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A 4 K GIFFORD-McMAHON REFRIGERATOR FOR RADIO ASTRONOMY

Richard Plambeck, Niranjan Thatte, and Patrick Sykes
Radio Astronomy Lab, University of California
Berkeley, CA 94720

ABSTRACT

We have built a 3-stage Gifford-McMahon refrigerator which is designed to cool a superconducting junction to 4 K on a radio telescope. Using 50 grams of Er_3Ni spheres as the third stage regenerator, we measure no-load temperatures as low as 3.8 K at a cycle frequency of 72 rpm, and 2.2 K at 30 rpm. The third stage temperature can be maintained at 3.5 K with heat loads of 10 W on the first stage, 1 W on the second stage, and 50 mW on the third stage. At 72 rpm the refrigerator performance is impaired by the substantial pressure drop through the first and second stage regenerators; using a pressure transducer connected through a capillary tube to the third stage, we find that the helium pressure swing in the third stage expansion volume increases by 50 percent as the cycle frequency is decreased from 72 to 30 rpm.

Our prototype refrigerators exhibit occasional 0.5 to 1 K temperature excursions which occur over periods of a few minutes to a few hours. Tests suggest that this erratic behavior is primarily attributable to leakage of warm gas past the third stage seal.

INTRODUCTION

The most sensitive receivers available for millimeter-wavelength radio astronomy employ SIS (superconductor-insulator-superconductor) tunnel junction mixers which operate at temperatures of 4.5 K or lower. Such receivers are expected to operate continuously on radio telescopes for many months with minimal maintenance. Although SIS receivers commonly are cooled with hybrid Joule-Thomson/Gifford-McMahon refrigerators, JT circuits have a number of drawbacks: the heat exchangers are relatively bulky, the expansion valves tend to clog, and a separate helium compressor stage is required to handle the JT return gas. Typically the JT/GM coolers used in radio astronomy have refrigeration capacities of 1 to 3 watts at 4.2 K. This is far greater than necessary: with careful design, the heat load on an SIS mixer can be kept to a few milliwatts.

In the past few years a number of groups[1,2] have demonstrated that Gifford-McMahon cryocoolers utilizing Er_3Ni as a regenerator material can achieve refrigeration capacities of several hundred milliwatts at 4 K. Such refrigerators appear to be well-suited for use in cooling SIS receivers; they are considerably more compact than JT/GM systems, cool more quickly, and require only a single helium compressor.

We are constructing radio receivers for the Berkeley-Illinois-Maryland array (BIMA), an aperture synthesis instrument consisting of 9 millimeter-wave telescopes. Each telescope will be outfitted with a radio receiver covering 4 frequency bands, each requiring an SIS mixer. In this paper we describe the design and initial tests of 4 K GM refrigerators which will cool these receivers.

DESIGN

Two-stage GM cryocoolers described in the literature[1,2], with refrigeration capacities of up to 0.8 W at 4.2 K, typically use several hundred grams of Er_3Ni as the 2nd stage regenerator material. Because Er_3Ni spheres are expensive, and because our cooling requirements at 4 K are expected to be $\leq$ 25 mW, we chose to build a 3-stage refrigerator instead, using only about 50 g of Er_3Ni in the 3rd stage regenerator. We estimate that the heat loads on the refrigerator's 1st and 2nd stages will be 6 W and 0.5 W.

Thus far we have constructed 3 prototype refrigerators. We begin with a standard 2-stage GM cryocooler, machine off the plug at the end of the 2nd stage cylinder, and weld on a 3rd stage. Refrigerator #1 is a CTI model 350 cryocooler with an 8.9 cm long 3rd stage; refrigerators #2 and #3 are CTI model 1020CP cryocoolers with 15.2 cm and 11.4 cm 3rd stages, respectively. The inner diameter of the 3rd stage cylinder is 1.27 cm on all 3 prototypes. Several displacers of different designs were tested in each of the prototype refrigerators.

Figure 1 presents a cross sectional view of the 3rd stage cylinder and a typical displacer for refrigerator #3. Both the cylinder and the displacer are fabricated from 304 stainless steel. An 0.4 to 0.8 mm thick sheath of graphite-loaded polyimide (Envex 1315; Rogers Corp) epoxied to the outside of the displacer tube serves as a bearing surface. We attempt to maintain a radial clearance of 5 to 10 microns between the Envex bearing and the cylinder wall, to act as a clearance seal. A groove machined into the displacer also accommodates a split piston ring seal (CTI model 21 second stage seal).

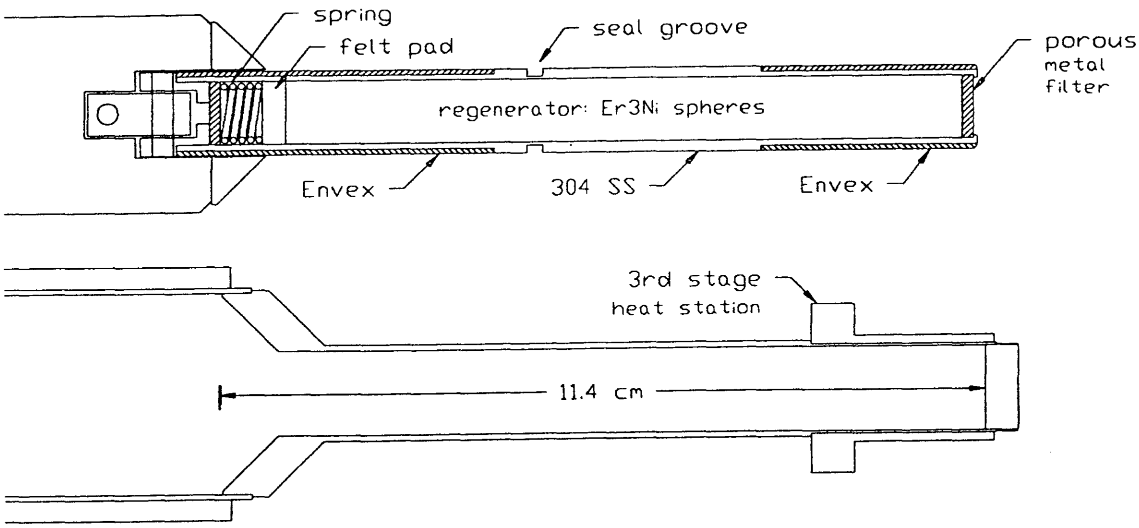

Fig 1. Cross sectional views of a 3rd stage cylinder and typical displacer.

