Cooling the Dark Energy Camera CCD array using a closed-loop, two-phase liquid nitrogen system

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ABSTRACT

The Dark Energy Camera (DECam) is the new wide field prime-focus imager for the Blanco 4m telescope at CTIO. This instrument is a 3 sq. deg. camera with a 45 cm diameter focal plane consisting of 62 2k x 4k CCDs and 12 2k x 2k CCDs and was developed for the Dark Energy Survey that will start operations at CTIO in 2011. The DECam CCD array is inside the imager vessel. The focal plate is cooled using a closed loop liquid nitrogen system. As part of the development of the mechanical and cooling design, a full scale prototype imager vessel has been constructed and is now being used for Multi-CCD readout tests. The cryogenic cooling system and thermal controls are described along with cooling results from the prototype camera. The cooling system layout on the Blanco telescope in Chile is described.

Keyword list: DES, DECAM, CTIO, NOAO, CCD, liquid nitrogen, pump, camera cooling

1. INTRODUCTION

The Dark Energy Camera (DECam)[1], will be the primary instrument used in the Dark Energy Survey[2]. DECam will be a 3 sq. deg. mosaic camera mounted at the prime focus of the Blanco 4m telescope at the Cerro-Tololo International Observatory (CTIO). The camera imager[3] is a vacuum vessel that houses the CCD[4] array, the focal plane support plate, and the liquid nitrogen heat exchanger used to cool the array. The cooling strategy was determined by comparing various cooling techniques and methods used on other telescope instruments. The method best suited for this application was determined to be a closed loop, two phase liquid nitrogen system.

The liquid nitrogen system is a closed loop, two phase circulation system. Liquid is pumped from the liquid nitrogen vessel to the imager vessel heat exchanger and back. The heat exchanger is a simple tube heat exchanger. Flexible copper straps connect the simple tube heat exchanger to the back surface of the focal plane support plate that supports the CCD array. The focal plate operating temperature is maintained at 173K with a heat load of 113Watts. An electric heater and Resistance Temperature Detector (RTD) are installed on each of the flexible copper straps. The power to each heater is modulated to control CCD array temperature. The cooling fluid from the heat exchanger returns back to the liquid nitrogen vessel and is separated into liquid and gaseous phases. The gaseous phase is condensed using a cryocooler. The imager cooling system circulates liquid nitrogen through the heat exchanger. To maintain a closed loop system, the overall system heat load must be less than the cryocooler capacity.

A prototype closed loop liquid nitrogen system was constructed in late 2008 and is used to cool the Multi-CCD test vessel[5]. The prototype system is described and heat load measurements for the total system are shown. A second final system is in construction now. Modifications from the original system to help further mitigate system thermal loads are described. The cooling path on the CTIO telescope is briefly shown.

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2. COOLING SYSTEM DESIGN REQUIREMENTS

A detailed list of the design requirements[6,7] that apply to the liquid nitrogen closed loop cooling system have been compiled. They pertain to the operating temperature of the detector, stability of the operating conditions, and the site environmental conditions. The focal plane operating temperature is -100°C with a maximum temperature variation of ≤ 10 degrees. The temperature is to be stable within ±0.25 K stability over any 12 hour period. The camera vessel vacuum must be $<2\times10^{-4}$ torr before cooling below ambient and should be $<10^{-5}$ torr during normal operations. The system shall perform to the specifications for all possible telescope orientations. The outdoor temperature is -5° to 27°C depending on the season. The site altitude is 2200 m above sea level, with an atmospheric pressure of 77kPa.

3. LIQUID NITROGEN DESIGN BASIS

3.1 Liquid nitrogen cooling

Liquid nitrogen cooling has several distinct advantages. The temperature difference between the liquid nitrogen and the focal plate is large enough to allow small flexible thermal links between the heat exchanger and the focal plate. Liquid nitrogen has been used successfully many times in the past. Existing cameras at CTIO and other facilities use manually filled liquid nitrogen reservoirs. The cooling capacity required for DECam prohibits manual filling a local reservoir due to the large size and the frequency of fills that would be needed. Nitrogen circulation has the advantages of stable temperature, low vibration and low space usage near the camera.

