Preliminary Test Results for a 25 K Sorption Cryocooler Designed for the UCSB Long Duration Balloon Cosmic Microwave Background Radiation Experiment

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ABSTRACT

A continuous operation, vibration-free, long-life 25 K sorption cryocooler has been built and is now in final integration and performance testing. This cooler will be flown on the University of California at Santa Barbara (UCSB) Long Duration Balloon (LDB) Cosmic Microwave Background Radiation experiment. The UCSB LDB experiment will be flown at Antarctica in December 1997. The cooler will refrigerate a focal plane composed of four microwave feedhorns, two working at 30 GHz and two at 42 GHz, with InP High Electron Mobility Transistor amplifiers. This will be the first hydride sorption cooler used to support an astrophysics experiment. As such, it is an important milestone in the development of vibration-free coolers for astrophysics applications.

The cooler uses hydrogen as the refrigerant and $LaNi_{4.8}Sn_{0.2}$ as the hydride sorbent. The materials, components, design margins and assembly procedures are entirely consistent with space-flight qualification requirements. Several features have been incorporated into the cooler design for long term reliability and temperature stability. A high pressure tank and low pressure sorbent bed are used to stabilize the cold end temperature to better than 1 mK/sec. Small ZrNi compressors are utilized to activate the compressor element gas-gap thermal switches without valves. To greatly enhance contamination tolerance, commercially available porous metal flow restrictors are used as the Joule-Thomson plug. Passive check valves direct the refrigerant flow, simplifying cooler operation enormously. A design description and preliminary test results are presented. Also presented are the results of flow tests conducted to determine the relationship between pressure drop and hydrogen mass flow rate as a function of temperature for a range of commercially available flow restrictors.

INTRODUCTION

Since the detection of anisotropy in the Cosmic Microwave Background (CMB) by the COBE DMR instrument[1], there have been a number of experiments to measure anisotropy in the CMB at higher spatial resolution. An anisotropy map with much higher spatial resolution (<0.5°) than the 7° achieved by the COBE DMR can be used to determine the Hubble constant, and thus the age of the universe, the density of the universe, and the fraction of that density that is made up of baryons. Finally, this information provides a crucial test for theories predicting how structure originated in the universe.

A team at the [University of California at Santa Barbara (UCSB) is now constructing a payload to map the anisotropy of the CMB at the 0.3 degree angular scale. One of the requirements for this experiment to succeed is the use of active cryogenic cooling. The advantages of hydrogen sorption cooler technology make it the most desirable cryogenic cooler for this experiment and substantially reduces the system mass through elimination of the 500 liter helium dewar that would otherwise be required. Thus, a sorption cooler has been constructed and is now being tested in preparation for delivery to UCSB in late 1996. The cooler was designed and assembled to offer reliable, stable, and efficient long term cooling. Presented in this paper is a summary of the design and assembly processes for the UCSB hydrogen sorption cooler and preliminary test results. included are results from the hydrogen flow tests that were required to design the Joule-Thomson expander used in the cooler cryostat.

COSMIC MICROWAVE BACKGROUND EXPERIMENT

The Cosmic Microwave Background (CMB) is understood to be the remnant of a hot, dense, early phase of the universe when matter and energy were in thermal equilibrium, and its existence and characteristics remain the most convincing evidence for the Big Bang. After the Big hang, the universe expanded and the temperature of matter and radiation decreased. When the mean energy of the photons fell below the ionization energy for hydrogen, free electrons combined with protons to form hydrogen. This caused matter and radiation to decouple because neutral hydrogen only weakly scatters photons as compared to free electrons. As the universe has continued to expand, the CMB photons have continued to cool. Since the CMB photons have interacted primarily through gravitation since recombination, measurements of the CMB can be used to probe density fluctuations during recombination as well as gravitational processes since then.

On large angular scales the CMB points to physical conditions right after the Big hang. on smaller angular scales, anisotropy in the CMB is influenced by factors that control the expansion rate of the universe and formation of large scale structure such as the cosmological constant, the matter density, and the existence and nature of dark matter. Measurements of the anisotropy of the CMB will hopefully be able to discriminate between competing theories that predict the primordial mass distribution and help advance understanding of the gravitational collapse that led to galaxy formation.