The 3rd stage regenerator consists of Er_3Ni spheres, diameter range 180-450 microns, purchased from Toshiba America Electronics. We do not attempt to compress the spheres with a packing rod after pouring them into the displacer; instead, we install a spring-loaded felt pad at the warm end of the displacer to maintain pressure on the regenerator as settling occurs. Sintered stainless steel filters, with a pore size of 40 microns, are pressed into each end of the displacer to make certain that no Er_3Ni spheres escape.

The pin connections between the 1st, 2nd, and 3rd stage displacers are deliberately sloppy, to accomodate slight misalignments of the 3 cylinder sections. This makes it difficult to insert the displacer assembly into the cylinder, particularly if the refrigerator is mounted horizontally, as it will be on our radio telescopes. Accordingly, we machine a 45-degree chamfer into the warm end of the 3rd stage cylinder, and attach a mating cone to the end of the 2nd stage displacer. In this way the 2nd and 3rd stage displacers slip easily into their respective cylinder sections. We make no other modifications to the 1st or 2nd stage displacers.

On refrigerator #1 the 3rd stage displacer stroke is adjustable from 1.90 to 2.54 cm. On refrigerators #2 and #3, the displacer stroke for all 3 stages can be reduced from 3.18 to 2.54 cm, if desired, by substituting the crankshaft from a model 350 refrigerator. A 3-phase digital power inverter (Lenze Power Systems model 8101) and Scott-T transformer allow us to operate the refrigerators at any cycle frequency from 4 to 100 rpm. All tests are done with a standard CTI model 1020 helium compressor.

TEST RESULTS

Refrigerators were installed in a test dewar with radiation shields attached to the 1st and 2nd stages. All 3 refrigerator stages were instrumented with silicon diode temperature sensors. The 3rd stage temperature was monitored independently with a germanium resistance thermometer and, at times, with a helium vapor gauge; temperatures measured with the silicon diode, GRT, and vapor gauge agreed within 0.1 K.

A computer connected to an a/d converter recorded the temperature of each stage at 15 second intervals. These measurements were done by sampling each sensor 100 times per second for 8 seconds; the temperature recorded was the mean of the highest and lowest values obtained during this interval. To monitor the temperature swings which are synchronized with each refrigerator cycle, we could also sample and record temperatures up to 200 times per second for short intervals. Pressure transducers in the helium supply and return lines near the expander also were monitored by the computer. Heaters were mounted on all 3 refrigerator stages to perform load tests.

A typical cooldown curve is shown in Figure 2. Operated at its normal cycle frequency of 72 rpm, the refrigerator cooled to 4.8 K in approximately 1.3 hours. Lower 3rd stage temperatures are reached by reducing the cycle frequency. In the example in Figure 2, the 3rd stage temperature drops rapidly to 3.7 K when the cycle frequency is reduced to 30 rpm. The 1st and 2nd stage cooling capacities decrease at 30 rpm, so these stages warm up slightly.

Measurements of the no-load 3rd stage temperature as a function of cycle frequency are shown in Figure 3 for five different displacers. Displacer parameters and regenerator masses are given in the figure caption. Note that lead spheres were used as the regenerator material for curve A, which reaches 4.75 K at 30 rpm. The heat leak onto the 3rd stage was measured to be approximately 10 mW during these tests.

Load tests showed that the 1st, 2nd, and 3rd stage temperatures were well isolated. An example is shown in Figure 4. Here, 50 mW applied to the 3rd stage raises its temperature from 4.25 to 4.7 K, but has no discernible effect on the 2nd stage; 2 W applied to the 2nd stage increases its temperature from 13.8 to 16.0 K, but increases the 3rd stage temperature by only 0.15 K.

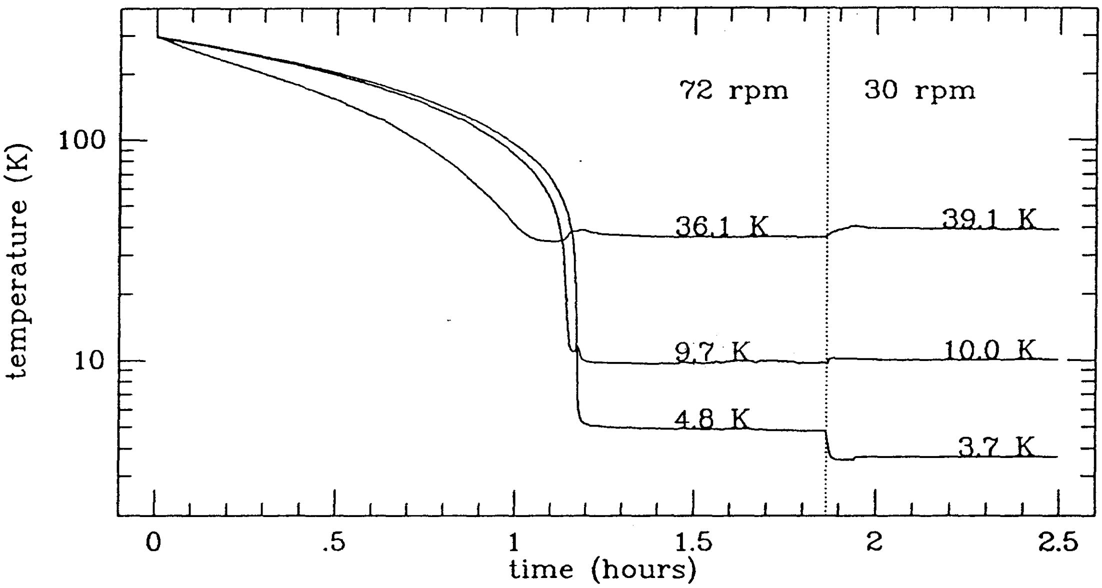

Fig 2. Typical cooldown curve. Temperatures of stages 1, 2, and 3 are plotted on a logarithmic scale. At 1.86 hours, the refrigerator was slowed from 72 to 30 rpm.

