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The LSST Camera 500 watt -130 ˚C Mixed Refrigerant Cooling System

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ABSTRACT

The LSST Camera has a higher cryogenic heat load than previous CCD telescope cameras due to its large size (634 mm diameter focal plane, 3.2 Giga pixels) and its close coupled front-end electronics operating at low temperature inside the cryostat. Various refrigeration technologies are considered for this telescope/camera environment. MMR-Technology's Mixed Refrigerant technology was chosen. A collaboration with that company was started in 2009. The system, based on a cluster of Joule-Thomson refrigerators running a special blend of mixed refrigerants is described. Both the advantages and problems of applying this technology to telescope camera refrigeration are discussed. Test results from a prototype refrigerator running in a realistic telescope configuration are reported. Current and future stages of the development program are described.

Keywords: LSST Camera refrigeration, mixed refrigerants

1. INTRODUCTION

The **L**arge **S**ynoptic **S**urvey **T**elescope (LSST) camera has a 3.2 Giga-pixel CCD array covering a 634mm diameter focal plane. This array will operate at -80˚C to -100˚C in a cryostat vacuum vessel (fig.1). Unlike most previous detectors for ground-based astronomy, the LSST camera has its image processing electronics located directly behind the focal plane, inside the cryostat vacuum at -130˚C. Placing these electronics inside the camera cryostat adds ~400 additional watts to the 100 watt IR window heat load and heat conduction down the mechanical supports.

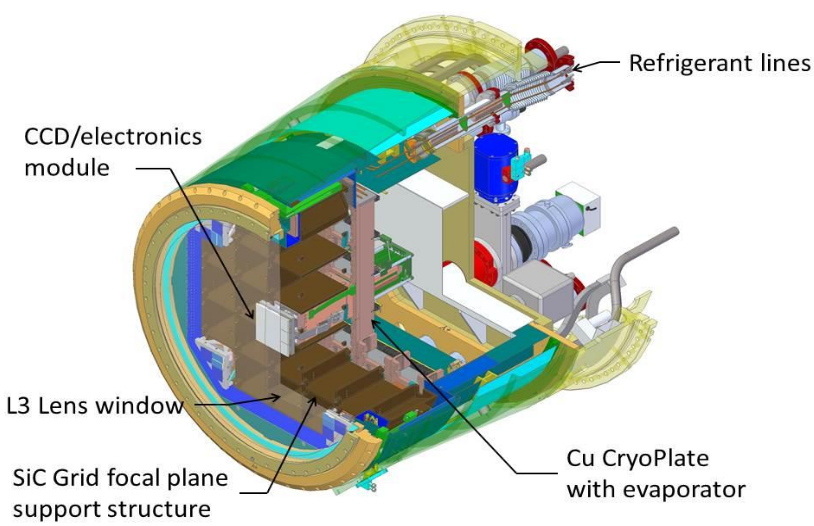

Figure 1. LSST Camera cryostat

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This cryogenic heat load is nearly ten times higher than early astronomical CCD cameras. The refrigeration system must operate 25 meters up at the telescope prime focus, with negligible vibration, independent of changes in height and the direction of gravity as the telescope surveys the night sky.

2. FEASIBLE REFRIGERATION TECHNOLOGIES

Optimal CCD detector operating temperatures for the telescope camera are in the range of -80˚C to -100˚C. Sufficient ΔT to conduct heat from the focal plane to the refrigeration system will require a refrigeration system ~ 30˚C colder. Refrigeration temperatures in the region of -130˚C are much colder than the -20˚C, and -40˚C typically used in food storage refrigeration. But CCD camera operating temperatures are significantly warmer than true cryogenic technologies such as LN_2. While no widespread refrigeration technology exactly matches this temperature range, a number of approaches suggest themselves.

2.1 LN_2 boil-off

Liquid nitrogen has been the traditional refrigerant for telescope cameras. Early cameras had small heat loads of 30 to 50 watts and carried liquid nitrogen dewar reservoirs which had to be filled twice a day. When LN_2 is used, the large ΔT between CCD's and cryogen is handled by thermal resistors. LSST camera's heat load of 500 watts would correspond to vaporization of 217 kg/day of liquid nitrogen. Storing this much LN_2 on the camera and disposing of the resulting cold vapor is a problem.

2.2 LN_2 recirculation with evaporation

Recirculation of LN_2 has recently been implemented on the Dark Energy Camera (DECam)[1][2]. That system uses commercial cryocoolers to condense nitrogen in a pump reservoir dewar located on the floor of the telescope dome. Liquid is pumped from there up through vacuum insulated flex lines to the camera on the telescope and returned, partially vaporized, back down to the pump reservoir dewar where it is re-condensed. A significant fraction of the supplied refrigeration is consumed refrigerating the long transfer lines to the camera. This is the largest capacity telescope camera refrigeration system currently operating.

