NEWS

Desalination Freshens Up

Cheaper materials, more efficient equipment, and some promising new approaches could make large-scale extraction of clean water a major force in the battle against global thirst

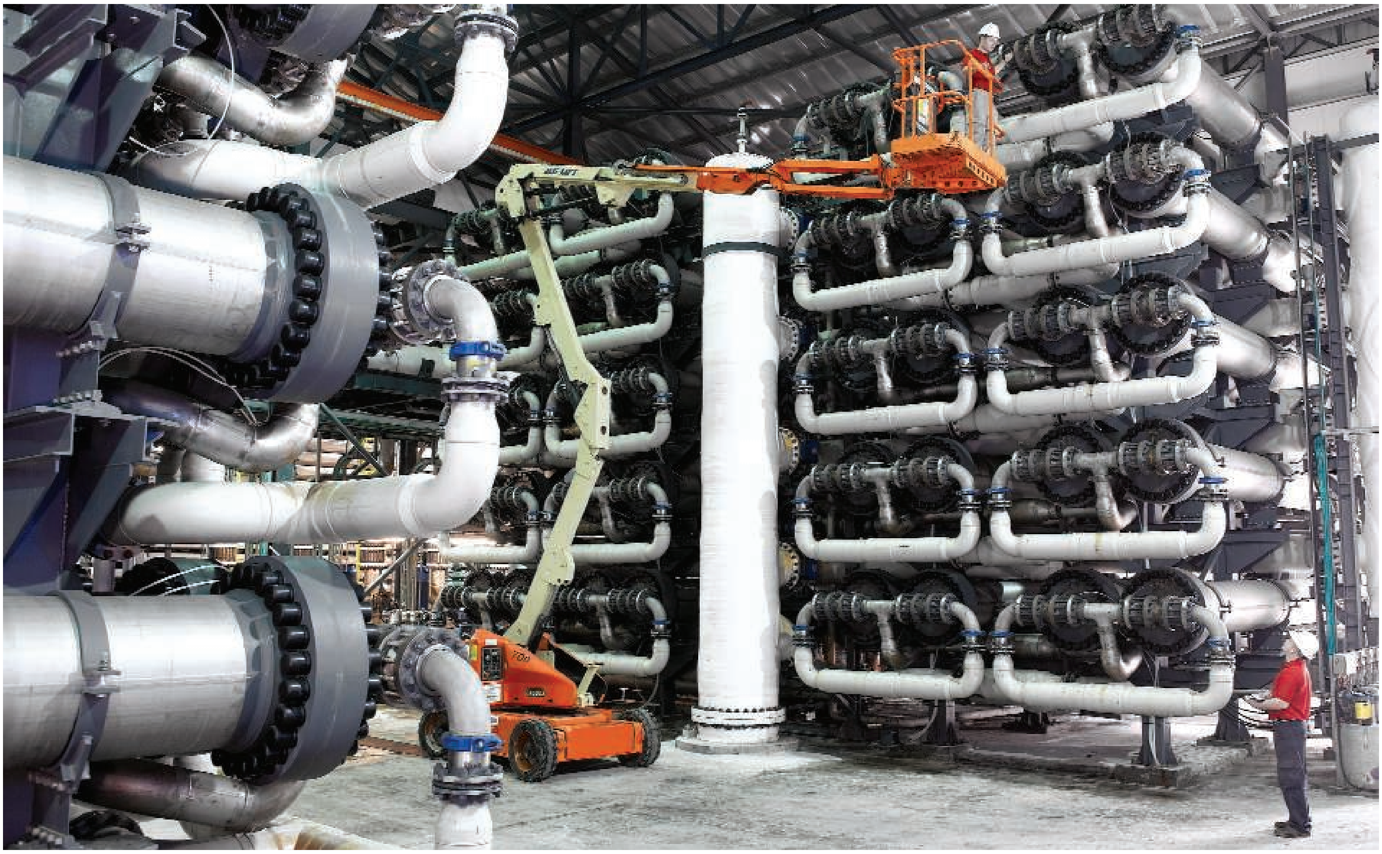
Efforts to provide clean, fresh water for the world's inhabitants seem to be moving in the wrong direction. According to the World Health Organization, 1 billion people do not have access to clean, piped water. A World Resources Institute analysis adds that 2.3 billion people—41% of Earth's population—live in water-stressed areas, a number expected to climb to 3.5 billion by 2025. To make matters worse, global population is rising by 80 million a year, and with it the demand for new sources of fresh water.