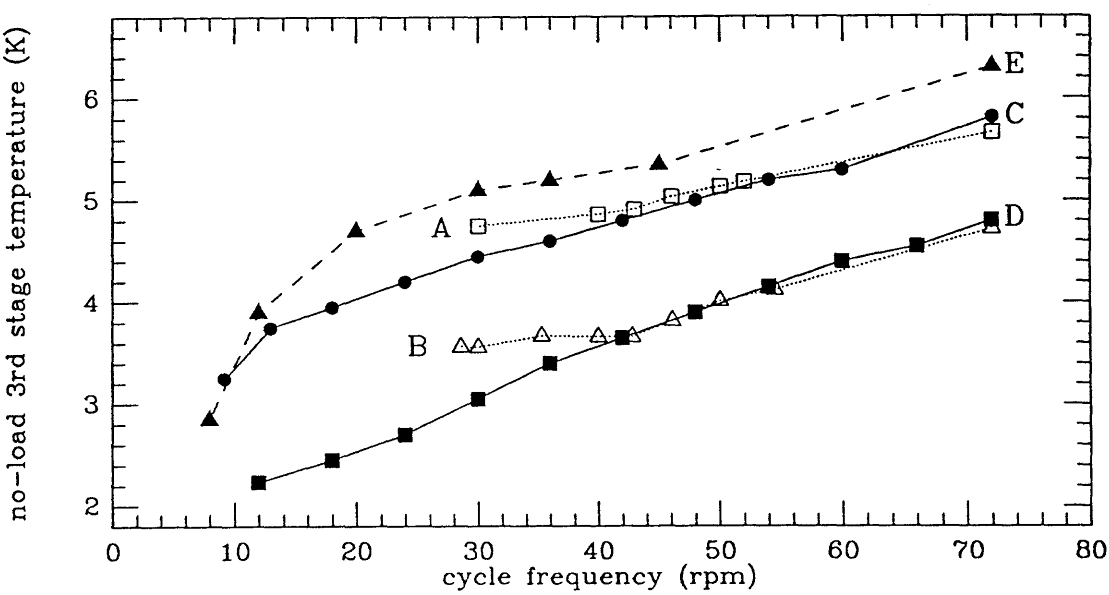

Fig. 3. No-load temperature vs. cycle frequency for 5 different displacers: A - refrigerator #1, 46 g of 350 micron diameter Pb spheres, 1.9 cm stroke, clearance seal; B - refrigerator #1, 30 g Er_3Ni, 1.90 cm stroke, clearance seal; C - refrigerator #2, 57 g Er_3Ni, 2.54 cm stroke, CTI seal; D - refrigerator #2, 53 g Er_3Ni, 3.18 cm stroke, CTI seal; E - refrigerator #3, 46 g Er_3Ni, 2.54 cm stroke, clearance seal.

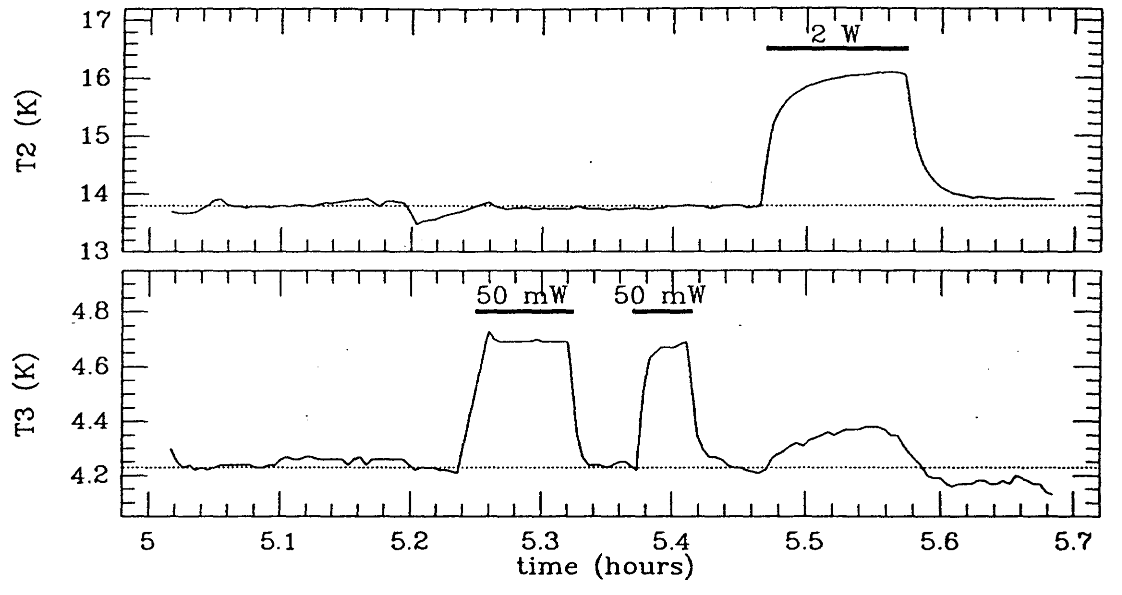

Fig. 4. Load test, demonstrating the excellent isolation between stages. (Refrigerator #3, 2.54 cm stroke, 42 g Er_3Ni, 30 rpm, CTI seal.)