3.2 Saturated liquid circulation details

Saturated liquid circulation was chosen as the most temperature stable fluid condition. Saturation pressure at the camera heat exchanger can be easily measured and controlled regardless of telescope elevation. Two-phase flow pressure drop calculations and flow regime mapping were used to select pipe sizes. To decrease bubble size at the highest point at the camera heat exchanger, the operating pressure is increased to 0.76MPa. This pressure is easily contained with ordinary piping components. The difference in elevation between the circulation pump and the heat exchanger at zenith is the largest contribution to the entrained bubble size. To mitigate large bubbles at zenith, the pump and liquid nitrogen vessel will be installed at the highest convenient location in the dome.

Nitrogen system design basis

- Operating pressure is 0.76 MPa
- Fluid Operating temperature is 100 Kelvin
- Flow rate is 226 grams/second (7.5 l/min)
- 200 watt camera heat load, including contingency
- Pump elevation is 12 meters below camera top

Calculations of thermodynamic conditions were made at notable points along the cooling circuit[8], taking into account heat loads, piping pressure drop and elevation. The fluid at the pump discharge is subcooled, as the fluid goes to the maximum elevation at zenith and heat is added, the flow becomes two-phase dispersed bubble regime. The return flow back to the pump, again becomes subcooled until it reaches the LN2 reservoir where the gas phase is separated and condensed using a cryocooler with a condenser.

4. THE PROTOTYPE COOLING SYSTEM DESCRIPTION

4.1 Cooling Equipment

The heart of the cooling system is the liquid nitrogen vessel and its attached components. The liquid nitrogen vessel is the reservoir of nitrogen for the cooling system, has a LN2 pump for circulation, a cryocooler and a copper condenser for gas condensation. A drawing of the vessel and its internal components is shown in Figure 1. The top flange carries all of the vessel feed-through ports and is not insulated. The first 4.5 inches of the vessel neck is also not insulated. When the liquid nitrogen vessel is filled to the fill try-cock level, the liquid is 24.1 inches from the top flange. Conduction in the system is dominated by the stainless steel vessel walls and internal piping. The vessel wall is constructed of 18 inch sch. 10 pipe. A 6 inch diameter, 0.120 inch wall stainless tube supports the circulation pump. The supply and return lines are 1 inch sch.

40 pipe. The supply and return pipes are insulated from the vessel top flange using 12 inch vacuum jacketed bayonets. The liquid nitrogen pump is a centrifugal pump with a submerged motor. A centrifugal pump from Barber-Nichols was chosen because it is a simple design, easy to operate under a variety of conditions and very reliable. The submerged motor was chosen because it has no shaft seal and it has low static heat leak. The pump is equipped with variable speed drive. It can be run at high speed initially then slowed to half speed for normal operation. Lower speed operation should increase the pump bearing life and reduce the heat load put into the liquid.

Figure 1. Liquid nitrogen vessel and foam insulated valve box located outside the building.

Mounted to the top flange of the liquid nitrogen vessel is the cryocooler and gaseous nitrogen condenser. The cryocooler is an AL-300 manufactured by Cryomech Inc. At 77 Kelvin the capacity of the cryocooler is about 300 Watts. Extrapolating to the operating temperature of about 90 Kelvin, the cryocooler has about 360 watts. In order to maintain a closed system, the total system heat load needs to be less than the cryocooler capacity at the operating temperature. The cryocooler is used to condense the gas that boiled in the cooling system. Any additional vapor created that is not condensed is vented out a pressure regulator valve to the atmosphere. The cryocooler is a single stage Gifford-McMahon model AL-300. The heat rejected by the cryocooler compressor is taken out by a facility water-glycol system and is eventually rejected away from the dome. The copper nitrogen condenser is attached directly to the cryocooler cold finger and the assembly will be mounted inside the pump dewar. The cryocooler vessel, the coldhead and the condenser are shown in Figure 2.