Long Duration Balloon (LDB) flights will be able to make two dimensional maps of the sky. unlike normal 8 to 48 hour balloon flights, with substantially reduced atmospheric noise as compared to ground based experiments. Since liquid cryogens are impractical in a balloon-borne experiment longer than two weeks, a cryogenic cooler will be required to refrigerate High Electron Mobility Transistor (HEMT) receivers. The unique advantages of hydrogen sorption cooler technology will make it the cooler of choice for long duration balloon experiments. Not only will the LDB flight give interesting scientific results, but it will also provide valuable experience in the use of sorption cooler technology that will be useful for any mission, balloon-borne or space based, that requires active cooling for cryogenic detectors.

In June 1997 the UCSB LDB payload will test fly in the US, and it will fly in December, 1997 on a zero-pressure balloon in a two week long Antarctic circumpolar trajectory. The experiment will measure the CMB anisotropy with a beam full width at half maximum of about 0.3 degrees using an off-axis Gregorian telescope, Two receivers will measure a band centered at 30 GHz and another two will measure a band centered at 42 GHz. Having four antennae will not only allow for observation at more than one frequency, but will also give better sky coverage and increase the signal to noise ratio. The signal from the antennae will be fed to HEMT amplifiers which will be cooled to 25 K by a hydrogen sorption cooler to take advantage of their low noise properties. The sky coverage for the LDB experiment will be 10^3 to 10^4 square degrees.

SORPTION COOLER REQUIREMENTS

The primary mission requirement for the UCSB LDB cooler to achieve reliable and safe operation for at least two years with little maintenance and while in flight for up to three months at a time with no maintenance. This has to be achieved after repeated transport and test flights in New Mexico or Texas, and transport to and flight in Antarctica At the conclusion of each flight, the balloon is separated and the science instrument parachutes to the earth from an altitude of approximately **40** km. Substantial repairs between flights are often required due to the generally rough nature of the landing, All of the major components can be isolated by hand valves to permit removal and repair as required.

The UCSB LDB experiment requires 480 mW of refrigeration at 25 K to cool the radiometer. The radiometer focal plane temperature must remain constant to within 1 mK per second to avoid introducing noise into the experiment. This requirement is derived from the measured sensitivity of the InP HEMT amplifiers which vary linearly with temperature. As the cryostat and compressor may be separated by as much as two meters, the pressure drop through the intermediate lines must be low. In addition, the cryostat must be able to operate in any orientation and the compressor must be able to rotate on two axes. The compressor should be relatively light and compact due to LDB payload size and weight limitations.

25 K LDB COOLER OPERATION AND DESIGN

The 25 K LDB cooler follows the classic continuous operation sorption cooler concept design. Figure 1 shows a schematic of this cooler integrated with the LDB radiometer. The cooler is comprised of a compressor assembly, made up of four $LaNi_{4.8}Sn_{0.2}$ hydride sorption beds, connected to a J-T cryostat assembly. During operation of the cooler, hydrogen at a pressure of 10 MPa is desorbed by a heated sorption bed at 530 K. The hydrogen, at a mass flow rate of 0.0025 g/s, is expanded through a J-T orifice to create a gas/liquid refrigerant mixture. The liquid evaporates as it absorbs heat from the detectors and is then absorbed at pressure of 0.12 MPa in a cool, 300 K, bed. When the cool bed is reheated, the hydrogen is repressurized thus creating a fully reversible closed-cycle system. During each 800 second quarter cycle, one bed is hot (desorption), one is cool (absorption), one is heating up (pressurization), and one is cooling down (repressurization). The cooler requires a measured 220 W of input power which will be rejected in flight at 275 K in a 3 torr environment and at approximately 300 K in one atmosphere in the laboratory. A cold end temperature of 23.0 K is predicted from the sorbent composition, operating temperature, and measured cryostat performance.

The primary reliability concern for any J--T cooler is contamination. Hence, particular attention was paid to minimizing contamination levels through proper materials selection and fabrication process design. The approach selected was to make the entire system as clean as possible. This was accomplished by starting with clean materials and hardware, building the compressor in a monitored pure argon atmosphere glovebox, filling the beds with ultra-high purity refrigerant, filtering the cold refrigerant during operation, and using a porous plug for the J-T. The Department of Energy Ames Laboratory at Iowa State [University provided the $LaNi_{4.8}Sn_{0.2}$ hydride with a purity level over 10,000 times better than that used for fabrication of any sorption cooler before this. The hydrogen refrigerant is supplied by a 20 ppb total contamination semiconductor grade facility.