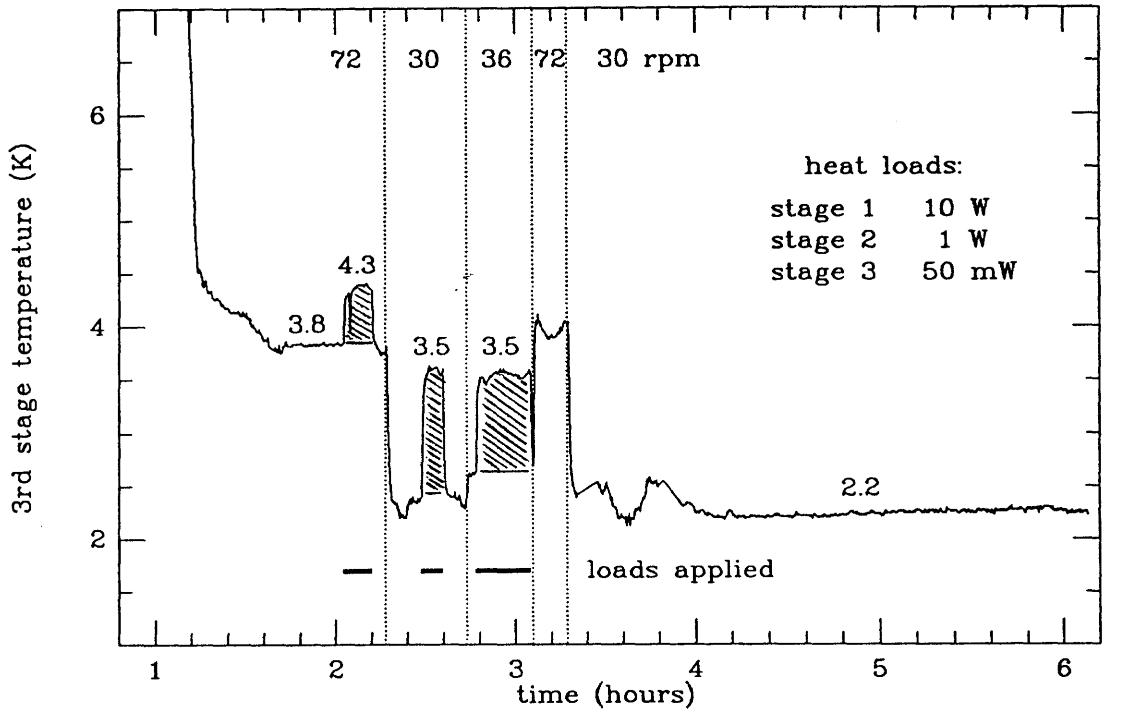

Fig. 5. Cooldown and load test of refrigerator #2, with 53 g. of Er_3Ni in the 3rd stage regenerator, a 2.54 cm stroke length, and a CTI seal.

Our best results to date, obtained with 53 g of Er_3Ni in refrigerator #2 (the long cylinder), are shown in Figure 5. With no loads applied, the 3rd stage cooled to 3.8 K at 72 rpm, 2.2 K at 30 rpm. With heat loads of 10 W on stage 1, 1 W on stage 2, and 50 mW on stage 3, the 3rd stage temperature was 4.3 K at 72 rpm and 3.5 K at 36 rpm. At 36 rpm the 1st and 2nd stage temperatures stabilize at 65 K and 13.6 K with the loads applied.

WHY IS IT NECESSARY TO REDUCE THE CYCLE FREQUENCY?

Our results, as well as those of other groups[1,2], indicate that it is essential to reduce the refrigerator cycle frequency in order to achieve the very lowest temperatures. Why is this so?

(1) limited thermal diffusivity of Er_3Ni?

Ogawa et al.[3] have measured the thermal conductivity of Er_3Ni at low temperatures (it is slightly lower than that of stainless steel), and have calculated the penetration depth for heat as a function of cycle frequency. Their calculations show that heat transfer in spheres of radius 0.1 to 0.2 mm, as used in our regenerator, is essentially perfect at a cycle frequency of 60 rpm. Indeed, our data (curve A in Figure 3) show that reducing the cycle frequency also lowers the 3rd stage temperature for a lead regenerator, even though lead has a thermal diffusivity more than 3 orders of magnitude greater than Er_3Ni.

(2) improved heat transfer?

Halving the mass flow rate through the regenerator reduces the heat transfer coefficient by about 40%, but doubles the time that gas spends inside the regenerator. Thus, reducing the cycle frequency might be expected to lower the 3rd stage temperature by improving heat transfer in the regenerator. To test this hypothesis experimentally, we tested lead spheres of 3 different diameters in one refrigerator. At 72 rpm the 3rd stage cooled to 6.4 K with 33 g of 350 micron diameter Pb spheres; to 6.5 K with 31 g of 200 micron spheres; and to 6.9 K with 34 g of 100 micron spheres. The corresponding temperatures at 30 rpm were 6.1 K, 6.1 K, and 6.3 K. Although the heat transfer coefficient increases by a factor of 5 as the sphere diameter decreases from 350 to 100 microns, the 3rd stage temperatures did not improve. Thus, heat transfer does not appear to limit the regenerator efficiency.

(3) flow channeling?

When spheres are packed into a tube, there is a disordered zone next to the wall. If helium flows preferentially through this zone, heat transfer to the regenerator matrix will be reduced. Slowing the cycle frequency might allow thermal diffusion laterally within the regenerator, minimizing the effect. In an attempt to test the importance of flow channeling, we artificially increased the displacer wall area by inserting a V-shaped piece of brass shim stock down the length of the displacer before filling it with Er_3Ni spheres. This increased the effective regenerator perimeter by a factor of almost 2. Third stage temperatures measured with and without the shim stock in place were equal within 0.1 K; thus, there is no evidence that flow channeling limits the regenerator performance.

(4) pressure drops

Having ruled out the 3 possibilities listed above, we focussed on pressure drops within the regenerator as a possible factor limiting the refrigerator performance at higher cycle speeds. In order to monitor the helium pressure at the cold end of a refrigerator, we drilled a hole into the end of refrigerator #3 and connected a room temperature pressure transducer to the cold end via a capillary tube (length 50 cm, ID 0.8 mm). The additional void volume and heat leakage introduced by the capillary tube had little deleterious effect except at very low cycle frequencies: at 6 rpm the 3rd stage reached 2.4 K without the capillary, 3.2 K with it.

