ULTRACAM REVIEW DOCUMENT

"Ultracam Camera Head"

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May 2001

Version: A (draft 0)

Issued By UKATC

Revision Control

1.	Revision Version #:	A(draft 0)
	Date:	17^{th} April 2001
	Revised by:	David Atkinson
	Reasons for/items changed	Original version

Section 1. Introduction

1-1.0 Background

ULTRACAM is an ultra-fast, triple-beam photometer using the latest in Charge Coupled Device (CCD) technology, providing UK astronomers with the capability to do high-speed, multi-wavelength optical photometry [1]. The optical design of the device includes collimating fore-optics to collimate the light from the telescope and two dichroic beamsplitters to split the light into blue, green, and red wavelengths. Each band of light is filtered and re-focused onto a CCD chip housed within its own camera head, as illustrated in Figure 1 [1]. The CCD chips will be frame transfer CCD47-20 devices from Marconi Applied Technologies enabling an image field of up to 5 arcminutes with essentially no dead-time simultaneously in three different colours.

The instrument will be assembled at the University of Sheffield, and the UKATC will deliver the detector system. It will be commissioned at the GHRIL focus of the 4.2m William Herschel Telescope (WHT) in La Palma for high temporal resolution investigation of interacting binary stars. It is anticipated that in addition to operation on the WHT it will also be utilised on other telescopes, such as the 2.5m Isaac Newton Telescope, 2-m Liverpool Telescope, 1.9m Radcliffe Telescope, and the 9.2m South African Large Telescope.

1-1.1 Purpose of Document

This document describes the requirements and design of each of Ultracam's three camera heads. It provides information on the mechanical design, thermal and electrical interfaces. The intended audience for this document is the Ultracam team and the reviewers of the Ultracam system.

Section 2. Requirements

2-1.1 Introduction

This section is concerned with the requirements of the camera heads utilised to house each of Ultracam's CCD chips. There will be three identical camera heads, one for each of the CCDs.

2-1.2 Overview

The camera heads are designed to hold the CCDs in their required position relative to the main instrument assembly. The heads should allow the CCDs to be adequately cooled to meet the required dark current rates. They should also ensure that no condensation forms on the active silicon of each of the three detectors. Likewise they should allow the CCDs to be mounted to the instrument in the correct position and orientation. However there will be no facilities on the mechanical heads themselves for accurate X-Y pixel alignment. This facility must be part of the main instrument body itself as supplied by the customer. This will probably take the form of X-Y translation stages to which the CCD heads mount.

2-1.3 Optical

Each camera head must provide a light tight housing for the CCD sensor. The design and manufacture of the camera head lid, which will incorporate an optical window, and mechanical translation stage, will be carried out at the University of Sheffield.

2-1.4 Thermal

The desired dark current rate for ULTRACAM is 0.1electrons/pixel/second (e/p/s). The CCD being utilised is the Marconi Applied Technologies (MAT) CCD47-20 (Backthinned), whose dark current is given by Equation 1.1[2].

$$DC = \frac{1.14\times10^{6}\times T^{3}\times e^{\frac{-9080}{T}}}{DC_0} \qquad \mathbf{1.1}$$

Where,

T = CCD Temperature in Kelvin

DC_0 = Dark signal at 293K, specified as 250e/p/s typical or 500e/p/s worst case.

Assuming the worst case value for DC_0 the dark current versus temperature curve is presented in Figure 2. Here it can be seen that a temperature of 233K (-40°C) is required for a dark current of less than 0.1e/p/s. Consequently, the CCD chip needs to be cooled to at least 233K. It should be noted that MAT have been requested to provide CCD chips with at least typical dark current values.

2-1.5 Mechanical

The camera head must provide a light tight housing and facilitate all the necessary thermal and electrical interfaces. No formal weight or size restrictions were placed on the design of the camera head. However, since Ultracam is a portable instrument the heads will be kept small and relatively light (under 10kg per head).

2-1.6 Electronics

The CCD is to be mounted on a detector board which will route all the necessary clock, bias and video signals to and from the CCD. It will also provide gain to the video signal at the detector head. An SDSU controller will be used to generate all the necessary clocks and biases for the CCD, and to electronically process the generated video signal.

All cabling external to the camera head will utilise military style connectors due to their robust nature and since they are the standard at the UK ATC. Therefore, each camera head must facilitate connections to three such cables: (1) for the analogue signals to the CCD, (2) for the digital clocks to the CCD, (3) for service electronics. It is a requirement that all three connector sockets be of differing sizes, thereby ensuring that none of them are accidentally connected to the wrong cable.

Section 3. Camera Head Description

3-1.1 Introduction

This section provides a description of the camera head design.

3-1.2 Overview

As discussed a temperature of –40°C is required to meet the dark current requirements. Consequently the CCD will be cooled with a multistage Thermoelectric Cooler (TEC). To ensure that no condensation forms on the active silicon of each the detector, each head will be designed as a vacuum enclosure and will be pumped down prior to use. The camera head is rectangular is shape and its base is a water-cooled copper heat exchanger, enabling the heat pumped by the TEC to be removed. The three electrical connectors attached to the box are hermetically sealed military connectors, (1) for digital signals, (2) analogue bias and video signals, and (3) TEC power supply and temperature sensor signals.

3-1.2 Optical

The focal plane of the CCD is 9.25mm from the top of the camera head (without lid), as illustrated in Figure 3. Note that the top plane of the CCD is 7.26mm from the top of the box (without lid). The CCD is a frame transfer device and consequently the imaging area is off the centre of the chip. However, this is accommodated for such that the centre of the CCD imaging area is located at the centre of the camera head's lateral dimensions, as illustrated in Figure 3.

3-1.2 Mechanical

The camera head is a rectangular box, whose base is a copper/brass heat exchanger, and whose main body is a topless and bottomless aluminium box. The lid of the box is being designed at the University of Sheffield, although a temporary lid with glass window has been used for laboratory test purposes.

Three of the faces of the aluminium box have appropriate detail machined into them to accommodate the three required hermetic connectors for the electronics, and two standard vacuum attachments. Viton “O” rings are utilised in conjunction with the hermetic connectors and vacuum attachments to maintain the vacuum seal.

The heat exchanger is a copper block with a channel milled into it to form a coolant path. A brass plate is soldered onto the copper block to seal off the channel and to provide two 1/8” British standard pipe thread (BSPT) locations for inlet and outlet pipe fittings. A Viton “O” ring forms a vacuum seal between the aluminium body and the heat exchanger base. The overall dimensions of the box (without lid) are 152mm x 172mm x 57mm. The overall weight of the head, including all fittings and internal parts is approximately 5kg.

The assembly detail is illustrated in Figure 4. Figure 4 (a) shows the brass backplate. Figure 4 (b) shows the copper heat exchanger, which is soldered onto the brass backplate. Figure 4(c) includes the TEC stack, copper coldfinger and mounting screws. Note that disc springs are used here to generate a downward force onto the TEC stack from the coldfinger. Figure 4(d) includes the detector printed circuit board (PCB), which is mounted on G10 pillars. As can be seen the copper coldfinger protrudes through a hole in the centre of the PCB. ‘Micro-D’ PCB mount connectors are also shown, which are utilised to interface the video, clock, and bias wiring to the PCB. Figure 4(e) includes the CCD and a thin G10 cover plate. This flexible plate is screwed onto mounting pillars to generate a downward force onto the CCD. Finally, Figure 4(f) shows the main aluminium body of the camera head. Here the three electronic connector mounting locations and two vacuum connector locations can be seen. Furthermore, various photographs of the assembled head are provided in Figure 5. For interest Figure 5(d) shows a picture of Ultracam with a camera lens attached to it and Figure 6 displays a photograph of the laboratory taken with Ultracam arranged as such.

3-1.2 Thermal

To achieve the required dark current rates Ultracam uses a TEC device to cool the CCD. TECs are solid state heat pumps that utilise the Peltier effect. During operation, DC current flows through the TEC causing heat to be transferred from one of its sides to the other, creating a cold and hot side. As discussed above, the hot side of the TEC stack is mounted directly on top of the copper heat exchanger, and as illustrated in Figure 7, a copper 'coldfinger' interfaces the cold side of the TEC to the underside of the CCD through a hole in the detector board. It is predicted that the TEC stack will be required to remove approximately 2W of heat, see Appendix A for details. Furthermore, given the thermal performance of the copper heat exchanger, as detailed in Appendix B, a temperature difference of a least 57°C will be required. The heat transferred to the hot side of the TEC, and the active heat generated by the TEC itself will be dissipated via the water cooled copper heat exchanger, which forms the base of the camera head.

When buying a TEC the manufacturers state the device's ΔT_{Max}, and Q_{Max}. ΔT_{Max} is the maximum temperature difference that the TEC can provide. This can only be achieved when there is no heat load. Conversely, Q_{Max} is the heat load that will reduce the device's temperature difference to zero. Therefore, for a given TEC the greater the heat load (i.e. closer to Q_{Max}), the lower the temperature difference that it can produce. After consultation with various TEC companies a 3-stage Melcor TEC stack was selected. (Melcor 3 CP 085 065-71-31-17). This device has a ΔT_{max} of 97°C and a Q_{max} of 15.6W.

