A high capacity 250 mK ^{3}He/^{4}He refrigeration system based on a pulse tube cooler.

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Abstract

We present the design of a completely closed-cycle refrigeration system. The system consists of four stages; the first two, 40.5 K and 2.7 K, are provided by a pulse tube cooler, the third and fourth stages by helium adsorption refrigerators. The adsorption refrigerators use ^{4}He and ^{3}He with base temperatures of 700 mK and 250 mK respectively. With a load of 15 μK, a temperature below 286 mK can be maintained for 72 hours.

Key words: cryogen-free, ^{3}He adsorption refrigerator, pulse tube cooler

1 Introduction

The next generation of facility instruments for mm-wave telescopes will use arrays of bolometric detectors cooled to below 300 mK. Such Facility instruments must have long hold-times and require little or no operator intervention. We are constructing a 90 GHz receiver containing 64 TES detectors (see Benford et al.[1] for details of these detectors). The receiver will be placed on the new 100 m diameter Green Bank Telescope [1] (GBT) in West Virginia, USA [2].

Up to 8 receivers on the GBT are housed on a rotating turret which allows the telescope to switch operating frequencies without down-time. The turret housing is located at the secondary focus 135 m above the ground and is inaccessible during operation. It can tilt between -13° and +72° from the horizontal (corresponding to observing angles of 90° and 5° above the horizon). Because the turret rotates mounting a receiver at an angle will not ensure it stays within ±45° of the horizontal so any receiver must be able to withstand

[1] see http://www.gb.nrao.edu/GBT/GBT.shtml

being tipped by 72° in any direction. The refrigeration system described in this paper was designed to provide cooling for our array on the GBT.

2 System Requirements

The following list of requirements was determined based on telescope and observing restrictions.

- The system must provide 15 μW of cooling at temperatures below 290 mK maintained at angles of at least 57° from the vertical (corresponding to observations 20° above the horizon). Due to atmospheric opacity, observations less than 20° above the horizon are restricted consequently full cooling capacity is not needed.
- When the receiver is not in use it may be tipped by up to 72° in any direction and after this it must be ready to use within 90 minutes of being returned upright.
- To allow for deep observations, the receiver must stay cold for over 24 hours at a time.
- The receiver must be operated remotely by members of the astronomical community who are not familiar with cryogenics.

The system described below meets each of these requirements.

3 System overview

An outline of our system is shown in Figure 1. There are four temperature stages, the first two, at 40.5 K and 2.7 K are provided by a pulse tube cooler, the third stage is a ^{4}He adsorption refrigerator, and the fourth stage is a ^{3}He adsorption refrigerator. The following sections cover each of these stages.

3.1 The pulse tube cooler

Expendable liquid cryogens are impractical on the GBT. Access to the receiver is limited, replenishing cryogens would be prohibitively difficult. Other GBT receivers are cooled (to 15 K) using closed cycle Gifford-McMahon (GM) cryocoolers. The high pressure helium required by such cryocoolers is supplied by compressors located at the base of the telescope. There are several commercial cryocoolers capable of cooling to below 4 K including the PT405 made by

