Abstract

Modern society relies very much on readily available cooling. Magnetic refrigeration based on the magnetocaloric effect (MCE) has become a promising competitive technology for the conventional gas-compression/expansion technique in use today.

The magnetocaloric effect is the change in temperature of a material as a result of the alignment of its magnetic spins that occurs on exposure to an external magnetic field. The phenomenon forms the basis for magnetic refrigeration.

Since the 1930s magnetic refrigeration has been a standard technique in low-temperature physics. In 1976 Brown constructed the first magnetic refrigerator to work at room temperature. Subsequently a number of patents describing such refrigerators were registered.

In this seminar the history of discovery and use, the theoretical basics of the phenomenon and the current state of the development for room-temperature applications is described.
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1 Introduction

The magnetocaloric effect (MCE), or adiabatic temperature change ($\Delta T_{ad}$), which is detected as the heating or the cooling of magnetic materials due to a varying magnetic field, was originally discovered in iron by Warburg in 1881.

In 1890 Tesla and in 1892 Edison independently and unsuccessfully tried to benefit from this effect by running heat engines. In 1918 Weiss and Piccard explained the magnetocaloric effect. Later, Debye and Giauque proposed a method of magnetic refrigeration for low-temperature physics in order to obtain sub-Kelvin temperatures. In 1933 Giauque and MacDougall successfully verified the method by experiment.

Since the 1930s magnetic refrigeration has been a standard technique in low-temperature physics. In 1976 Brown designed the first magnetic refrigerator working at room temperature. About 15 years later, Green et al. built a device which actually cooled a load other than the magnetocaloric material itself and the heat exchange fluid. The major breakthrough, however, occurred in 1997 when the Ames Laboratory/Astronautics proof-of-principle refrigerator showed that magnetic refrigeration could be competitive with conventional gas-compression cooling. The early prototypes were able to reach high magnetic flux densities in the magnetocaloric material only if superconducting magnets were applied. The first “room-temperature magnetic refrigerator” containing permanent magnets was designed and built in 2001 by the same group at Astronautics Corporation. [1]

Later, numerous prototypes based on permanent magnets were built [9]. Research today is focused on improvements to magnetocaloric materials, magnets and the optimal design of devices.

The interest in magnetic refrigeration as a new solid-state cooling technology competitive with the conventional vapor-compression approach has grown considerably over the past 10 years, coinciding with rising international concerns about global warming due to an ever-increasing energy consumption. As shown in Fig. (1), the number of published papers per annum on the magnetocaloric effect has grown at an exponential rate in the past 10 years.

2 Theoretical basics

The MCE is intrinsic to all magnetic materials and is due to the coupling of the magnetic sublattice with the magnetic field, which changes the magnetic part of the entropy of a solid. Just as the compression of a gas, the isothermal magnetizing of a paramagnet or a soft ferromagnet reduces the entropy and, in a reversible process, demagnetizing (which is similar to the expansion of a gas) restores the zero-field magnetic entropy of a system.

At constant pressure the entropy of a magnetic solid, $S(T,H)$, which is a function of both the magnetic field strength ($H$) and the absolute temperature ($T$), is the combined total of the magnetic, $S_M$ and lattice, $S_{Lat}$ contribution:

$$S(T, H) = S_M(T, H) + S_{Lat}(T)$$  (1)

In Fig. (2) an $S(T)$ graph for a ferromagnetic material in two constant magnetic fields (zero magnetic field, $H_0$, and a non-zero magnetic field, $H_1$), together with the corresponding magnetic and non-magnetic terms is shown. When the magnetic field is applied
Figure 1: The number of research papers published annually over the past 80 years containing the word “magnetocaloric” in the title, abstract, or among the keywords. The values for 2007 (triangle) are based on the number of papers abstracted during the first three-fourths of the year [1].
adiabatically (i.e. when the total entropy of the system remains constant during the magnetic field change) in a reversible process, the magnetocaloric effect (i.e. the adiabatic temperature rise, $\Delta T_{ad} = T_1 - T_0$) can be visualized as the isentropic difference between the corresponding $S(T)_H$ functions, which is represented in Fig. 2 by a horizontal arrow.