The copper heat exchanger is cooled using a *Nestlab Merlin-33 recirculation chiller*, which regulates the temperature to 8°C and can sink approximately 700W of heat at this temperature [4]. One unit will be utilised to cool all three heads and the SDSU controller in series, as illustrated in Figure 8. Power is supplied to the TEC using an *Alpha Omega series 800* PID controller. This controller can supply 120W of power (8A @ 15V). The TEC cold side temperature is fed back to the controller via an *AD590* temperature sensor embedded within the copper coldfinger.

3-1.2 Electronics

A 12 slot CCD controller supplied by SDSU will be utilised for Ultracam. This controller includes a 250MHz Timing board, 3 clock boards, 3 CCD video boards, and a 250MHz PCI board. The controller will consist of 6 video inputs to allow each of the 2 outputs from the 3 CCDs to be readout in parallel. The controller will feed the image data to a SDSU supplied PCI interface card via a fibre link and subsequently to a PC, and will receive commands via another fibre link from the same PCI interface. Furthermore, the SDSU controller will supply a synchronisation pulse to the PC for time stamping purposes.

Each camera head will have three cables attached to it: (1) to supply the clock signals to the CCD from the SDSU controller; (2) to supply the bias signals to the CCD from the SDSU controller, and to return the video signal to the SDSU controller; (3) to supply the TEC power from the Alpha-Omega TEC controller, and feedback the cold side temperature to the Alpha-Omega TEC controller. The PC will also have 3 RS232 ports to communicate with the three Alpha-Omega TEC controllers. An overview of the cabling is illustrated in Figure 9.

A detector / pre-amp board will be located within the camera head to house the CCD chip and route the necessary clock, bias and video signals to and from the CCD. Connections are made to the PCB board via two PCB mount 'Micro-D' connectors, one for the clock signals, and the other for the video and bias signals. Mating 'Micro-D' connectors are wired to the relevant hermetic connectors with light weight (7/0.12) copper wire. The PCB board also provides gain to the video signal (probably a x10 stage), and electrostatic discharge (ESD) protection for the CCD by utilising the ESD *SP720* protection chip.

Section 4. Issues

To achieve Ultracam's dark current requirements it is predicted that the CCD must be cooled to at least –40°C. As discussed this will be achieve using a multistage Thermoelectric Cooler (TEC). To eliminate convective heat loading on the TEC (thereby enhancing its performance) and condensation each camera head is designed as a vacuum enclosure. It is desired that the heads hold a suitable vacuum for several weeks or even months to reduce the frequency of re-pumps. Ideally, a vacuum of below $1x10^{-3}$Torr ($1.3x10^{-3}$mBar) is desired since convective heat loading on the TEC can then be ignored. With this heat load eliminated the TEC can generate a larger temperature difference. However, the only requirement on the vacuum is that it ensures no condensation forms on the CCD, and that the thermal performance of the TEC can achieve the required dark current rate. Consequently, vacuum pressures greater than this may be sufficient. For example, Robinson and Osborne [7] describe a CCD camera system, which utilises TEC cooling. The CCD and TEC are housed within a vacuum enclosure to ensure no condensation forms on the CCD, with repumping suggested for pressures above 1Torr.

4-1.1 Vacuum Hold Time

A camera head was assembled and vacuum tests were performed. After an initial pump down was carried out, a pinch-off head pressure of around $1x10^{-5}$mBar was achieved. The hold response for 2 hours is shown in Figure 10, series 1 and as can be seen the pressure increased to above 10^{-2}mBar within an hour. It should be noted that during this pressure measurement the TEC cooled the coldfinger and subsequently CCD to –40°C. Leak tests were carried out on the assembled head and no *real* leaks were found, therefore it was assumed that this rise in pressure was due to *virtual* leaks, that is out-gassing of materials and the release of trapped air within the enclosure. The camera heads have a fairly large internal surface area to volume ratio, which increases the significance of virtual leaks. Furthermore, the coldest surface within the enclosure is the coldfinger, which is only around the order of –40°C so there is limited cryo-pumping effect. A 'clean' assembly was then carried out and long pump down (7 days) was performed. Series 2 on Figure 10 indicates the hold response after this procedure was carried out. There has been a slight improvement, however, the hold time is still poor.

In an attempt to combat the virtual leak problem a vacuum getter was added to the camera head assembly. This was done by boring a hole (diameter 10mm, 12.8mm deep) into the copper coldfinger (which is the coldest object within the camera head), filling it with charcoal, then adding a framed wire mesh to contain the charcoal within the coldfinger. A photograph of this arrangement is provided in Figure 12. The coldfinger was baked out at 100°C in a vacuum oven for 3 hours then added back into the camera head for an overnight pump-down. During the pump-down the TEC was used to heat the coldfinger, and subsequently the charcoal getter, to +45°C. The TEC was then set to cool the coldfinger to –40°C and the hold response was measured. The result is shown in Figure 10 series 3, where it can be seen that a vast improvement has been achieved over the first 2 hours. This experiment was then repeated, but this time only using the TEC to bake out the coldfinger at +45°C during pump-down. The hold time response can be seen on Figure 10, series 4. It can be seen that the improved response is repeatable simply using the TEC to heat the getter during pump-down. At this stage it was thought that this simple getter arrangement had solved the hold time problem. However, continuing the hold time analysis for several days revealed that the response began to rapidly decline, as illustrated in Figure 11, series 4. It is thought that this is due to continued out-gassing within the enclosure after the getter as reached sorption capacity. Encouragement can be taken from the fact that the getter improved the initial hold time response of the vacuum enclosure. Consequently, a getter arrangement with a larger sorption capacity could prove fruitful.

Unfortunately, while the introduction of the charcoal getter into the coldfinger improved the initial hold time response it had a negative impact on the TEC's performance. That is the TEC controller had to supply more power to the TEC to maintain –40°C. It is though that this is the result of getter increasing the surface area of the coldfinger and consequently the radiative load on the TEC (see Appendix A for radiative load definition). The next section discusses the influence of the load characteristics on the TEC performance.

4-1.2 TEC Performance Evaluation: Influence of Load on TEC

Convective Load

The camera head was assembled with only the TEC, and coldfinger internal to the enclosure. The power supplied to the TEC to maintain a cold side temperature of –40°C at various pressures was investigated to evaluate the influence of conductive heat loads on the TEC performance. To get a measurement for atmospheric pressure, while ensuring that no condensation formed on the CCD, the heads were back filled with dry Nitrogen. In addition, a measurement was taken with the head subjected to a continual dry Nitrogen flow, which was passed through the head via an inlet and outlet valve. The results are displayed below in Table 1.

Pressure (mBar)	Power supplied to TEC
3.7×10^{-5}	8.4W
5×10^{-4}	8.4W
5×10^{-3}	8.4W
1×10^{-3}	8.4W
5×10^{-2}	8.9W
1×10^{-2}	9.5W
5×10^{-1}	11.6W
1×10^{-1}	14.3W
Atmosphere: Back filled with Dry N2	24.8W
Atmosphere: Dry N2 Flow	Unachievable (-32°C minimum)

Table 1: *Pressure vs power supplied to TEC for -40°C*

It can be see that at low pressures the power supplied to the TEC to maintain -40°C is only 8.4W and that this remains constant for pressures below $1x10^{-3}$mBar (note that 1.3mBar equals 1Torr). Therefore, it can be seen that conductive loading begins to have an influence on the TEC's performance at pressures above $1x10^{-3}$mBar. With the camera head enclosure back filled with dry Nitrogen, the TEC requires 24.8W of power to maintain -40°C. Furthermore, it can be seen that a dry N2 flow cripples the TEC response resulting in a minimum achievable temperature of only -32°C. It should be noted that this minimum temperature was achieved with 41W supplied to the TEC. For powers greater than this the TEC begins to self-heat and the cold side temperature rises.

Radiative and Conductive loads

Various loading conditions were then investigated to see their influence on the TECs performance. While these measurements were taken the heads were continuously pumped to achieve pressures below $1x10^{-3}$Torr, thereby removing the influence of convective loading. The following conditions were investigated.

1. Only the coldfinger and TEC are internal to the camera head. Therefore, the TEC is only cooling the coldfinger, and subsequently the only heat load to be removed is the radiative heat load on the coldfinger.
2. The PCB and CCD are added to head. Therefore, the coldfinger and CCD are now loading the TEC. The extra surface area of the CCD increases the radiative loading on the TEC. In addition, there is conductive loading via the copper tracks on the PCB and the pins of the CCD. It should be noted that the copper wiring looms were not connected to the PCB.
3. The copper wiring looms were plugged into the PCB board (via the 'Micro-D' connectors). This increases the conductive heat loading to the TEC.

Under these three conditions the power required to realise a cold side of -40°C was noted. Following this the coldest temperature possible under each loading condition was noted. The results are shown in Table 2.

Loading Condition	α–Ω power to maintain -40°C	Minimum achieved Temperature
1	8.4W	-50°C (@ 23.9W)
2	12.9W	-46.7°C
3	17.3W	-43.7°C

Table 2: *Loading Conditions influence on TEC performance*

For condition 1 it can be seen that TEC required 8.4W to maintain -40°C, and that furthermore a minimum cold-side temperature of -50°C was achieved with 23.9W. This is the lowest measurable temperature with the AD590 sensor arrangement. For the other conditions minimum temperatures were achieved with approximately 40W of power supplied to the TEC. For power inputs greater than this the TEC begins to self-heat, and consequently loses temperature difference. It can be seen from condition 2 that with the addition of the CCD and PCB board, the TEC requires 12.9W of power to maintain a cold side temperature of -40°C. Furthermore, the minimum achievable cold side temperature has risen to –46.7°C. This is due to the introduction of a conductive load via the copper tracks of the PCB and pins of the CCD, and an increase in the radiative loading. Furthermore, condition 3 shows that the additional conductive load introduced by connecting the copper wire looms to the PCB has a detrimental effect on the performance of the TEC, with a minimum temperature of only –43.7°C achieved. These results highlight the significance of minimising the heat load on the TEC.

