experiments can be done with relatively conventional room-temperature microwave apparatus, he said, but at high frequencies, a helium-cooled infrared device is needed.

At wavelengths near the peak, one can measure the cosmic background radiation by inference from the energy-level populations of interstellar molecules, which can be observed in optical absorption lines in the spectra of certain stars. At frequencies below the peak, measurements can have errors of about 10%. Beyond the peak, however, Richards said, these measurements are much less accurate.

At balloon altitudes, for high frequencies the atmospheric emission has been rising as the third or fourth power of frequency, overwhelming the background radiation, which has been falling exponentially. So there is a high-frequency limit to the measurements. But below this limit, Richards notes, improvements in infrared techniques made by several groups have permitted infrared measurements that are more accurate than most of the earlier low-frequency results.

In the figure, the rms sum of all of the experimental errors is shown as the shaded region with plus or minus one standard deviation error limits. Gaps are left in the data at the frequencies of strong atmospheric lines (roughly 14, 16, 18 and 23 cm^{-1}), where the errors become very large. The integrated flux of the radiation is equivalent to that from a blackbody at 2.96 (+0.04 and −0.06). This spectrum is plotted as a solid line in the figure. For an accurate test of the statistical significance of a fit to a blackbody curve, a distinction was made in the published paper between errors from sources such as detector noise or the atmospheric model, which are essentially uncorrelated across the spectral range, and errors from sources such as the instrumental gain, which move the overall curve up or down. The results of this analysis gave a statistical significance of five standard deviations.

The shape of the spectrum and measurements at different altitudes put strong constraints on possible local sources of the deviation, Woody and Richards say. The same shape occurs in all of the scans (covering about 1.7 steradian of the sky); so the possibility of a few bright sources appears dim. The shape does not fit a power-law spectrum, and its magnitude is much larger that the continuum emission expected from the apparatus, Earth or galactic dust clouds. By measuring at different zenith angles, the experimenters place an 85% confidence level limit on the deviation not being caused by the atmosphere. No significant structure of the type expected for molecular emission shows in the deviation at resolutions down to 0.13 cm^{-1}.

What is the explanation of the results? Richards feels there is no doubt that the cosmic background follows an approximate blackbody curve and is consistent with a big-bang origin for the universe. But it is possible that something has happened to distort its shape. Many papers have discussed the source of possible distortions. However, the Berkeley results do not correspond to any of the likely theories, Richards told us. For example, one theory proposes that photons are scattered by hot electrons, thus heating the photons. This mechanism would cause the spectrum to fall less slowly. Berkeley sees the opposite result. Nevertheless, as Richards notes, "Cosmologists have almost infinite imagination."

Could the Berkeley result be in error? At one level, Richards feels that the Berkeley group has done a good experiment. But at another level, he feels that because the answer is so important, the Berkeley result should be verified before starting to modify one's world view. He worries about the risk of undetected systematic errors and is now changing the observing method as much as possible for a second attempt.

Instead of using a Fourier transform ir spectrometer, he will use narrow-band filters. Instead of subtracting atmospheric emission by fitting it with a computer model, Richards and some new collaborators at Berkeley will scan the sky from close to the zenith to close to the horizon. Because the instrument will be looking through different slant paths, one can evaluate atmospheric effects. He hopes to fly the new apparatus in about one year.

Cosmic Background Explorer. Meanwhile, John Mather, who as a graduate student of Richards started looking with Richards for deviations from a blackbody spectrum nine years ago, is in charge of plans for the Cosmic Background Explorer.[3] Members of the COBE satellite science steering group are Mather and Michael Hauser of Goddard Space Flight Center, Samuel Gulkis of the Jet Propulsion Lab, George Smoot of Berkeley, Rainer Weiss of MIT and David Wilkinson of Princeton. The mission could be launched in 1984 or 1985 if approved by NASA headquarters. The Explorer series has already been approved by Congress.

COBE would carry three experiments: The first would also be an infrared Fourier transform spectrophotometer, but it would go down as far as 0.1 mm and, to calibrate the spectrophotometer, would compare the cosmic background spectrum directly to that of a blackbody source on the satellite.