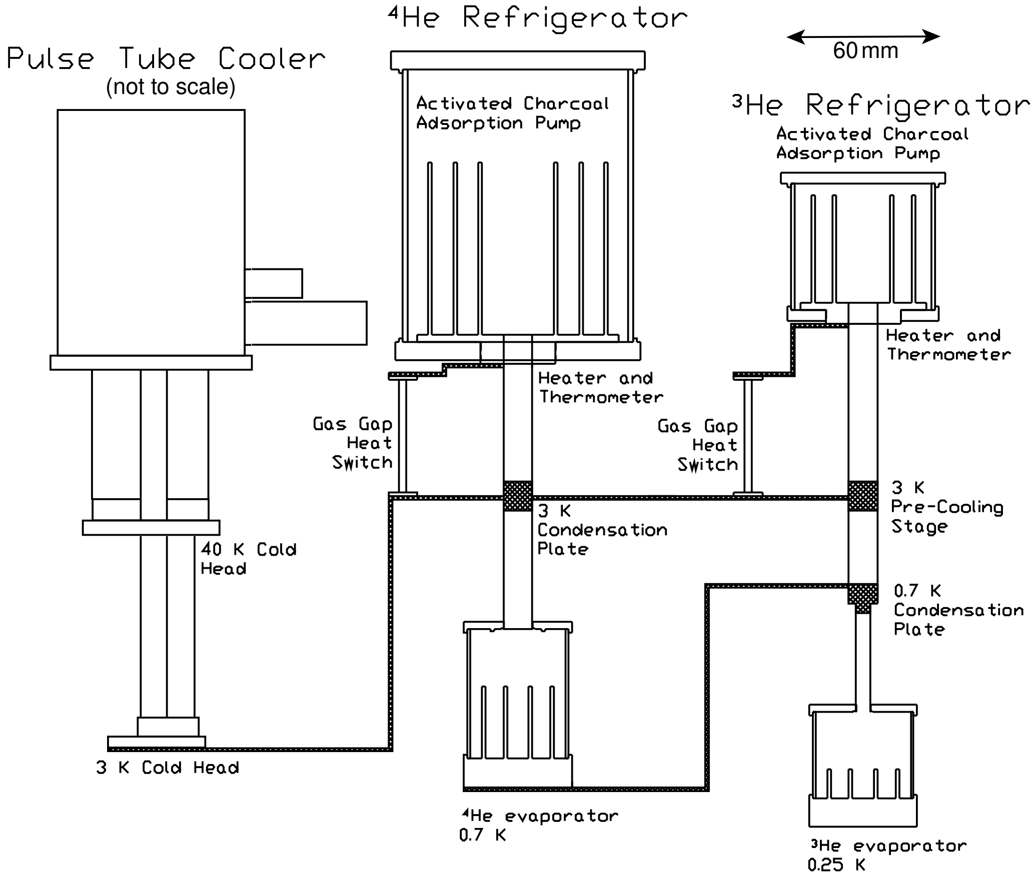

Fig. 1. A schematic of our cryogenic system and how the different stages are connected.

Cryomech [2], a two stage pulse tube cooler[3] with a cooling capacity of 30 W and 0.5 W at 55 K and 4.2 K respectively. Base temperatures around 2.6 K are achieved. Unlike GM cryocoolers, pulse tubes have no mechanical displacers so wear on seals and the vibrations associated with GM cryocoolers are reduced. However the PT405 is designed to operate vertically. At operating angles >30° from the vertical its capacity is reduced. We have investigated this effect on the performance of the entire system, and have found it to be acceptable down to 57°from the vertical.

3.2 The adsorption refrigerators

Adsorption refrigerators have three parts; a pump filled with a sorbent material, a cooled condensation point, and an evaporator (which can also be the condensation point). These elements are connected by a tube of low thermal conductivity and filled with gas, in this case ^{3}He or ^{4}He. To operate the refrigerator the helium is liquefied by cooling the condensation point to below

[2] see http://www.cryomech.com

the critical temperature of helium while keeping the pump above ~25 K – hot enough to prevent helium being adsorbed by the sorbant material. The pump is then cooled via a heatswitch and it adsorbs the gaseous helium, lowering the pressure in the evaporator. The helium cools until its vapor pressure is equal to the pressure in the evaporator, then the refrigerator will stay at this temperature until all the helium has evaporated. At this point the pump is heated up so as to desorb the helium and the cycle is repeated.

The condensation efficiency in a adsorption refrigerator is a strong function of the condensation temperature. For the ^{3}He refrigerator described in this paper simple calculations which assume equilibrium is reached before the charcoal is cooled were carried out. These showed that if the charcoal is cooled with the the condensation point at 3 K, by the time the evaporator has cooled below 0.3 K, less than 23% of the ^{3}He is left as liquid. Cooling the condensation point to 1.2 K condenses 96% of the available helium and by the time it has cooled to 0.3 K over 80% is left as liquid and is available for cooling the detectors. Although the PT405 could in principle cycle a ^{3}He refrigerator, in practice the extra load from the ^{3}He refrigerator would warm the 2nd stage of the PT405 above 3 K. Efficient cycling of ^{3}He adsorption refrigerators from the 2nd stage of the PT405 is not possible.

To overcome this, a ^{4}He adsorption refrigerator was added between the pulse tube and the ^{3}He refrigerator's condenser. Simple models for our ^{4}He adsorption refrigerator predicted that even with a condenser at 3.5 K, 91.5% of the ^{4}He gas would condense and after cooling to 0.8 K over 70% would still remain as liquid. Once cycled, the ^{4}He stage is then used to cool and condense the ^{3}He gas in the ^{3}He stage.

