REVIEW OF GIFFORD-MCMAHON REFRIGERATORS FOR 4K

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In this report, I assemble data on several commercially available cryocoolers that reach 4K by a two-stage Gifford-McMahon (GM) cycle. I also discuss some recent papers on these devices, and experience at other radio observatories. Whereas there is so far no such experience at the NRAO, this discussion is aimed at deciding whether these devices are candidates for use on the Millimeter Array.

Refrigeration cycles that rely on regenerative heat exchange, including GM and Sterling, are limited by the rapid loss of heat capacity of the regenerator material at low temperatures. The minimum temperature with no external load is that at which the efficiency drops to the point that the pumping capacity equals the parasitic load due to internal losses. Traditional GM refrigerators employing Pb shot in the regenerator are thus limited to about 12K, and they achieve reasonable efficiency by pumping significant heat only down to about 20K. However, a few rare-earth elements and compounds have been found to retain significant heat capacity at 4K [1], including Nd, Er3Ni, ErCo, and others. Various groups [2] in Japan [3,4] and in the U.S. [5,6] have developed 2-stage GM refrigerators using these materials, achieving minimum temperatures around 3K and pumping 0.1 to 1W at 4.2K.

Three companies now produce commercial systems of this type for sale in the U.S. They are listed in Table 1 along with some of their properties. Other Japanese companies, including Mitsubishi[3] and Toshiba[1,4], have published papers on similar systems but do not have products on the U.S. market. Toshiba has developed an SIS mixer receiver with such a refrigerator under contract to Nobeyama Radio Observatory [2]. Related experimental work has been done at Tokyo Institute of Technology [7] and U.C. Berkeley [6,8,9].

Table 1: Commercial 4K G-M Cryocoolers

Mfgr	Model	Load@4.2K	MinTemp	System Price	Input Power
Daikin[1]	CSW210	0.8 W	3.0 K	$35k	6.7 kW
Sumitomo[2]	SRDK408	1.0	3.1	39k	7.5
Sumitomo[2]	SRDK405	0.5	?	24k	2.5
Leybold	4.2GM	0.5	3.4	37.5k	6.5
Boreas[3]	B100	0.9	3.1	38.5k	3.0

Model	1stStg Q@T	P1,atm	P2,atm	He flow	Eff/Carnot[4]	
CSW210	35W @41K	21.8	7.1	85 Nm^3/h	.041	.0084
SRDK408	37W @40K	23.4	6.8	80	.041	.0094
SRDK405	10W @40K	?	?	30	.040	.0141
4.2GM	50W @50K	22.1	7.5	88	.044	.0054
B100	2.5W@80K	21	1.0	20	.023	.0211

Notes:
[1] Represented in U.S. by APD Cryogenics, Inc.
[2] Represented in U.S. by Janis. SRDK405 is new, promised in 4Q97.
[3] Not GM, but a proprietary hybrid cycle, partially recuperative.

[4] Efficiencies relative to Carnot, first with specified loads on both stages, then with zero 1st stage load but same power consumption.
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TEMPERATURE STABILITY

An important issue with these refrigerators, as with any cyclic refrigeration process, is the modulation of load temperature over the cycle. Cooling occurs only during the expansion portion of the cycle, so if the heat flow from the load is constant then the temperature necessarily increases during other portions of the cycle by the ratio of heat transferred per cycle to the heat capacity of the cold stage materials. For the devices considered here, the temperature on the unloaded second stage typically varies by 200-400mK (peak-peak) over the cycle. The variation can be damped by a massive heat sink, but this is difficult because the heat capacity of most materials is very small at 4K. Also, the cycle frequency is generally lower than for 20K GM systems (0.5-1 Hz vs. 2-3 Hz), requiring longer time constants for effective damping.

Long-term temperature stability is also an issue. Leaks past the regenerator seals, freeze-out of contaminants, physical re-packing of the regenerator material, and perhaps other effects can lead to loss of efficiency after operation for days, weeks, or months. Both Daikin and Sumitomo recommend factory overhaul of a refrigerator after every 10000 hrs of operation. It is not clear what is done during the overhaul, but it is reasonable to assume that the regenerator seals are replaced. Plambek [9] has observed slow loss of capacity that can be restored by a brief warmup ("defrost" cycle) to 7K. This and other instabilities are not fully understood.

A group at Princeton [10] achieved 2mK peak-to-peak at their SIS mixer block by adding a heat sink consisting of about 20-30 cm^3 of stainless steel [11]. This system uses a Sumitomo SRDK408 with about 400-500mW load (mostly from a HEMT IF amplifier). This result can be compared with 250mK p-p at the cold finger prior to adding the stainless steel. The low thermal conductivity of stainless steel requires that it be coupled to the load over a large area to be effective. A multi-layer sandwich of Cu and stainless steel is recommended. Their mixer gain is still modulated at the refrigerator rate, but only by 1e-5 p-p; this gives a coefficient of 5e-6/mK. [While this result is encouraging, it is hard to explain from calculations. The volume specific heat of stainless steel at 4K is larger than that of pure metals but is still small. Using 30cm^3 of Er3Ni, whose specific heat is much larger than that of stainless steel, gives a heat capacity of only 3 J/K, or 133 mK/sec at 400 mW.]