A second experiment, using differential microwave radiometers, would improve the measurement of anisotropy done by Smoot, Richard Muller and Marc Gorenstein, using a U-2 airplane, and by Wilkinson, using a balloon (PHYSICS TODAY, January 1978, page 17). Because the satellite would hover over the Earth's twilight zone, the entire sky would be scanned over a year's time. The antenna would have a 7-deg beam width, the same as the first COBE experiment and the U-2 experiment, but would be far more sensitive because of the long observing time and the full sky coverage.

The third experiment would look for diffuse infrared background radiation from 2 to 300 microns, a region where only local and galactic sources are known.

—GBL

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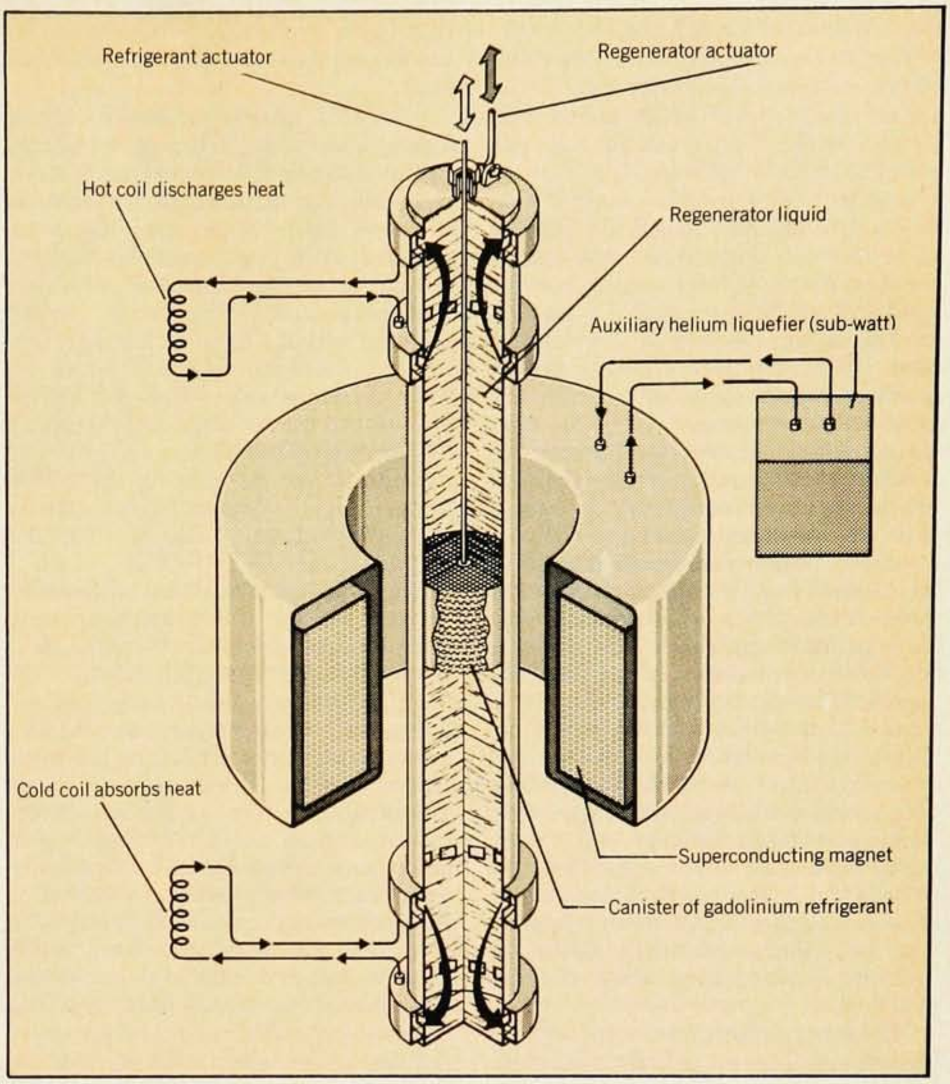
Magnetic refrigerator–heat pump

For almost half a century low-temperature physicists have been exploiting the adiabatic demagnetization of paramagnetic materials to achieve temperatures near absolute zero. Until recently the potential utility of the magnetic cycle for refrigeration and heat pumping near room temperature has not been taken seriously for two reasons: First of all, the degree of magnetic order achievable in paramagnetic materials at practical field strength becomes very small at room temperature. Thus the entropy change that pumps heat when magnetic fields are applied and withdrawn becomes too small to be useful. Furthermore, by 20 K the lattice entropy changes of typical paramagnetic salts and the magnetic entropy changes from which they must be subtracted in a Carnot refrigeration cycle are comparable.

