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AUTHOR(S): J. A. Barclay, P-10
W. A. Steyert, P-10

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University of California

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545
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MAGNETIC REFRIGERATION FOR SPACE APPLICATIONS*

J. A. Barclay and W. A. Steyert

Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

Magnetic refrigeration is briefly analyzed and thermodynamically compared to gas refrigeration. The characteristics of magnetic refrigerators with respect to spacecraft applications are discussed and indicate that high reliability coupled with high efficiency is possible. The latest experimental results on several wheel and reciprocating magnetic refrigerators are summarized.

INTRODUCTION

The requirements of refrigeration for detectors, instruments and experiments in spacecraft are increasing because of the desire to improve the signal to noise ratio and the desire to extend experimental capabilities. These requirements are for lower temperatures (down to 0.3 K) and higher cooling power (many W). The available technology is developing but remains a serious limitation. For example, in a recent article [1] that discussed potential applications of superconductivity in space, the authors said, "Refrigeration requirements are without doubt the greatest impediments to broader use of superconducting devices." Most cooling techniques for spacecraft are listed in Table I [2].

TABLE I

Spacecraft Refrigeration Methods

Cooling Method	Practical Temperature Range (K)	Useable Refrigeration Load for Year Mission
Radiant Coolers	70-100	0-10 mW
Stored Solid Cryogen Coolers	10-90	0-80 MW
Mechanical Coolers	4-100	0-300 W
Stored Liquid Helium Coolers	1.5-4.2	0-100 μW
He^3 Coolers	0.3	0-100 μW
Dilution Refrigerators/ Adiabaic Refrigerator	.001-0.3	0-100 μW
Thermoelectric	'75-300	500-800 mW
Absorption Refrigerator	----	----
Magnetic Refrigerator	1-300	mW-W (potentially)

For a particular application and spacecraft, the cooling method has to meet the power, mass, volume and reliability constraints. Table I shows that at present only mechanical coolers and possibly magnetic refrigerators can provide many watts

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of cooling power over a wide temperature range. Mechanical coolers have great difficulty in meeting the reliability requirements for long-term missions. We intend to review magnetic refrigeration and its potential for future space missions.

PRINCIPLES OF MAGNETIC REFRIGERATION

Magnetic refrigerators utilize the temperature and field dependence of the magnetic entropy to extract heat from a low temperature source and dump it in a higher-temperature sink. The entropy change is given by

$$dS = \left(\frac{\delta S}{\delta T}\right)_B dT + \left(\frac{\delta S}{\delta B}\right)_T dB = \frac{C_B}{T}\, dT + \left(\frac{\delta M}{\delta T}\right)_B dB \qquad (1)$$

where S is entropy, B is field, C_B is heat capacity, M is magnetization, and T is temperature. Paramagnets at low temperature (1-20 k) and ferromagnets near their Curie temperature (> 20 K) show appreciable entropy changes with field as illustrated in Fig. 1.

Several cycles such as Brayton, Stirling, Ericsson, and Carnot can be used for a refrigerator depending on the temperature range and design. The magnitude of the magnetic entropy change and temperature change are compared to a gas system in Table II. The conclusions drawn from Table II are that

TABLE II

Comparison of Magnetic and Gas System

	Isothermal Entropy Change*				Adiab. Temp. Change ($\Delta T/T$)	
	J/Mole K		J/ℓK			
Temp (K)	Gas	Mag Solid	Gas	Mag. Solid	Gas	Mag Solid
2	-19.2	-17.3+	-10.2**	-303	1.5	12.5+
4	-19.2	-17.0+	-80.8	-298	1.5	5.8+
10	-19.2	- 8.5+	-24.0	-149	1.5	1.7+
20	-19.2	- 9.1 +	-11.7	-318	1.5	1.0++
50	-19.2	- 6.6	- 4.66	-231	1.5	0.36
80	-19.2	- 5.0	- 2.93	-175	1.5	0.20
200	-19.2	- 3.3	- 1.17	-116	1.5	0.09
300	-19.2	- 2.5	- 0.78	- 87	1.5	0.06