2.3 Cryocoolers: Gifford-McMahon, Pulse Tube, and Stirling Refrigerators

These refrigerator types are commercially available over a wide range of temperatures (down to 4K) and capacities (up to 600 watts). They are reliable with maintenance intervals over a year. In most cases the working fluid is helium. Their cold head would be mounted to the camera cryostat and fed with high pressure room temperature gas from a compressor on the dome floor or outside. All of these devices use a pressure cycle to move heat from low temperature to high temperature. Their main drawback for telescope application is vibration. The Gifford-McMahon has a moving 'displacer' which carries heat from cold end to the warm end of the cold head. The Pulse Tube refrigerator transports heat with a 1-60 Hz pressure cycle using a rotary valve on the cold head which ports gas between supply and return. Vibration associated with these mechanical refrigeration cycles grows with the size of the refrigerator as does the weight of equipment which must be mounted on the camera cryostat (a 600 watt Gifford-McMahon unit weighs over 200 kg). The thermodynamics of Cryocoolers is reviewed in [3] and the current state of their art can be found in [4]. A recent example of small Stirling refrigerators applied to astronomical cameras is found in [5].

2.4 Joule-Thomson Mixed Refrigerant

The majority of the world's refrigeration systems, from home refrigerators to large industrial plants for the liquefaction of nitrogen and distillation of air are based on Joule-Thomson (JT) constant enthalpy expansion. Refrigerant is compressed and heat of compression is removed in an after-cooler. High pressure refrigerant is then expanded through a valve or capillary restrictor where isenthalpic expansion produces cooling; either a drop in temperature or an evaporation of liquid. This cooling effect depends on molecular interaction energies. (An ideal gas of non-interacting particles does not change temperature upon free isenthalpic expansion.) Approximately 1 billion domestic home refrigerators using long lived inexpensive oil lubricated hermetic compressors and efficient fluorocarbon refrigerants operate today at -20˚C. They often run maintenance-free for 25 years.

Extension of common domestic refrigerator technology down toward liquid nitrogen temperatures was first reported by A.P.Kleemenko[6] in 1960 using "mixed refrigerants". In our application, mixed refrigerants are organic or fluorocarbon vapors mixed with cryogenic gasses such as nitrogen or argon. Such a refrigerant mixture can reach liquid nitrogen temperatures with low pressure single stage compressors if an efficient counter-flow heat exchanger is used to insulate the cryogenic portion of the refrigeration circuit from the warm room temperature compressor. Small 30 watt refrigeration units of this type have been commercially available since the mid 1990's and are currently being applied to CCD camera refrigeration [7]. A recent review of this refrigeration technology can be found in [8]. The technology is attractive for refrigeration of telescope cameras because it avoids both the bulky vacuum insulated cryogenic transfer lines and cryogenic pumps needed for LN_2 systems as well as the mechanical vibration and weight of Gifford-McMahon and Pulse Tube cryocoolers. There are no low temperature components outside the cryostat. Heat loads on long cryogenic transfer lines are avoided. Low temperature heat exchangers mounted on the camera are compact with little vibration and relatively low mass. At this point, the major drawback to this approach is the lack of commercial refrigeration units with sufficient capacity to refrigerate the 500 watt LSST camera.

3. LSST CAMERA CRYOGENIC COOLING SYSTEM

To reach 500 watt cooling capacity, the LSST camera cryogenic system is composed of a cluster of 6 parallel cooling circuits; each with 80-90 watts capacity at -130˚C. Mixed refrigerant JT cryocoolers for this application have been under development at MMR-Technologies and SLAC National Accelerator Laboratory since 2009. Each circuit has its own 26 cc 1KW hermetic compressor. Compressors are grouped together on the floor of the observatory dome or in an auxiliary room. They are connected to the camera by 80 meters of metal tubing which bridges the telescope altitude and azimuth rotations with flexible metal hose. A third flexible section at the rear of the camera allows the camera to rotate 90 degrees around its optical axis. In a vacuum space at the back of the camera, high pressure room temperature refrigerant is delivered to expansion capillaries on the refrigerator's low temperature heat exchanger. Two-phase, -130˚C, refrigerant from the cold end of the heat exchanger is delivered to the evaporator cooling coils brazed to a 'Cryo-Plate' in the camera cryostat. Returning refrigerant is then sent back through the heat exchanger and returns to the compressor as low pressure room temperature vapor. The circuit is illustrated in figure 2.