Wealthy countries are by no means immune. In arid parts of the United States and many other countries, groundwater resources are already dwindling, and supplies that remain are becoming increasingly brackish. Environmental concerns have drastically limited the building of new dams in recent decades. In many areas, "we are already wringing all the water out of the systems that they have," says Thomas Hinkebein, a geochemist at Sandia National Laboratories in Albuquerque, New Mexico. "[We] have to start developing new sources of water."

Such concerns have made desalination—the process of removing salts and suspended solids from brackish water and seawater—a fast-growing alternative. According to a 2004 report by the U.S. National Research Council, more than 15,000 desalination plants now operate in more than 125 countries, with a total capacity of turning out 32.4 million cubic meters (m^3) of water a day, about one-quarter of the amount consumed by U.S. communities each year. With numerous areas around the globe facing long-term severe water shortages, "I don't see [the demand for desalination] slowing down any," says Michelle Chapman, a physical scientist at the U.S. Bureau of Reclamation in Denver, Colorado, and co-chair of a desalination research program funded by the U.S. Office of Naval Research.

But desalination faces its own problems. The two technologies at the heart of conventional desalination plants—evaporation and reverse osmosis (RO), which involves pushing water through a semipermeable membrane that blocks dissolved salts—both require huge amounts of energy. A typical seawater RO plant, for example, requires 1.5 to 2.5 kilowatt-hours (kWh) of electricity to produce 1 m^3 of water; a thermal distillation plant sucks up to 10 times that amount. Countries such as Saudi Arabia may be able to afford to run such facilities, but for most other countries, the cost was already too high even before oil prices went through the roof.

Yet despite those worrisome trends, the prospects for desalination have brightened considerably in the past few years. New engineering designs have slashed the cost of desalination plants, particularly membrane-based RO systems, and new technologies as



High flow. This reverse-osmosis plant in Ashkelon, Israel, will eventually turn out 100 million cubic meters of fresh water a year.

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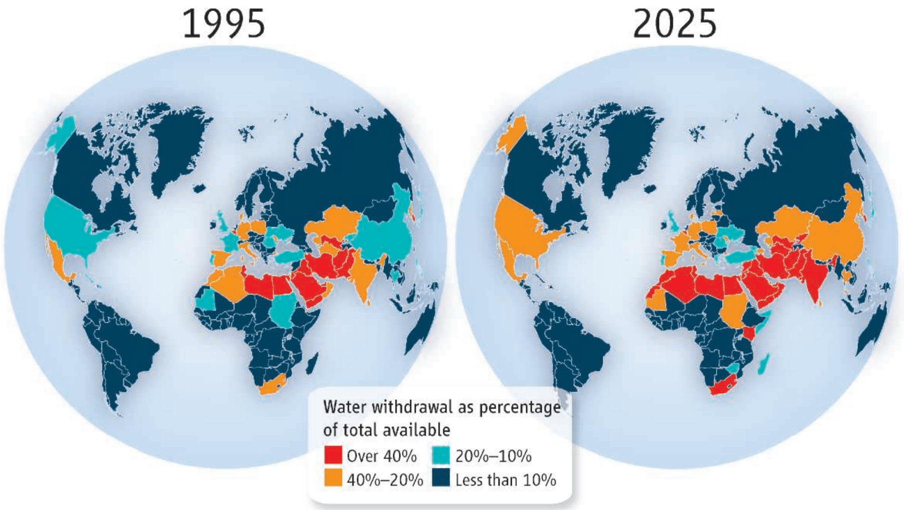

Stressed out. Spreading water shortages underscore the need for new solutions.

SOURCE: WORLD METEOROLOGICAL ORGANIZATION; GLOBAL ENVIRONMENT OUTLOOK, UNEP

diverse as nanotechnology and novel polymers are expected to drive down operating costs in the years ahead. “There is a huge body of research going on,” says Hinkebein, who also oversees a broad collaboration on charting a future road map for desalination technology. “Progress has been a bit incremental for a number of years,” adds Anne Mayes, a materials scientist and membrane specialist at the Massachusetts Institute of Technology (MIT) in Cambridge. “But now new opportunities are starting to open up. We’re going to see some very different technologies being developed in the near future.”

Faster, cheaper, better

Desalination has ancient roots. Aristotle and Hippocrates described the process of evaporating salt water to make fresh water in the 4th century B.C.E. In modern times, desalination kicked into gear in the early 20th century. By the mid-1950s, hundreds of desalination plants were on line. Most were based on evaporation, a technique that continues to turn out about half of the globe’s desalinated water. Although typically more expensive, the technique remains popular in the Middle East, largely because it is well-suited for dealing with the high levels of salts and suspended solids in the water of the Persian Gulf.

