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**Final Report on NRIP-Funded
Magnetic Refrigerator Development Project**

July 1, 1975—October 1, 1977

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FINAL REPORT ON NRIP*-FUNDED MAGNETIC REFRIGERATOR DEVELOPMENT PROJECT

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by

W. A. Steyert

ABSTRACT

Los Alamos Scientific Laboratory work on magnetic refrigeration is covered in five publications. Two discuss the rudimentary refrigerators built at Los Alamos; two, the performance expected from more advanced designs; and one, the heat transfer experiments performed to provide the data necessary for implementation of those designs. We briefly describe the work discussed in each of these publications and the overall conclusions.

I. INTRODUCTION

The goal of this program, as stated in the original proposal, was to "demonstrate the technical and economic feasibility of magnetic refrigeration as an efficient, reliable means of cooling large cryogenic systems (e.g., applications of superconductivity to electric power networks) to temperatures in the region between 4 K and 20 K. Because magnetic refrigeration involves few moving parts and is inherently capable of operation at 100% of Carnot efficiency, it offers the promise of superior performance and reliability when compared with conventional gas-expansion refrigerators now being considered for the above mission."

The progress toward this goal has been covered in five publications. Here, we discuss the content of these publications in order of their preparation and present an overall conclusion about the work.

II. A CONTINUOUS DEMAGNETIZATION REFRIGERATOR OPERATING NEAR 2 K AND A STUDY OF MAGNETIC REFRIGERANTS¹

A. The Refrigerator

In the refrigerator, a paramagnetic working material, gadolinium sulfate octahydrate in the form of a wheel rim, is rotated between a high-temperature reservoir of liquid helium at 4 K and a low-temperature reservoir of superfluid helium at 2.10 K. The working material expels heat into the high-temperature reservoir as it is subjected to a high magnetic field. As the working material moves into the low-temperature reservoir, the field becomes smaller and eventually decreases to zero. The demagnetization process causes the working material to absorb heat from the low-temperature reservoir. The lowest temperature attained for thermal loads of 200 mW or less was 2.10 K, which is

*New Research Initiatives Program

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below the liquid helium lambda point of 2.16 K at local atmospheric pressure. At a rotation rate of 0.77 Hz and a thermal load of 530 mW, a temperature of 2.75 K was attained.

B. The Magnetic Refrigerants

As a first step, we have measured the thermodynamic properties of $\text{Dy}_2\text{Ti}_2\text{O}_7$, $\text{Gd}(\text{OH})_3$, $\text{Gd}(\text{PO}_4)_3$, $\text{Gd}_2(\text{SO}_4)_3 \cdot 8\text{H}_2\text{O}$, $\text{Gd}_2\text{Al}_2\text{O}_7$, Er_2O_3 , Dy_2O_3 , and DyPO_4 for use below 20 K. Specific heat measurements were carried out in a calorimeter located in the bore of a 10-tesla superconducting magnet. A commercially available (Lawless type) glass capacitance thermometer was used to measure the temperature of the refrigerant under test. This type of thermometer is not sensitive to magnetic fields. The temperature of the sample drifts, and a heat pulse of known magnitude and duration is applied. This pulse warms the sample a few tenths of a degree, and then the temperature slowly drifts again. The heat capacity is determined by extracting the net temperature rise due to the heat pulse from the drift rates in its absence. Measurements of the specific heat in a variety of fields then determine the required thermodynamic properties.

C. Conclusions

We planned for 2 W of refrigeration at 2 K, but achieved only 0.2 W. The lack of forced convection through the center of a porous wheel to carry the heat caused the lower capacity. All future devices will use porous wheels with forced convection for heat transport.

III. STIRLING CYCLE ROTATING MAGNETIC REFRIGERATORS AND HEAT ENGINES FOR USE AT NEAR ROOM TEMPERATURE

A. The Heat Engine and Refrigerator

The heat engine and refrigerator concepts are detailed in Ref. 2; it describes the proposed construction and the detailed mathematical calculations of expected performance.