To circumvent these obstacles in the path of a practical room-temperature magnetic refrigerator–heat pump, Gerald V. Brown and his colleagues at NASA's Lewis Research Center in Cleveland have chosen gadolinium, a ferromagnetic rare earth with a Curie temperature of 293 K, as their magnetic refrigerant. Brown's group has recently reported the successful demonstration of a gadolinium magnetic refrigerator–heat pump,[1] operating near room temperature and producing a temperature difference of 80 kelvins between source and sink. Though the heat-pumping power of this laboratory prototype is still quite modest (maximum 34 watts), Brown considers that the temperature range already achieved makes this device interesting for indoor climate-control applications. A refrigerator and a heat pump are of course the same thing, depending on which end one is looking at.

Three years ago Brown suggested[2] a room-temperature ferromagnetic heat pump employing gadolinium. The design he suggested and has now demonstrated employs the reciprocating motion of the gadolinium refrigerant through a cylinder of regenerator fluid, which acts as a kind of thermal flywheel. J. R. Van Geuns of Leyden had proposed a similar design for low-temperature pumping with a paramagnetic refrigerant in 1966. Brown credits this arrangement for the achievement of an 80-K temperature span with a 7-tesla magnet, but the reciprocating motion of the system has until now made it difficult to achieve cycle times much faster than a minute. Higher frequencies tend to cause turbulent mixing of regenerator fluid, upsetting the thermal gradient necessary for efficient heat pumping.

In 1977 William Steyert and his colleagues at Los Alamos reported[3] the successful operation at 2 K of a low-temperature magnetic refrigerator with a rotating paramagnetic wheel. Last year Steyert added a regenerative component to this design, by arranging for counter-rotating liquid helium to flow through the porous wheel. Replacing the paramagnetic material with ferromagnetic gadolinium and the helium with water, Steyert has now adapted this design[4] to study refrigeration at room temperature. Although his ferromagnetic device is still being tested and results have not yet been reported, Steyert told us that he has been able to achieve a maximum refrigeration power of 500 watts with a cycle time of 5 seconds, with only 1.2 tesla of field variation. This power output is comparable to Brown's, per cycle, per tesla and per pound of gadolinium. But the simplicity of rotary operation permits the faster cycle time that results in Steyert's greater heat-pumping power. Steyert has achieved a source-to-sink temperature span of only 9 kelvins, but he believes he can significantly improve on this figure by increasing the magnetic-field variation through which the wheel is allowed to rotate.



A possible magnetic heat-pump configuration suggested by Gerald Brown for room-temperature operation. Because it is difficult to turn the superconducting magnet on and off rapidly, this design has both the gadolinium refrigerant and the cylinder of regenerating water moving up and down. When the refrigerant assembly is at rest in the center of magnet's field, the cylinder moves up. When the refrigerant is at rest outside the field, the cylinder moves down again. (From Lewis Research.)

Curie temperature. When a magnetic field is applied to a magnetic substance, heat is generated as the degree of alignment of the atomic magnets increases. For a ferromagnetic material, this "magnetocaloric" effect is greatest near the Curie temperature, where the ordering influence of the ferromagnetic exchange interaction and the disordering effect of thermal agitations are in approximate balance. At higher temperatures the material responds only paramagnetically, and at significantly lower temperatures the spontaneous magnetization approaches saturation, so that applying an external field has little effect on the magnetic order.