Suggestions

It has been shown that reducing the load on the TEC can significantly improve its performance. Consequently, it is suggested that a reiteration of the head design be carried out to improve the vacuum hold time and minimise the TEC heat load. Firstly, to reduce the conductive loading the copper wiring looms internal to the camera head will be replaced with a material of low thermal conductivity such as Constantan or Manganin.

In addition, minimising the surface area of the coldfinger, and its emissivity can reduce the radiative heat load. The emissivity can be lowered by either applying a gold finish to the copper block or by changing the material to Aluminium with a polished finish.

To minimise convective loading and reduce the frequency of vacuum re-pumps the vacuum hold time needs to be improved. The current detector PCB includes silk screen, which will out-gas, consequently the PCB will be remanufactured without silk screen. Replacing all viton o-rings with indium o-rings can make a further improvement. A reduction of the number of o-rings is also proposed. Firstly, the heat exchanger could be incorporated into the main body of the camera head. That is, the head would be a topless box machined from one piece of metal with the exchanger channel milled into its base. In addition the number of vacuum ports could be reduced from two to one, and including the TEC power supply and temperature sensor connections to the clock cable could reduce the number of electronic connectors from three to two. Furthermore, it is proposed that a molecular sieve desiccant be incorporated into the camera head.

It should be reiterated that the only requirement on the vacuum is that it ensures no condensation forms on the CCD, and that the thermal performance of the TEC can achieve the required dark current rate. To date, only an engineering CCD47-20 device has been utilised in the lab, which displays a poor dark current response. Once the scientific devices have been added to the system real measurements of achieved dark current rates can be made. In fact this document assumes a cold side temperature of –40°C is required to meet the dark current requirements. This is based on worst case figures for the scientific devices, that is a DC_0 (Dark signal at 293K) of 500e/p/s. In fact, two of the supplied scientific devices have DC_0 values specified as 150e/p/s. Consequently, on application of Equation 1.1 it can be deduced that a cold side temperature of only –33°C is required to meet a dark current rate of 0.1e/p/s. However, the third scientific CCD device has a DC_0 of 450e/p/s, resulting in a required cold side temperature of –39°C. When purchasing the scientific CCDs a DC_0 of at most typical (250e/p/s) was specified. Consequently, the 3rd scientific device is likely to be returned if it can not meet our requirements.

Bibliography

[1] ULTRACAM web site: http://www.shef.ac.uk/uni/academic/N-Q/phys/people/vdhillon/ultracam/index.html

[2] CCD47-20 Data Sheet, http://www.marconi-technologies.co.uk/

[3] Marlow Industries, Inc. 'Thermoelectric Cooling Systems Design Guide', http://www.marlow.com

[4] NESLAB, http://www.neslabinc.com

[5] D.J. Burt 'CCD Performance Limitations: Theory and Practice', CCD Technical Note 18, EEV Limited, Waterhouse Lane, Chelmsford, Essex, England.

[6] Frank P. Incropera, and David P. DeWitt, *Introduction to Heat Transfer 3rd Edition*, John Wiley & Sons, New York, 1996.

[7] L. Robinson and J. Osborne, 'A CCD TV Camera for Telescope Guiding', *Publications of the Astronomical Society of the Pacific*, **99**, 1987, pp234-239

Figures

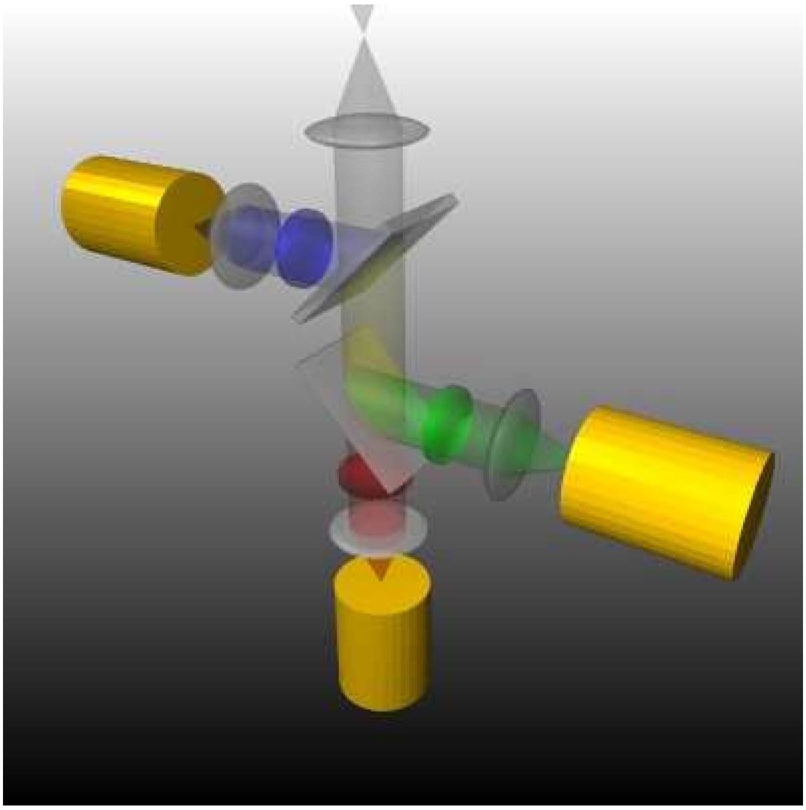


Figure 1: *ULTRACAM Optical Design*

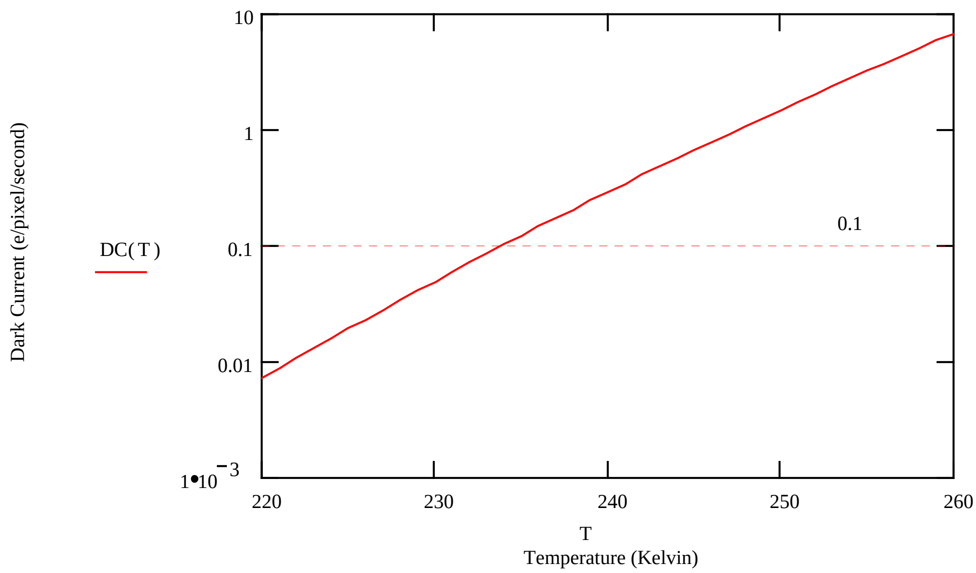
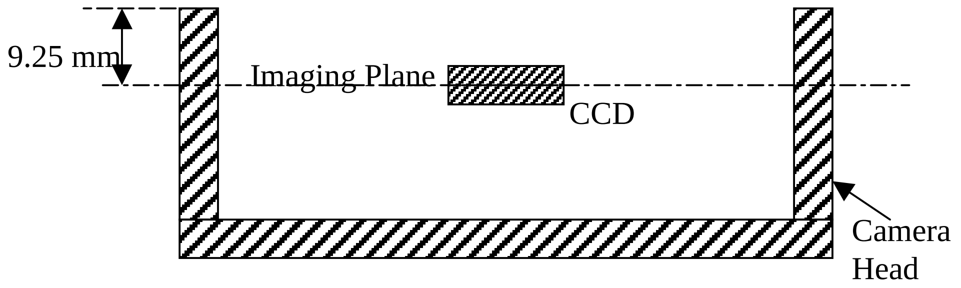
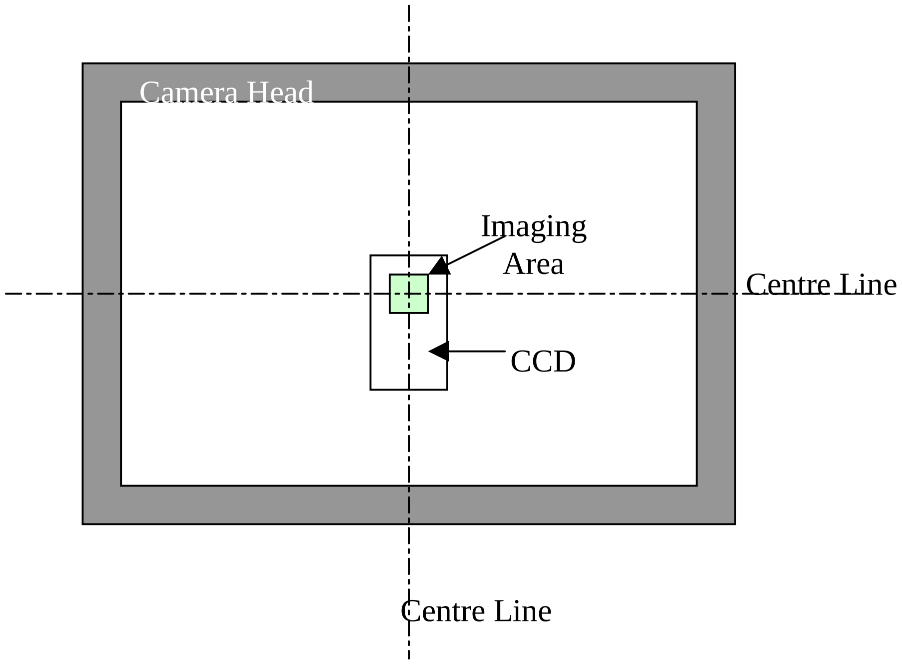