Figure 2. Left: Cryocooler insert. Upper right: Al-300 cryocooler. Lower right: copper gas condenser.

A foam insulated instrument and valve box is directly next to the liquid nitrogen vessel. The valve box has cool down valves, pressure gages, and a flow meter. The transfer line from the valve box to the Multi-CCD test vessel is a 20 foot long vacuum jacketed line. Between the transfer line and the Multi-CCD test vessel is an electrical isolation connection in both the liquid line and the vacuum jacket line. The electrical isolation in the transfer line reduces any chances of an electrical charge from being put on the CCD vessel due to an electrical problem in any of the instruments, the heaters or the circulation pump. The Multi-CCD test vessel attached to the electrical isolation joint and 20 foot transfer line is shown in the lab in Figure 3. Inside the vessel is a loop heat exchanger which is connected to the back side of the focal plate using flexible copper braids. Each copper braid is instrumented with a 25 watt heater and temperature sensor for feedback. The braid's aluminum mounting foot is attached to the braid with an electrical isolation joint.

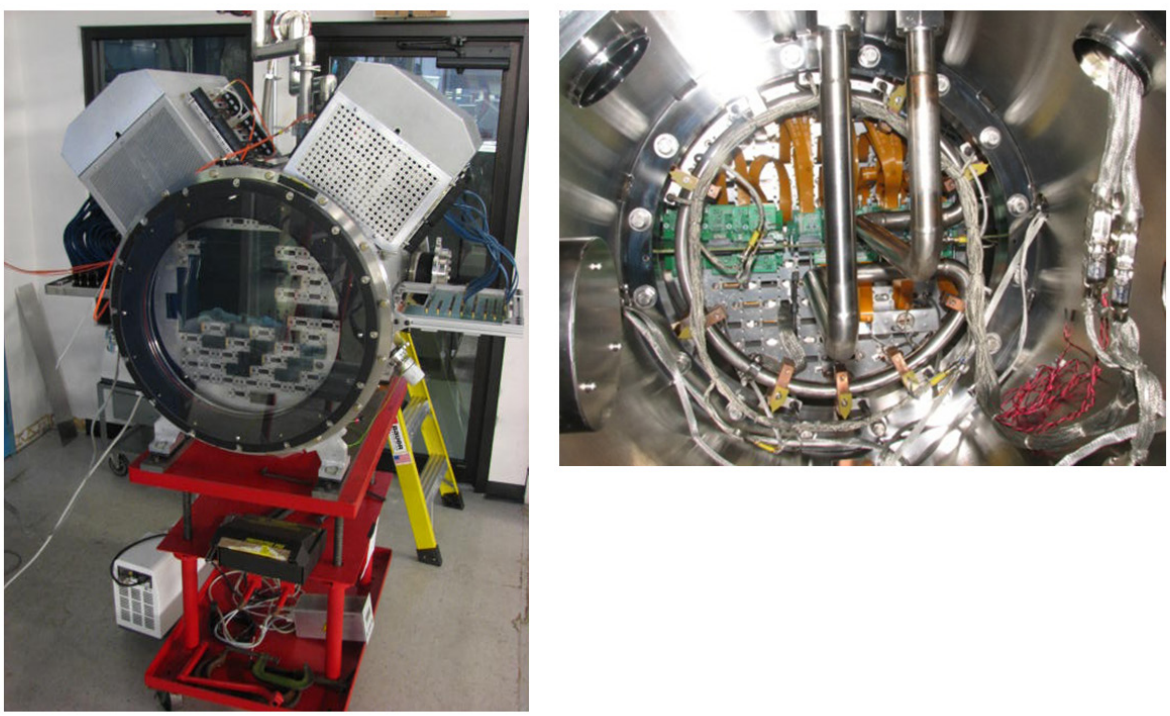

Figure 3. Left: Multi-CCD Test Vessel front side. Right: Multi-CCD test vessel open from the back side.