This phenomenon has been known for a long time. Edison and Tesla received patents (1887 and 1890) for heat-engine designs based on the inverse of this effect. But at that time transition metals such as iron and nickel were the only known ferromagnetic substances, and these are not much good on two counts—they have very high Curie temperatures, and they have low net electron angular momentum, J. The fact that ferromagnetic rare earths have higher spins ($J = 7/2$ for gadolinium) is a significant advantage, because the magnetocaloric effect increases as the square of J.

Lewis Research work. Brown believes his group is the first to design and construct a device suitable for operation at room temperature. They subjected the gadolinium refrigerant to the turning on and off of a field of 7 tesla. Even at the Curie temperature, such a field produces an adiabatic temperature rise (or fall) of only 14 kelvins, too small a temperature span for a practical room-temperature heat pump. If one considers a magnetic Carnot cycle (adiabatic followed by isothermal demagnetization, and then a return to the original state by adiabatic and isothermal magnetization), the 7-tesla span reduces the temperature range still further. Furthermore, the entropy and hence the heat pumped by such a Carnot cycle is too small to be useful, because the entropy given up by the lattice and the conduction electrons during the adiabatic cooling must be absorbed by the magnetic-moment system.

To lift this load of the lattice and conduction-electron entropies from the magnetic subsystem doing all the work, Brown replaced the Carnot cycle by the magnetic analog of the Stirling engine (invented in 1816). In the magnetic Stirling cycle, the two Carnot adiabats are replaced by lines of constant applied field (one at 7 T, the return leg at zero applied field). The temperature transition between the hotter and colder isotherm is accomplished by maintaining a steady temperature gradient in a second thermodynamic system in thermal contact with the gadolinium refrigerant, a liquid "regenerator," through which the gadolinium passes back and forth.

This regenerator acts as a thermal flywheel, storing the heat given up by the lattice in one part of the cycle and later giving it back. Thus the entire magnetic effect is available for isothermal heat exchange with the external source and sink. Not only does the regenerative Stirling cycle increase the entropy that can be pumped per cycle for a given magnetic-field and temperature span. It has, according to Brown, an even more important virtue: Because the temperature gradient is built up cumulatively in the regenerator over many cycles, the temperature range between the hot and cold isotherms can be much greater than the maximum 14 kelvins traversed by a single adiabatic (de)magnetization of 7 T.

Brown's magnetic refrigerator consists of an assembly of thin gadolinium plates placed at the center of a solenoidal magnet capable of applying a 7-tesla field to the 0.9 kg of gadolinium refrigerant. The gadolinium assembly remains fixed at the center of the field, but fits and slides freely in a 1-meter-long, 5-cm-diameter hollow cylinder, coaxial with the solenoid. The cylinder is filled with a regenerator liquid of water and ethanol (antifreeze), and is attached to a motor that can move it back and forth along the solenoid axis. The regenerator liquid flows freely between the thin gadolinium plates as the cylinder oscillates along the axis of the solenoid.

The refrigeration cycle begins with the cylinder at its lowest position, so that the gadolinium refrigerant assembly is immersed in regenerator liquid at the top of the cylinder. At this point the magnetic field is raised from 0 to 7 T in a few seconds, heating the gadolinium, which heats the liquid. With the applied field held constant at 7 T, the cylinder is moved upward along the magnet axis until the fixed refrigerant reaches its bottom. At this point the field is reduced to zero in a few seconds, cooling the gadolinium plates and hence the liquid at the bottom of the cylinder. Then with zero field applied, the cylinder is lowered to its starting position, and the cycle recommences.

With each succeeding cycle a thermal gradient is built up in the regenerator liquid as the refrigerant pumps heat from the bottom to the top of the cylinder. After dozens of cycles the system reaches a steady-state equilibrium gradient, whose temperature span depends on the coupling to heat sources and sinks at the ends of the otherwise insulated cylinder, and on the losses in the system. The heat delivered at the top end equals the heat taken up at the cold end plus the magnetic work done in the Stirling cycle, less losses. In principle, the Stirling cycle has Carnot efficiency, to the extent that the specific heat of the refrigerant is independent of its magnetization. For an ideal Carnot refrigerator, the ratio of Q_C, the heat taken out of the cold source, to the work W is $Q_C/W = T_C/(T_H - T_C)$, where T_C and T_H are the source and sink temperatures.