Figure 2: The S-T diagram illustrating the existence of the magnetocaloric effect. The solid lines represent the total entropy in two different magnetic fields: $H_0 = 0$ and $H_1 > 0$. The horizontal arrow shows $\Delta T_{ad}$ and the vertical arrow shows $\Delta S_M$ when the magnetic field is changed from $H_0$ to $H_1$. The dotted line shows the lattice (non-magnetic) entropy, and dashed lines show the magnetic entropy in the two fields. $S_0$ and $T_0$ are zero field entropy and temperature, $S_1$ and $T_1$ are entropy and temperature at the elevated magnetic field $H_1$. [2]

The MCE can also be expressed by means of the isothermal magnetic entropy change, $\Delta S_M = S_1 - S_0$, when the magnetic field is applied isothermally as shown in Fig. 2 by the vertical arrow. Therefore, $\Delta T_{ad}$ and $\Delta S_M$ represent the two quantitative characteristics of the magnetocaloric effect, and it is obvious that both $\Delta T_{ad}$ and $\Delta S_M$ are functions of the initial temperature, $T_0$, and the magnetic field change, $\Delta H = H_1 - H_0$.

The values of $\Delta T_{ad}$ and $\Delta S_M$ can be calculated by using one of the fundamental Maxwell relations:

$$\left( \frac{\partial S(T, H)}{\partial H} \right)_T = \left( \frac{\partial M(T, H)}{\partial T} \right)_H,$$

which after integration (for an isothermal-isobaric process) yields:

$$\Delta S_M(T, \Delta H) = \int_{H_1}^{H_2} \left( \frac{\partial M(T, H)}{\partial T} \right)_H \, dH.$$

5
Using equation (2) and the fundamental equations \( CdT = dQ \) and \( dQ = -TdS \) (when the magnetic entropy decreases the lattice heat increases) we get for infinitesimal adiabatic temperature rise:

\[
dT = - \left( \frac{T}{C(T,H)} \right)_M \left( \frac{\partial M(T,H)}{\partial T} \right)_H dH. \tag{4}
\]

After integrating Eq. (4) we obtain the value of the magnetocaloric effect as [2]:

\[
\Delta T_{ad}(T, \Delta H) = - \int_{H_1}^{H_2} \left( \frac{T}{C(T,H)} \right)_M \left( \frac{\partial M(T,H)}{\partial T} \right)_H dH. \tag{5}
\]

On the other hand, the magnetic-entropy change can be obtained more directly from a calorimetric measurement of the field dependence of the heat capacity by the integration

\[
\Delta S_M(T, B) = \int_{T_0}^{T'} \frac{C(T', B) - C(T', 0)}{T'} dT', \tag{6}
\]

where \( C(T, B) \) and \( C(T, 0) \) are the values of the heat capacity measured in a field \( B \) and in zero field, respectively. It has been confirmed that the values of \( \Delta S_M(T, B) \) derived from the magnetization measurement coincide with the values from calorimetric measurement. [10]

Some additional point shall be made at this point. First, since the magnetization at constant field of paramagnets and simple ferromagnets decreases with increasing temperature [i.e. \( \langle \partial M/\partial T \rangle_H < 0 \)], then \( \Delta S_M(T)_{\Delta H} \) should be negative (Eqs. (2) and (3)), while \( \Delta T_{ad}(T)_{\Delta H} \) should be positive (Eqs. (4) and (5)), which agrees with Fig. 2.

Second, in ferromagnets \( \langle \partial M/\partial T \rangle_H \) is the largest at the \( T_C \), and therefore, \( |\Delta S_M(T)_{\Delta H}| \) should peak at \( T_C \) (Eqs. (2) and (3)).