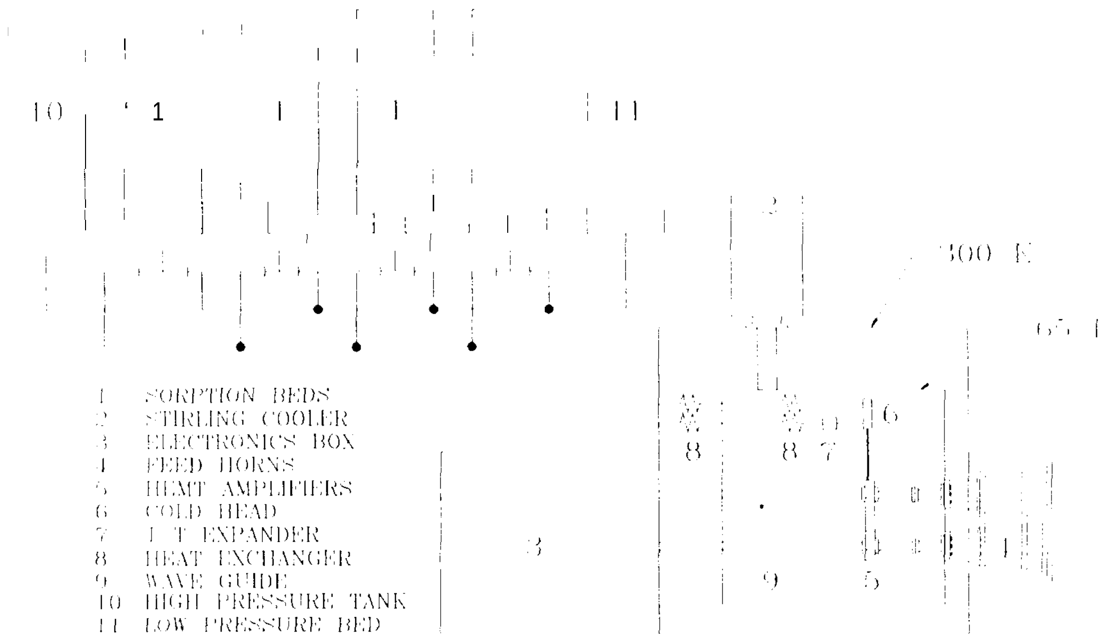

Figure 1. Schematic of the sorption *cooler* and focal plane assembly.

To achieve high reliability and to provide a better foundation for future flight missions the cooler structure is entirely made of 316L VIM/VAR stainless steel. All refrigerant scaling joints arc welded to support the high vibration levels and abusive handling expected during transportation and test flights. The 25 K LDB cooler was built at a level equivalent to flight engineering model hardware. All of the materials selected, fabrication and assembly techniques ant] design and safety margins are consistent with flight hardware requirements,

Cold tip temperature stability is primarily set by the liquid reservoir pressure as the heat load into the focal plane is nearly constant. Therefore, to meet the instrument temperature stability requirement, high pressure tanks are incorporated into the compressor assembly. These tanks limit pressure variations at the inlet to the J-T flow restrictor to less than 0.5 MPa over the 800 second resorption. A constant temperature, low pressure sorbent bed, identical in mechanical design to the four active compressor elements, is used to regulate the pressure over the liquid reservoir by acting as the equivalent of a 120 liter plenum. Approximately 2 W of power is required to stabilize the low pressure sorbent bed temperature such that the average low pressure seen during an 800 second absorption phase corresponds to the equilibrium pressure at the middle of the absorption plateau. Acting in concert with an absorbing compressor, the low pressure sorbent bed will maintain the low pressure stability such that the calculated liquid reservoir temperature stability is 0.36 mK/s. As the FPA mass attached to the liquid reservoir is greater than 2.0 kg, the final temperature stability at the HEMT amplifiers will be far better than the 1 mK/s requirement.. Finally, several 200-mesh copper screen cylinders are incorporated into the liquid reservoir to ensure, through wicking, even distribution of liquid hydrogen over the reservoir surface and to prevent pool boiling with its associated temperature fluctuations.