Figure 2: *Dark Current versus Temperature for CCD47-20*



Section view sketch of camera head and CCD



Plan View sketch of camera head and CCD

Figure 3: *CCD location within camera head*

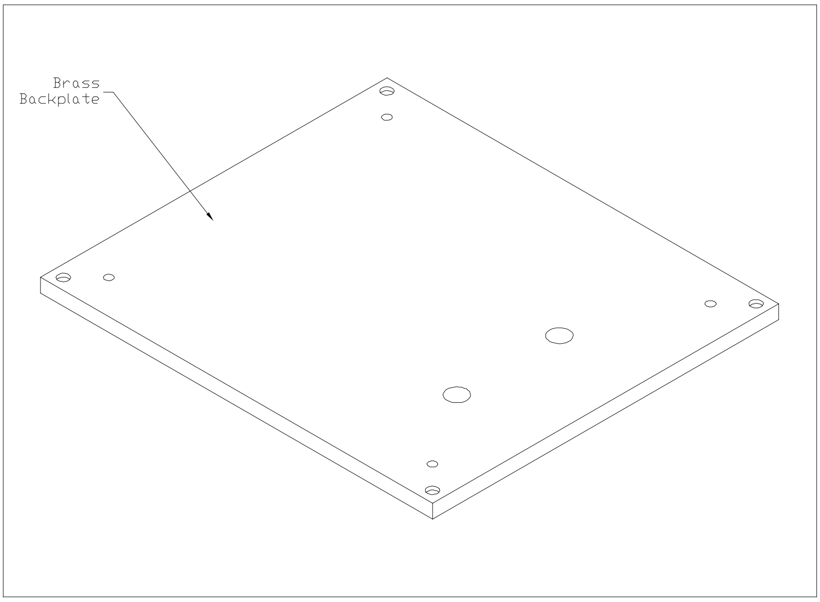


Figure 4 (a): *Camera Head Assembly - backplate*

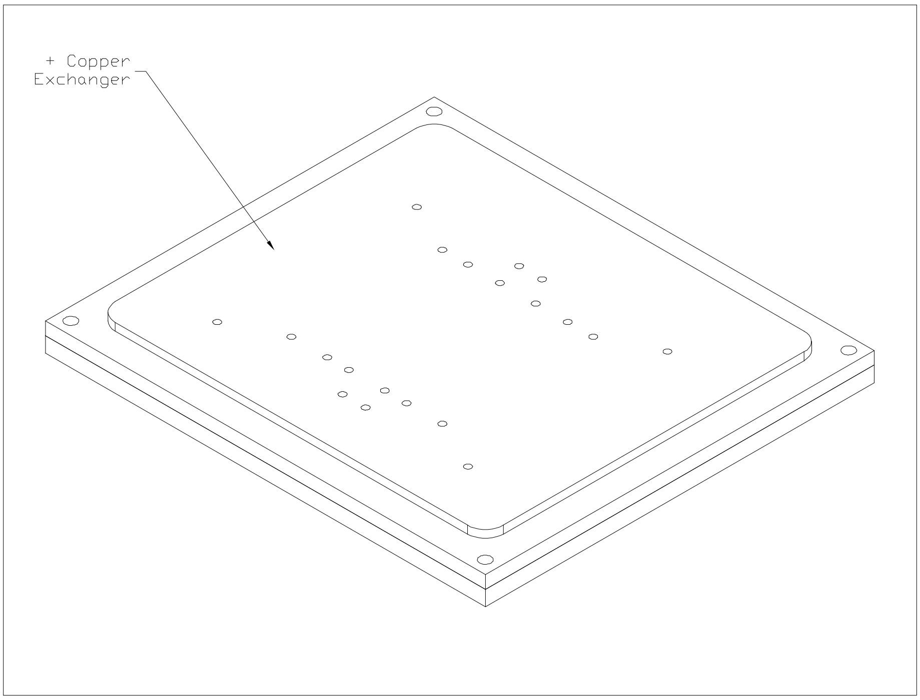


Figure 4 (b): *Camera Head Assembly – Copper heat exchanger*

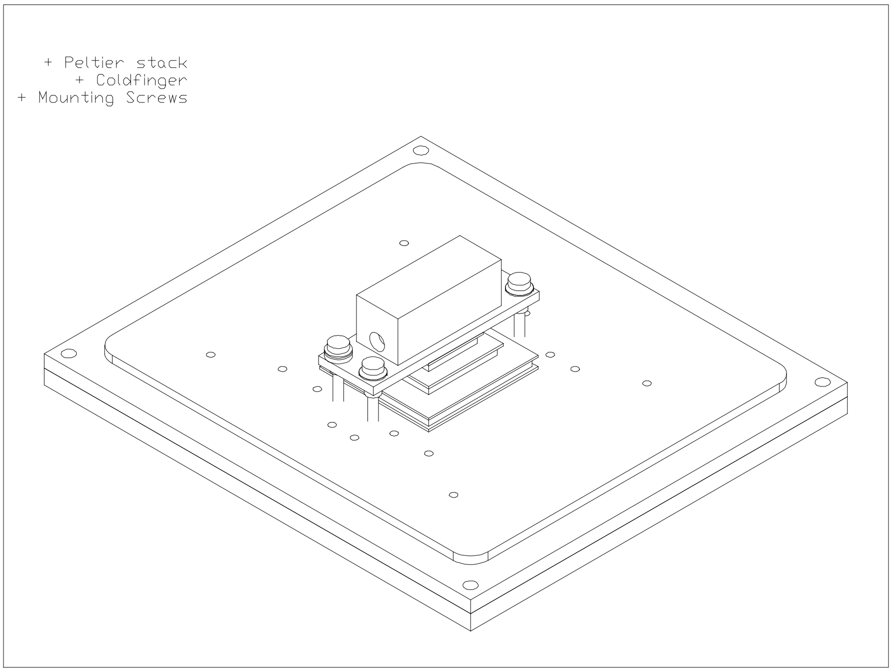


Figure 4 (c): *Camera Head Assembly – TEC and coldfingerr*

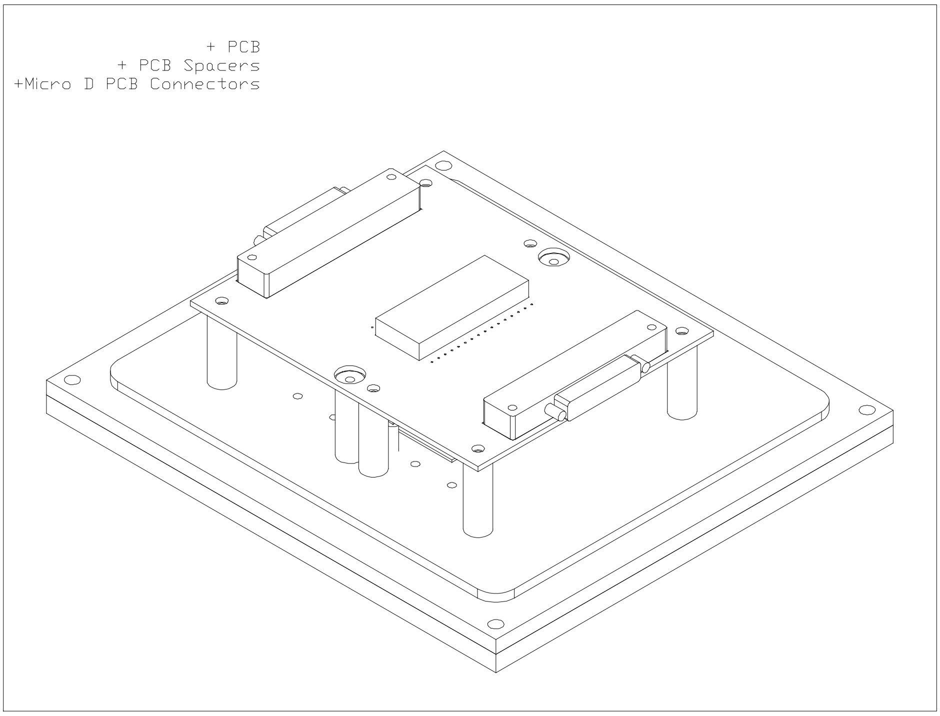