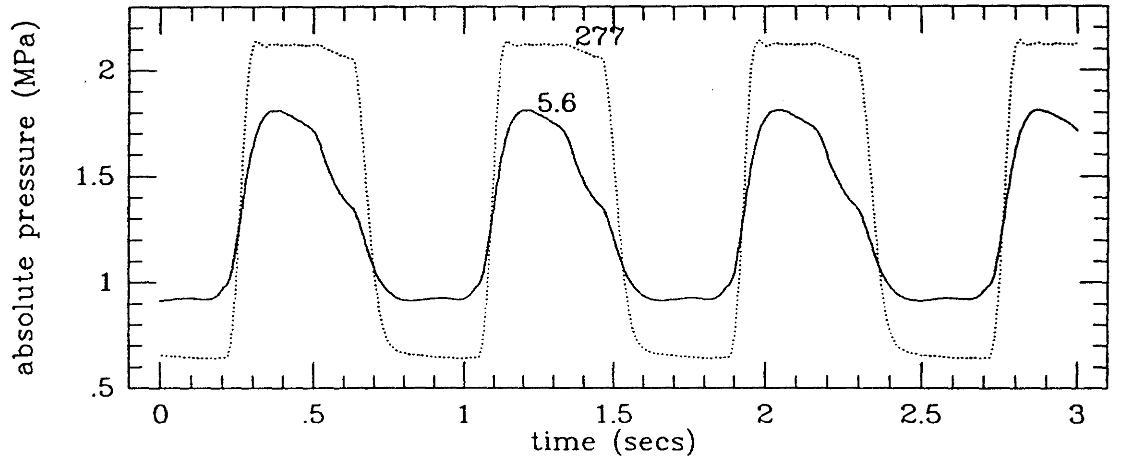

Fig. 6. Helium pressure swing in the 3rd stage expansion volume, monitored through a capillary tube with a room temperature transducer. The refrigerator cycle frequency is 72 rpm. The dotted curve was obtained when the 3rd stage was at 277 K, the solid curve when it had cooled to 5.6 K. (Refrigerator #3, 2.54 cm stroke, 45 g Er_3Ni, clearance seal.)

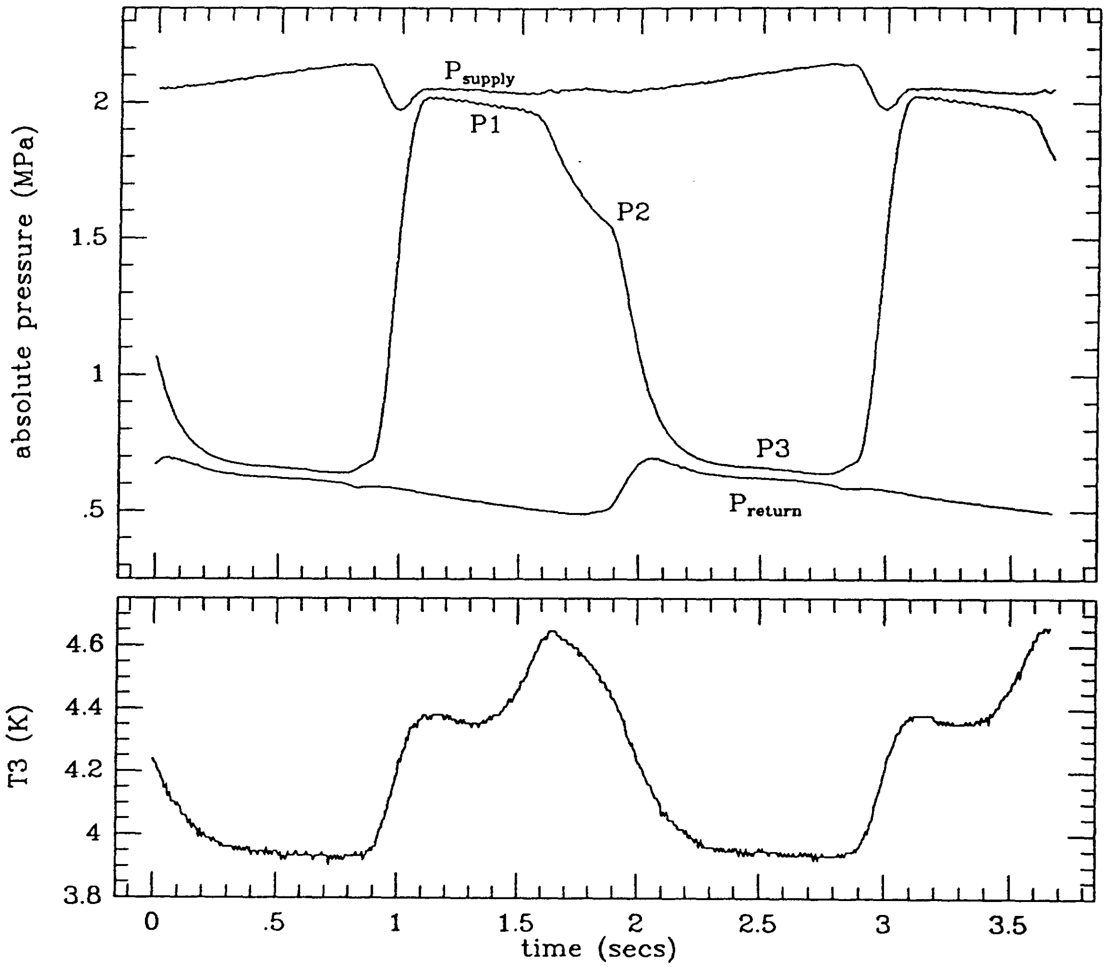

Fig. 7. (top panel) Helium pressures in the 3rd stage expansion volume, and in the supply and return lines just outside the expander, at 30 rpm cycle frequency. The inlet valve closes at about 1.6 seconds on this plot; the exhaust valve opens at about 1.9 seconds. (bottom panel) Corresponding 3rd stage temperature swing. (Refrigerator #3, 2.54 cm stroke, 45 g Er_3Ni, clearance seal.)