Elsewhere, most new plants being built today use RO because the process requires far less energy. As its name implies, the technology reverses the process of osmosis: the natural tendency of water molecules to flow through a semipermeable membrane to dilute a chemical solution on the other side, in this case seawater. To force water molecules to travel the other way requires pressure—at least 3 megapascals (MPa), but more typically 6 MPa—which in turn requires electricity. Historically, an RO plant has used 10 to 15 kWh of electricity to produce 1 m^3 of fresh water.

Between 1980 and 2000, improvements in pumps and other equipment in RO plants dropped the amount of energy needed to produce fresh water by about half, says John MacHarg, CEO of the Affordable Desalination Coalition (ADC), a San Leandro, California–based group of 22 municipalities, state agencies, and desalination companies looking to improve seawater desalination technology. Since 2000, energy requirements have again dropped by about half, thanks to new energy-recovery devices called isobaric chambers that redirect pressure from the waste brine to low-pressure incoming water. These devices recover up to 97% of the energy. Their resounding success has already made them an integral part of the newly designed desalination plants. In one such plant, which started up last fall in Ashkelon, Israel, for example, isobaric chambers have helped lower the cost of desalinated water to \$0.527 cents per m^3, among the cheapest ever by a desalination facility.

Such price drops are now widely expected to continue. By combining energy-recovery devices with new low-pressure membranes and other commercially available advances, this spring ADC members set a new world record for low-cost desalination, dropping the energy needed to 1.58 kWh per m^3 of water produced. At that rate, a seawater desalination plant could supply a typical U.S. household with fresh water for the amount of power needed to light an 80-watt light bulb, MacHarg says. That figure, he adds, could change the equation of how to supply places such as southern California with water, because it takes the same amount of energy to pump freshwater from northern California to Los Angeles.

Juggling act

Still, MacHarg and others say there is plenty of room for improvement, particularly with the membranes at the heart of RO systems. “Basically, [membrane] technology hasn’t changed much in the last 40 years,” says Thomas Mayer, a desalination expert at Sandia. “The polymer films are fairly standard nylon-type materials that work reasonably well.”

These membranes need to accomplish two somewhat contradictory goals at the same time: They must allow water to flow through at a high rate while blocking nearly all dissolved salts. Conventional membranes are made of plastics called aromatic polyamides, which prevent 99.9% of salt ions from passing through but still allow a reasonable flux of water. The plastics can strike the balance because they contain charged chemical groups that repel salt ions, while under high pressure the neutral water molecules actually dissolve into the continuous membrane sheet and pass through to the other side.

The aromatic polyamides were initially so much better than their predecessors that researchers have only recently begun to look for ways to improve them, says Benny Freeman, a polymer chemist at the University of Texas (UT), Austin. They do have big drawbacks: They require high pressure, and therefore energy, to push the water through, and they are also prone to biofouling, in which thin films of organic material coat the surface of the membrane and block water from going through.

One simple way to stop fouling is to add chlorine, much as municipal water treatment plants do to fight pathogens. Unfortunately, chlorine attacks the nitrogen-hydrogen bonds that hold polyamide polymers together, opening holes that allow salts to wiggle through the membranes. So Freeman’s group, in conjunction with chemist James McGrath of Virginia Polytechnic Institute and State University (VT) in Blacksburg, has recently begun developing new chlorine-resistant polymers. The researchers have designed membranes made of sulfonated polysulfones, which lack the vulnerable N-H bonds that chlorine attacks. Other researchers had previously tried to add sulfonated groups to membrane polymers after the polymers were already made, McGrath says, an approach that made them difficult to reproduce, and they often degraded quickly. Instead, the UT-VT team created sulfonated polymer building blocks that they then linked together in a more tightly controlled manner.

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The strategy seems to be working. In May at a meeting of the North American Membrane Society in Chicago, Illinois, Freeman reported that the UT-VT group's new membranes transmit more water than traditional aromatic polyamides do while screening 99% of the salt ions. Whereas conventional membranes begin to break down after 8000 hours of exposure to chlorinated water, the new membranes show no signs of decay—meaning it may be possible to make membranes that don't have to be replaced. Freeman and his team are now tweaking the formula for the plastic in hopes of improving the 99% salt-rejection figure.

Mayes is taking a different tack to improve desalination membranes. Her group at MIT creates membranes from polymer molecules reminiscent of tiny combs. In this case, the combs' "backbone" is made up of water-fleeing molecules such as polyvinylidene fluoride (PVF), a common membrane component. Attached to this backbone are myriad "teeth" composed of short water-attracting polyethylene oxide (PEO) segments. As the polymer forms, these two different segments try to separate from one another, just as the water-fleeing and water-loving properties of oil and water cause them to separate. The result is that the PEO segments circle around one another, creating an array of tiny 2-nanometer-diameter pores in the PVF membrane.

