

## Passive cooling doesn't cost the planet

Inexpensive ingredients and scalable processes yield a material that can emit more energy than it absorbs, even under direct sunlight.

Just over 10% of the electricity in the US is generated by the mechanical energy of wind and water. Almost all the rest is produced from heat: from fuel combustion, nuclear fission, geothermal energy, or concentrated sunlight.

The conversion from thermal to electrical energy is inevitably inefficient, so thermal power stations must dispose of a lot of waste heat. Usually that's done by cooling their turbines and reactors with water. But water is a finite resource that's not always plentiful around the ideal sites for power plants. An alternative is dry cooling with air instead of water, but those systems are expensive to build, and the large fans that circulate the air consume around 1% of the generated power.

Furthermore, discharging heat into the environment, whether by air or water, means that cooling can't go below the ambient temperature. Because a thermodynamic cycle's efficiency is a function of its temperature range, power plants generate significantly less power on hot days—when the demand for electricity is greatest—than they do on cold ones.

Motivated by the challenge of cooling power plants in hot weather, Ronggui Yang, Xiaobo Yin (both of the University of Colorado Boulder), and their colleagues have created a material capable of round-the-clock cooling to below the ambient temperature.<sup>1</sup> The material, a 50- $\mu\text{m}$ -thick glass-polymer film backed with a 200-nm-thick silver coating, can be cost-effectively manufactured by standard industrial roll-to-roll methods, as shown in figure 1. Its cooling power is on the order of 100 W/m<sup>2</sup>, so around a square kilometer of it could meet the cooling needs of a power plant, and 10–20 m<sup>2</sup> could rival the power of a residential air conditioner. A lot of work remains to be done before either of those



GLENN ASAKAWA, UNIVERSITY OF COLORADO

applications can be realized. But obtaining enough of the material isn't expected to be a limiting factor.

### Balance of power

The second law of thermodynamics dictates that heat can't spontaneously flow from a cooler object to a warmer one, all else being equal. Air conditioners and refrigerators therefore require energy to create and maintain an inside temperature lower than that of the outside air. But the Boulder group's material, astonishingly, is completely passive. It can cool itself and its surroundings to below the ambient temperature with no power input.

**FIGURE 1. YAOGUANG MA, XIAOBO YIN, AND RONGGUI YANG** (left to right) oversee the roll-to-roll production of the glass-polymer film used in their radiative cooling experiments.

Key to the operation is the atmospheric window: the band of IR wavelengths between 8 and 13  $\mu\text{m}$  over which the atmosphere, greenhouse gases and all, is nearly transparent. As shown in figure 2, the window coincides with the peak range of thermal radiation at typical terrestrial temperatures. It thus creates a thermal link that allows heat to flow directly between outer space and

objects on Earth, bypassing the atmosphere. Space, with notably rare exceptions, is colder than Earth, so it acts as a thermal sink.

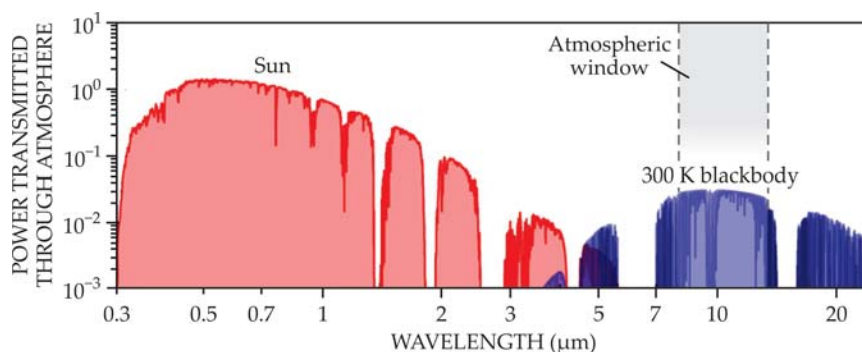
A material's temperature drops if it can shed more heat than it absorbs. Figure 3 shows the major sources that can contribute to that absorption: sunlight, thermal radiation from the atmosphere outside the 8–13  $\mu\text{m}$  window, and non-radiative heat exchange with the immediate environment. The ideal cooling material, then, should emit strongly across the atmospheric window while absorbing little at other wavelengths.

The mechanism of passive radiative cooling has been understood for a long time, and demonstrations of cooling to below the ambient temperature<sup>2</sup> date back to the 1970s. But nearly all of those experiments were performed at night, when solar heating is not an issue. That made the proof of principle much easier, but in practice, the demand for cooling is greatest during the day. So despite some prototype designs for radiatively cooled rooftop panels, the idea never gained much traction.