5. TESTING THE PROTOTYPE COOLING SYSTEM

5.1 Closed loop liquid nitrogen testing program

The liquid nitrogen cooling system test program began in early 2009. The first test was to simulate the operating conditions when the imager vessel would be mounted to the telescope pointing in the zenith direction. This is the most extreme case since the circulation pump needs to deliver a full pressure to overcome the head height, and also with the thermal load creating bubbles in the system. At the zenith position the bubbles are the largest due to the elevation difference between the circulation pump location and the imager vessel. The remaining test program is to make thermal measurements on the system and to reduce the overall thermal load as much as possible so that the system can remain a closed loop system.

5.2 Cooling when the Imager vessel is at Zenith

This test will measure cooling performance and vibration at the imager vessel heat exchanger. The heat exchanger is 40 feet (12 m) above the circulation pump in the liquid nitrogen dewar to simulate telescope conditions at Zenith. The Multi-CCD test vessel was too large to lift, so the heat exchanger was mounted inside a foam box. The heat exchanger was connected to the liquid nitrogen transfer line. The foam box was lifted with a man lift to a 40 foot elevation. At this elevation, the transfer line and heat exchanger was cooled to the operating temperature. The heat exchanger successfully reached the operating temperature and the LN2 pump had enough pressure to overcome the head pressure and keep the vapor entrained in the liquid flow. The overall thermal load on the system was measured to be 710 Watts. This is significantly higher than the expected total thermal load. Excess boil off gas that is created beyond the capacity of the cryocooler is vented out a regulator valve. The cryocooler capacity plus the heat loss due to excessive boil off is added together to obtain the total system thermal load. The test setup is shown in Figure 4. At no time did the two phase flow in the heat exchanger cause significant vibrations in the heat exchanger.

Figure 4. 40 foot elevation operating test simulating the telescope at Zenith.

5.3 Flow regimes
The fluid flow regime is not easily measured. The only indication of the flow conditions during testing is cooling efficiency in the heat exchanger. Another is if the circulation flow rate is temporarily increased, any large trapped gas pockets will be purged from the system. The liquid level in the liquid nitrogen vessel will lower when liquid replaces the vapor pocket in the cooling system. The liquid level probe is sensitive enough to notice changes in the liquid level of about 1% the cooling system volume.

5.4 Thermal performance
The thermal performance of the system is measured regularly during operations. The total system thermal load is measured by measuring the heater power required to maintain the pressure in the liquid nitrogen vessel at 100 psig. If no heat power is required, and some of the vapor is being vented out the regulator, then the cryocooler capacity is not enough to maintain the closed loop system. The vent rate is then measured and the additional thermal load is measured as nitrogen boil off. Various parts of the system can also be isolated and the subsets of the total power can be measured by a combination of measuring the boil off rate and power at the cryocooler.

5.5 Prototype cooling System Heat Load
Heat loads for the Multi-CCD test vessel are summarized in Table 1. Calculated heat loads for the focal plate have been confirmed by testing. Heat loads for the liquid nitrogen circulation system are summarized in Table 1. They are based on calculations and test results. The cryocooler chosen to refrigerate this system has a capacity of 360 watts at an operating temperature of 90 K.

Table 1. Summary of measured and calculated heat Loads on the prototype cooling system

Item			
Imager vessel	Focal Plate	Thermal Radiation to window	43.0 Watts
		Conductivity Supports	0.67 Watts
	CCD Electronics	Conductivity cables	10.3 Watts
		CCD JFET (70 CCDs)	0.6 Watts
		CCD output amplifier (70 CCDs)	2.8 Watts
		VIB Interface Card Amps.	28 Watts
	Thermal Control	Trim Heaters	19 Watts
	Heat Exchanger	Radiation	7.6 Watts
		Conductivity Supports	1.0 Watts
Imager Vessel Total			113 Watts
Foam insulated valve box			107 Watts
20 foot Transfer lines			50 Watts
LN2 reservoir			90 Watts
Circulation pump operating at 52 hz (3100rpm)			55 Watts
System Total			415 Watts