On the other hand, the Berkeley group [9] has been successful with active stabilization. By keeping the load very small, they can afford a significant thermal resistance from the mixer to the cold finger (0.15K/mW); this allows tight control with only a few mW of added heat. Because the loop is software driven, they correct only for long term fluctuations and not for the cyclic modulation, although the latter should be possible with a faster loop. This keeps long term variations to 1.8mK rms. They observe an SIS mixer gain coefficient of 1.5e-3/mK at 107 GHz, much larger than that seen by the

Princeton group.

For now, I recommend assuming that passive stabilization of the cyclic modulation will be practical at the 20-30mK level. To achieve tighter control, active stabilization (with a small heater on the mixer block) may be needed. Either will require very careful thermal design so as to separate the critical (SIS mixer) and less-critical (HEMT amplifier, feed) heat paths while controlling the thermal resistance and heat capacity of each. This should be considered early in the design.

COMMENTS ON SPECIFIC DEVICES

The information in Table 1 was obtained from published data sheets and from telephone conversations with the manufacturers. The load at 4.2K assumes that the specified first stage load is also applied; the minimum temperature assumes no external load on either stage. The price is for a turn-key system, including compressor and helium hoses, quantity 1, as of August 1997. All manufacturers are reluctant to sell the cold heads separately, but indicated that this might be negotiable. The power consumption is for the supplied compressor, under steady-state conditions with the specified loads on both stages; higher power is usually needed during startup and cooldown. In most cases, it appears that the compressor has no excess capacity, so there is no room for improved efficiency on the compressor side; for the Leybold 4.2GM, the compressor uses a Hitachi 500RHH pump at maximum flow (no bypass), and we believe that the Daikin CSW210 and the Sumitomo SRDK408 are similar.

The efficiency relative to Carnot is calculated using the given power consumption and assuming either the given first stage load and temperature or no first stage load. It can be seen that all give about the same efficiency when the first stage load is included, but that there are large differences if only the 4.2K load is considered. This is somewhat hard to interpret because it is not known how the given helium flow is partitioned between the two stages. For the three larger systems (CSW210, SRDK408, and 4.2GM) the manufacturers have supplied load maps. These show very little change in second stage capacity with first stage load; in fact, strangely, the second stage temperature decreases slightly with increasing load on the first stage. Further discussion of efficiency is given under each system, below.

Daikin CSW210: This system has been available in Japan for several years, but has only become available in the U.S. this year (via APD Cryogenics Inc.). We are not yet in contact with any users who can give an independent evaluation. I have been invited to visit the APD factory in Allentown, PA, and I plan to do this in October 1997. Daikin also makes a JT system with 2.25W capacity at 4.2K, and several of these have been purchased by SAO for the SMA telescope; they seem to be working well. APD makes their own 1W JT system, as well as a full range of 15K GM systems, some designed as direct replacements for CTI products. The compressor for the CSW210 is water cooled.

Sumitomo SRDK408, SRDK405: The SRDK408 has also been available in the U.S. only since late 1996, but has been on the market in Japan for about five years; it is used primarily in medical imaging systems. The regenerator uses a combination of four different rare earth compounds, now proprietary (to be disclosed after patents are received). The 1W SRDK408 has been used by the Princeton University Physics Department in an SIS receiver for a CMBR telescope [10], and we have been referred to another user at JPL. It is available with either a water cooled (SRDK408BW) or air cooled (SRDK408BA) compressor. The 0.5W system (SRDK405) is new, and is supposed to be available in October 1997. It is said to use the same technology as the 1W system, so no improvement in efficiency is expected. The much lower power consumption (0.33x) could be very attractive to the MMA if the capacity is sufficient. The helium flow is lower by 0.38x, first stage capacity by 0.33x, and second stage capacity by 0.50x. This implies that a larger fraction of the flow is used in the second stage compared to the 1W system.

Leybold 4.2GM: This is the only U.S.-made system of this type. It uses Neodymium spheres in the regenerator, rather than the Er compounds used by others. The refrigerator is nearly identical to the Leybold (formerly Balzers) model UHC130, which is a (10W,75W) system for (15K,50K) and is used as the first two stages of recent NRAO JT systems in Tucson; changing it to a 4.2GM might involve only replacement of the regenerator material and operation at a lower cycle frequency. The latter is adjustable by the user, so it can be optimized as a function of load. The compressor (model UCC110S) is identical to those sold for the conventional GM systems; it is water cooled, and uses a Hitachi 500RHH scroll-type pump. It appears that Leybold is selling these systems in fairly large numbers (in fact, they say that Toshiba buys them for medical imaging, even though Toshiba has its own large cryogenics division), but not for astronomy as far as we know.