## Something new under the Sun

Adding sunlight to the mix makes cooling considerably harder. Absorption of just 10% or so of the Sun's radiation can negate all of a material's IR cooling power. A daytime cooling material must therefore be almost perfectly transparent to the solar spectrum. In a simple configuration, in which the cooling material is used as a coating to lower the temperature of an object underneath, a layer of reflective metal under the material can reflect away the sunlight. But then the sunlight must pass through the material twice, so it has two chances to be absorbed.

In 2014 Stanford University's Shanhui Fan and his colleagues demonstrated daytime radiative cooling to 5 K below the ambient temperature.<sup>3</sup> To get the necessary combination of solar reflection and IR emission, they used a nanophotonic material with alternating layers of silicon dioxide and hafnium dioxide. A phonon resonance in  $\text{SiO}_2$  causes strong IR absorption and emission at around 9  $\mu\text{m}$ , and the layering with  $\text{HfO}_2$  creates interference effects that broaden the resonance to encompass the entire atmospheric window. To make the layers with



**FIGURE 2. THERMAL RADIATION** from the Sun and from a room-temperature object on Earth have little spectral overlap, as shown by these logarithmic plots of the radiative power transmitted through the atmosphere. It's possible, therefore, to design a material that emits strongly into the 8–13  $\mu\text{m}$  atmospheric-transparency window while being transparent to sunlight. (Adapted from ref. 1.)

precise thicknesses ranging from 13 nm to 688 nm, Fan and company fabricated their material using electron beam evaporation under cleanroom conditions—a process that doesn't easily lend itself to mass production.

The Boulder group achieved a similar effect with a much less precisely structured material:  $\text{SiO}_2$  microbeads dispersed in a transparent polymer film. (For their demonstration, the researchers used polymethylpentene, a polymer widely used in medical products. But, they say, any optically transparent polymer should work.) The basis of the IR absorption is the same  $\text{SiO}_2$  phonon resonance, enhanced and broadened by the beads' surface modes and collective interactions.

Crucially, no effort was made to control the beads' exact positions, and their overall arrangement was random—the beads' diameter (8  $\mu\text{m}$ ) and concentration (6% by volume) turned out to generate the required spectral properties by themselves. "We usually think of photonic structures as having to be periodic," says Yin, "so we were surprised that this random optical structure could work." That structural freedom allowed the researchers to use scalable production techniques to fabricate their material at a rate of 1.5  $\text{m}^2$  per minute, or hundreds of square meters over the course of their experiment.

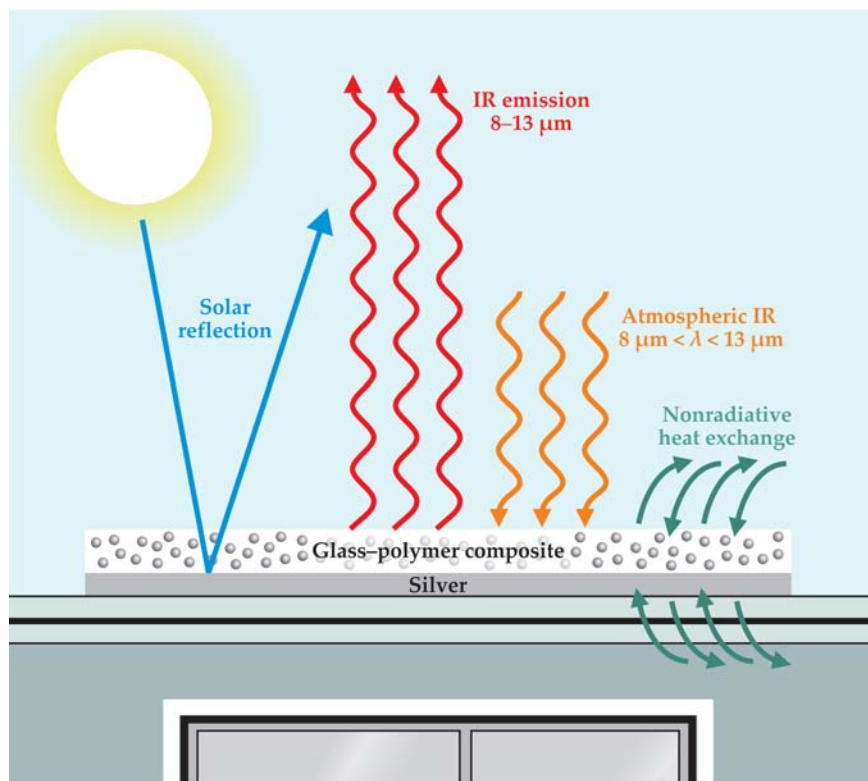
To measure the material's cooling power, the researchers connected it to a feedback-controlled electric heater; the rate at which energy was shed into space would match the rate of heating re-

quired to keep the system at exactly the ambient temperature. Over three days, they found an average cooling power of 93  $\text{W}/\text{m}^2$  at midday and well over 100  $\text{W}/\text{m}^2$  at night.