Third, for the same \( \Delta S_M(T)_{\Delta H} \), the \( \Delta T_{ad}(T)_{\Delta H} \) will be larger at a higher absolute temperature, and also when the total heat capacity of the solid is lower (Eq. (5)). The latter point is critical in understanding the fact that paramagnets display significant \( \Delta T_{ad}(T, \Delta H) \) only at temperatures close to absolute zero, where the limited value of \( |\langle \partial M/\partial T \rangle_H| \) is easily offset by the negligible lattice heat capacity.

Furthermore, at high temperatures the measurable adiabatic heating (or cooling) is expected only if the solid orders spontaneously, i.e. when the value of \( |\langle \partial M/\partial T \rangle_H| \) becomes significant.

The magnetocaloric effect can be measured directly or indirectly using the equations written above. The direct technique consists of measuring the temperature of the sample before and after the application of magnetic field. Unlike the direct MCE measurements, which only yield the adiabatic temperature change, the indirect experiments allow a calculation of both \( \Delta T_{ad}(T)_{\Delta H} \) and \( \Delta S_M(T)_{\Delta H} \), from heat-capacity measurements. The magnetization measured experimentally as a function of temperature and magnetic field provides \( \Delta S_M(T)_{\Delta H} \) after the numerical integration of Eq. (3).

### 2.1 MCE in paramagnets

The magnetocaloric effect was first used close to absolute zero where the enhanced, but still limited\( |\langle \partial M/\partial T \rangle_H| \) is easily offset by the negligible lattice heat capacity of the solid.
The Debye model predicts, for a low temperature limit of heat capacity, the expression:

\[
\frac{C_V}{N k_B} \sim \frac{12\pi^4}{5} \left( \frac{T}{T_D} \right)^3,
\]

where \( N \) is the number of atoms in the sample, \( k_B \) is the Boltzmann constant and \( t_D \) is the Debye temperature. Early research on the magnetocaloric effect in paramagnets was carried out because of the drive to reach ultra-low temperature by adiabatic demagnetization cooling. It is worth noting that the pioneering work of Giauque and MacDougall, who studied low-temperature magnetocaloric properties of paramagnetic \( \text{Gd}_2(\text{SO}_4)_3 \cdot 8\text{H}_2\text{O} \), showed that a temperature of less than 1 K could be reached. This work and other important contributions to the low-temperature behaviors of solids resulted in Giauque winning the 1949 Nobel prize in chemistry. Many years later the low-temperature magnetocaloric effect was reported in a variety of paramagnetic salts including ferric ammonium alum, chromic potassium alum, and cerous magnesium nitrate. [2]

The low thermal conductivity of paramagnetic salts is detrimental for adiabatic demagnetization applications, and therefore, paramagnetic intermetallic compounds have attracted some attention with respect to their magnetocaloric properties. One of the most studied materials was \( \text{PrNi}_5 \), which is still successfully used in nuclear adiabatic demagnetization devices.

### 2.2 The magnetocaloric effect and the order-disorder magnetic phase transition

Spontaneous magnetic ordering of paramagnetic solids upon lowering the temperature is a cooperative phenomenon, that occurs at various temperatures, depending both on the nature of the magnetic sublattice and on the strength of the exchange interaction. When spontaneous magnetic ordering occurs, the magnetic order parameter as well as the bulk magnetization of a solid undergo large changes in a relatively narrow temperature interval close to the Curie temperature contributing to a large \(|(\partial M/\partial T)_H|\) and thus making it possible for a practical utilization of the MCE (see Eqs. (2)-(5)).

Even though it is not the absolute magnetization, but the derivative of the magnetization with respect to temperature that must be large to yield a large MCE, the 4f metals (lanthanides) and their alloys have been studied much more extensively (shown in fig. (3)) than 3d metals and their alloys simply because the available theoretical magnetic entropy in the former is considerably larger than in the latter. Most of the research on the MCE has been associated with either soft ferromagnetic materials ordering from \( \sim 4 \) to \( \sim 77 \) K for applications such as helium and hydrogen liquefaction, or materials ordering near room temperature for applications such as conventional air conditioning and refrigeration.