* 10:1 Pressure ratio helium gas; $\Delta B = 10T$
** 0.1 atm @ 2.6 K He gas
\+ paramagnet e.g., $GdPO_4$, 0.20 kg/mole, 3500 kg/m^3
\++ ferromagnet, e.g., EuB_6, 0.20 kg/mole, 7000 kg/m^3

magnetic refrigerators should be superior to gas refrigerators at low temperatures, competitive at intermediate temperatures, and inferior to gas refrigerators at high temperatures (from a thermodynamic point of view). However, the high density (large entropy change per unit volume) means that low frequencies can be used (~ 1 Hz) and this suggests high reliability. Magnetic refrigerators also eliminate the high-pressure compressor, needing only a small feed compressor. Since the high-pressure compressor is a large source of irreversible entropy creation, and generally has low reliability; its elimination should markedly improve performance. Magnetic refrigerators do have the disadvantage of requiring a superconducting magnet and associated cryogenics but if 4 K refrigeration is needed for the spacecraft, then the magnet is only a small parasitic load. The magnetic field could be a serious problem for some systems, e.g., SQUID detectors. The magnetic cycle can operate at nearly 100% of Carnot efficiency. Losses such as heat flows across temperature gradients, frictional losses in moving parts and moving fluids, eddy currents, and heat leaks are readily anticipated and can be minimized. The expected high efficiency of magnetic refrigerators should put a minimum demand on spacecraft power sources.

PROTOTYPE DESIGNS AND RESULTS

Wheel Type

Two basic designs of magnetic refrigerators are evolving, the wheel-type and the reciprocating-type. The wheel concept [3] illustrated in Fig. 2 provides continuous refrigeration but has limited temperature span. The first operational device used $Gd_2(SO_4)_3 \cdot 8H_2O$ and continuously pumped 200 mW from 2.1 K, 500 mW from 2.75 K to 4.0 K while rotating at 0.25 Hz with a maximum field of 2.1 T. [4] . The key problem with the Carnot-cycle design was heat transfer. The analysis indicated that porous material was required for high-power heat transfer, particularly in non-metallic samples at low temperatures. A later wheel device using Gd metal pumped 500 W across a 7 K span near room temperature while rotating at 0.2 Hz with a ΔB of 1.2 T. [5] The operation of this Brayton-cycle refrigerator was more complex than the low-temperature device because of the regenerative stages of the cycle. The analysis of the refrigerator operation indicated that there were three basic, but not fundamental, problems in the device. The heat transfer was limited, apparently by flow variations and imperfections in the manufacture of the porous bed. There was an internal heat load due to entrained fluid in the porous material; the mechanism designed to compensate for this load was only partially successful, again because of flow variations. The third problem was with the magnetic-field profile. In the Brayton-cycle device, the total field change should occur across the adiabatic sections of the cycle and this was difficult to achieve with a 0.15 m diameter wheel. The latest wheel design is a 4 K to 20 K refrigerator that uses $Gd(OH)_3$ as the working material. This design is shown in Fig. 3 and eliminates most of the problems discovered in the previous two designs. [6] . A compact, rotational-cooling design has also been reported.[7].

Reciprocating Type

The basic concept of reciprocating designs is illustrated in Fig. 4. This design was the first one suggested for use above 1 K [8] . The use of a regenerator increases the temperature span that can be covered at the expense of completely continuous refrigeration. The magnet can be a simple solenoid and entrained fluid does not cause problems. However, the regenerator losses can be serious, particularly since mixing of fluid along the temperature gradient can rapidly create entropy. The results from a room-temperature prototype using Gd metal reported pumping 35 W across a 90 K span. [9]. Alcohol-water mixtures were used for the regenerator fluid and one of the key problems was mixing. A 4 K reciprocating design that used $Gd_2(SO_4)_3 \cdot 8H_2O$ and a liquid helium regenerator reported 52 mW of cooling at 1/60 Hz. [10] The key problem in this design was mixing of the regenerator fluid. Recent low and high temperature designs have eliminated the mixing problem by using a magnetic regenerator concept [6] [11] . The principle is that a suitably designed ...

magnetic material can act as a long-blow regenerator and provide refrigeration at the same time. Several encouraging experiments have been performed using Gd with air or water as the heat transfer fluid.