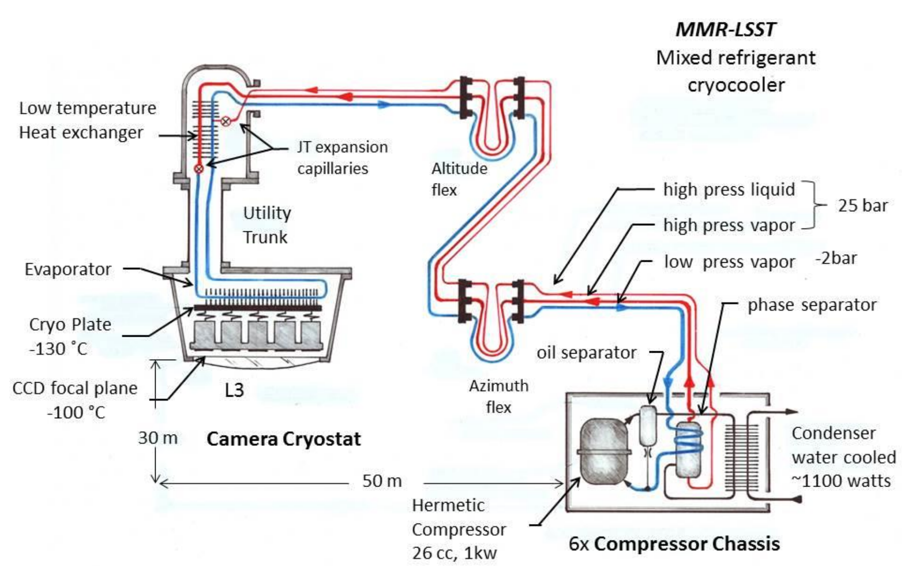

Figure 2 Cryostat refrigeration circuit 6x

3.1 MMR "Kleemenko" type auto-cascade cooling circuit

The cooling circuit supplies both high pressure liquid and vapor refrigerant components at ambient temperature to the heat exchangers located at the back of the camera (fig.2). This 'auto-cascade' thermodynamic cycle is characteristic of MMR-Technologies mixed refrigerant cryocoolers and is protected by US Patents 5,617,739, 5,644,502 and 5,724,832. In effect it allows a single compressor to supply two cascaded sections of the refrigerator heat exchanger operating over different temperature ranges with different refrigerant compositions. Both high pressure liquid and vapor streams are expanded to low pressure through two distinct fixed capillaries located at different locations along the heat exchanger. High boiling point condensed liquid is used in the upper warm end of the heat exchanger to pre-cool low boiling point vapor before it is condensed at the cold end of the heat exchanger and expanded into the evaporator to refrigerate the camera. Separating the refrigerant mixture into liquid and vapor compositions has several advantages. Separated refrigerants can be better matched to heat transfer conditions which vary along the length of the heat exchanger. Furthermore, a liquid/vapor phase separator on the compressor chassis can be used to wash compressor oil contamination out of the high pressure vapor stream into the liquid phase stream which is a strong solvent for the oil. Oil contamination is then confined to the warm end of the heat exchanger where it will not freeze and plug the system. Residual oil contamination left in the vapor phase which does reach the lowest temperatures is now low enough to avoid separation and freezing in the 1.32 mm diameter JT expansion capillary.

3.2 Compressor Chassis

The system is built around commercial hermetic oil lubricated single stage compressors such as are found in domestic refrigerators. After 80 years of development this is a mature technology. The use of refrigerant mixtures rather than a single component refrigerant allows cryogenic temperatures to be reached with a single stage compressor delivering only 25 bar. Compressors employed are 26 cc single stage reciprocating Danfoss GS26-MFX units. This type of compressor is housed in a welded steel pressure case. The 50 or 60 Hz AC motor is housed inside the case. Compressor bearings are lubricated with oil drawn up from the sump through the hollow bore of the motor /crankshaft by centrifugal force. Compressor intake and discharge are reed valves. The motor runs under load at 2850 or 3450 rpm, supported on coil springs inside the case. In normal applications these compressors are air cooled by fans. For LSST, water cooling jackets have been stud-welded to the outside of the case. Figure 3 shows the design cross section.