6. Future Plans

6.1 Planned upgrades
The planned upgrades are based on reducing the thermal load and adding cooling capacity to the system. The two largest heat leaks in the prototype system are the liquid nitrogen vessel and the foam insulated valve box. Replacing the prototype units with ones optimized for thermal losses can significantly reduce the overall heat load. The LN2 vessel shown in Figure 5 replaces the prototype with a vessel that has a smaller diameter neck, further away for the liquid

surface. The supply, return, and cryocooler condenser drip lines are all vacuum jacketed with vacuum jackets of at least 18 inches long. The foam insulated valve box is replaced with a vacuum insulated box. For extra contingency on the thermal budget, a second AL-300 cryocooler is added to the system. If the thermal load is below the capacity of a single cryocooler, then the second will act as a hot swappable spare.

Figure 5. Left: Liquid nitrogen vessel and valve box for use at CTIO. Right: Imager Vessel

The Imager vessel will be tested with all of the new cooling system components. The testing cooling hardware will be similar to the hardware that will be used to cool the Imager vessel in the Coude room at CTIO. The Imager vessel, internal cooling ring, and copper braids are shown in Figure 6.

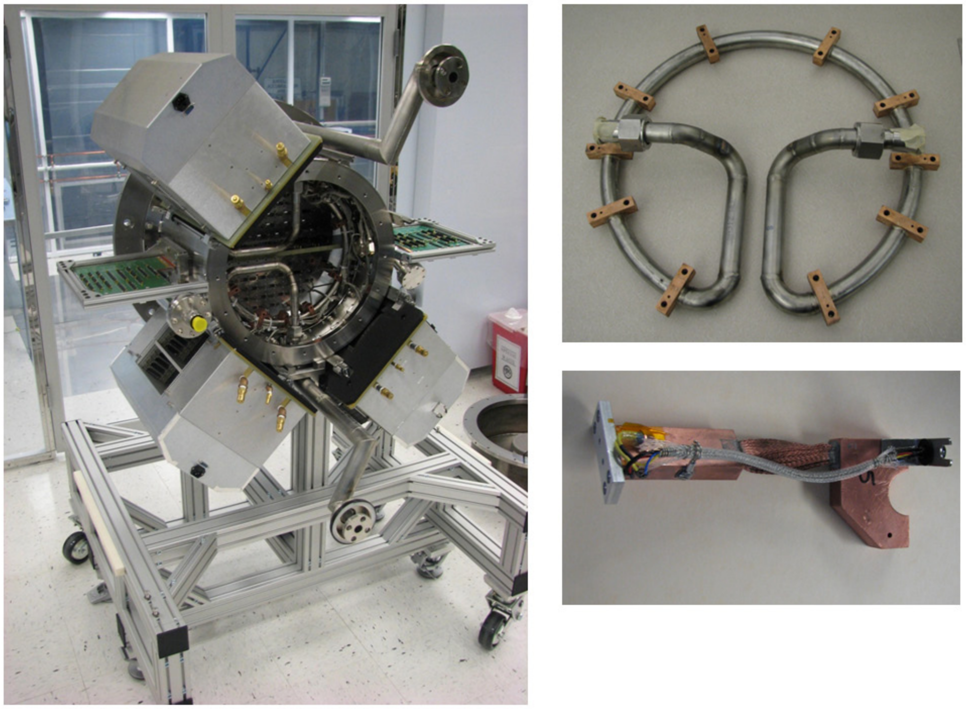

Figure 6. Left: Imager Vessel. Upper Right: Internal heat exchanger cooling ring. Lower Right: Copper braid with heater, temperature sensor, thermal protection switch, electrical isolation joint.