### 2.3 Intermediate temperatures: MCE in the range \( \sim 80-\sim 250 \) K

This temperature range has not received nearly as much attention as the other two ranges (10-80 K and \( > 250 \) K). First, there is the lack of the driving force for magnetocaloric cooling to these temperatures. The second reason is the inherent minimum of the \( T/C \) ratio (where \( C \) is only the lattice and electronic heat capacity) as shown for typical metal (Cu) in Fig. (4) suggesting that the adiabatic heating and cooling would be minimal in
Figure 3: $\Delta S_m^{max}$ vs. $T_C$ of RCo$_2$-based compounds (filled circles—first order transition, open circles—second order transition (SOT)) and (R,R')Al$_2$-based compounds (open squares—SOT) for a field change of 5 T [3].
this temperature range (Eqs. (4) and (5)). One of the best magnetic refrigerant materials for the intermediate temperatures is pure Dy, with $\Delta T_{ad}$ reaching $\sim 12$ K at $\sim 180$ K for $\Delta H = 7T$.

Figure 4: The $T/CT$ versus $T$ from lattice and electronic contribution in a typical metallic material.

3 Near-room-temperature MCE

The prototype material for the room-temperature range is the lanthanide metal Gd, which orders ferromagnetically at 294 K. Its magnetocaloric effect has been studied independently by many authors [7, 8] and the $\Delta T_{ad}/\Delta H$ values at $T_C$ are $\sim 3$ K/T in low magnetic fields, which falls to $\sim 2$ K/T in higher magnetic fields. A variety of Gd-R alloys, where R is another lanthanide metal (such as Tb, Dy, Ho, or Er) and/or Y were prepared in an attempt to improve the MCE in Gd. However, all alloying additions just shift the Curie temperature of Gd to lower temperatures without any noticeable improvement in its MCE. Most known MC materials are compared as $\Delta S_M$ vs. $T_C$ in Fig.(5).

As noted by Gschneidner et al. (2005) there are a number of other factors which must be taken into account before a final decision is made concerning the magnetic regenerative material to be used in a commercial magnetic refrigerator in addition to the magnetic entropy change, $\Delta S_M$, and $\Delta T_{ad}$. These include: raw material costs, preparation (and production) costs, fabrication costs, hysteresis, environmental concerns (e.g., are the components of the magnetic material poisonous, or carcinogenic), corrosion, stability, and the time dependence of $\Delta T_{ad}$; see Table 1.

3.1 First-order magnetic phase transition and the giant MCE

There is a number of alloys that undergo a so called first-order magnetic phase transition (FOMT). When the temperature or the applied magnetic field is changed, these
Figure 5: The magnetic entropy change for $\Delta H = 50$ kOe for the RCo$_2$, RAl$_2$, Gd$_5$(Si$_{1-x}$Ge$_x$)$_4$, Mn(As$_{1-x}$Sb$_x$), MnFe(P$_{1-x}$As$_x$) and La(Fe$_{13-x}$Si$_x$)$_3$ families plus a number of individual compounds versus the Curie temperature. The solid lines tie together those members of a family which exhibit a FOMT, while the dashed line and dotted line tie together those compounds of a family which have a SOMT. For the Gd$_5$(Si$_{1-x}$Ge$_x$)$_4$ family the solid squares are for those compounds which exhibit a FOMT O(antiferomagnetic I)–O(ferromagnetic II) transition, the solid triangles represent those for the FOMT O(I)–M transition, while the solid dots are for the SOMT O(I) ferromagnetic-paramagnetic transition. The values in square brackets after the compounds in the legend identifying the compounds are the densities in units of g cm$^{-3}$. [5]
alloys undergo a simultaneous change of crystallographic symmetry and magnetic order. This type of transformation is extremely rare. Some of the most researched alloys are Gd$_5$(Si$_{1-x}$Ge$_x$)$_4$, La(Fe$_x$Si$_{1-x}$)$_{13}$ and MnAs$_{1-x}$Sb$_x$.