Figure 4 (d): *Camera Head Assembly – PCB and MicroD connectorsr*

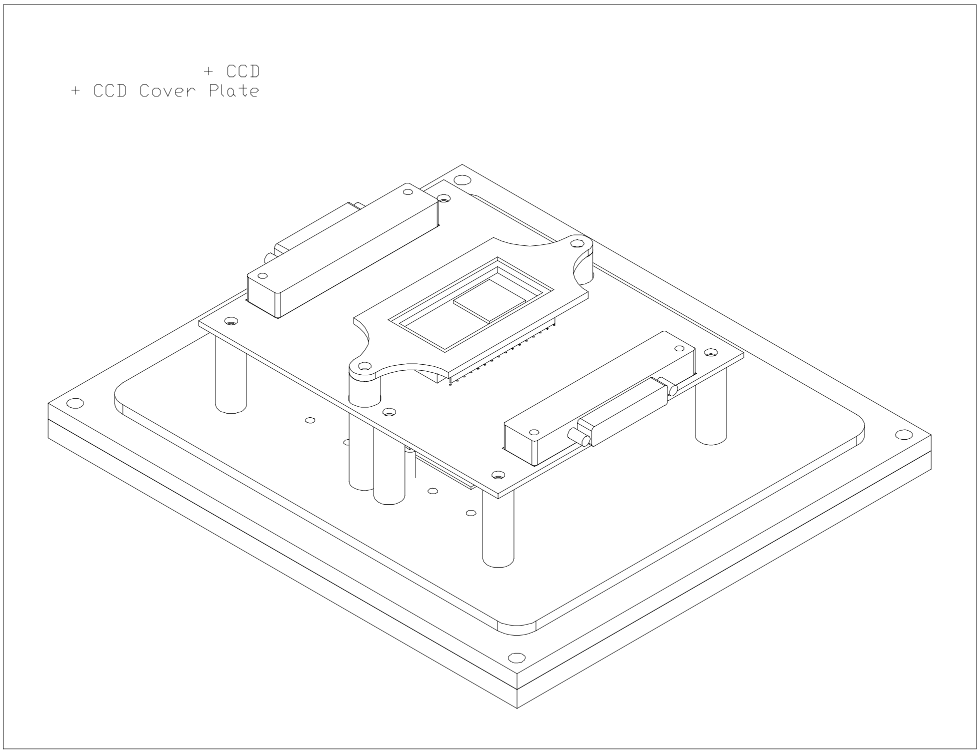


Figure 4 (e): *Camera Head Assembly – CCD and CCD Cover plate*

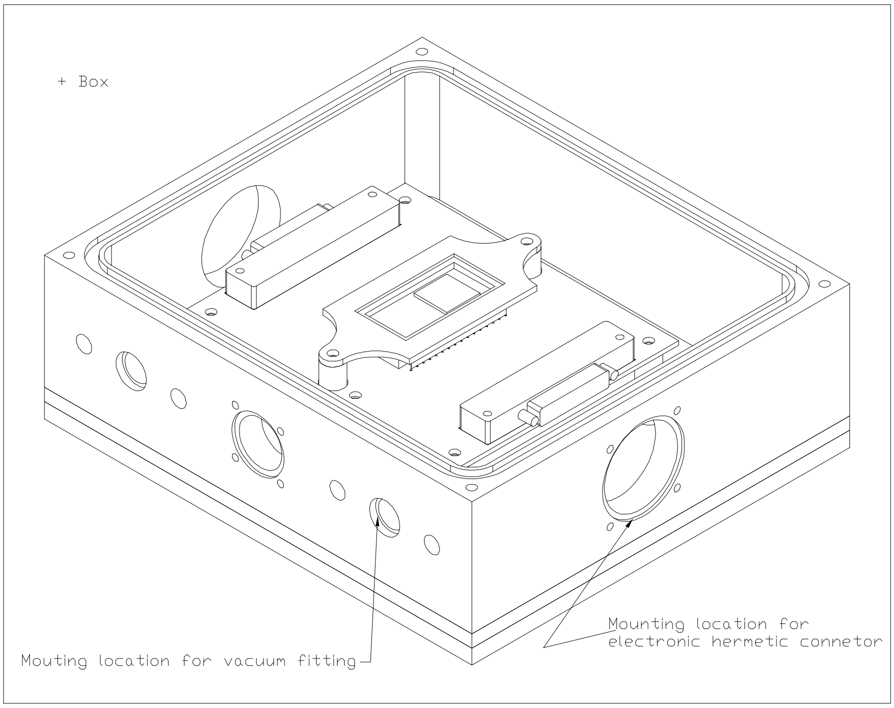


Figure 4 (e): *Camera Head Assembly – Aluminium Box*

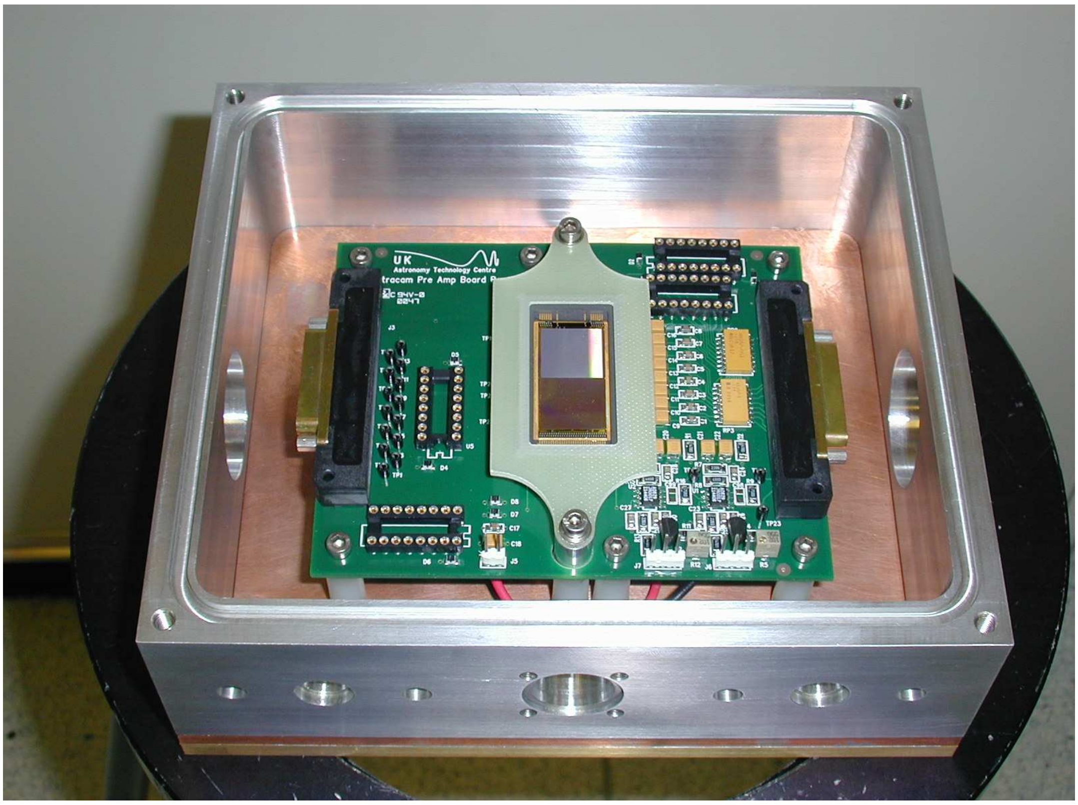


Figure 5 (a): *Photo of Partially Assembled Camera Head.*

Copper heat exchanger, aluminium box with connector mount locations can be seen. In addition, PCB board, CCD47-20, and G10 CCD cover are visible.