6.2 Start-up testing on the CTIO cooling system

The imager vessel will first be cooled down in a bench test environment. The imager will be sitting on its cart on the floor. The CTIO cooling system will be attached to the imager vessel and operated there. Thermal measurements on the system will take place to measure the thermal load on the new vacuum jacketed valve box and liquid nitrogen vessel. Once the cooling system thermal measurements are taken, and the system is fully operational, the imager vessel will be moved to the telescope simulator. This is the first time the cooling system will be operated cold in a dynamic situation. The imager vessel will be positioned in various elevations, inclinations, and rotations to ensure the operating system works when the imager vessel is in all orientations.

6.3 CTIO Piping System Description

The piping system includes all of the vacuum jacketed piping from the liquid nitrogen vessel on the control room roof to the imager vessel mounted in the telescope. The imager vessel is also serviced in the Coude room. The Coude room operations are not considered in this text, the piping is thermally isolated from the rest of the plumbing system using valves. A general layout of the piping on the telescope is shown in Figure 7. Vacuum jacketed flex hose will be used to negotiate the various rotation axes on the telescope. Helium service valves, piping, and joints will be used whenever possible. Joints are VCR joints on the internal cooling line and a retractable vacuum bellows in the vacuum jacket for access to the VCR joint. A vacuum break will be at each joint with a vacuum pump out port. There will be about 160 feet of hard pipe, 75 feet of hose in each supply and return line for a total of 470 feet of piping.