With this laboratory device, whose function, according to Brown, is to demonstrate the principle rather than to serve as an engineering prototype, a maximum 80-kelvin temperature span has been achieved, with cycle time of about a minute and no external heat load attached. The maximum refrigeration power achieved with 0.9 kg of gadolinium was only 34 watts at startup, and 6 watts at the 80-kelvin temperature span. But Brown believes this can be increased to kilowatts by speeding up the cycle by two orders of magnitude and by making the plates thinner than the present 1-mm thickness to improve heat exchange with the liquid.

Brown has calculated that with an optimized version of his magnetic heat pump, one could achieve 60% of the ideal Carnot efficiency, a significant improvement on ordinary heat pumps and refrigerators. The heat energy delivered by a heat pump is not limited by the work done in its cycle. The extra energy comes of course from the cold heat source. Unlike a furnace or electric heater, a heat pump can deliver for space heating many times the number of joules of electrical or chemical energy consumed. A magnetic heat pump can perhaps be made much smaller than conventional pumps of the same power because the heat absorbing capacity per unit volume of the solid gadolinium far exceeds that of a gas.

The Lewis demonstration device used a water-cooled magnet that consumed much more power than the pump delivered. A commercial device would need a superconducting magnet. One must then consider the economics of the power consumption of the magnet's cryogenic system.

The other members of Brown's group are Susan Benford, Willard Coles, Dennis Flood, Erwin Meyn and Stephen Papell.

Steyert's refrigerator, which he and John Barclay are building as a laboratory test device for the Electric Power Research Institute, employs a 2.3-kg gadolinium wheel, six inches in diameter. The porous wheel rotates between high and low-field regions differing by 1.2 tesla, with a cycle time of 5 seconds, exchanging heat with water that is forced to counter-rotate through the wheel on its path between source and sink. In place of Brown's Stirling cycle, Steyert employs a Brayton cycle. This cycle, consisting of two constant-field steps connected by two adiabats, is also borrowed from a 19th-century gas engine, the Brayton "ready motor," the constant-field steps being analogs of constant-pressure lines.

With his small magnetic-field variation, Steyert achieves a maximum temperature span of only 9 kelvins, but when source and sink differ by 7 kelvins he obtains a refrigerating power of 500 watts, with an external heat load. In general, the power achievable in heat pumps decreases as the temperature span increases. Steyert and Barclay have also run their heat pump in reverse, as a heat engine, converting heat flow across a 10-kelvin temperature difference into mechanical energy.

Low-temperature applications. Steyert believes that the refrigerating power of current magnetic-pump designs is limited, presenting an obstacle to their widespread application at room temperature. He feels that in the near future their major application will be in low-temperature refrigeration—2 to 70 K. Brown agrees that cyclic magnetic refrigerators show promise for low-temperature applications, but he is optimistic about their usefulness at room temperature.

In the past, magnetic refrigeration has generally employed "one-shot" devices, in contrast to the continuous, cyclic heat pumps described here. Steyert points out that low-temperature refrigeration is becoming increasingly important for such applications as Josephson computers (PHYSICS TODAY, June 1978, page 17), superconducting electric-power generators, sensing devices on space probes and the production of liquid oxygen for steel mills. An important advantage of magnetic refrigerators over the helium refrigerators that currently dominate the region above 2 K, he told us, is greater reliability, resulting from fewer moving parts. And the parts that do move do so much more slowly than the high-speed turbines required by helium refrigerators. —BMS

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Uri Pestov develops high-resolution spark counter

A new kind of spark counter for high-energy physics is being developed by Uri Pestov and his collaborators at the Institute of Nuclear Physics in Novosibirsk. One model of the Pestov or planar counter was used a year ago as part of a picosecond time-of-flight spectrometer in experiments on the VEPP-2M electron–positron storage ring. Resolution time of the spark counter itself was 30 picosec.

Time resolution is important in time-of-flight systems that are used to separate different kinds of particles. Such a time-of-flight system, employing scintillation counters, was used to detect charmed mesons in a magnetic detector at