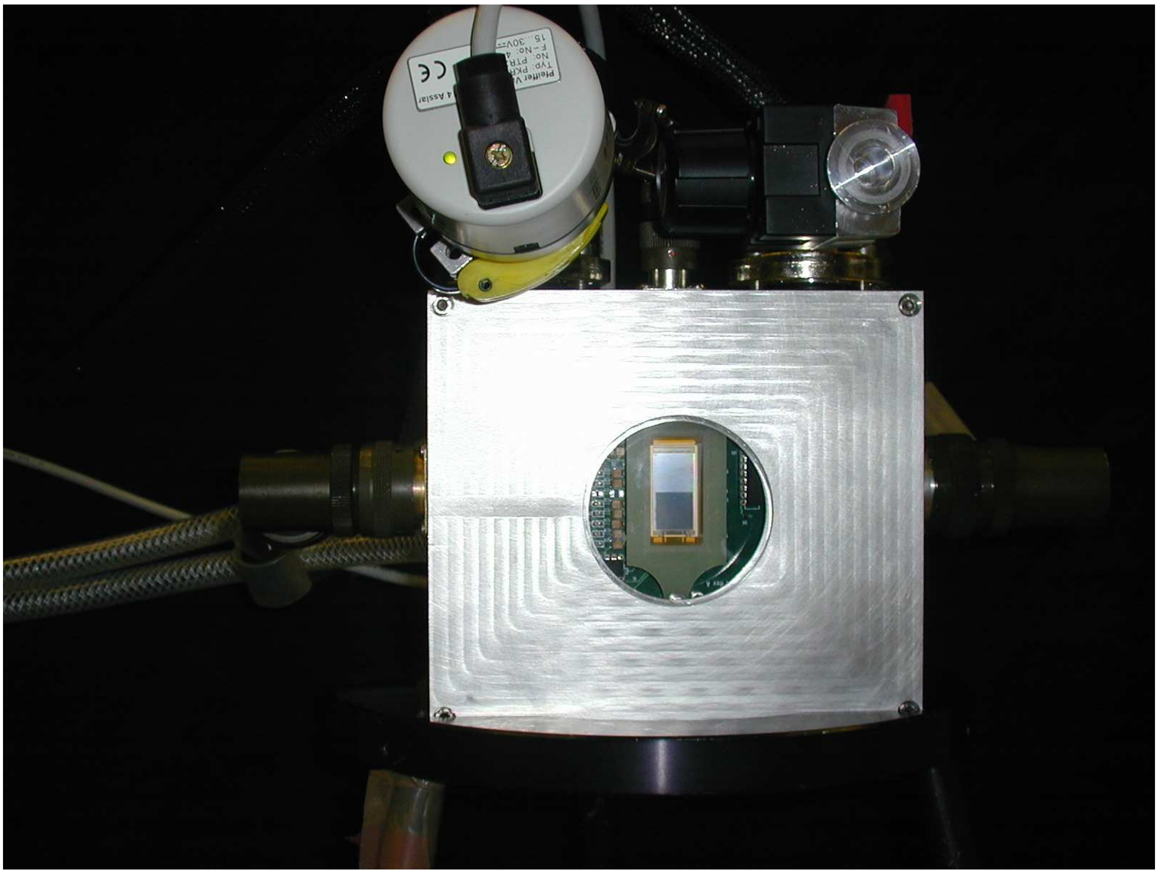


Figure 5 (b): *Assembled Camera Head with temporary lid.*

Pressure valve and gauge can be seen at the top side of the camera head. Electronic cables are also visible.

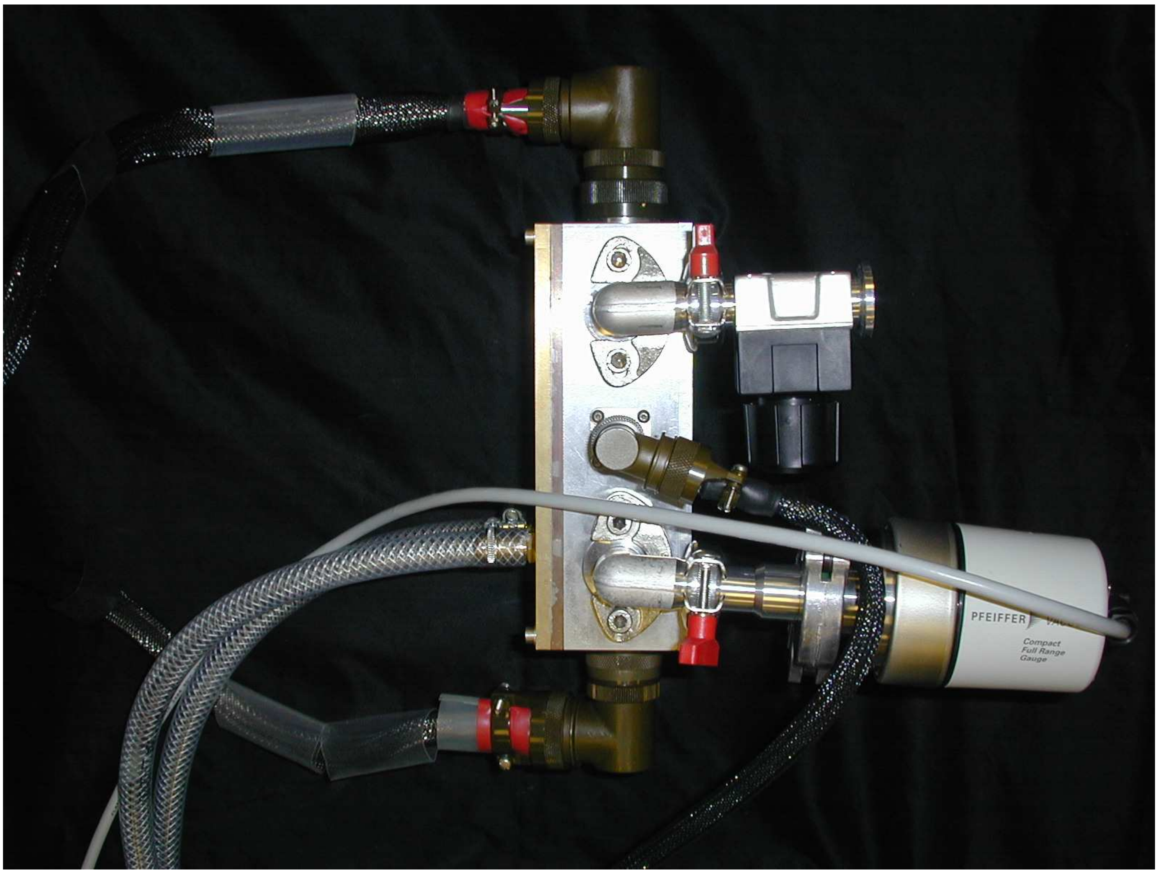


Figure 5 (c): *Assembled Camera Head with temporary lid (side view). Pressure valve and gauge can be seen on front facing side in addition to the TEC power/sensor cable. The two other electronic cables can be seen on the visible sides of the Aluminium body, and the plumbing inlet and outlet hoses can be seen connected to the brass backplate.*

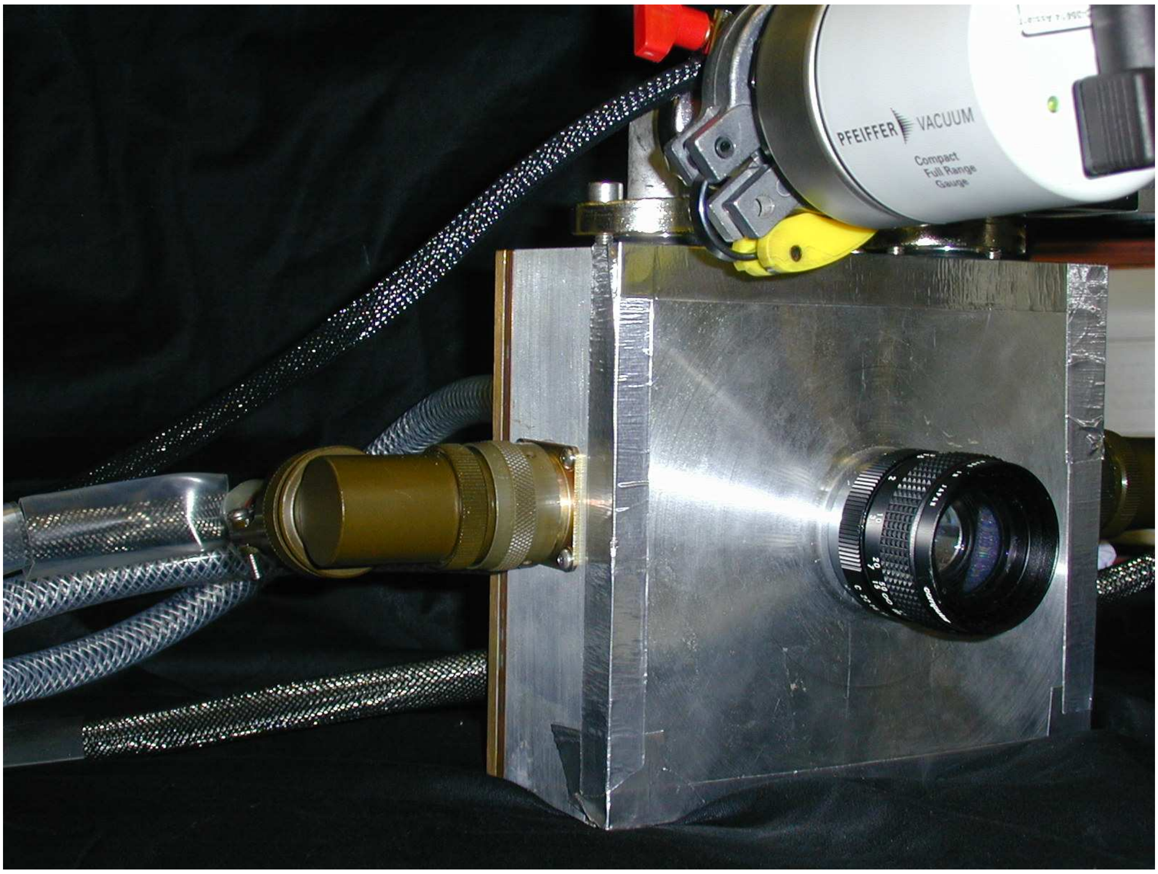


Figure 5 (d): *Assembled Camera Head with additional camera lens lid attached to front of temporary lid. This enabled photographs to be taken with the camera in the lab.*