Boreas B100: This is not really a GM system, but it is included here for comparison because its characteristics are similar from a user's perspective. It has two GM stages followed by a third stage that uses a patented hybrid cycle which is partly regenerative (like GM) and partly recuperative (like JT). This was invented at MIT in 1984 and the inventors spawned Boreas to commercialize it. The company had financial difficulties and filed for bankruptcy about 2 years ago; it was then purchased by Hypress, Inc., which hired new management and provided new capital. The B100 is its main product, which is now claimed to be in production. We do not yet know of any users who can provide independent evaluation. From the published specifications (Table 1), the efficiency with only the last stage loaded is substantially better than the competition, but the first stage capacity is small and when the latter is fully loaded the overall efficiency is not so competitive. (The second stage, at 20K, is not available for loading by the user. Earlier data sheets promised 10W at 80K as well as 1W at 4.2K, but the latest data sheet deletes all mention of first stage capacity, and other data from the company shows 105K and 4.5K at 10W and 0.5W, respectively.) It is sold with active stabilization of the last stage at 4.2K. The compressor is air cooled and uses two stages because the return must be at 1 atm. The overall power consumption is low, making this system potentially attractive for the MMA. If 1W at 4K is needed, then this is currently the cheapest way to achieve it.

CONCLUSIONS AND ADDITIONAL COMMENTS

This survey suggests that none of these systems is particularly efficient, and that the best way to minimize power consumption for the MMA is to be sure that the capacity is well matched to the requirements; overkill is expensive. The variation in power consumption among these systems (2.5kW to 7.5kW) is mostly explained by their variation in capacity.

For the MMA, we require so many systems that we should consider the possibility of buying a custom-designed (or custom-modified standard) product whose capacity at each stage matches our needs. It should be fairly easy to change the relative flow through different stages of a given design by replacing only the displacers. The total flow can be changed from outside by adjusting the supply and return pressures. In fact, efficiency can be substantially improved by reducing the pressure ratio below the usual 3:1, although the capacity falls off rapidly.

Alternative systems may be more efficient. Consider the Daikin V308SCPR+U308CW GM/JT system used by the SMA: it pumps 2.25W at 4.2K using less power (6.4kW) than the 1W model CSW210 (6.7kW). Pulse tubes should also be considered; these will be reviewed in a later report of this series.

At present, it appears that the main advantage of 2-stage GM refrigerators is their simplicity and hence their expected higher reliability compared with 3-stage GM/JT systems. A disadvantage is the inherent cyclic temperature variation and the need for special measures (active or passive) to remove it at the mixer. I recommend that we purchase at least one off-the-shelf system for in-house experimentation. We should test various temperature stabilization schemes, and we should try modifications and adjustments for better matching the capacity to our loads, thereby reducing power consumption.

REFERENCES

[1] R. Li, O. Yoshida, and T. Hashimoto, "Measurement of ineffectiveness on regenerators packed with magnetic regenerator materials between 4 and 35K." Advances in Cryogenic Engineering, v 35, p 1183-9, 1990.

[2] N. Tozai, "Recent progress in 4.2-K G-M refrigeration." Superconductor Industry, Winter 1996 issue, pp 53-4.

[3] M. Nagao et al., "Helium liquefaction by a Gifford-McMahon cycle cryocooler." Advances in Cryo. Engr., v 35, pp 1251-60, 1990.

[4] T. Kuriyama et al., "Helium liquefaction by a two-stage Gifford-McMahon-cycle refrigerator using new regenerator material of Er3Ni." Jpn. J. Appl. Phys., v. 31, pp L1206-8, 1992.

[5] J. Chafe, G. Green, and R. Riedy, "Neodymium regenerator test results in a standard Gifford-McMahon refrigerator." Conference

paper, exact source unknown, 1993. (Navy-Balzers collaboration.)

[6] R. Plambek, N. Thatte, and P. Sykes, "A 4K Gifford-McMahon refrigerator for radio astronomy." 7th International Cryocooler Conference, 1992.

[7] R. Li, M. Ogawa, and T. Hashimoto, "Magnetic intermetallic compounds for cryogenic regenerator." Cryogenics, v.30, pp 521-6, 1990.

[8] R. Plambek, "Improved seal for a 4K Gifford-McMahon cryocooler." 8th International Cryocooler Conference, 1994.

[9] R. Plambek, "Long-term performance of 4K Gifford-McMahon refrigerators on the BIMA array." Cryogenic Engineering Conference, Portland, July 1997.

[10] L. D'Addario, "Visit to Princeton Physics Department." Internal NRAO memorandum, 27 June 1997. Copies available from the author.

[11] T. Herbig, Princeton University Physics Department, private communication.

APPENDIX: ADDRESSES, CONTACT PERSONS, AND TELEPHONE NUMBERS

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