4 Detailed design

A cross-section of the ^{3}He and ^{4}He refrigerators is shown in Figure 1. By designing the refrigerators as separate units that bolt together construction was simplified and in the future it will be possible to use one stage without the other.

4.1 The ^{4}He refrigerator

The ^{4}He refrigerator is assembled around a piece of thin-walled 316 stainless steel tubing. The condenser, which also acts as the mounting point for the refrigerator, is an OFHC coper disk silver soldered approximately halfway down the tube. The evaporator has an OFHC copper bottom with concentric rings cut on the inside so as to decrease the effect of thermal boundary (Kapitza) resistance.

The pump is a stainless steel cylinder filled with OFHC copper fins which make thermal contact to the activated charcoal[4] which is used as the sorbant material. The fins are joined to a copper plug in the wall of the pump to which a resistive heater and a thermometer are attached. The capacity of the ^{4}He refrigerator (28 S.T.P. litres gas) was designed to be enough to cycle the ^{3}He stage and provide 50 J of additional cooling. The amount of charcoal in the pump is set to be enough to adsorb all the helium with a safety margin of 2[5]. To ensure efficient recycling the whole refrigerator is filled to 500 psi (at 300 K).

To connect the charcoal pumps to the PT405, solid state, mechanical and gas-gap heatswitches were considered. Mechanical heatswitches have the advantages of a very high on/off ratio and that power is only required to change the state of the switch. However these devices tend to be bulky and they require high current leads to drive the motor. Most importantly they are more prone to failure than the other options. Solid state heatswitches have the advantage of being totally passive devices, however high on/off ratios are hard to achieve. If used they would give either an unacceptably high load on the PT405 or result in a long cool-down time when cycling the refrigerator. Gas-gap heatswitches[6] can be run using low current wiring and are very reliable. Although $\sim$2 mW of power must be applied in order to keep them on, with a closed cycle system this is not a consideration. For these reasons we chose gas-gap heatswitches to run the refrigerators [3].

Superfluid ^{4}He can climb the walls of the evaporator and travel up the pump tube where it evaporates. This flow can easily be the equivalent of 1–2 mW additional parasitic load on the evaporator (compared to 70 μW from thermal conduction down the pump tube). If the ^{4}He stage was to be used only to cycle the ^{3}He refrigerator, then this would not be a problem, however we require a temperature stage between the pulse tube and the ^{3}He refrigerator (to cool additional cold optics and reduce the loading on the ^{3}He stage). Other projects [7] have used an additional ^{3}He stage but this was ruled out for cost and simplicity reasons.

To reduce the superfluid leak we use a thin diaphragm with a 1.54 mm hole in it at the exit of the evaporator. Using the highest measured superfluid leak rate in the literature [8] we calculated the small circumference of the hole should restrict the superfluid leak to less than 0.1 mW. At the same time it is important for the hole to be big enough not to restrict the flow of gas from the evaporator to the charcoal pump. Gas flow in the pump tube is difficult

[3] Chase Research : model #CR-GHS-005

to model as it is in the transition regime between laminar and molecular flow and the temperature is unknown. However, a range of models including some based on results scaled from our earlier ^{3}He refrigerators all showed that with 9 mW load, the ^{4}He evaporator should be below 1 K and $>$ 30 mW is needed to heat the evaporator above 1.3 K.

4.2 The ^{3}He refrigerator

The ^{3}He refrigerator is of very similar design to the ^{4}He stage with two important differences. First, ^{3}He does not become superfluid until below 2 mK, so the diaphragm is not needed. Secondly, there is an extra heat exchanger between the condenser and the charcoal. During cycling ^{3}He gas leaving the charcoal is precooled by the second stage of the PT405 before reaching the condenser. This reduces the amount of ^{4}He needed to condense the ^{3}He by a factor of approximately 6. The overall design has been scaled to hold 6.15 S.T.P. litres ^{3}He gas at a pressure of 500 psi (at 300 K). Again a high pressure ensures efficient cycling. Models predict that if the refrigerator is cycled with the condenser at 0.7 K, 5.65 J of cooling should be available, with a cycling efficiency of 90%.