**Gd$_5$(Si$_{1-x}$Ge$_x$)$_4$**

The giant MCE effect in Gd$_5$Ge$_2$Si$_2$ was first described by V. K. Pecharsky [4]. Gd$_5$(Si$_{1-x}$Ge$_x$)$_4$ alloys are some of the more extensively researched MC materials. The phase transitions for Gd$_5$Ge$_2$Si$_2$ are shown in Fig. (6) as anomalies in the heat capacity at zero field. For alloys with 0.24 $\leq x \leq$ 0.5, a transformation from a paramagnetic monoclinic Gd$_5$(Si$_2$Ge$_2$)-type structure to a ferromagnetic orthorhombic Gd$_5$Si$_4$ occurs. For alloys with 0 $\leq x \leq$ 0.2, a transformation from the antiferromagnetic Sm$_5$Ge$_2$-type structure to the ferromagnetic orthorhombic Gd$_5$Si$_4$-type structure occurs, but only at low temperatures. These two groups of alloys exhibit a giant magnetocaloric effect (GMCE). However, the first group is more interesting due to its higher transition temperatures. The alloys with $x \geq 0.5$ exhibit a second-order phase transition (SOMT). The size of the MCE depends strongly on a proper heat treatment and the purity of the starting elements. The drawbacks of using these alloys are the high prices and the high hysteresis losses. It has been reported [6] that hysteresis losses can be reduced (up to 90%) by adding a small amount of iron to the alloy. The iron suppresses the formation of the orthorhombic phase, making the transition second order, which reduces the hysteresis losses.
Figure 6: The zero magnetic field heat capacity of Gd$_5$(Si$_2$Ge$_2$) from 3.5 to 350 K. The arrows point to a heat-capacity anomaly due to a second-order paramagnetic ↔ ferromagnetic (I) transformation at 299 K and a first-order ferromagnetic (I) ↔ ferromagnetic (II) transition at 276 K. [4]
La(Fe\textsubscript{x}Si\textsubscript{1−x})\textsubscript{13}

It has been demonstrated that La(Fe\textsubscript{x}Si\textsubscript{1−x})\textsubscript{13} in the concentration range 0.86 ≤ x ≤ 0.90 shows a thermally induced first-order magnetic phase transition from the ferromagnetic (F) to the paramagnetic (P) phase at the Curie temperature \(T_C\), as well as the magnetic-field-induced first-order transition from the P to the F phase, just above \(T_C \sim 200\text{K}\). It has been reported \[11\] that \(T_C\) is increased by hydrogen absorption into La(Fe\textsubscript{x}Si\textsubscript{1−x})\textsubscript{13} up to room temperature with preserving the magnetic field induced transition. Fig. (7) shows the temperature dependence of magnetization for La(Fe\textsubscript{x}Si\textsubscript{1−x})\textsubscript{13}H\textsubscript{y} compounds \((y = 0.0, 1.1\text{ and } 1.6)\) in a magnetic field of 0.5 T.

![Figure 7](image)

Figure 7: Thermomagnetization curves of La(Fe\textsubscript{0.88}Si\textsubscript{0.12})\textsubscript{13}H\textsubscript{y} \((y = 0.0, 1.1\text{ and } 1.6)\) compounds in a magnetic field of 0.5 T. The position of \(T_C\) is clearly dependent on the amount of absorbed hydrogen. \[11\]

It has been discussed \[11\] that the candidate for magnetic refrigerants should have not only large MCEs but also sufficient thermal conductivity \(\kappa\) and stability against thermal cycles. \(\kappa\) in range 200–330K for the La(Fe\textsubscript{x}Si\textsubscript{1−x})\textsubscript{13} compounds and their hydrides is comparable with that of Gd metal, while the values of Gd\textsubscript{5}Ge\textsubscript{2}Si\textsubscript{2} and MnAs are much lower in this temperature range. Furthermore, it is also stressed that all constituent elements of the present compounds have low cost and no toxicity against human body and environments. Consequently, the La(Fe\textsubscript{x}Si\textsubscript{1−x})\textsubscript{13}H\textsubscript{y} compounds are some of the practical candidates for magnetic refrigerants working in a wide temperature range.
MnAs$_{1-x}$Sb$_x$

