
iii) Minimum reservoir surface area.
iv) Select material with low emissivity.

b) Maximise Capacity of reservoir within space available.

c) Connect all supports & feedthroughs to intermediate LN2 shroud at 77.35 °K.

Proposed design gives a He capacity of 35.842 litres,
(= 0.035842 m^3 = 4.47672 kg He(l)).

A 5 tube convoluted support is being used to increase length. The central support is shorter to accommodate the Microcontrole translation units.

Q' (per outer support) = 0.18203 W.
Q' central support = 0.42518 W.

Total Q' up support = 0.78924 W.

Total Q' to reservoir = 0.865201 W.

Latent Heat of vaporisation of He(l) = 20.9 J/g
=> He reservoir requires 93.563 kJ for complete boil-off.

To vaporise all He(l) in reservoir will take 93 563.45 / 0.865201 seconds or approximately 30 hours.

A 100 litre dewar will provide 2.79 re-charges sufficient to last approximately 83 hours, (approx. 3.5 days). This will reduce significantly if the He reservoir is continuously pumped to reduce temperatures still further.

Appendix C. Support Loads.

To obtain the stress in each support we require the following loads :

i) Weight of Graphite Crystals. Mass = 1.17 kg
ii) Weight of Cadmium Backing Plate + 2 end pieces. Mass = 20.04 kg
iii) Helium reservoir weight. Mass = 114.19 kg
iv) Weight of liquid Helium. Mass = 4.48 kg
v) Supply Pipework. Mass = 4.54 kg

Total = 143.25 kg

vi) Liquid Nitrogen Shield weight. Mass = 33.05 kg
vii) Aluminium Foil Window weight. Mass = 0.62 kg
viii) Cadmium Shield weight. Mass = 14.27 kg
ix) Supply Pipework. Mass = 5.02 kg

Total = 52.96 kg

Total Mass to be supported = 197.38 kg.

The smallest tube in the convoluted support is 0.5 inch outside diameter with wall thickness of 0.006 inches.

Cross section area = 6.0075 mm^2.

Load in each support = 645.44 N

Stress in each support = 645.44 / 6.0075 = 107.44 N/mm^2.

Allow a safety factor of 5.

For Stainless Steel tensile strength is typically 550 N/mm^2 so the safety factor is not exceeded.
(In reality the smallest diameter tube is loaded in compression, the 2nd & 4th tubes are loaded in tension).

Appendix D. Support Static Deflection.

Load in each support = 645.44 N

Young's Modulus for Stainless Steel = 210×10^9 N/m^2.

Stress in each support = 107.44 N/mm^2 (Nominal).

Support Tube Number	Support Tube Length (m).	Support Tube X-section Area (m^2).	Direct Stress (N/m^2)	Tensile or Compressive .	Change in length (m).
1	0.1667	6.0075×10^{-6}	107.4398×10^6	Compressive	-8.5287×10^{-5}
2	0.1407	8.5313×10^{-6}	75.6561×10^6	Tensile	5.0689×10^{-5}
3	0.1407	10.4405×10^{-6}	61.8212×10^6	Compressive	-4.1420×10^{-5}
4	0.1407	13.9723×10^{-6}	46.1946×10^6	Tensile	3.0950×10^{-5}
5	0.1707	16.6842×10^{-6}	38.6859×10^6	Compressive	-3.1446×10^{-5}
Total Length	0.7595				-7.6514×10^{-5}

Length of Tube welded joint sections = 0.07 m.
Total support length = 0.8295 m

Appendix E. Thermal Contraction of Support.

Coefficient of linear expansion for stainless steel = 11×10^{-6} per °K.

Assuming the whole support is cooled to 4.2 °K (in reality a temperature gradient exists) the maximum thermal contraction of the support is:-

= 11×10^{-6} (298 - 4.2) (0.8295) = 2.68078×10^{-3} m or 2.68078 mm.

Total reduction in analyser height under operating conditions = 2.7573 mm.

This will have to be allowed for during the surveying operation. (The support design allows for up to 10.0 mm adjustment in height).

Appendix F. List of Figures

Volume 1

Graphs.

Volume 2

Ray Diagrams.

Detail Explanatory Views.

Component Drawings.

General Arrangements.

Graphite Mounting Components.

Helium Reservoir Components.

Liquid Nitrogen Shield Components.

Cryogen Feed Components.

Tooling Drawings.