5 Cycling procedure

Figure 2 shows a typical cycle. The data were taken using ROX resistance thermometers[4] measured using a scanning resistance bridge controlled via the GPIB bus by a Labview program. The same Labview program also controls the heatswitches and the heaters on the charcoal pumps. When the cycle is started power to both heatswitches is turned off. As the response of the gas-gap heatswitches is not instantaneous, there is a 5 minute delay before 1.6 W and 0.2 W are applied to the ^{4}He and ^{3}He charcoal pumps respectively. These powers are left on until the charcoal has reached predetermined temperatures; 35 K for ^{3}He and 50 K for ^{4}He. These temperatures were chosen empirically to give a quick, efficient cycle. The program then waits until the ^{4}He evaporator cools to 3.5 K before applying power to close the ^{4}He charcoal heatswitch and to cool the ^{4}He refrigerator. The program then waits for the ^{3}He evaporator to cool to 0.75 K before closing the ^{3}He heatswitch and completing the cycle. Typically the whole process takes 4.5 hours and is limited by how long it takes to remove energy through the second stage of the PT405. The installation of a better thermal link or a more powerful cryocooler would speed up this process. No fine tuning of thermal loads or thermal links was needed.

[4] Lakeshore Cryogenics part #RX-202A-AA-M

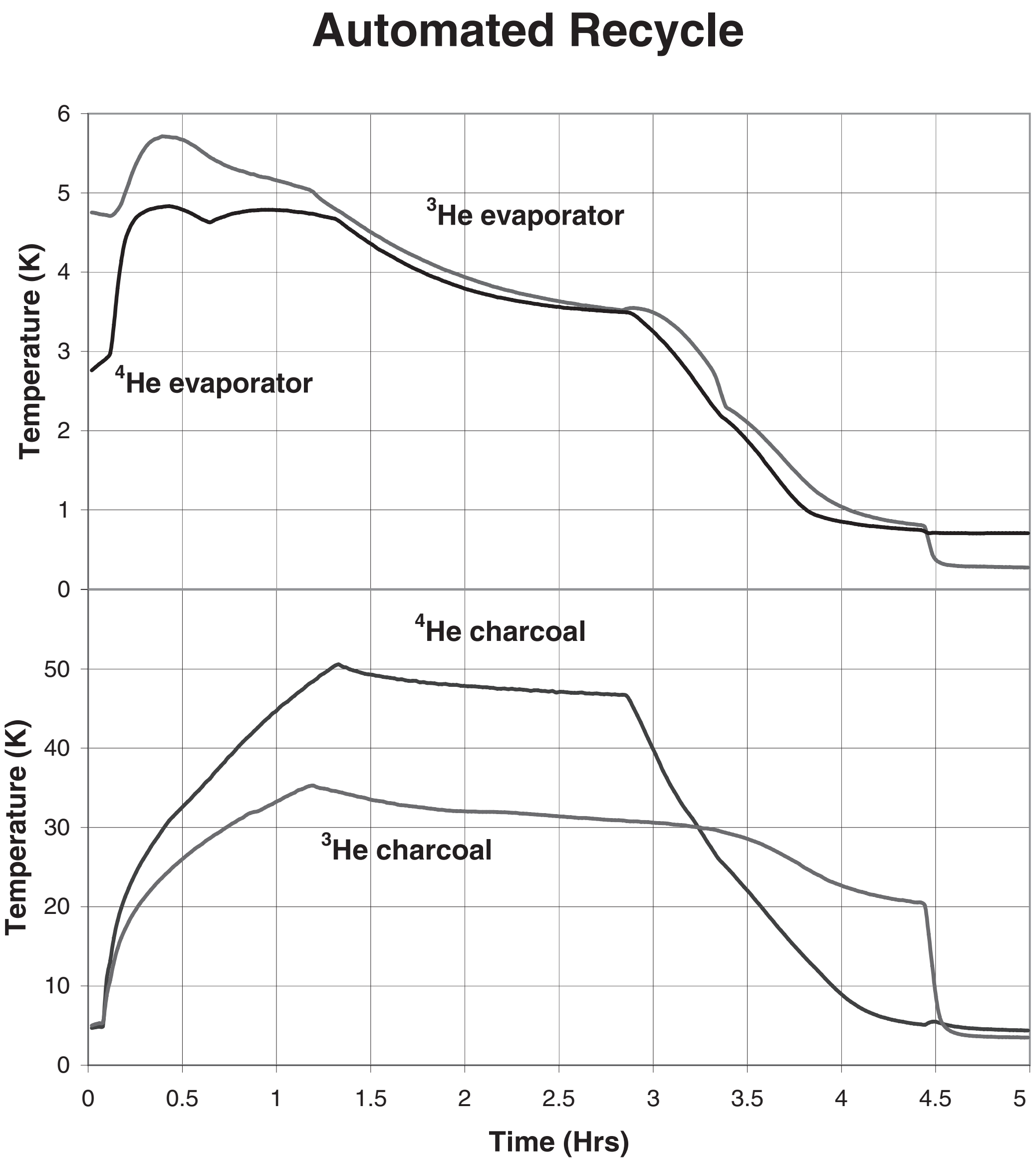

Fig. 2. A typical automated cycle of both adsorption refrigerators. At 0:00 the heatswitches were turned off and at 0:05 1.6 W and 0.2 W was applied to heat the ^{4}He and ^{3}He charcoal. At 1:20 the heaters are turned off and at 2:51 the ^{4}He has condensed and cooled to 3.5 K so the ^{4}He heatswitch is closed. At 4:24 the ^{3}He has condensed and the ^{3}He heatswitch is closed ending the cycle.

This cycling procedure has been shown to be robust and efficient in condensing the helium. Because the procedure waits for the evaporator to cool to preset values (rather than waiting for set amounts of time) it works with the PT405 tipped by 45 degrees where its cooling power is greatly reduced.

6 Performance

6.1 The ^{4}He system