Recently, giant MCEs of MnAs$_{1-x}$Sb$_x$ near room temperature, have been found. MnAs with the hexagonal NiAs-type structure is a ferromagnet with a Curie temperature, $T_C$, of 317 K. This compound undergoes a first-order magnetic transition at $T_C$ accompanied by a structural transformation from the hexagonal NiAs-type structure to the orthorhombic MnP-type structure. The $\Delta S_M$ of MnAs exceeds 30 JK/kg in a field change of 5T. This value is about twice as large as that of Gd$_5$Si$_2$Ge$_2$. The $\Delta T_{ad}$ reaches 13K in a field change of 5T. The substitution of Sb for As stabilizes the NiAs-type structure. The $T_C$ is lowered from 317 to 220 K with an increase in $x$ from 0 to 0.3. These results indicate that MnAs$_{1-x}$Sb$_x$ is a possible candidate for magnetic refrigerant materials near room temperature. [13]

MnAs$_{1-x}$Sb$_x$ also exhibits a so-called barocaloric effect. The external pressure increases the band width and tends to reduce the magnetization and magnetic ordering temperature. In Fig. (8), the total magnetization as a function of temperature for $B = 1$ T at ambient pressure ($p_0$) and for applied pressures of 0.4 GPa ($p_1$); 0.8 GPa ($p_2$) and 1.2 GPa ($p_3$), is plotted.

Figure 8: Magnetization in Mn(As$_{0.7}$Sb$_{0.3}$) for B = 1 T at ambient pressure ($p_0$) and for 0.4 GPa ($p_1$); 0.8 GPa ($p_2$) and 1.2 GPa ($p_3$). The lines represent theoretical predictions and the symbols represent experimental data. [14]

4 Room temperature refrigeration

The most common thermodynamic cycle for magnetic refrigeration is the Brayton cycle. Consider the reversible thermodynamic cycle WXYZ in the ($S, T$) coordinates which is shown in Fig. (9). Here $S$ is the total entropy of a magnetic material. When the magnetic
field is changed by $\Delta H = H - O = H$, the material is magnetized adiabatically, it follows the path WX, and its temperature is changed by $\Delta T(H, T_W) = T_X - T_W$ due to the magnetocaloric effect. When the adiabatic part of the cycle is completed, the magnetic material is connected to a hot sink ($T_{hot} < T_X$) and it follows the path XY, giving up a finite amount of energy and reduces its entropy from $S_X$ to $S_Y$ and its temperature from $T_X$ to $T_Y$. After that the material is disconnected from the hot sink, the magnetic field is reduced to zero, and the sample is demagnetized adiabatically (the path YZ), during which time its temperature is reduced from $T_Y$ to $T_Z$ due to the inverse MCE. Finally, the material is connected to a cold sink ($T_{cold} > T_Z$), where it absorbs a finite amount of energy following the path ZW and increases its entropy from $S_Z$ to $S_W$ and its temperature from $T_Z$ to $T_W$, thus completing the thermodynamic cycle WXYZ [7].

Figure 9: An example of an ideal reversible thermodynamic cycle. The thin solid lines represent the total entropy curves at zero magnetic field, $S_{total}(0)$, and at an elevated magnetic field, $S_{total}(H)$. The thick solid lines outline the thermodynamic cycle WXYZ. $S_W$, $S_X$, $S_Y$, $S_Z$, and $T_W$, $T_X$, $T_Y$, $T_Z$ represent the entropy and the temperature of the material at the positions W, X, Y, and Z of the cycle, respectively. [7]

Currently, studies on the room temperature magnetic refrigeration cycle mainly concentrate on the research of cycle performance and cycle optimization analysis. The most advanced of all the prototypes are the three devices made by Zimm et. al (1998, 2006, 2007) which seem to be setting the trend for magnetic refrigeration development. Their work is therefore here briefly described.
**First generation**