The compressor assembly can be remote] y located from the cryostat without performance penalty because of the low 0.0025 g/s mass flow rate. The compressor has a mass of only 21,5 kg and dimensions of 87.5 cm by 50 cm by 23 cm. The cryostat masses 3 kg and easily fits within a volume 15 cm in diameter and 46 cm long.

Sorption Bed Design

The compressor assembly, pictured in Figure 2, has four active $LaNi_{4.8}Sn_{0.2}$ hydride compressor elements, each surrounded by a gas-gap thermal switch. The compressor elements

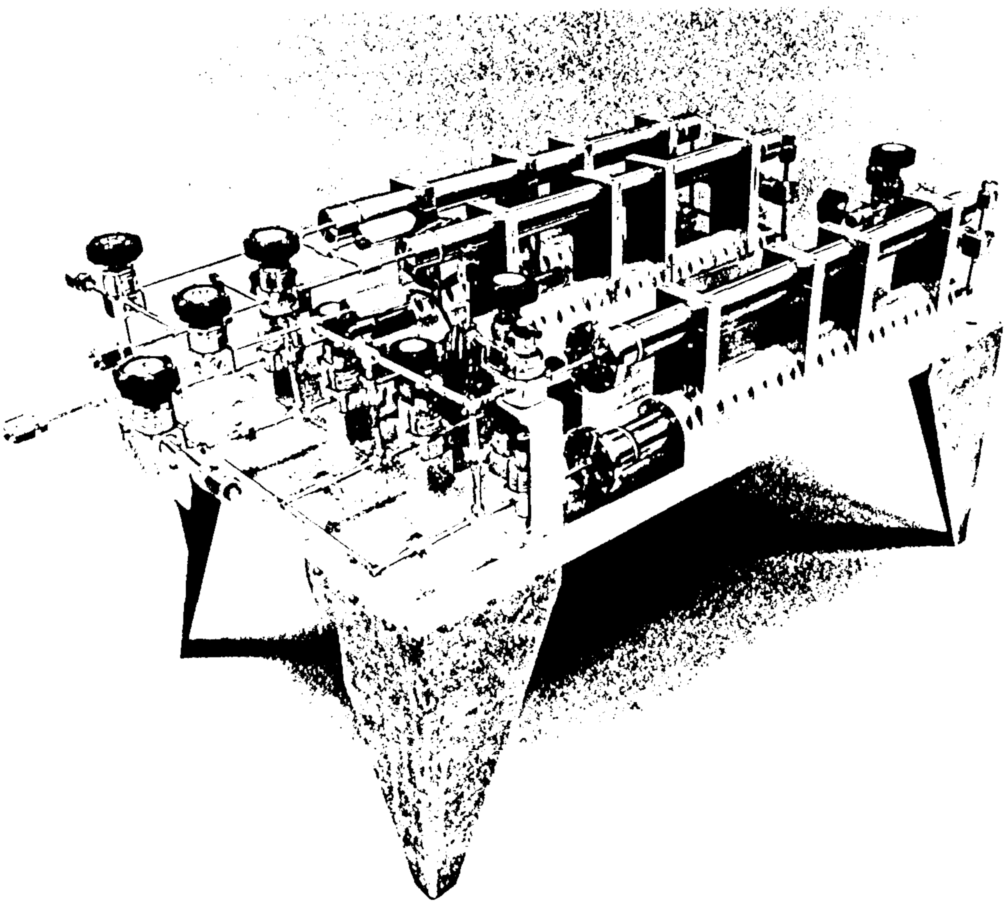

Figure 2. The compressor assembly is shown complete just prior to the installation of the cabling.

are connected to the high and low pressure manifolds through passive check valves, which direct gas flows along appropriate paths. The gas-gap thermal switch in each compressor element assembly is activated when it is pressurized to 14 torr by heating a small (2.5 cm long x 0.6 cm dia) ZrNi compressor to 450 K via a Kapton tape heater. This requires approximately 2.5 W of input power, The gas-gap switch is turned 'off' by allowing the ZrNi compressor to cool to 300 K which causes it to evacuate the gas-gap volume to 0.0044 torr.