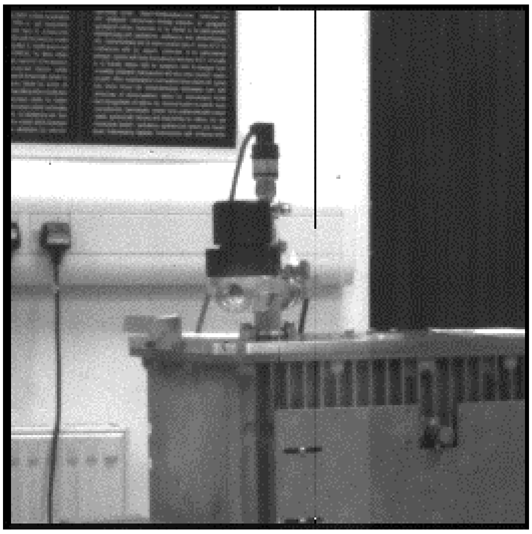


Figure 6: *Photo taken with Ultracam in laboratory*

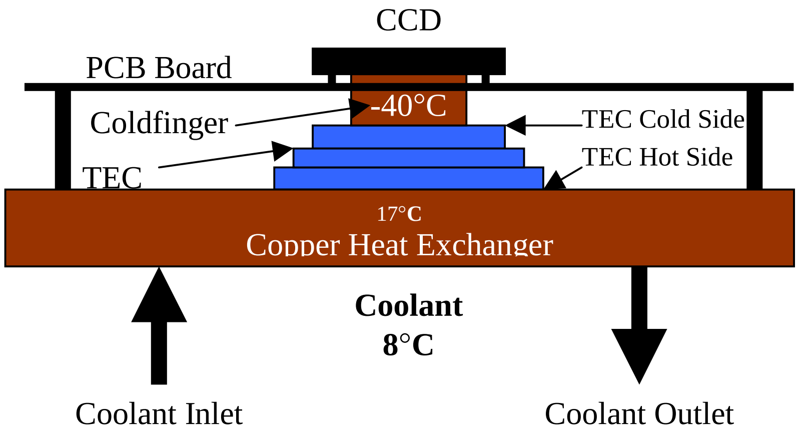


Figure 7: *CCD cooling system*

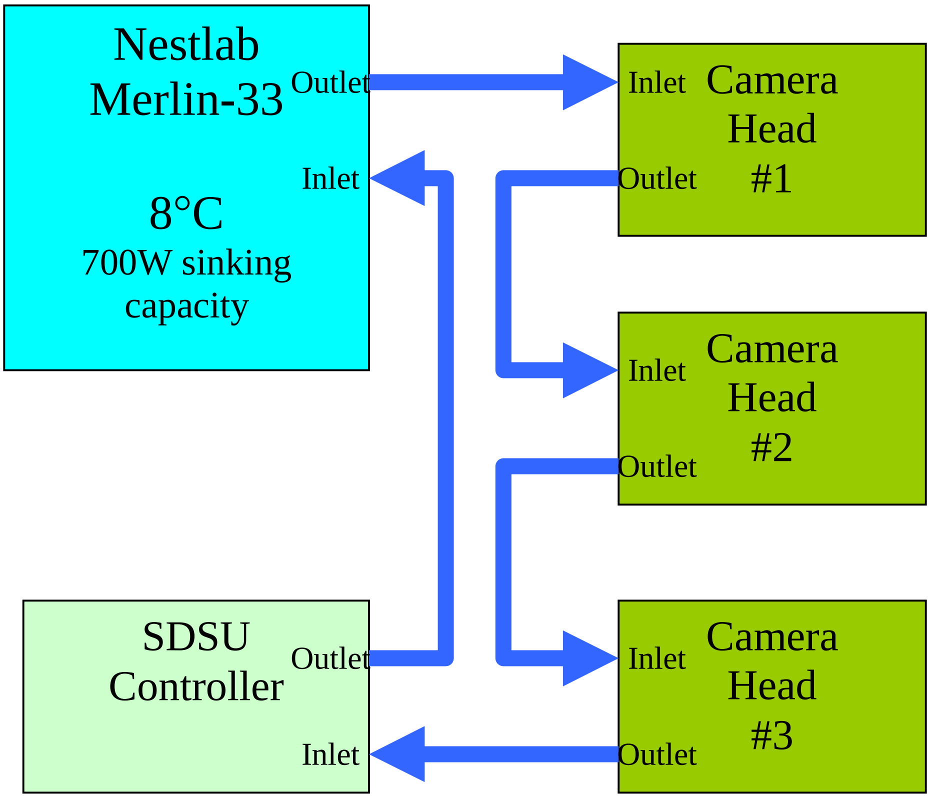


Figure 8: *Coolant Flow diagram*

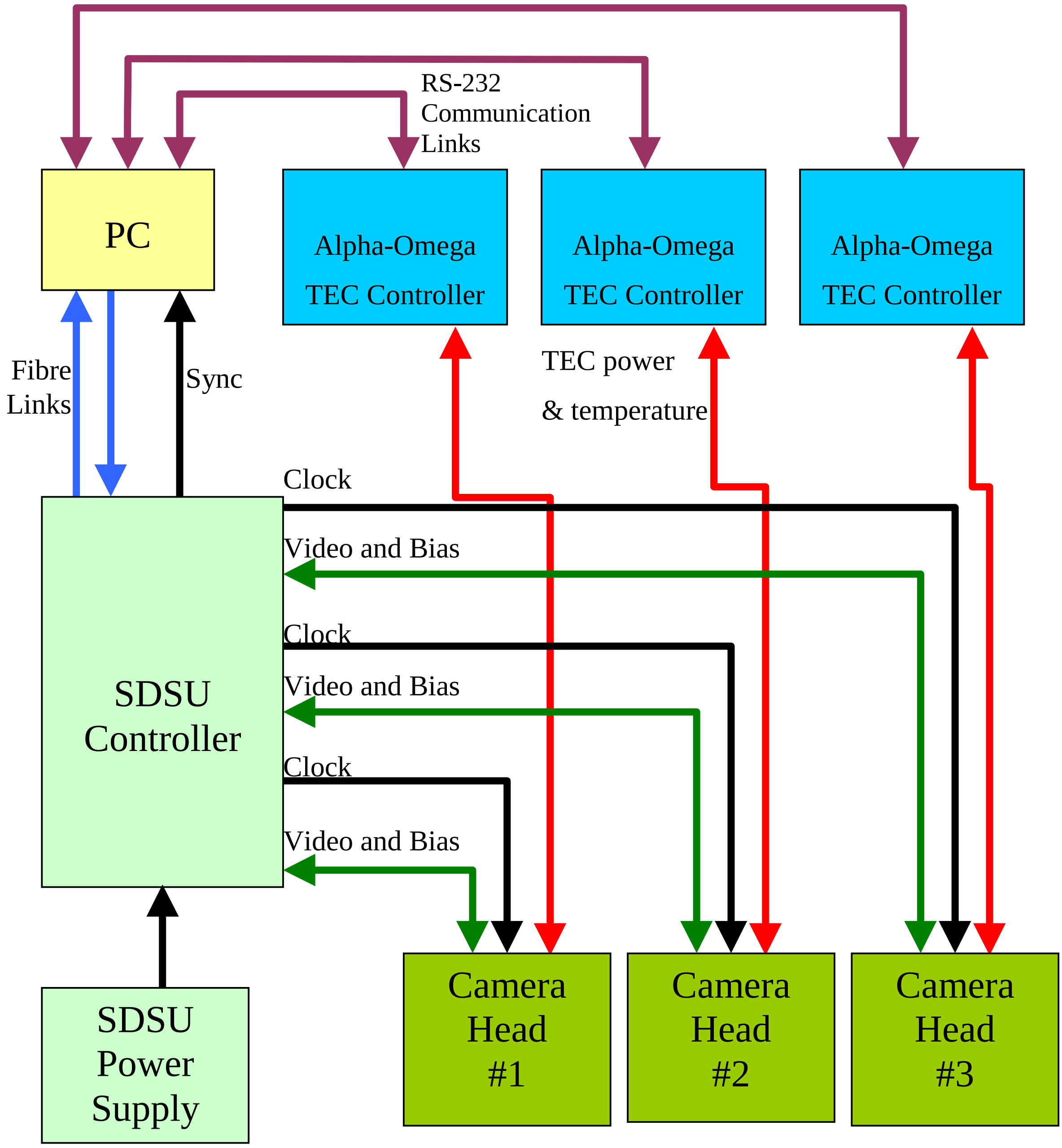


Figure 9: *Electronic Cabling*

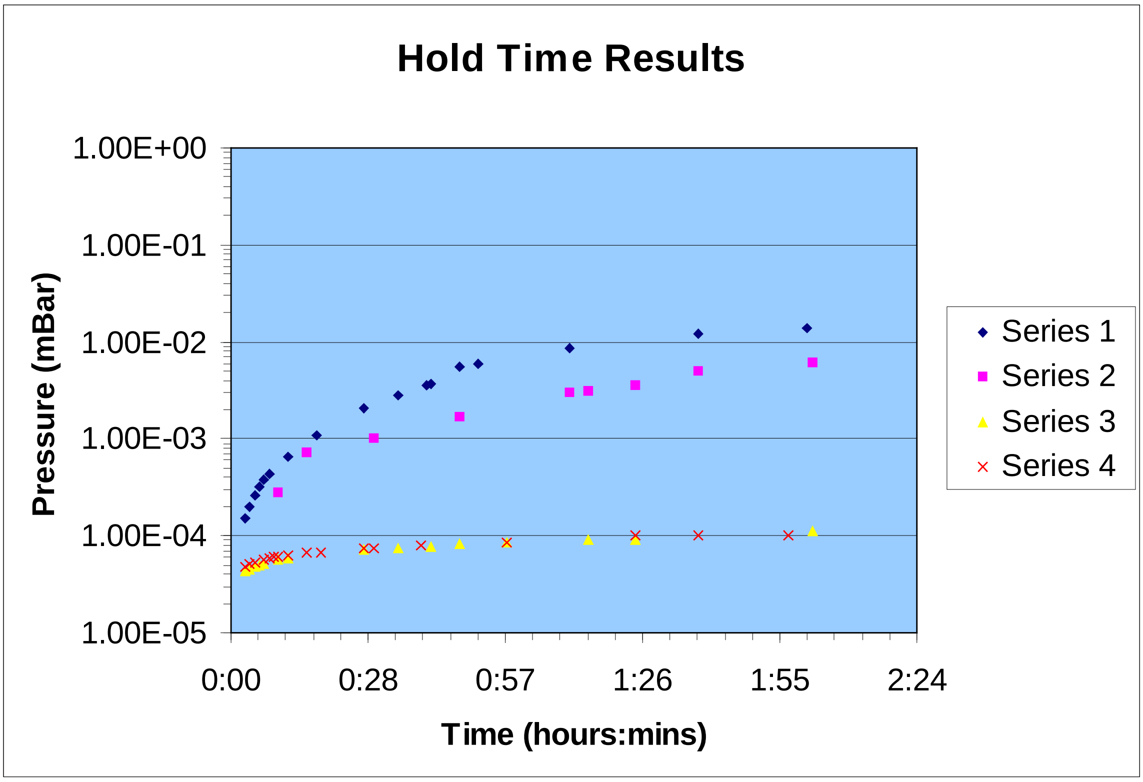


Figure 10: *Vacuum Hold Time Responses*

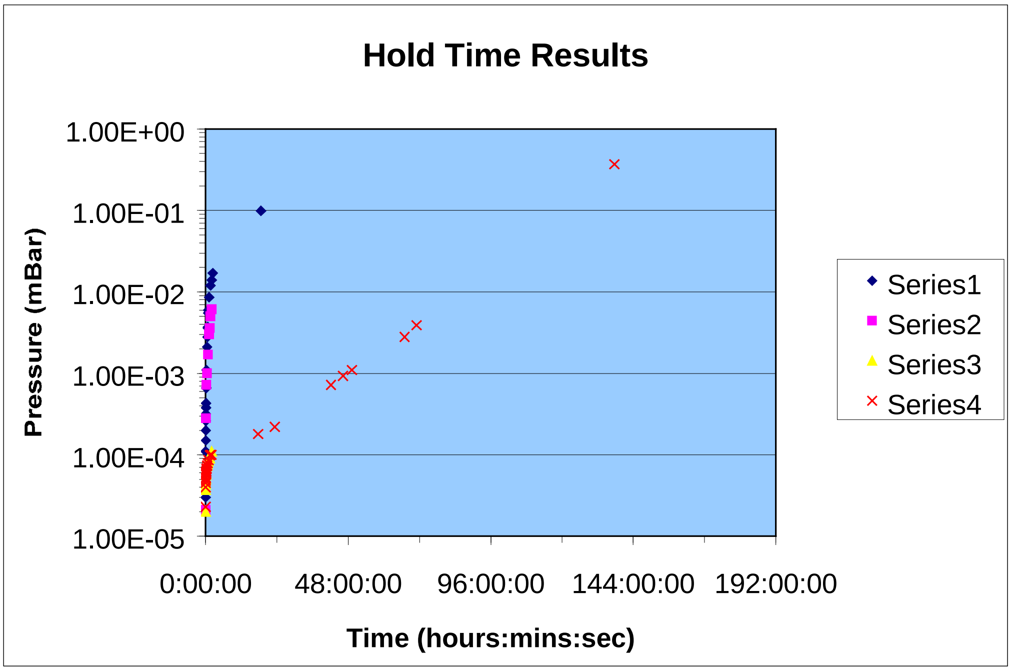


Figure 11: *Extended vacuum Hold Time Response with Charcoal Getter*

Figure 12: *Photograph of coldfinger with getter added*

Appendix A: Heat load on TEC Stack

Consider the heat load on the TEC, which can be established from Equation A.1 [3].

$$Q_{TEC-LOAD} = Q_{ACT-CCD} + Q_{RAD} + Q_{CONV} + Q_{COND} \qquad \textbf{A.1}$$

Where,

$Q_{ACT\text{-}CCD}$ = Heat generated by CCD

Q_{RAD} = Radiative heat load

Q_{CONV} = Convective heat load

Q_{COND} = Conductive heat load

Active Heat Load

CCD electrodes present a largely capacitive load. If the voltage across a capacitor *C* is pulsed with amplitude *V* at a frequency of *f*, then in each cycle a charge of *CV* is stored, and subsequently discharged to ground. The net current flow is thus *CVf*. Consequently the power dissipated is given by Equation A1 [5].

$$Q_{ACT-CCD} = V \times I = V^2 \times C \times f \qquad \textbf{A.1}$$

V = 15volts

f = 500kHz (maximum)

C = 3.5nF (maximum)

Therefore, $Q_{ACT\text{-}CCD}$ = **0.4W**

Radiative Heat Load

The radiative heat load is given by Equation 3.3 [3].

$$Q_{RAD} = F \times E \times \sigma \times A \times \left(T_{AMB}{}^{4} - T_{COLD}{}^{4}\right) \quad \textbf{A.2}$$

Where,

F = shape factor (1 worst case)

E = emissivity (1 worst case)

σ = Stefan-Boltzmann Constant ($5.66 \times 10^{-8} W/m^2K^4$)

A = area of cooled surface (area of CCD, and area of cold finger)

= $0.005m^2$

T_{COLD} = TEC cold temp (K)

= 233K

T_{AMB} = Ambient temp (K) of the surfaces the cooled surface ‘sees’

= 293K (worst case)

Therefore, Q_{RAD} = **1.3W**

Convective Heat Load

The TEC will be operating in a vacuum enclosure and so the convective heat load is negligible.

Conductive Heat Load

For each conduction path to the CCD array (i.e. wires leading to CCD input pins) there will be a conduction path. There are 32 pins on the CCD47-20, and therefore the conductive heat load given is given by Equation 3.5[3].

$$Q_{COND} = \frac{32 \times k \times A \times \Delta T}{L} \quad \textbf{3.5}$$

Where,

k: Thermal conductivity of material (W/mK)

A: cross sectional area of conductor

L: Length of conductor

ΔT: Temperature difference along heat path ($T_{AMB} – T_{COLD}$)

