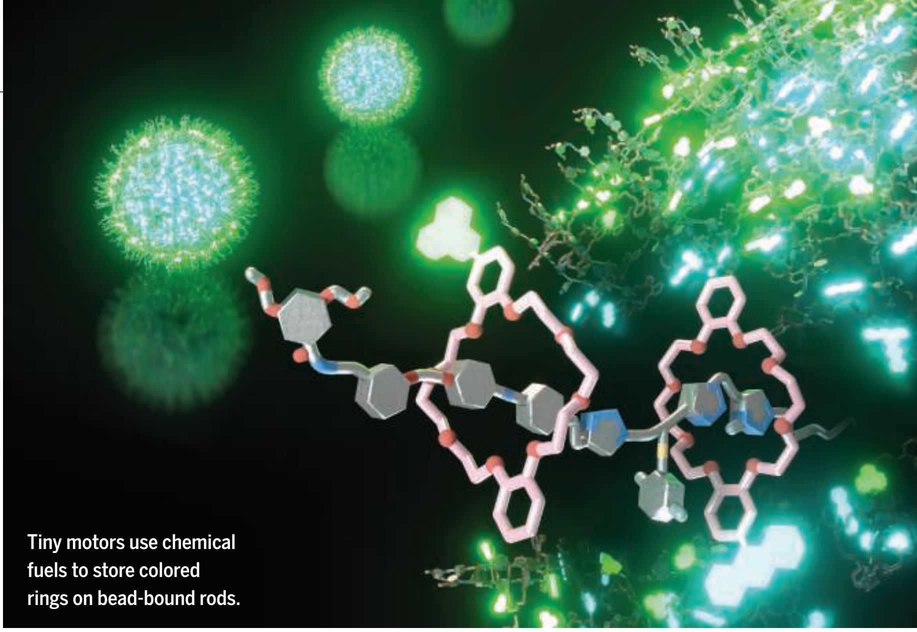

Tiny motors use chemical fuels to store colored rings on bead-bound rods.

IMAGE: ANNA TANCZOS/SCICOMM STUDIOS

CHEMISTRY

Tiny labmade motors are poised to do useful work

Molecular-scale pumps that mimic the body's miniature machines could clean air and harvest precious metals

By **Robert F. Service**

Tiny molecular machines make life possible. Spinning rotary motors generate the chemical fuel our tissues need, miniature walkers carry nutrients around cells, and minute construction crews build proteins. Now, chemists are building their own smaller and simpler versions of these biological machines, hoping to harness their powers.

The puny molecular pumps and motors scientists describe in three recent studies are not quite ready to make their real-world debut. But the work shows it's possible to get teams of motors all working in the same direction to concentrate target chemicals in a confined space—the same feat that protein motors perform in our cells. The feat raises hopes that future motors could suck carbon dioxide from the air and harvest valuable metals from seawater.

"These are very important steps toward useful real-life molecular machines," says Ivan Aprahamian, a chemist at Dartmouth College who wasn't involved with the recent set of studies.

It isn't easy for a molecular-scale motor to do useful work. Because of the vanishingly small size of molecules, a chemical reaction that causes a molecular rotor to spin clockwise is equally likely to spin it counterclockwise. And heat jostles molecules randomly in all directions. "At such small scales, random chaotic motion of components and molecules is inevitable," says Nathalie Katsonis, a chemist at the University of Groningen.

Fraser Stoddart has been working to overcome this challenge for years. The organic chemist at Northwestern University created some of the world's first small, chemical-based molecular machines, sharing a Nobel Prize for his research in 2016. His team designed rings that would slip on and off a molecular axle in response to different chemicals. But because those machines drifted around randomly in solution, collections of them didn't coordinate their tasks in any particular direction, which meant they couldn't perform useful work.

Stoddart and his colleagues have now gotten past that hurdle. As they reported in *Science* in December 2021, they immobilized a new breed of molecular pumps on solid particles made from materials known as metal organic frameworks. These particles have a Tinker Toy–like architecture that chemists can control at the atomic level, enabling them to graft their molecular pumps to the particle surfaces in a consistent orientation.

The scientists then showed that by feeding their system a pair of chemicals, they could drive multiple rings onto each grafted rod, increasing their concentration at the surface to a higher level than in solution. Although the researchers haven't done anything useful so far with their minipumps, Stoddart says further tinkering could create teeny machines that pluck carbon dioxide molecules from the air to fight climate change, perhaps by pumping the gas across a membrane that allows it to be captured and sequestered.

Another stride toward making useful molecular pumps came last week, from David Leigh, a chemist at the University of Manchester, and his colleagues. The team immobilized tiny organic molecular rods on micrometer-size plastic beads. Then, like the Stoddart group, they showed that by repeatedly adding a pulse of a chemical fuel, they could thread multiple organic rings onto the rods.

In a twist, the team used two kinds of fluorescent rings, one emitting green light and the other blue, and showed that by delivering pulses of two different chemical fuels, they could thread rings of alternating colors onto the rods, they reported in *Nature Nanotechnology*. One possible use, Leigh says, is a high-density data storage system in which data are written or read by moving rings on or off the rods. Another: using the ring to collect toxins in the blood stream and deliver them to the hollow beads, which could sequester them.

In a final study, published last week in *Nature*, Leigh's team created a rotating motor that spins continuously as long as fuel is present. In this case, a chemical group called a pyrrole-2-carbonyl acts as a rotor that revolves above a stationary group called a phenyl-2-carbonyl. When no fuel is present, another group called a diacid that is attached to the rotor acts as a stop. It bumps into the stationary group, preventing rotation.

A combination of two fuel compounds changes the configuration of the diacid, creating a kind of ratchet. The first compound eliminates the blockage, which allows the rotor to spin; the second locks the rotor and prevents it from spinning backward. Additional pairs of fuel molecules spin it again. "Our motor will spin as long as fuel is present," Leigh says. Although it's not yet clear just what scientists will do with this 26-atom rotary motor, a larger biological analog uses rotational motion to generate adenosine triphosphate, the fuel that powers cells.

For now, the fuel-driven rotor's spin isn't very fast, only about three revolutions per day. But Leigh notes that chemists are still learning the rules for making molecular machines more efficient. The next big hurdle will be finding a way to harness these machines to carry out useful tasks. Minuscule biological motors sustain even the most massive life forms, and Leigh and others think that in industry and medicine, their artificial versions could have an equally potent impact. "It will be a game changer," he says. ■