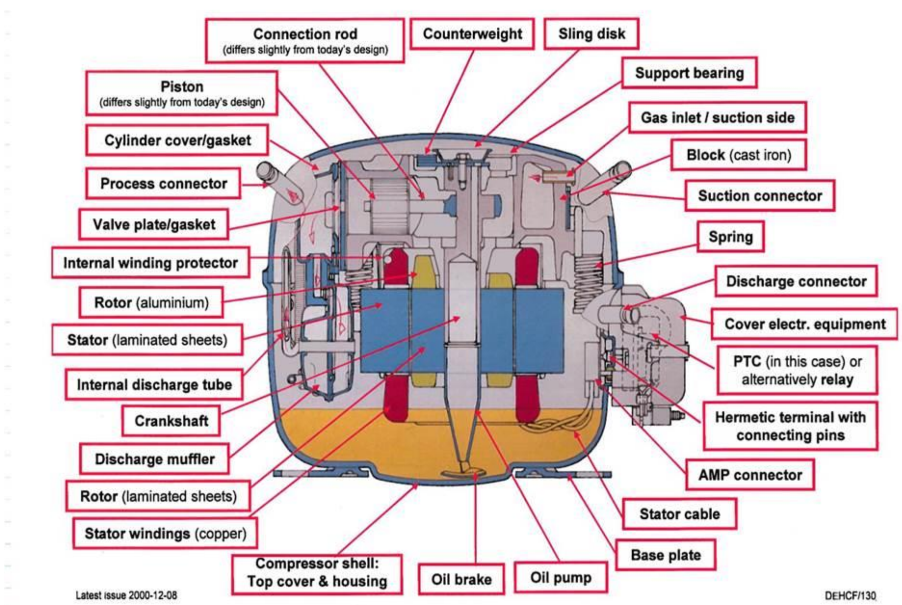

Figure 3. Cross section of a hermetic oil -lubricated reciprocating compressor.

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In addition to the compressor, the chassis also houses a hot oil separator to filter oil mist from the compressor discharge and return it to the compressor sump via the compressor suction line. Typical compressor discharge is 100 ˚C. This heat is removed by a water cooled after-cooler. Discharge at 25 bar is then separated into vapor and liquid streams in a water cooled phase separator. Chilled water is supplied to the chassis at ~13 ˚C. The compressor chassis is shown in figure 4.