Figure 6 compares the 3rd stage pressure curves measured through the capillary shortly after the refrigerator was turned on (277 K) and after it was fully cold (5.6 K). At 72 rpm the cold end pressure swing decreases dramatically as the refrigerator cools and the helium mass flow increases. In part this is because the compressor capacity is marginal; in part it is due to pressure drops in the regenerators or valves. Most of the regenerator pressure drop should occur in 1st or 2nd stages; the pressure drop through the 3rd stage regenerator is expected to be very low (probably less than 0.01 MPa) owing to the high density and low viscosity of helium below 10 K.

The pressure swing in the 3rd stage expansion volume increases considerably as the cycle frequency is reduced. Figure 7 shows the pressure and temperature curves measured at 30 rpm. At this speed the pressure drop through the regenerators and valves is small, about 0.05 MPa. The inlet valve closes well before the displacer reaches maximum cold volume; in the interval before the exhaust valve opens, helium continues to flow through the cold displacer, and the pressure decreases from P1 = 2.0 MPa to P2 = 1.55 MPa. Thus, the pressure drop P2–P3 which occurs as the exhaust valve opens is only 0.9 MPa. The 3rd stage temperature follows the gas pressure swing, although the temperature increase near the end of the inlet stroke (at about 1.65 secs on the plot) suggests that warm gas leaks into the expansion volume along the outside of the regenerator.

We generated plots like the one in Figure 7 for seven different cycle speeds, from 72 rpm to 6 rpm. Figure 8 displays the pressures and temperatures measured from these data. As in Figure 7, P_{supply} and P1 are measured about 1/3 of the way through the inlet stroke; P3, P_{return}, and T_{low} are measured midway through the exhaust stroke; and P2 is the cold end pressure just before the exhaust valve opens. Helium in the 3rd stage working volume cools more as the pressure differential (P2–P3) increases. Thus, even if the regenerator efficiency does not improve as the cycle frequency decreases, the 3rd stage reaches lower temperatures. Clearly, maximizing the pressure swing at the cold end of the refrigerator is crucial to obtaining good performance.

(5) regeneration of leakage gas

At cycle frequencies below 30 rpm, the curves in Figure 8 show that the helium pressure swing in the 3rd stage working volume remains relatively constant, yet in some of our tests the 3rd stage cools dramatically as the cycle frequency is reduced to very low values. For example, curve E in Figure 3 drops from 5.1 K at 30 rpm to 2.85 K at 8 rpm. Evidently, some other factor can act to improve the regenerator performance at very slow speed. We speculate that in such cases warm gas leaking past the 3rd stage seal degrades the refrigerator performance at higher cycle frequencies, whereas at very low cycle frequencies heat transfer through the displacer wall is sufficient to bring the leakage gas into thermal equilibrium with the regenerator, leading to a dramatic improvement in performance.

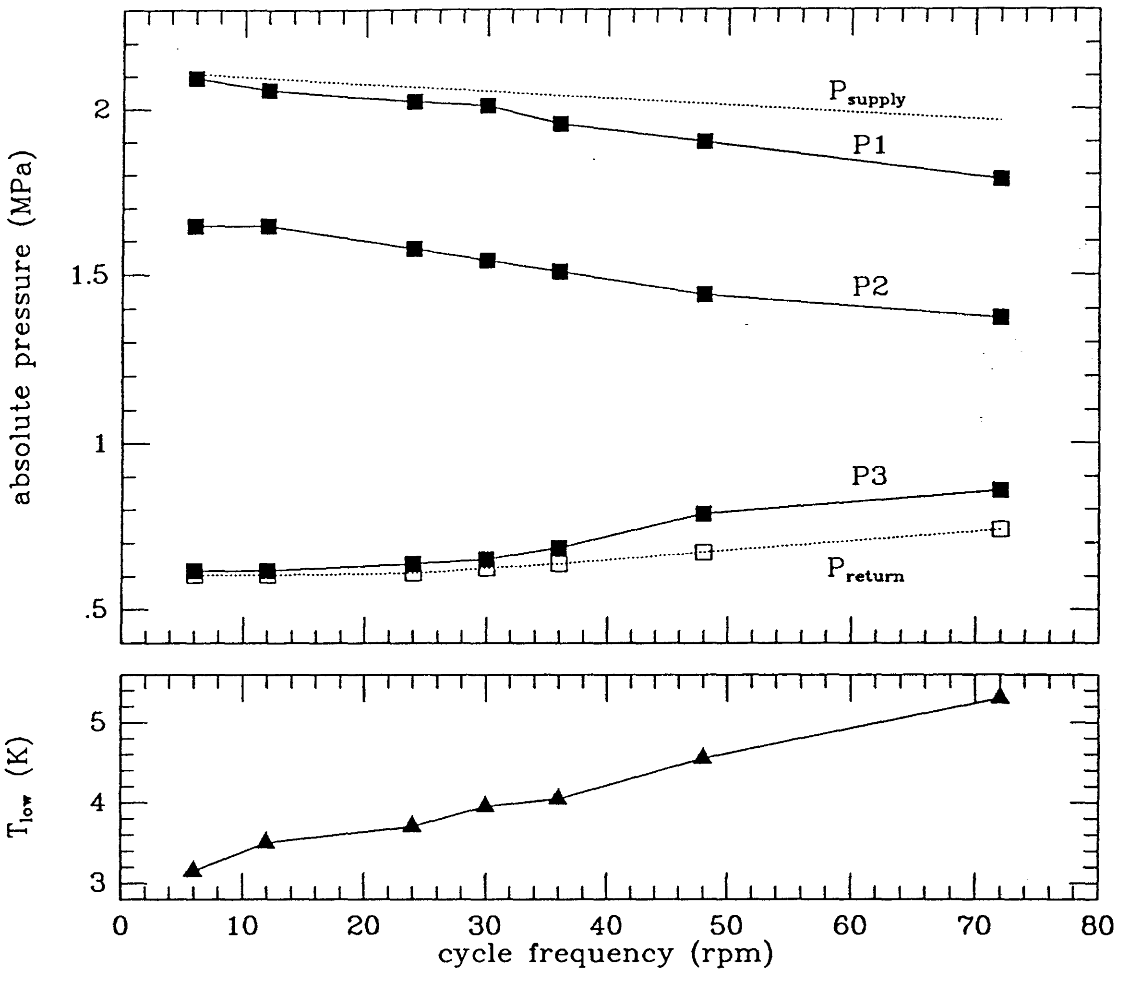

Fig. 8. (top panel) Helium pressures in the 3rd stage expansion volume, monitored at 7 different cycle frequencies; P_{supply}, P1, P2, P3, and P_{return} are measured as indicated in Figure 7. (bottom panel) Lowest 3rd stage temperature as a function of cycle frequency. (Refrigerator #3, 2.54 cm stroke, 45 g Er_3Ni, clearance seal.)