In the heat engine, a wheel rim of gadolinium metal is positioned with about 1/3 of its circumference in a strong magnetic field. The gadolinium is cooled to below its Curie temperature (294 K) outside the field. It is thus very magnetic, and it is rotated into the field with a large amount of torque. In the high-field region, it is heated above its Curie point, so it loses most of its magnetism and can be rotated out of the field with very little expenditure of energy. A net torque thus provided on the wheel produces mechanical energy from heat.

The refrigerator is the heat engine operated in reverse; the gadolinium is cooled in the field and heated outside it. The torque is opposite to the rotation direction, so work must be supplied and heat is pumped from a lower to a higher temperature.

B. Conclusions

High efficiencies (up to 80% of Carnot) are expected, but an improved heat transfer mechanism is required before an economically competitive device is possible for operation at or near room temperature.

IV. ROTATING CARNOT CYCLE MAGNETIC REFRIGERATORS FOR USE NEAR 2 K

A. The Refrigerator

This proposed device⁸ is similar to the refrigerator and heat engine just discussed. However, the wheel rim is made of pressed $\text{Gd}_2(\text{SO}_4)_3 \cdot 8\text{H}_2\text{O}$, which is suitable for low-temperature refrigeration. Also, the cycle executed is the magnetic analog of the gas Carnot cycle, instead of the Stirling cycle. The proposed construction and expected performance are calculated in detail.

B. Conclusions

A 15-cm-diam wheel will pump 100 W of heat from 2 to 11 K with about 85 or 90% of Carnot efficiency. Cost and energy savings from use of this device will be very large. Magnetic refrigeration of some kind eventually will replace most gas refrigeration in this temperature range.

V. A CONTINUOUS MAGNETIC REFRIGERATOR OPERATING AT NEAR ROOM TEMPERATURE*

A. The Refrigerator-Engine

This device was designed to demonstrate the device described conceptually in Ref. 2. It used a thin, 5-cm-diam wheel made of 1/2 mm-thick sheets of gadolinium, and a 1-tesla permanent magnet.

B. Conclusions

Although this device demonstrated the room-temperature, Stirling-cycle, heat engine and refrigerator, it could not be tested fully because of mechanical problems. The large field gradient from the permanent magnet distorted the gadolinium sheets and produced unacceptable friction. More attention must be paid to magnetic forces in future devices.

VI. HEAT TRANSFER AND FLOW FRICTION IN VERY FINE POROUS MEDIA*

A. The Experiment

The wheel-shaped devices described above rely on very rapid heat transfer to make a high rotation rate possible. The fluid must flow through wheels of porous refrigerants to transfer its heat. This series of heat transfer experiments was carried out for two reasons.

1. To extend flow friction and heat transfer study to smaller dimensions.

2. To gain heat transfer experience.

Fine screens (100-mesh) and beds of 1- μ m to 0.4-cm particles were studied.

B. Conclusions

We found no deviations, outside of experimental uncertainty, from the results expected on the basis of dimensionless empirical scaling laws deduced from measurement of coarser structures. Heat transfer measurements with some of the finer struc-

tures were almost impossible because the heat transfer is so good.

VII. OVERALL CONCLUSIONS

The theory and experimental numbers are now established well enough so that the following conclusions are clear.

Operation at Near Room Temperature

Economically competitive refrigerators and heat engines will require a factor of 10 improvement in heat transfer. Nevertheless, because of the ease of experimentation, the first experimental high-power engines and refrigerators will work at near room temperature.

Operation at 2 K

A modest effort could make 2 K devices economically feasible now. The wheel device discussed in Ref. 3 is only one approach. The fundamentals of magnetic refrigeration are so sound that a number of approaches can be envisioned.

Operation at Near Liquid Nitrogen Temperatures

The demands on heat transfer during operation at near liquid nitrogen temperatures are not so great as those at room temperature. (Beryllium-based rare earth intermetallic compounds have a very low lattice specific heat even at liquid nitrogen temperatures.) An application would be in cheaper, less energy-consuming oxygen separation for steel production.

VIII. CURRENT PROGRAM STATUS

This program is now being supported, in part, by the Electrical Power Research Institute under the terms of Contract No. EY-77-Y-04-4053 RP-7867-1, signed on September 19, 1977.

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