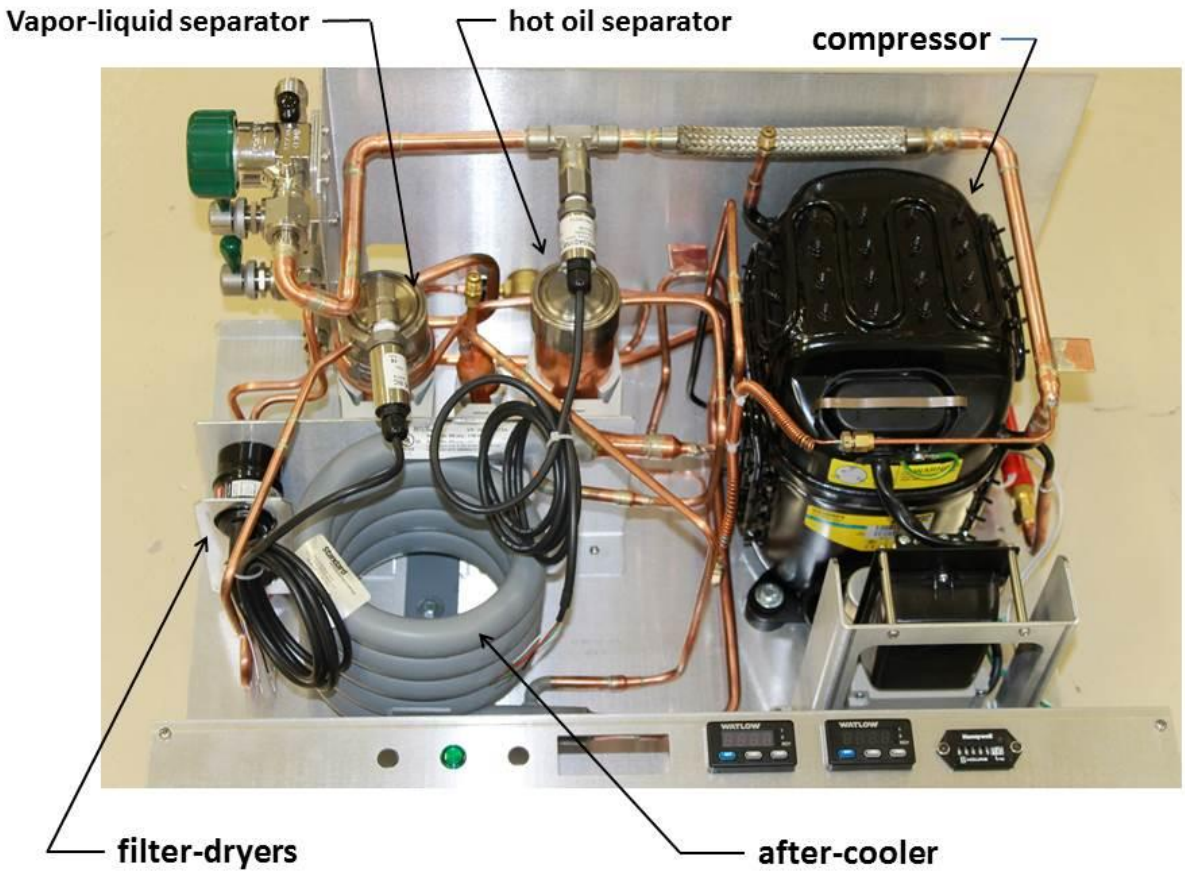

Figure 4. One of 6 compressor chassis for the LSST camera cryogenic cooling system

3.3 Low temperature counter-flow heat exchanger

Low temperature counter-flow heat exchangers are located in an insulating vacuum at the back of the camera. They convert high pressure ambient temperature refrigerant to low pressure -130˚C liquid refrigerant for evaporative cooling. Several prototype ~6 m long counter-flow heat exchangers have been made from copper tubing with 25 bar high pressure flow in 7 parallel tubes, 3.2 mm OD, 1.6 mm ID inside an 11 mm ID copper jacket which carries the 2 bar low pressure return flow. High pressure liquid refrigerant is injected into the low pressure return flow ~2 m down from the warm end of the heat exchanger for evaporative precooling of the incoming vapor. Heat exchangers are rolled into compact coils as shown in figure 5.

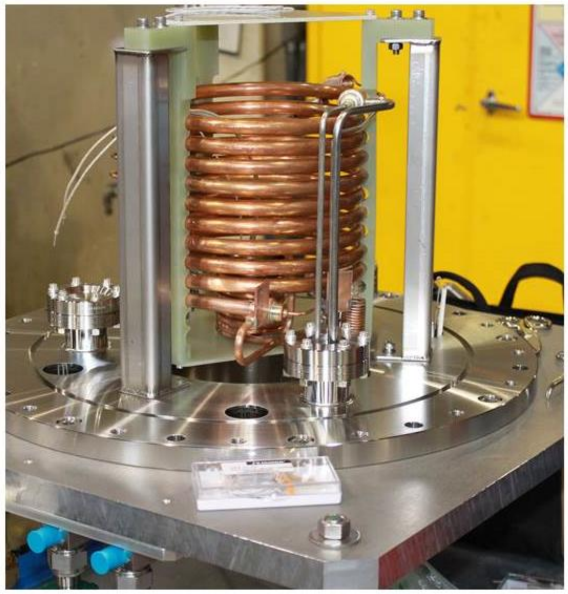

Figure 5. Prototype counter flow low temperature heat exchanger in test vacuum tank

3.4 Cryo-Plate evaporator

Evaporative cooling for the CCD focal plane and front-end electronics occurs on a large copper Cryo-Plate mounted behind the front-end electronics modules shown in figure 6. The Cryo-plate contains 6 separate evaporative cooling circuits each arranged to cover the entire plate. This is the only place where the 6 independent cryocoolers thermally communicate.