Figure 3 shows a cross sectional view of an individual compressor element. The outer gas-gap shell is 3.81 cm in diameter. The 1.91 cm o.d. by 0.165 cm wall inner compressor contains 284 g of $LaNi_{4.8}Sn_{0.2}$ hydride. In the center of the compressor is a hollow 0.635 cm o.d. sintered 3161, inter. "l'he filter allows the hydrogen refrigerant to flow longitudinally through the compressor and then flow a short radial distance into the hydride powder contained between the filter and the 1.91 cm tube, Surrounding the hydride containing compressor element are five band heaters which are not shown in Figure 3. The back end of the compressor clement is loosely supported by three pins, thereby accommodating longitudinal differential thermal expansion between it and the outer gas-gap shell as the temperature cycles during operation. Radiation shielding of each compressor clement is provided by two concentric 0.005 cm thick stainless steel cylinders. These cylinders are separated from each other by a helically wound 0.008 cm diameter NbTi wire which is periodically spot welded to the exterior surface of the inner cylindrical shield. The four gas-gap compressors, each filled with 0.8 g of ZrNi hydride, are pictured in Figure 4.

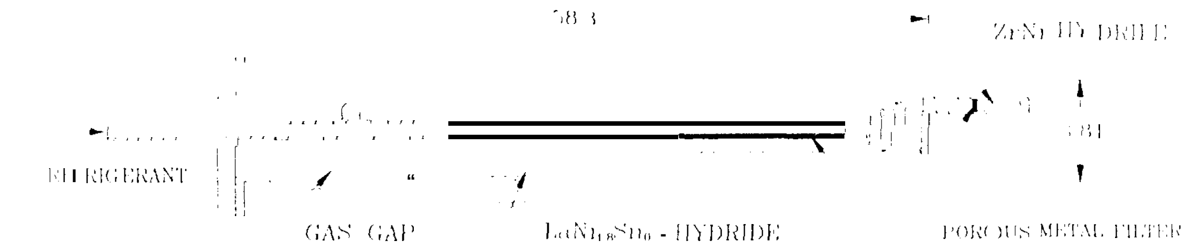

Figure 3. Cross sectional view of a compressor element assembly with dimensions in centimeters.

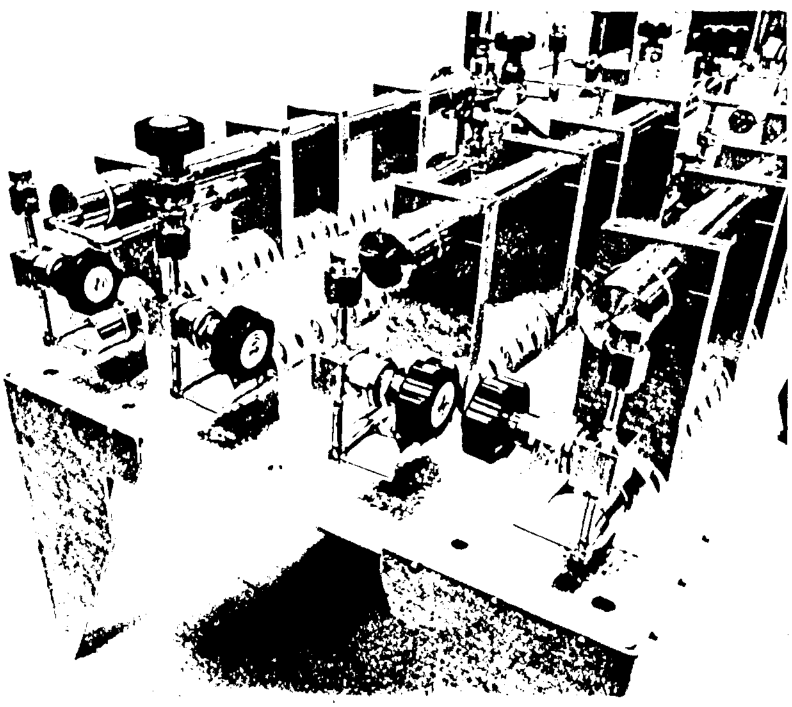

Figure 4. A view of the rear portion of the compressor assembly shows the ZrNi compressors used to activate the gas-gap thermal switch.