On February 1997 under the supervision of C.B. Zimm the Ames Laboratory/Astronautics Corporation of America (ACA) announced a successful operating proof-of-principle demonstration unit (Fig. 10), showing that magnetic refrigeration is a feasible and competitive technology for large-scale building air conditioning, and for refrigeration and freezing units in supermarkets and food-processing plants. The demonstration unit ran for over 5000 h during an 18-month period with no significant problems and only minor maintenance. This in itself is a significant achievement since any prior magnetic refrigerator at best had only been operational for a few days. This device operated in magnetic fields up to 50 kOe using a superconducting magnet, and it achieved a cooling power of 600 W, a maximum of 60% of Carnot efficiency with a 10 K temperature span (between 281 K and 291 K) in magnetic fields of 50 kOe.

![Diagram of magnetic refrigerator](image)

Figure 10: Ames Laboratory/Astronautics Corporation of America’s reciprocating proof-of-principle magnetic refrigerator. [1]

**Second generation**

Following the success of the proof-of-principle magnetic refrigerator the ACA scientists
and engineers evaluated its performance and concluded that the cycle time of 6 s (operating frequency of 0.16 Hz) for this reciprocating machine was too slow to be practical. An analysis indicated that for high frequencies, >1 Hz, a rotary device would be better than a reciprocating machine. Furthermore, a decision was made to build a small cooling machine using a permanent magnet as the field source rather than build a large size magnetic refrigerator using a superconducting magnet as the magnetic field source. Work on the second-generation magnetic cooling device—a rotary, room-temperature, permanent magnet, magnetic refrigerator (now called the Rotating Bed Magnetic Refrigerator—RBMR)—began in 1998.

![Image](image_url)

Figure 11: Astronautics Corporation of America laboratory prototype permanent magnet, rotating bed magnetic refrigerator (RBMR): (a) schematic and (b) photograph. [1]

In this refrigerator the porous beds of the magnetocaloric material, 160g (initially spheres of Gd and later both Gd and a 94%Gd–4%Er alloy in a layered bed), are rotated through a magnetic field of 15 kOe produced by a Nd$_2$Fe$_{14}$B permanent magnet with steel flux concentration poles. Water is used as the heat exchange fluid. The design of this laboratory demonstration unit easily allows it to operate over a range of frequencies from 0.5 to 4 Hz and at various fluid flows to achieve a range of cooling powers. The maximum temperature span was 25 K under a no load condition. The RBMR operated smoothly and reliably for more than 1500 h between 2001 and 2007.

**Third generation**

The third-generation magnetic refrigerator (the Rotating Magnet Magnetic Refrigerator—RMMR) consists of two 15 kOe modified Halbach magnets which rotate while 12 magnetocaloric beds remain fixed (see Fig. 7) (Zimm et al., 2007). The two rotating per-
manent magnets are arranged so that the moment of inertia of the magnet is minimized and the inertial forces are balanced. The main advantage of the fixed beds is that the valving and timing of the fluid flows through the beds and heat exchangers are simpler than that for the second-generation machine (RBMR) in which the beds rotate through a gap in the magnet. [1]

5 Conclusion

The future of magnetic cooling is bright, but there are still a number of challenges to overcome. Improved engineering to overcome the limitations of the currently available magnetic refrigerant regenerator materials, and the increase of the magnetic field strength of the permanent magnets while reducing the size, mass and cost are two critical areas which need to be continually addressed. On the other hand, scientists need to continue looking for new, and hopefully better magnetic materials, and to improve the critical properties of existing materials.

Environmental concerns may be a major push in the not too distant future with the strong worldwide apprehension about global warming. The reduced energy consumption of $\sim 20\%$ for magnetic cooling technology over conventional cooling devices (average home refrigerator uses about 1,5 kW of electric energy a day) may overcome the current cost disadvantage considering the ever-rising energy costs and be the deciding factor in moving magnetic refrigeration into the realm of commercial products.

References