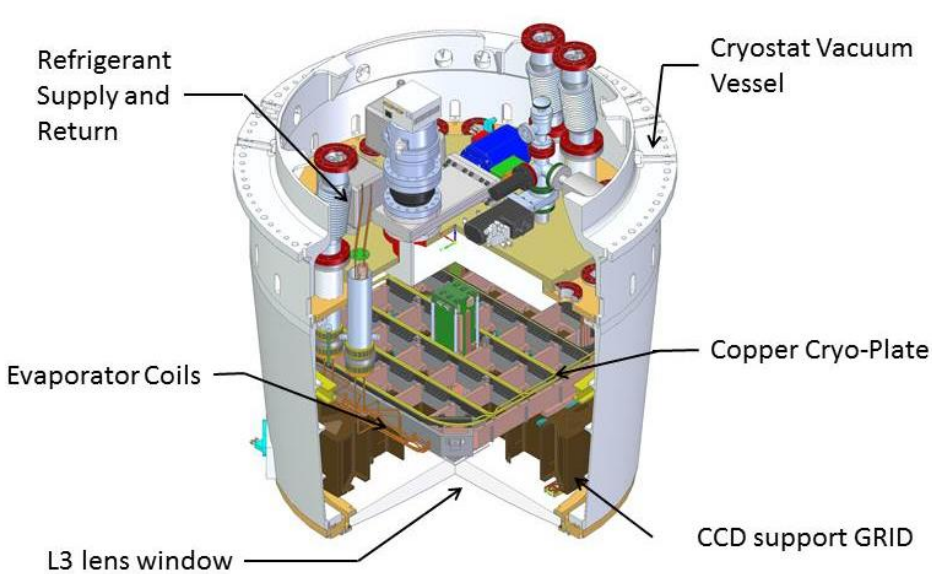

Figure 6. Cryostat section showing location of CryoPlat

3.5 Refrigerant Mixtures

Mixed refrigerants are crucial to the LSST cooling system. MMR-Technologies has developed four separate refrigerant blends during testing of this system. The thermodynamic properties of mixtures are markedly different from single component refrigerants. In general, combining warm boiling point refrigerants with cryogenic gasses greatly expands the range of temperatures and pressures over which liquid and vapor are in equilibrium. Most mixed refrigerant heat exchange processes involve vaporization and condensation. Temperature differences are small due to the large heats of vaporization. High boiling point components that, in their pure state would be frozen at cryogenic temperatures do not freeze out in mixtures. Development of mixed refrigerants for a specific temperature range requires much empirical testing[1].

The first mixture developed by MMR, LSST-3N was made from Argon, Methane, Ethane, Tetrafluoromethane, Trifluoromethane and a small amount of Iso-Pentane. This mixture gave good cooling capacity because of the hydrocarbon components but it was also classed as flammable. Pure Iso-Pentane is a liquid at room temperature and had to be separately charged into the circulating refrigerant while the system was running. Considerable running was done with a Krypton mixture, KR-15 which is largely Argon, Tetrafluoromethane (R14) and Trifluoromethane (R23) but has about 2 mole % Kr. This mix has no problems with flammability but it required injection of a small amount of liquid R123 while running under pressure. The most recent mixture, MX 29-18 based on Octafluoropropane (R218) is non-flammable and can be prepared and stored as a stable mixture of vapors.

4. Initial Testing

MMR-Technologies has extensive experience with mixed refrigerant cryocoolers down to LN_2 temperatures but the long plumbing lines and vertical head required for the LSST telescope operations are completely new. Testing space was found in an experimental hall with a 20 meter deep pit at the SLAC National Accelerator Laboratory. The compressor chassis was installed on the pit floor. Plumbing was run up the pit wall to a refrigerator with electrical load heater on the ground floor (figure7).

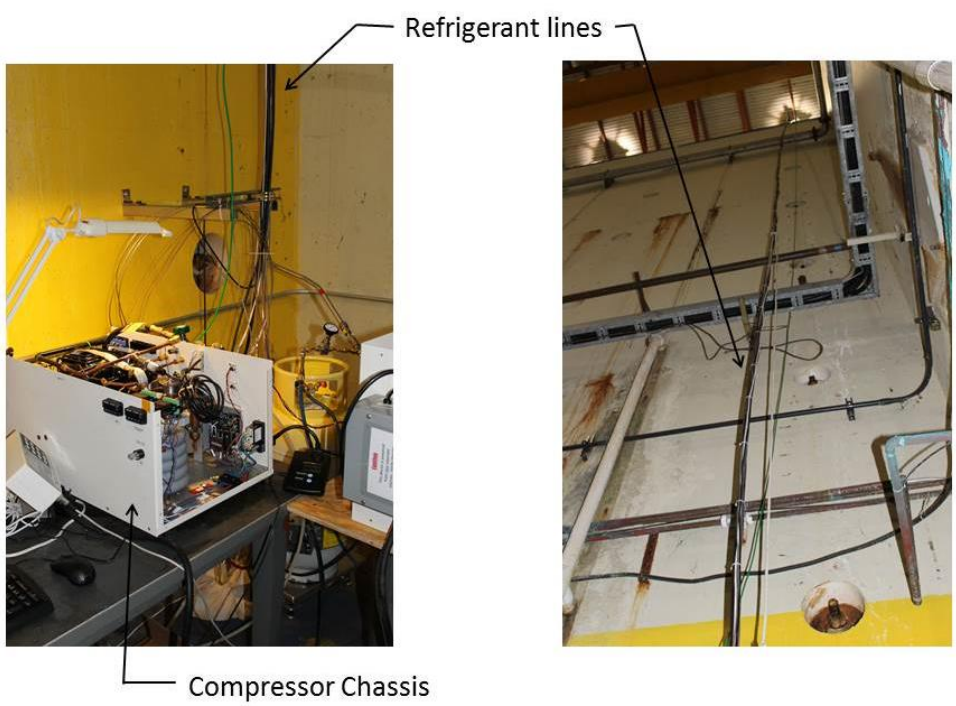

Figure7. Compressor chassis installed on pit floor (left) and refrigerant supply plumbing (left) running 20 m up the pit wall to the refrigerator.