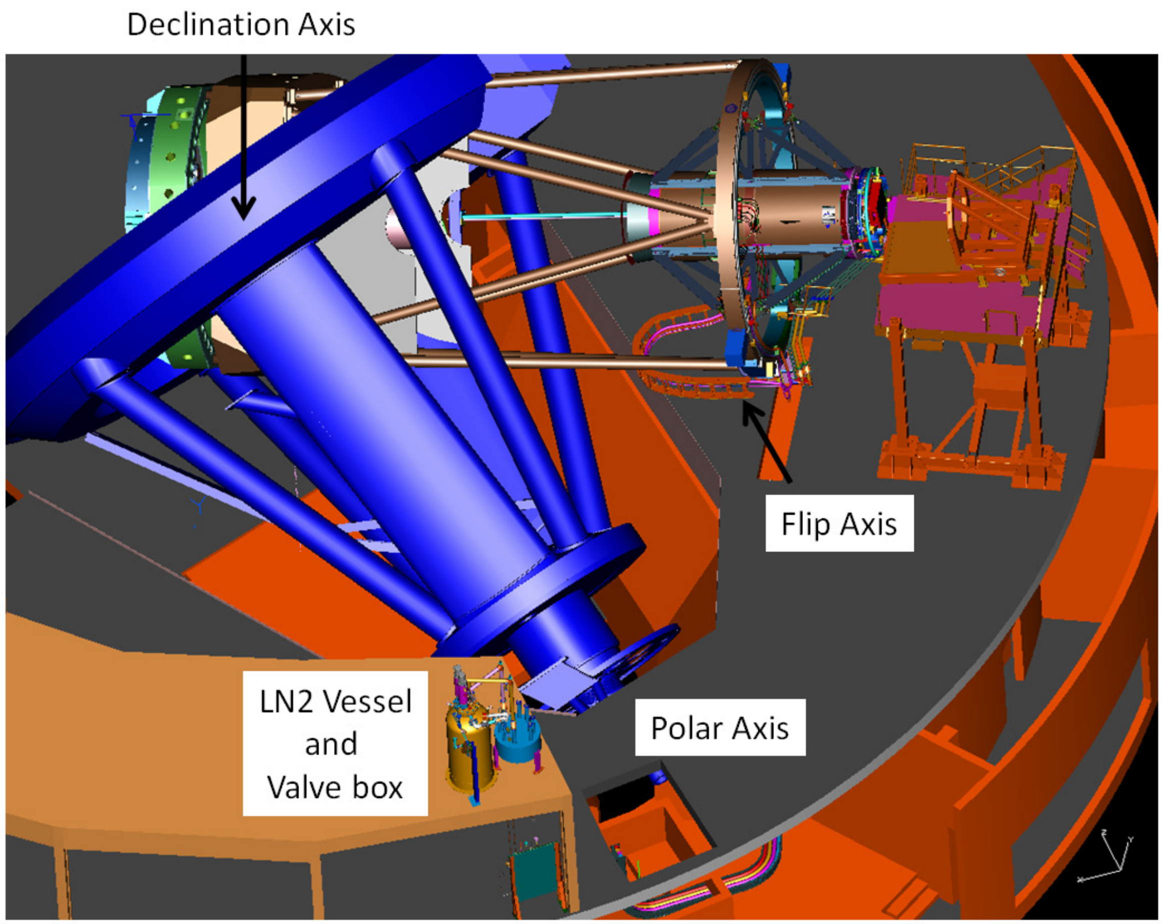

Figure 7, Piping Layout on the Telescope at CTIO

6.4 Predicted System Thermal Loads at CTIO

Vendor datasheets compare reasonably well with measurements that have been done at Fermilab on vacuum jacketed piping systems (FN-423, "An Experimental Study of Heat Transfer in MultiLayer Insulation."). The PHPK catalogue (http://www.phpk.com/PHPKCatalog.pdf) is used to compile thermal loads on vacuum jacket hard pipe, flexible hose, and valves. PHPK components have been selected for some of the valves and piping. A summary of the predicted heat loads for the CTIO system is shown in Table 2.

Table 2, Summary of the system heat loads.

Item			Heat Load
Imager vessel	Focal Plate	Thermal Radiation to window	43.0 Watts
		Conductivity Supports	0.67 Watts
	CCD Electronics	Conductivity cables	10.3 Watts
		CCD JFET (70 CCDs)	0.6 Watts
		CCD output amplifier (70 CCDs)	2.8 Watts
		VIB Interface Card Amps.	28 Watts
	Thermal Control	Trim Heaters	19 Watts
	Heat Exchanger	Radiation	7.6 Watts
		Conductivity Supports	1.0 Watts
Imager Vessel Total			113 Watts
Main vacuum insulated valve box			25 Watts
Hard pipe 1" x 2 ½" NPS (Helium service) – 470 feet, 0.09 Watts/ft			43 Watts
Flexible pipe 1" x 2 ½" NPS – 150 feet, 0.42 Watts/ft			63 Watts
Vacuum breaks -20 vacuum breaks in the system, 1 Watt/each			20 Watts
Flip ring bypass valves - three 3/4" NPS Valves, 1.3 watts/each			4 Watts
LN2 reservoir (reference Docdb 3093)			32 Watts
Circulation pump operating at 52 hz (3100rpm)			55 Watts
System Total			355 Watts

The number of vacuum breaks is minimized to reduce the total overall thermal load. The vacuum break style using a VCR connection on the inner line with a retractable bellows joint on the vacuum jacket are specified to have a thermal load less than 1 watt each. Standpipes are used to thermally isolate instruments on the transfer line. Stand pipes are specified to have thermal loads less than 1 watt each. The valves used in the valve box are rated for helium service. They have longer stems to reduce the thermal load and are pneumatically actuated.

The cooling capacity of the system using two Al-300 cryocoolers is expected to be over 700 Watts. To maintain the system operating pressure, heaters in the liquid nitrogen vessel will be used to control the pressure in the vessel to the desired operating pressure.

7. Summary

A prototype closed loop liquid nitrogen system has been providing cooling to the Multi-CCD test vessel for a year and a half. The system provides suitable cooling capacity to the test vessel and CCD array. All of the design requirements have been met. The prototype cooling system had a larger than desired heat load on the cooling system. To mitigate the system heat load, the valve box is replaced with a vacuum insulated valve box, and the liquid nitrogen vessel is replaced with a lower heat leak unit. To add additional cooling capacity to the system, a second cryocooler has been added to the design. The new system is scheduled to operate in June 2010 and will be used to cool the DES imager vessel. Following initial operations at Fermilab, the entire cooling system is scheduled for delivery to CTIO in 2011.

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