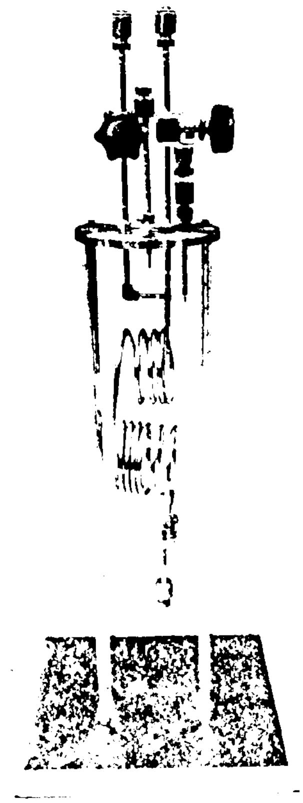

Figure 5. The cryostat tube-in-tube counterflow and precooking heat exchangers are shown prior to attachment of the J-T and liquid reservoir assembly.

Cryostat Design

The cryostat assembly, as shown in Figure 5, consists of a coiled 1.0 m long tube-in-tube warm heat exchanger, a 15 cm long precooking heat exchanger, which is connected to a Sunpower Stirling cooler, a coiled 1.6 m long cold tube-in-tube heat exchanger, a 0.01 micron contamination trap, the J-T assembly and the cryogen liquid reservoir. The tube-in-tube heat exchangers operate at >0.98 effectivity despite their simplicity (just a 0.3175 cm o.d. tube inside a 0.635 cm o.d. tube) due to the low refrigerant mass flow rate. The high pressure gas stream flows in the outer annulus, eliminating the need to weld components at the precooking heat exchanger. The penalty for this unusual configuration was found to be only a 3 Pa pressure drop per meter of heat exchanger in the low pressure gas stream. The temperature of the refrigerant at the large surface area 0.01 micron filter, located at the inlet of the J-T expansion assembly, will be approximately 35 K. At that temperature, even one ppm of air constituents, such as oxygen and nitrogen, are frozen solid and can be filtered out of the refrigerant stream before reaching the J-T assembly.

The commercially available porous metal flow restrictors[2] used in the cryostat have a diameter of approximately 0.2 cm for J-T expansion, rather than the <0.002 cm diameter orifices more commonly chosen. Flow testing of a wide range of flow restrictors has been initiated to enable the selection of the appropriate combination of flow restrictors to meet the specific pressure, mass flow rate, and temperature specifications of this cooler, The flow test results will also be extremely useful for the design of future sorption coolers, These porous metal flow restrictors are clearly the best choice for any sorption cooler designed to refrigerate loads of less than 100 mW at cryogenic temperatures.

Control and Data Acquisition Hardware

The electronics system to control the sorption cooler and to collect data was designed to be simple and reliable. The cooler is controlled from a commercial data acquisition and control system manufactured by Elexor Associates. It includes a 16 bit digital 1/0 card, a 15 channel, 12 bit A/D card, and a CPU. Currently, commands are sent to the CPU via RS-232 using the LabVIEW software package from an, IBM compatible PC. The rest of the cooler control hardware is contained in an electronics box that was designed and constructed at UCSB. It contains 16 latching relays, 12 temperature sensor channels, and two pressure sensor channels.

During the operation of the cooler, the 14 sensor values are measured every two seconds. The temperature is measured at each of the four sorption beds and the low pressure bed using platinum resistance thermometers. The temperature is also measured using silicon diode sensors at the compressor support/heat sink plate, two points on the refrigerant precooler in the cryostat, the J-T inlet, two points on the cold end, and the outlet from the cold end. Using pressure transducers, the pressure at the high pressure tanks and low pressure bed is also measured. The relays are used to turn on and off power to the heaters on the sorption beds as the cooler switches to the next quarter cycle as dictated by a simple timing sequence.

PROGRAM STATUS AND RESULTS

The cooler is in final integration and test. The compressor assembly input power, gas-gap parasitic and gas-gap thermal conductivity have been measured. The input power was measured as 216 W. The parasitic are approximately 25 W. The gas-gap thermal performance matched the required compressor element cool down time of 800 second with 13 torr of hydrogen in the gas gap. The $LaNi_{4.8}Sn_{0.2}$ hydride absorption plateaus were within 1 K of those predicted by the isotherms. One check valve was found to leak during these tests and will be replaced shortly. Final bake out of the assembly is currently underway with cryostat integration scheduled for the end of Summer 1996.