SUMMARY

Magnetic refrigeration is thermodynamically competetive with gas refrigeration over most of the temperatures of interest, but particularly at low temperatures. The high density of the working material suggests compact devices are possible. High cooling power per unit volume means low frequency operation and coupled with elimination of compressors, infers high reliability. All of these attributes and the potentially high efficiency makes magnetic refrigeration a bright prospect for spacecraft applications.

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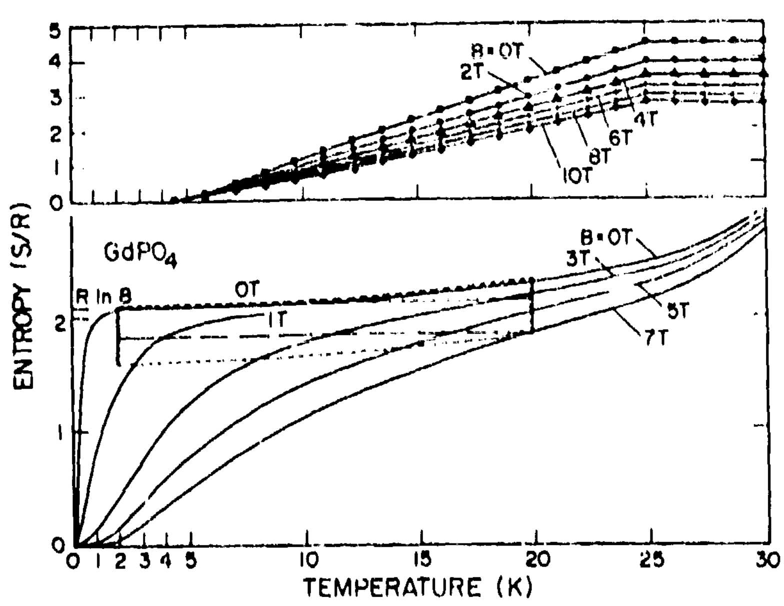

S-T curves for paramagnet and idealized ferromagnet

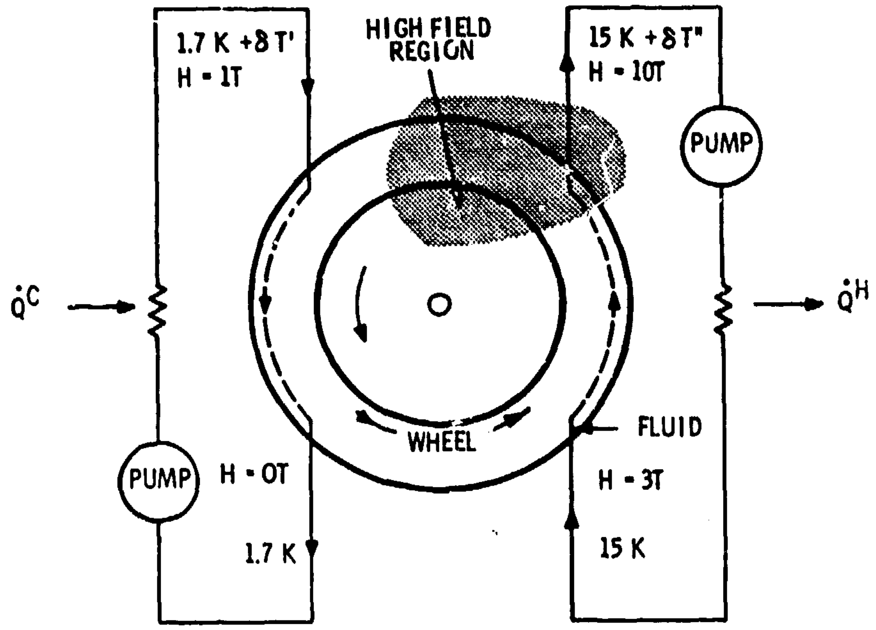

Fig. 2. Magnetic wheel in a Carnot cycle.