## Inconvenient truths

An air-conditioner replacement that consumes no power is an exciting prospect. "But that's a long-term goal," Yang stresses. "We will have to do a lot of thermal system engineering." Simply placing the cooling material on the roof won't cool an entire building if the roof is insulated. And most places don't need constant cooling at night and in the winter, so there would have to be a way to turn the cooling on and off. For example, the material could cool a reservoir of water that's then circulated through the building as needed. But the details have yet to be worked out.

Another challenge is in limiting or mitigating heat exchange with the environment. As the glass-polymer film drops below ambient temperature, heat flows conductively and convectively in proportion to the temperature difference, and the cooling power drops. In effect, the film cools the atmosphere above in addition to whatever's below. Because the Boulder researchers used the feedback heater to keep the film at ambient temperature, their measurements don't account for that efficiency drop. They did do a test without the feedback heater, in which they cooled some water to 8 K below the ambient temperature. But that was at night, without the complication of solar heating.



**FIGURE 3. A GLASS-POLYMER COOLING PANEL**, depicted here on the roof of a house, must emit more energy into space than it absorbs from other sources: from the Sun, from atmospheric thermal radiation, and from the environment via conductive and convective heat exchange. To keep the sunlight from warming the underlying roof, a film of silver reflects it away.

To best discharge heat into space, the film needs to face a clear, unobstructed patch of sky. Surrounding buildings,

trees, clouds, and dirt on the film's surface could all compromise the cooling efficiency by emitting their own thermal

radiation that the film then absorbs. Humidity, too, diminishes the atmosphere's transparency in the 8–13  $\mu\text{m}$  window and reduces the cooling effectiveness. The Boulder researchers did their tests under nearly ideal conditions: on a series of clear, dry days in an open space in Arizona. "We want to get a better understanding of how atmospheric and geological conditions affect cooling," says Yang, "but that's not our area of expertise. And we're just starting to study the effects of dirt on the film."

A more immediate application could be adhering the film (without the silver backing) to the surfaces of photovoltaic cells, which can lose efficiency when they get too hot. The researchers expect that the material could be ready for market in as little as a year or two. Beyond radiative cooling, they emphasize the potential to draw on the existing body of research on photonics and spectral engineering to create inexpensive, mass-producible materials. Says Yin, "You don't need a cleanroom to make a photonic structure."

Johanna Miller

## References

1. Y. Zhai et al., *Science* (in press), doi:10.1126/science.aai7899.
2. M. M. Hossain, M. Gu, *Adv. Sci.* **3**, 1500360 (2016) and references therein.
3. A. P. Raman et al., *Nature* **515**, 540 (2014).

# Magnetic trap snares methyl radicals

The ability to isolate the important reaction intermediates at subkelvin temperatures could be a boon to cold chemistry.

**B**y and large, physicists have succeeded in their quest to tame the atom. These days, atoms can be laser cooled to their ground states, stored in traps for minutes, and switched between internal states virtually at will. (See the article by Ignacio Cirac and Peter Zoller in *PHYSICS TODAY*, March 2004, page 38.)

Molecules, however, are wilder beasts. They are all but impervious to laser cooling, which demands a closed optical loop—that is, a sequence of photoexcitation and decay that can be repeated ad infinitum. Due to the additional degrees of freedom afforded by rotational and vibrational modes, molecules tend to

decay unpredictably, often to states that can't be optically addressed. Inevitably, the loop breaks.

Over the years, experimenters have devised strategies to overcome the optical-loop problem: creating cold molecules *in situ* from cold, trapped clouds of reactive atoms (see the article by Debbie Jin and Jun Ye, *PHYSICS TODAY*, May 2011, page 27); cooling molecules "sympathetically" by letting them thermalize with cold atoms; closing optical loops by using RF fields to periodically reset molecules' internal states (see *PHYSICS TODAY*, January 2010, page 9). But those methods generally either work only in limited cases

or yield gases that are too dilute for investigations of cold-molecule collisions, Bose-Einstein condensation, and other quantum phenomena of interest.

A fourth way to cool molecules into the quantum realm is simply to let them escape from a pressurized container into a vacuum. If the initial pressure is suitably high and the escape orifice suitably small, the temperature of the exiting molecules will fall to well below 1 K, cold enough that they behave more like waves than particles. For the experimenter set on interrogating them, however, there's a complication: The molecules will shoot from the orifice at roughly the speed of a rifle bullet.

In 2000 Gerard Meijer and his colleagues at the University of Nijmegen in the Netherlands showed that such beams could be slowed to a standstill using pulsed electric fields, provided the molecules had sufficiently strong electric