SHORT TERM TEMPERATURE STABILITY

An undesirable feature of the 4 K refrigerator, from our point of view, is the relatively large temperature swing (often about 0.5 K) which occurs with each cycle. We fear that such temperature variations will modulate the gain or noise properties of our SIS junctions. Because metals have very low specific heats at 4 K, the thermal mass associated with the SIS mixer block and mounting straps will do little to smooth out these temperature swings: at 4 K the 0.5 gram

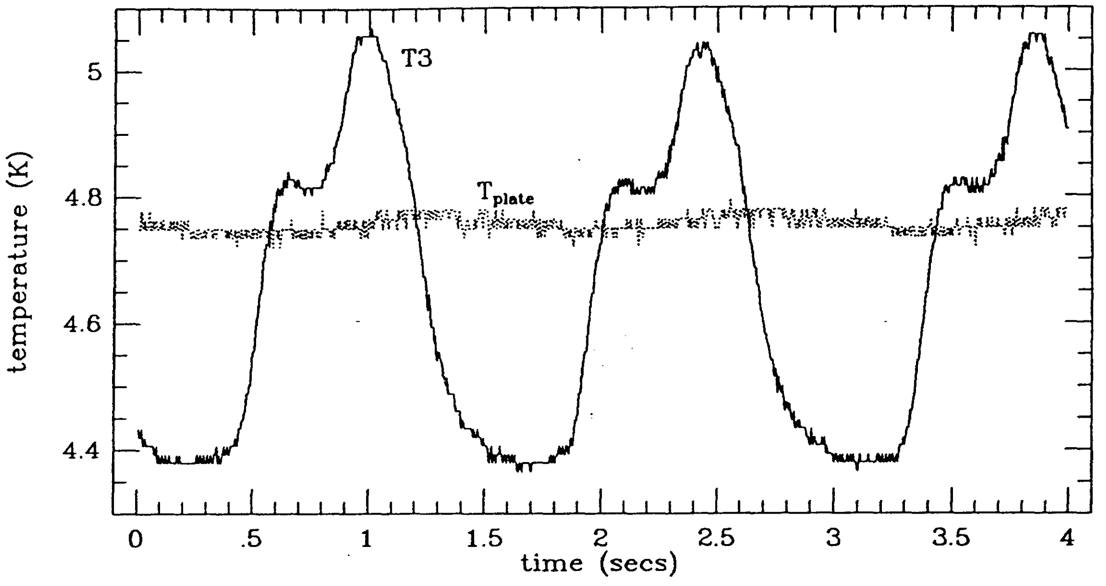

Fig 9. Temperature swing measured directly on the 3rd stage (T3) and on a plate thermally loaded with 10 g of Er_3Ni powder (T_{plate}). The cycle frequency is 42 rpm.

of helium in the refrigerator's 3rd stage has a heat capacity equal to that of 17 kilograms of copper!

Fortunately, the heat load on the SIS mixer block is expected to be so low that we can tolerate considerable thermal resistance between the mixer block and the 3rd stage heat station. A thermal "capacitor" consisting of a modest quantity of Er_3Ni or other high heat capacity material mounted on the mixer block then can filter out the 3rd stage temperature variations quite effectively. An experimental test of such a filter is shown in Figure 9. In this experiment the thermal capacitor consisted of 10 g of Er_3Ni powder which was mixed with thermally conductive epoxy and spread onto a copper plate. The plate was attached to the 3rd stage heat station by brass washers, designed to produce a thermal resistance of approximately 25 mK/mW. The temperatures of the 3rd stage heat station and the copper plate were monitored simultaneously with two silicon diode sensors. With the refrigerator operating at 42 rpm, the temperature swing measured directly on the 3rd stage was 0.68 K; the swing measured on the test plate was less than 0.05 K.