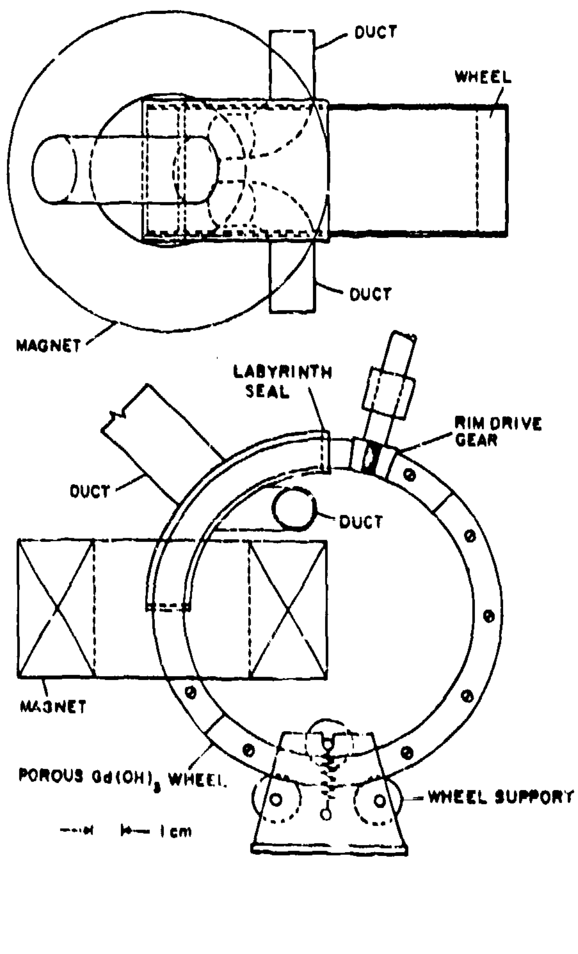

Fig. 3. 4 K to 20 K magnetic refrigerator.

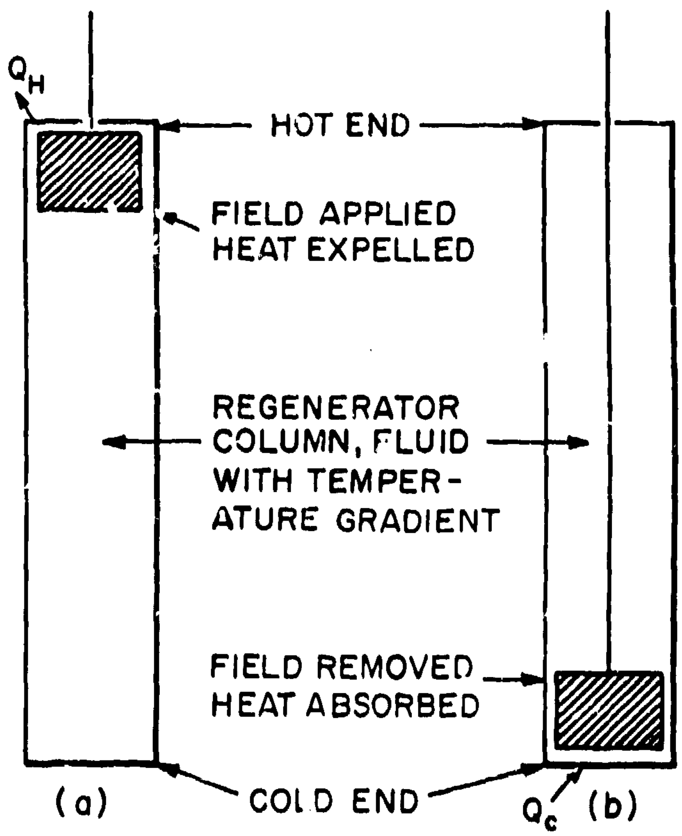

Fig. 4. Conceptual reciprocating magnetic refrigerator.