The ^{4}He refrigerator cools to a base temperature of 700 mK and is stable to better than 0.1 mK on timescales between 0.25 seconds and 10 minutes. Slow drifts up to 0.4 mK/hour where sometimes observed on longer timescales. For our application such drifts do not pose a problem. Typical cycles were shown to condense the expected amount of ^{4}He; 75 J, of which 55 J are left if the ^{3}He refrigerator is cycled. The load curve (figure 3) shows that for an applied power of 10 mW the evaporator is at 1 K, demonstrating that the diaphragm does not adversely affect the flow of gas. At higher powers the slope of the load curve starts to increase again. We attribute this to the charcoal pump being heated by the adsorption of the helium to the extent that it looses some of its efficiency. A better heatswitch would improve this situation.

If not used to cycle the ^{3}He refrigerator the ^{4}He refrigerator has a hold time of 24 hours. This corresponds to a parasitic load of 790 μW , significantly more than that expected due to conduction down the pump tubes (70 μW) and the superfluid leak (90 μW). The cause of this extra load is under investigation. There is a strong possibility of oxidization around the hole in the diaphragm. The thickness of a superfluid film is highly dependent on surface conditions so an oxide layer could increase film thickness and increase the superfluid leak rate.

6.2 The ^{3}He system

The ^{3}He refrigerator achieved a base temperature of 250 mK. After cycling, the refrigerator quickly cools below 290 mK. There is then a period of 1–2 hours while the temperature of the refrigerator stabilizes. The final temperature stability is ± 90 μK on timescales between 0.25 seconds and 10 minutes. Long term drifts drop below 0.2 mK/hour.

With a 15 μW load the ^{3}He refrigerator had a hold time of 72 hours - far longer than the ^{4}He refrigerator. However, load curves of the ^{3}He refrigerator (Figure 4) show operating temperatures (under 15 μW of loading) of 270 mK and 286 mK when the ^{4}He refrigerator is at 700 mK and 2.8 K respectively. This more than meets our cooling requirements allowing the entire 72 hour hold time to be used, giving the system a 94% duty cycle. The change in the base temperature when the ^{4}He refrigerator runs out is that expected due to the increased thermal conductance up the pump tube.