The cryostat heat exchanger performance has been measured to be ideal within the error of the instrumentation, The cold tip temperature stability was measured as being within 0,002 mK over many minutes under applied heat, indicating that the liquid reservoir performs very well. The conductance of the liquid reservoir from the focal plane interface to the liquid reservoir was found to be 0.379 W/K. Figure 6 shows the cold tip temperature as a function of applied load. The selection of the correct combination of porous plug flow restrictors has necessitated conducting a flow measurement experiment as the refrigerant flow rate at high pressure ratio (10 MPa to 0.12 MPa), coupled with real gas and phase change effects, is not easily predicted with any accuracy. These tests are still underway as the flow restriction was somewhat lower than was expected, The flow tests conducted, used hydrogen over a very wide. range of pressures, flow rates, and temperatures. A flow test cryostat was constructed that was identical to the flight cryostat except for the addition of VCR terminations at the cold heat exchanger high pressure outlet and low pressure inlet, This permited interchange of different J-'J' assemblies. Porous plugs rated at nitrogen gas flows over 30 psid between 250 seem and 1 seem were pressed into holders, with VCR fittings attached to both ends, to permit them to be combined as needed, For the 1 and 10 sccm plugs, samples were prepared that were pressed into holders and either welded or not welded.

High pressure hydrogen gas was supplied from commercial gas cylinders; some of which had been stored outdoors for four years without cover. No filtering of the hydrogen was done beyond the 0.01 micron filter at the J-'J' inlet. In none of the tests, some lasting 3 days, did the J-T show any signs of plugging. These tests were used to determine mass flow as a function of temperature (including the effects of real gas properties and liquefaction) and pressure difference/ratio (e.g. sonic exit effects).

While the flow tests are not yet complete, several interesting observations can be made from the preliminary results. A substantial increase in mass fJow rate, for a given pressure drop, upon initiation of hydrogen liquefaction is seen in the data presented in Figure 7. Figure 8 shows that the mass flow rate across a porous metal orifice is a linearly dependent on pressure drop for room temperature hydrogen in the ranges measured. No low pressure ratio measurements have been made to date. Therefore it is not yet possible to determine, through comparison with the high pressure ratio data presented in this paper, whether there is an additional sonic exit effect on the flow rate.

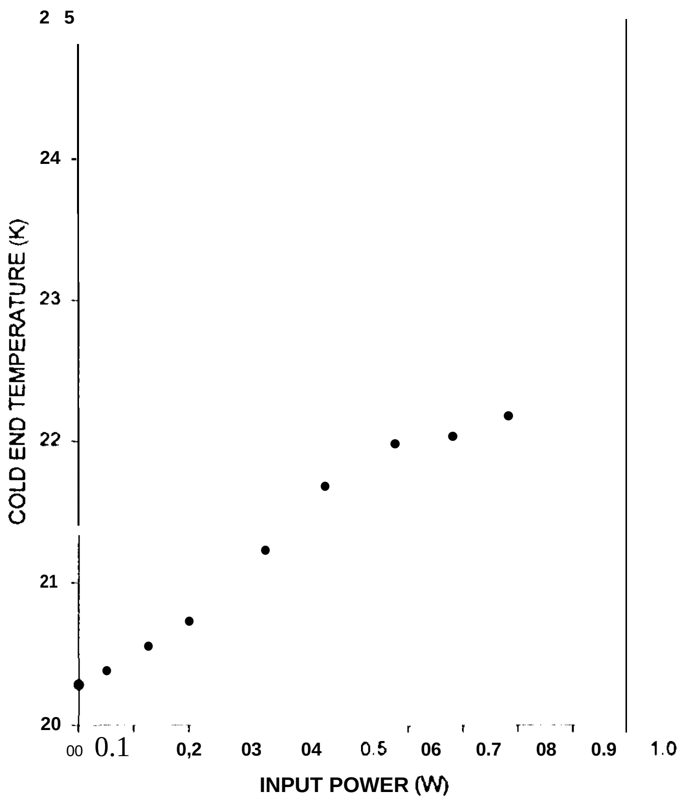

Figure 6. Cold tip temperature at the focal plane as a function of heat input.