[1] Given pressure and temperature, predicting the number of equilibrium phases, their mole fractions, and compositions is a difficult Gibbs energy minimization problem in a 6 or 7 dimension composition space which has only recently become solvable. Often, data on chemical interactions is missing even for simple cubic equations of state.

Gravity head reduces the liquid supply pressure by about 2 bar but this gravitational potential energy is relatively small compared to the refrigerant heat of vaporization. There is little performance difference between refrigerators run on short lines and long lines. The refrigerator was mounted on a tilt table to check the effect of camera orientation to gravity on refrigerator operation.

This setup has been run frequently over the last 2 years. The first compressor ran for approximately 3000 hrs before suffering bearing failure when it ran out of oil due to a braze joint leak in the plumbing. The longest continuous 24 hour operation lasted 78 days. A load-temperature performance curve is shown in figure (8). Preliminary tilt tests show temperature variations of 1 ˚C with tilt from the zenith down to 15° above the horizon.

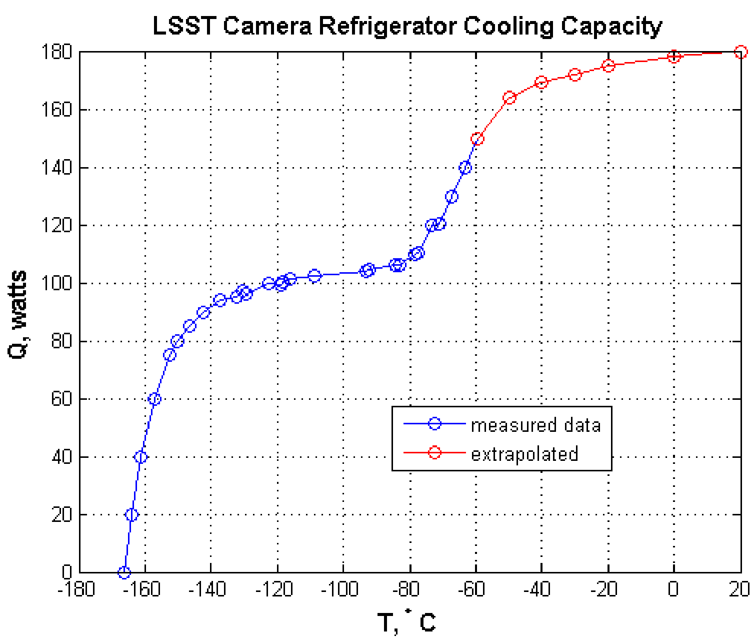

Figure 8. Cooling capacity vs temperature for a single LSST refrigerator unit with mixture KR15. This curve does not include conduction and radiation heat loads (~10 watts). Load capacity during cool-down is extrapolated from stable operation below -60˚C up to room temperature.

Refrigeration efficiency at -130˚C is approximately (95 watts/1000 watts of compressor power) = 0.095. The Carnot limit at -130˚C is (143K/(300K-143K)) = 0.91 which means that an ideal refrigeration system running a -130˚C could at best hope to expend 1 watt of compressor power to lift .91 watts of heat from -130˚C. Our 95 watts per 1000 watts of compressor power is about 0 .095/0.91 = 10.4 % of Carnot's limit. This is typical for small cryogenic systems.

Temperature stability of the refrigerator varies about 1˚C from day to night without feedback control. This is likely due to ambient temperature variations over the long lines connecting the compressor to the refrigerator. In the observatory installation, a layer of plastic foam and low power strip heaters on the line bundle could regulate its temperature. Another control option is variable frequency power for the AC compressor motors. Fine trimming of CCD and electronics temperature stability will be done independently with trim heaters.

The construction of a leak-tight refrigerant plumbing system with long lines and many joints was found to be challenging. Very small long term leaks lead to changes in the refrigerant composition. The combination of fluorocarbon refrigerants, hydroscopic polyol-ester lubricating oil and trace amounts of atmospheric water vapor is particularly aggressive. Welding of stainless steel and brazing of copper make leak tight joints but all demountable joints must have replaceable metal gaskets. Vacuum helium leak testing is impractical because of the long conductance. Leaks could only be located by charging lines to high pressure with refrigerant and using a halogen sniffer as is used in the refrigeration industry.