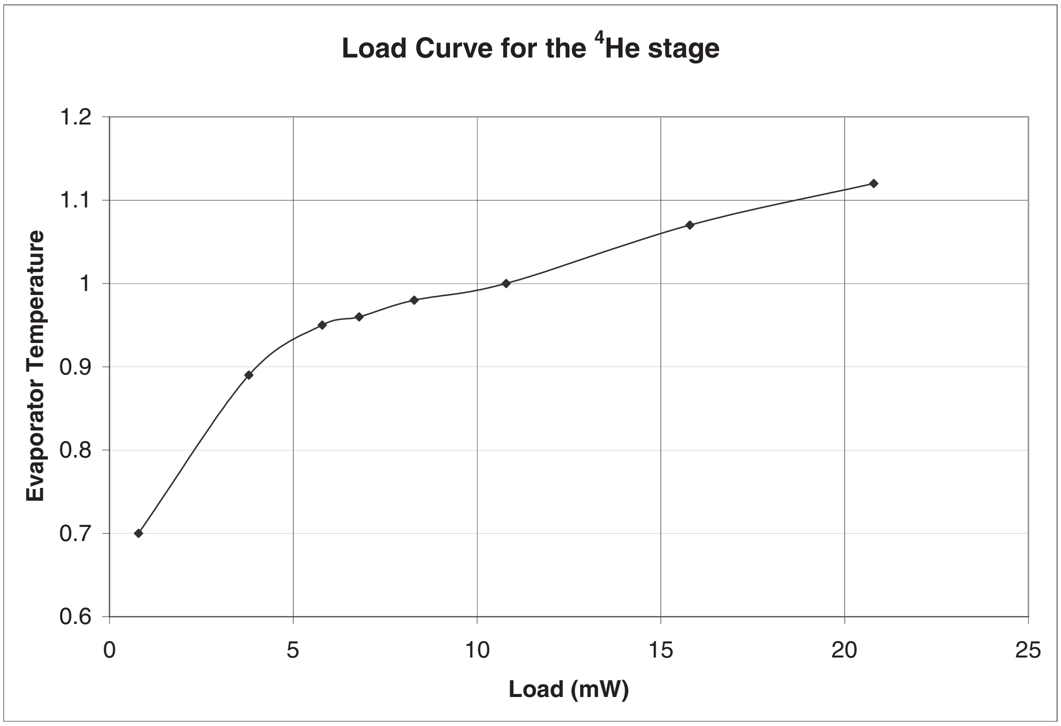

Fig. 3. The ^{4}He load curve. The flat response of this curve is confirmation that the diaphragm is not limiting the gas flow between the evaporator and the pump.

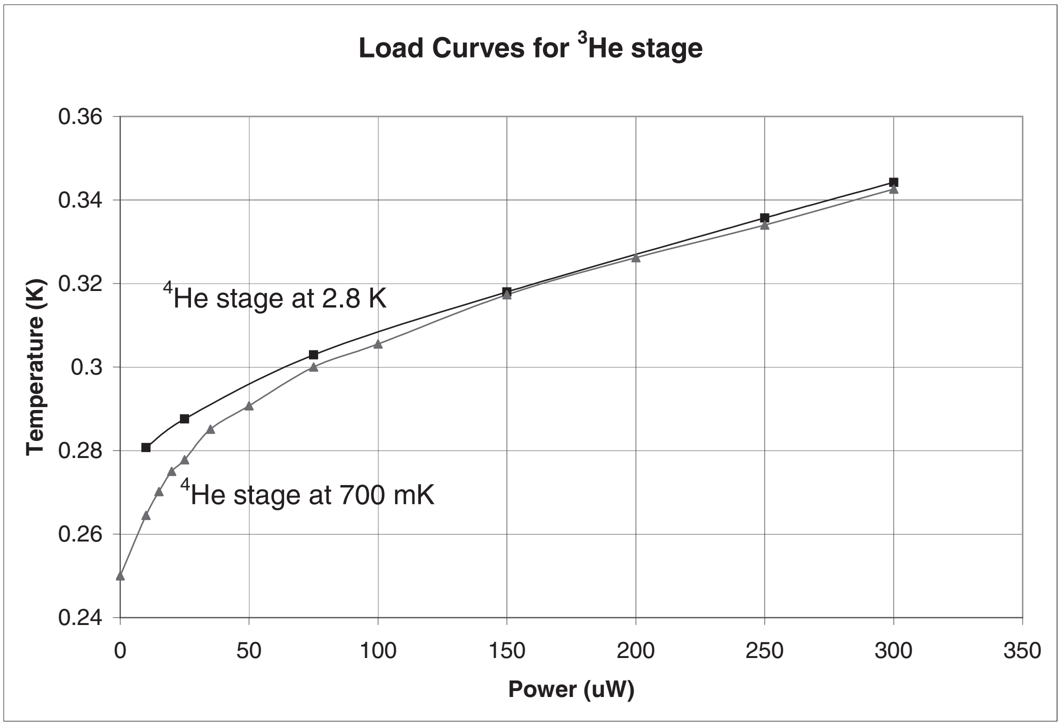

Fig. 4. Load curves for the ^{3}He refrigerator taken with the ^{4}He refrigerator at 700 mK and 2.8 K.