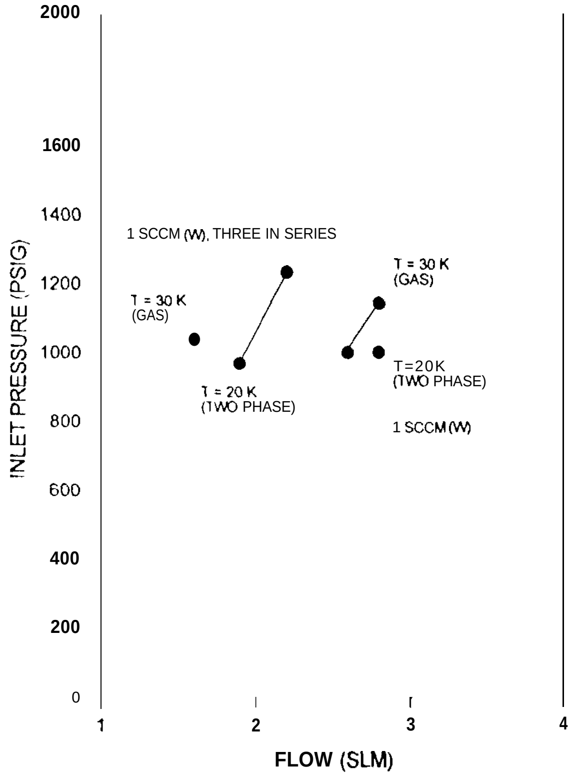

Figure 7. Cryogenic flow test results, with liquefaction, for 1 SCCM flow restrictors.

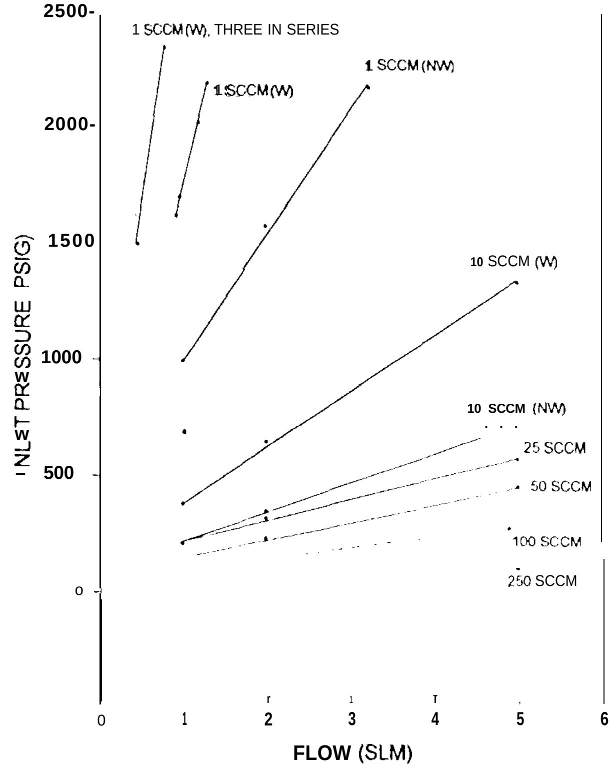

Figure 8. Room temperature flow test results for a series of different porous plug flow restrictors.

SUMMARY

A continuous operation 25 K single-stage cryocooler is currently in final integration and test at JPL in support of the first long-duration balloon experiment to measure anisotropy in the Cosmic Microwave Background radiation (CMB). Integration of this cooler with the flight radiometer is scheduled for late 1996. The UCSB LDB experiment is scheduled to fly in December of 1997 in Antarctica.

This is the first hydride sorption cooler to be used to help gather science data other than on the performance of the hydride cooler. It is therefore also the first to be designed to support science instrument requirements, The demonstration that a hydride sorption technology can be fabricated in a lightweight, integratable package, and operate reliably despite a challenging environment will substantial y advance the state-of-the art. "The materials selected, and the operational and assembly procedures used, are compliant with flight quality standards. The proof of sensor compatibility, as demonstrated by the quality of the science data gathered, and verification of cooler reliability will provide substantial heritage as sorption coolers are developed for future astrophysics missions.

ACKNOWLEDGMENTS

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