Oil control is a problem for any refrigeration system based on oil lubricated compressors. It is of particular concern for a cryogenic system with such long refrigerant lines. Even with a hot oil mist separator and refrigerant distillation in the compressor chassis, small amounts of oil remain dissolved in the refrigerant and are carried out into the plumbing system. So far we have not experienced any serious pooling of oil but in time, oil coats all internal plumbing surfaces. An oil layer just 25 microns thick over all tubing can deplete compressor oil sump by half. A compressor is now being fitted with auxiliary oil reservoir with level detector and sight gage.
Long plumbing lines also create problems for refrigerant purity. The quantity of moisture needed to form an ice plug in a 0.5 mm diameter JT expansion capillary is only 0.2 mg. The total refrigerant charge weighs about 1.5 kg so purity by weight must be better than (.2 x 10^{-3} grams/1500 grams) = 1.3 x 10^{-7}. Purities below 1 ppm are difficult to achieve. We found that once opened to the atmosphere, plumbing requires several recharges and several days of circulation before molecular sieve traps installed on the plumbing lines remove most of the adsorbed water.

5. Future development

The next stage of development (Figure 9) will test the refrigerator in a realistic camera configuration with the low temperature heat exchanger separated from the evaporator which is brazed to a large copper structure similar to the Cryo-Plate of the actual camera. This subscale Cryo-Plate has heaters to simulate readout electronics heat loads. The Sub-Scale Camera test will also have space for a single raft of CCD’s and their front-end electronics. The Sub-Scale Camera is the first system where two refrigerators will cool a common Cryo-Plate. Tests will be made of shut-down and start-up of one refrigerator while it is thermally coupled to a 2^{nd} running refrigerator.

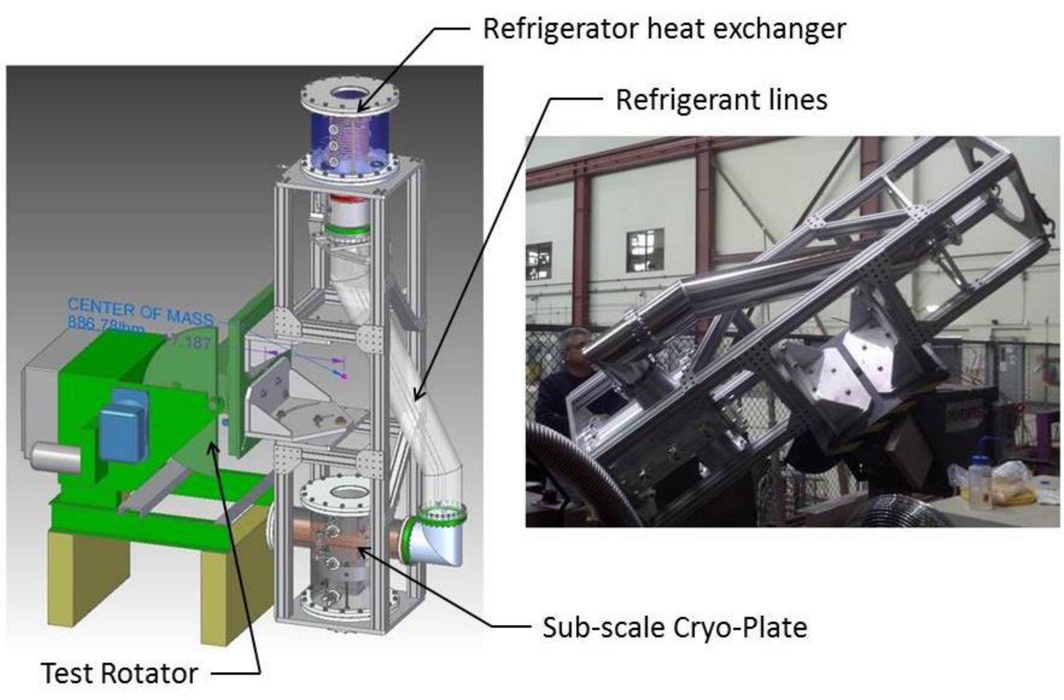

Figure 9. Sub-Scale Camera test

The Sub-Scale test fully replicates all the rotations that the actual camera will execute during operation. Because LSST is a survey telescope covering the night sky every 3 days, flexible refrigerant lines that bridge the 3 telescope and camera rotations will need long fatique life. Moving refrigerant flex line tests will be built over the open pit of the experimental hall to develop these components. The final stage of development will be construction of a full scale 6 unit refrigerator which will serve during assembly and final testing of the camera at SLAC.

Acknowledgements

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