The resulting membranes pass water with a very high flux. They also resist fouling, because the PEO units bind with water molecules so strongly that they give biomolecules few handholds to attach themselves to.

For now, however, the pores are still big enough that salt ions readily flow through. The membranes could still be useful as pretreatment filters to remove larger suspended solids before the water is sent to the RO filter, Mayes says. But she hopes to improve their salt-trapping ability, either by adding charged groups to the backbone portion of the molecules to repel charged ions or by shortening the PEO side chains to make the pores smaller.

Olgica Bakajin, a physicist at Lawrence Livermore National Laboratory in California, is also looking to tiny pores to improve her team's membranes. Bakajin and her colleagues have spent years studying how fluid moves through nano-sized devices. Their calculations showed that water would likely whisk quickly through the smooth, hollow centers of carbon nanotubes, each of which is only 1 or 2 nanometers across. So they decided to make a filter from an array of 89 tiny membranes, each 50 micrometers on a side and consisting of a silicon nitride film perforated by thousands of carbon nanotubes. In a paper published in the 19 May issue of *Science* (p. 1034), Bakajin and her team reported that it took only a single atmosphere of pressure (or 100 kPa) to get water to cross their membranes, although in this case they were tested with fresh water rather than salt water. "We thought our membrane had ruptured," Bakajin says. But it hadn't, and when they studied their pores in detail, they found that they were transporting 1000 times more water than expected.

Double duty. A pilot project at a California power plant purifies seawater used for cooling.

Sandia's Mayer says he is "very excited" about the new result: "We're sorry we didn't do it first." Bakajin acknowledges that she and her colleagues still don't know why nanotubes are such good water transporters. But if carbon nanotube–based membranes can be scaled up and made to exclude salts—both of which are big unknowns at this point—it could enable desalination facilities to sharply reduce the amount of energy required to purify water.

Other low-energy desalination techniques are also on the horizon. In one, called forward osmosis, researchers try to harness normal osmotic pressure for making freshwater. They start with freshwater and seawater separated by a membrane and spike the freshwater side with a high concentration of sugar. Freshwater flows through the membrane as it works to dilute the high sugar concentration. "The problem is that you end up with sweetened water," says Menachem Elimelech, an environmental engineer at Yale University. In place of sugar, Elimelech and colleagues have been experimenting with dissolved ammonium salts, such as ammonium bicarbonate. The salts draw fresh water through the membrane without the need for added pressure. Then, by heating the solution to 58°C, Elimelech's team causes the dissolved salts to form ammonia and carbon dioxide gases, which are easily separated from the water. "If we can use waste heat, the process can be very economical," Elimelech says.

Two other technologies are also looking to waste heat and very cheap starting materials to make easily affordable desalination systems. One, dubbed "dewvaporation," is the brainchild of James Beckman, a chemical engineer at Arizona State University, Tempe. The other, called membrane distillation, has been pioneered by Kamalesh Sirkar, a chemical engineer at the New Jersey Institute of Technology in Newark. Beckman's dewvaporation apparatus vaporizes water in one compartment, sending it over a barrier to another where it condenses; Sirkar's membrane distillation passes the water vapor through pores in a membrane that liquid water or larger ions cannot traverse. Both processes are well on their way to proving themselves in the real world. Sirkar's membrane-distillation system is now being put through its paces by United Technologies in East Hartford, Connecticut, and dewvaporation is being evaluated as an option to create freshwater by the city of Phoenix, Arizona.

Beckman and Sirkar say the advantage of their systems is that they can work with a variety of waste-heat sources, such as steam from industrial plants or even solar energy. That versatility could make them especially advantageous for developing countries. Chapman notes that such systems can be particularly useful as add-ons to conventional RO systems. RO plants typically convert only about 50% to 70% of salt water to fresh water and must treat and dispose of the waste brine—a costly process. Because these novel systems can potentially evaporate all the water and leave only solid salts behind, they promise to save governments a lot of money, Chapman says.

It's unclear whether such novel systems will be able to compete with industrial-scale RO and thermal desalination plants. But Chapman points out that the needs of different communities vary widely when it comes to water, depending on the quality of the water source among other factors. "All water sources are different," Chapman says. "So there will probably be a place for all of these technologies"—and no doubt plenty of thirsty users as well.

–ROBERT F. SERVICE

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