Assuming, 32 gauge (radius=0.1mm) copper wire of length 50mm leading from the PCB board to the camera head electrical input connectors.

k = 400 W/mK

ΔT = 63K

A = 1.571×10^{-8} m^2

L = 50×10^{-3}m

Q_{COND} = **0.25W**

Note that manganin wire (which has a thermal conductivity of 22.2 W/mK) may be used to reduce the conductive heat load.

Therefore, from Equation 3.1 the total heat load on the TEC can be estimated.

$Q_{TEC\text{-}LOAD}$ = 0.4W + 1.3W + 0.25W

= **1.95W**

Appendix B: Heat Exchanger Performance

Consider Ultracam's copper heat exchanger, which is an 8mm thick copper block with a channel milled into it to form a water path. The heat transfer capability of the copper Heat Exchanger is described by Equation B.1 [6]. Where, U is the heat transfer constant (Equation B.2), A is the characteristic area of the heat exchanger (area of the water channel), and ΔT is difference in temperature between the coolant and the hot side of the TEC (i.e. $\Delta T = T_{HOT}-T_{COOLANT}$)

$$Q_{EXC\text{-}LOAD} = U \times A \times \Delta T \qquad \textbf{B.1}$$

Where,

$$U = \frac{1}{\frac{1}{h}+\frac{x}{k}} \qquad \textbf{B.2}$$

The designed heat exchanger has the following characteristics.

A = Characteristic area of copper perpendicular to heat flow
= $0.003\ m^2$

h = Convective heat flow from copper to water
= $1500 W/m^2K$

x = Characteristic path length through copper (depth through copper to coolant)
= $3 \times 10^{-3} m$

k = Thermal conductivity of heat exchanger (i.e. copper)
= 400 W/mK

$Q_{EXC\text{-}LOAD}$ = The amount of heat loaded onto the copper heat exchanger, which is primarily the active heat of the TEC itself.

Now, 1/UA provides the heat exchanger's heat sink resistance (HSR), and in this case:

HSR = 0.225°C/W

Therefore, for every Watt of heat the copper block needs to exchange the TEC hot side will increase by 0.225°C. The NESLAB Merlin-33, is employed as the recirculating chiller, which will provide a coolant temperature of 8°C. Therefore,

$$T_{COOLANT} = 8°C,$$

Subsequently, the hot side temperature of TEC (T_{HOT}) can be calculated from Equation B.1 given an estimate of $Q_{EXC\text{-}LOAD}$. Following consultation with Melcor on their 3-stage TEC and our system requirements and initial estimate of 40W for $Q_{EXC\text{-}LOAD}$ was established. Therefore, an estimate of the hot side temperature of the TEC is:

$$T_{HOT} = \left(\frac{Q_{EXC_{LOAD}}}{UA}\right) + T_{COOLANT} \qquad \mathbf{= 17°C}$$

The desired cold side temperature of the CCD is 233K (-40°C). The hot side temperature has been estimated at 17°C using this heat exchanger. Consequently, the TEC needs to provide a temperature difference of at least 57°C.