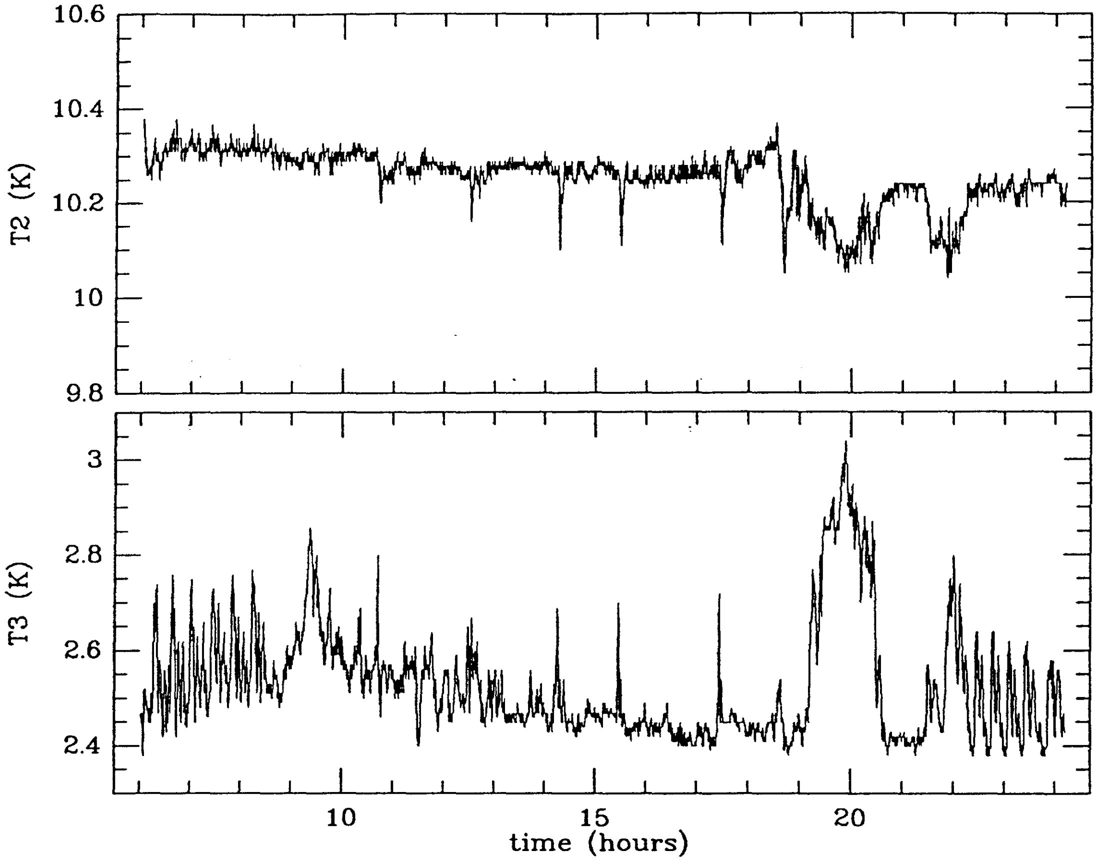

Fig. 10. Correlated 2nd and 3rd stage temperature fluctuations. Temperatures were measured every 15 seconds over an 18 hour interval. (Refrigerator #2, 3.18 cm stroke, 53 g Er_3Ni, CTI seal.)

LONG-TERM TEMPERATURE STABILITY

Our prototype refrigerators sometimes exhibit temperature excursions which occur over time scales of minutes to hours. An example of such behavior is shown in Figure 10, where we plot the 2nd and 3rd stage temperatures for a machine running at about 2.6 K. The temperatures were monitored every 15 seconds over a span of 18 hours. The 3rd stage temperature drops as low as 2.4 K, but spikes up to 2.7 K quasiperiodically. Many of the temperature spikes last only a minute or two, yet there is a period of 1.5 hours where the temperature hovers at about 2.8 K. Often the 2nd stage temperature decreases at the moment the 3rd stage temperature increases, suggesting that at these times cold gas bypasses the 3rd stage regenerator during the exhaust stroke.

Another example of temperature instability (one of the worst we have seen)

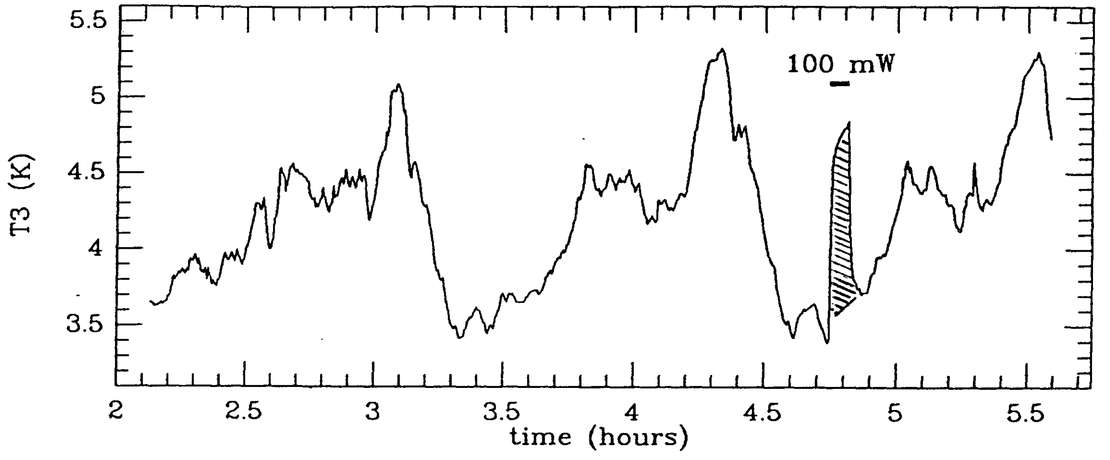

Fig. 11. "Worst case" temperature fluctuations on the 3rd stage. To calibrate the equivalent heat leak, a 100 mW load was applied partway through the run. (refrigerator #3, 2.54 cm stroke, 62 g Er_3Ni, CTI seal.)

is shown in Figure 11. In this case the temperature cycles between 3.5 K and 5 K with a period of about 1.2 hours. As shown in the figure, a 100 mW heat load raises the 3rd stage temperature by approximately 1 K. Therefore, we infer that an intermittent heat leak of about 150 mW is responsible for the temperature instability.

Significantly, the displacers used in both of these tests were outfitted with rubbing seals. Our tests show that displacers with clearance seals are less likely to show such extreme temperature swings. Thus, we suspect that most such temperature excursions are attributable to gas leaking intermittently past the third stage seal. Presumably, the quasiperiodic behavior arises because the seal rotates slowly in its groove.

CONCLUSIONS

A 3-stage Gifford-McMahon refrigerator utilizing 50 g of Er_3Ni spheres as the 3rd stage regenerator appears to be well suited for cooling SIS mixers in a radio astronomy receiver. A prototype refrigerator was able to maintain 1st, 2nd, and 3rd stage temperatures of 65 K, 13.6 K, and 3.5 K with heat loads of 10 W on the 1st stage, 1 W on the 2nd stage, and 50 mW on the 3rd stage. The 3rd stage temperature drops as low as 2.2 K with no load.

At a cycle frequency of 72 rpm the refrigerator performance is degraded by pressure drops within the displacers. As the cycle frequency is decreased, the helium pressure swing in the 3rd stage expansion volume increases markedly, allowing operation at lower temperatures. Intermittent gas leakage past the 3rd stage seal can cause erratic temperature excursions. Temperature cycling synchronous with the refrigerator cycle can easily be smoothed out by attaching a thermal mass – e.g., Er_3Ni powder embedded in epoxy – to the load.

ACKNOWLEDGEMENTS

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