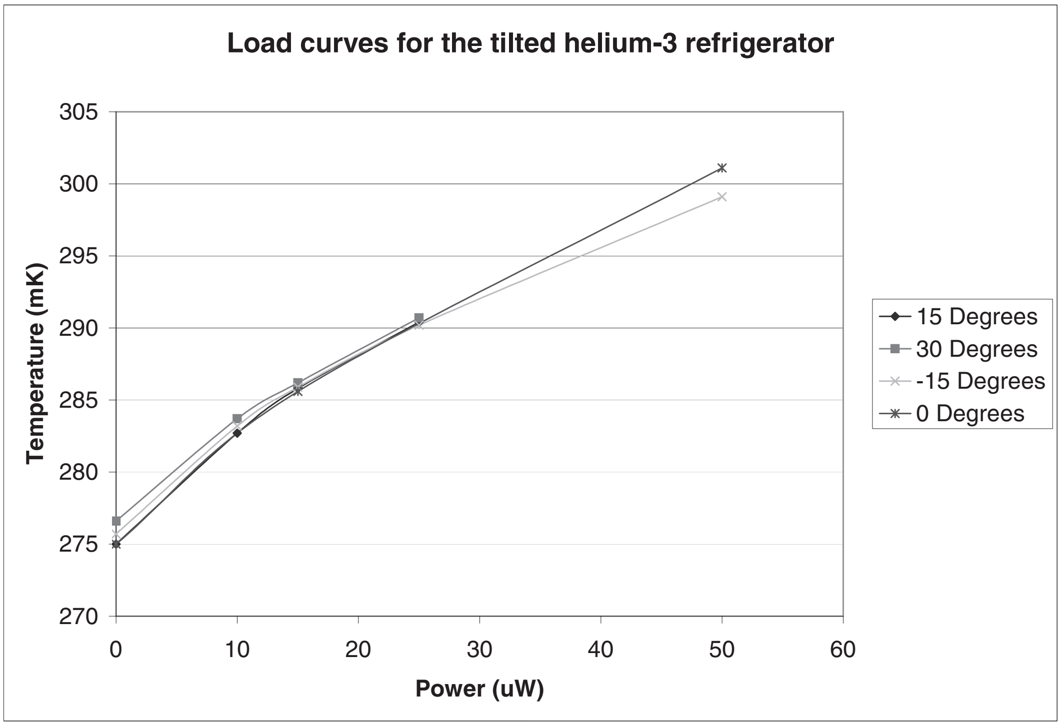

Fig. 5. Load curves for the ^{3}He refrigerator when tipped from the vertical and the ^{4}He refrigerator warm.

6.3 The response to tilt

To test the response of the system to tilt, the system was left at 57° (the limit of useful observations) and 72° (the hard limit of the telescope) from vertical for several hours, being returned vertical between each test. The behavior and recovery of the system was monitored. In addition, load curves of the ^{3}He refrigerator were taken at a range of angles. At 57° the efficiency of the first stage of the pulse tube drops rapidly and over two hours it warmed to 70 K. The second stage was relatively unaffected showing only a rapid warming to 3.4 K before becoming stable. Both the ^{3}He and ^{4}He stages were unaffected.

On tilting to 72° the second stage of the pulse tube warms to about 20 K in an hour. Because the charcoal pumps become hot the adsorption refrigerators no longer work. On tilting back to vertical the system recovers in less than 40 minutes. Such extreme tilting often acted to partly cycle the ^{4}He refrigerator. So far, no effects on the hold-time of the ^{3}He system have been seen.

Load curves of the ^{3}He refrigerator taken at different angles show little dependence on angle up to 30° (figure 5) (the maximum tested). This fact and that no increase in base temperature over the hold time of the refrigerators was observed demonstrates Kapitza resistance is not a problem. Calculations using the surface area of copper fins inside the evaporator in contact with the liquid helium provide confirmation of this result.

7 Conclusions

The refrigeration system we have designed and built has been shown to meet all our requirements for the Green Bank Telescope. Without using expendable cryogens, the system reaches a base temperature of 250 mK and can cool to 286 mK with loads of 15 μW and hold times of over 70 hours. This design should be easy to scale to other experiments.

8 Acknowledgments

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