quick study

Salty solutions

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As Earth's population grows and fresh water becomes an ever more precious resource, scientists and engineers are working to increase the efficiency and decrease the cost of desalination.

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A staggering 1 billion people worldwide—one-seventh of the world's population—lack access to safe drinking water. Millions of children lose their lives each year due to preventable, water-borne illness. And the compounding effects of changing climate, population growth, and increasingly calorific diets threaten to throttle our most essential, life-sustaining resource to a relative trickle.

Although they are reflective of the magnitude and urgency of the problem humankind faces, the above statements belie a more nuanced picture of global water scarcity in which local economics, climate, history, human settlement patterns, and societal development all affect the scarcity of fresh water. A rain-rich but sanitation-poor region does not require the same infrastructure as a large population center on a picturesque, if arid, seacoast. Since local problems are highly specific, their solutions must be locally tailored.

There are no global silver bullets. But there are broadly applicable bullets—if not silver ones—and those are desalination technologies. Capable of removing just about anything mixed in with water, desalination is the one approach that can both create pure water and increase the amount of fresh water in Earth's hydrologic cycle. Accomplishing those things is important because, according to some estimates, by 2025 the world's population may use 70% of the planet's renewable fresh water.

Reverse osmosis

The shiniest bullet is reverse osmosis (RO). First demonstrated in the late 1950s, RO now accounts for 65% of installed capacity for desalination and well more than 50% of the new capacity contracted over the past several years. (Panel a of the figure shows an RO plant in Barcelona, Spain.) The process is conceptually simple: A pressurized saline stream—typically at 60–70 bar for seawater systems—passes over a membrane that admits water molecules but rejects dissolved salts. As long as the hydraulic pressure of the saline stream exceeds its osmotic pressure (explained in panel b of the figure), fresh water passes across the membrane and leaves the brine behind. We still don't perfectly understand the rejection and transport mechanisms, but the most commonly accepted theory, called solution–diffusion, posits that water on the saline side dissolves into the membrane material and diffuses across to the pure side much faster than the salt does.

Ideally, an RO system should consume minimal energy and cash while rejecting maximal salt. Lower energy generally corresponds to lower mean driving pressure; lower cost generally reflects a membrane that's cheaper per unit area or one that can be made smaller because of its superior water permeability; and better salt rejection generally corresponds to a smaller salt permeability. Improved fouling resistance, which could be achieved through advanced membranes or better pretreatment of the seawater feed, would also drive down costs, as would other innovations, such as better systems for seawater intake and concentrated brine disposal. For this Quick Study I'll focus on pressure and permeability.

Energy and capital costs

Salt water and fresh water spontaneously mix. Therefore, according to the laws of thermodynamics, a minimum energy is required to unmix them—that is, to desalinate. For a typical seawater system producing a half kilogram of fresh water per kilogram of seawater, that minimum is about 1 kWh_e (kilowatt hour of electrical work) per cubic meter of fresh water, roughly the energy needed to run a window-unit air conditioner for an hour on a hot summer day. New, large-scale seawater RO plants generally use about 3–4 kWh_e/m^3; by way of contrast, the best large-scale evaporative desalination systems require a heat input equivalent to about 20 kWh_e/m^3. The takeaway here is that with modern RO, we cannot expect order-of-magnitude improvements to energy consumption—we're already pretty good.

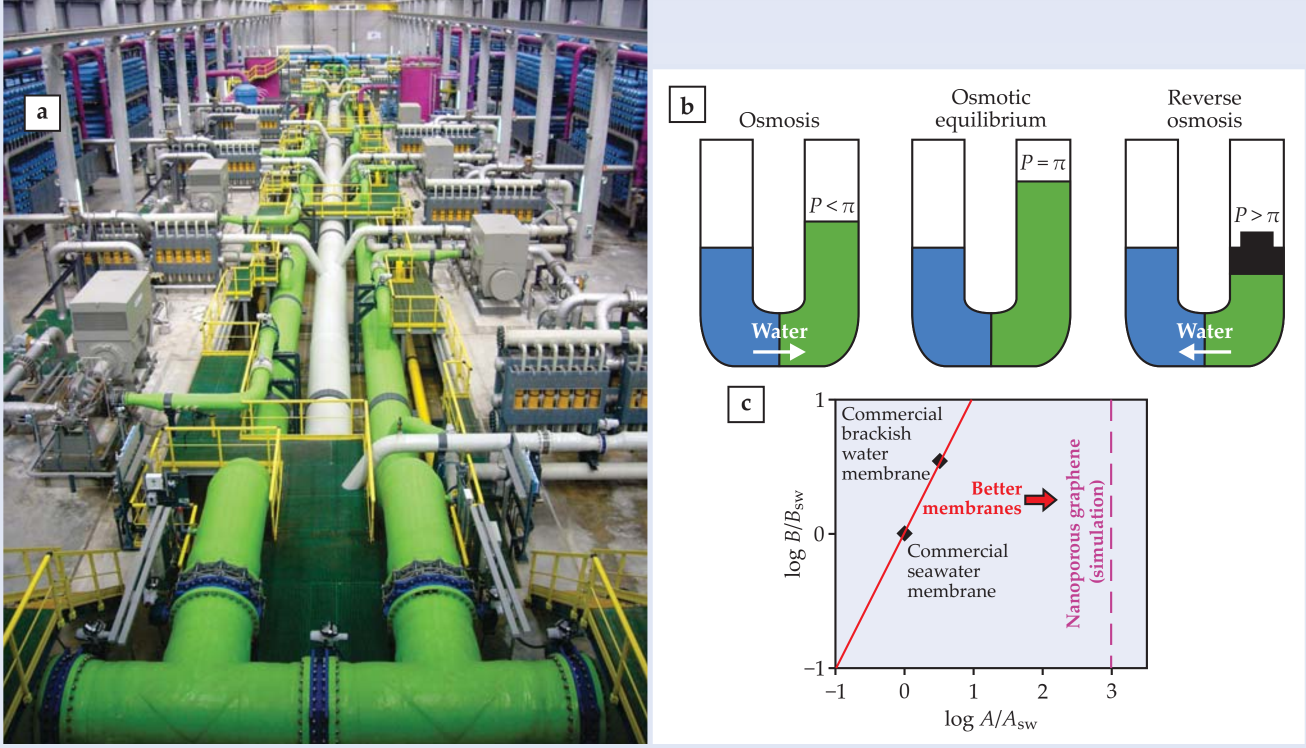
Nevertheless, improvements are possible. To drive pure water out of a saline feed, the pressure of the feed has to exceed its osmotic pressure. As the saline stream concentrates, its osmotic pressure increases. So the highest pressure in the system must exceed the highest osmotic pressure—that of the concentrated salt water—by enough to yield a reasonable water flux.

The RO process need not always run at its maximum pressure. In a staged system, the applied pressure is stepped up in accordance with increases in osmotic pressure. Much of the purifying flow occurs at relatively low pressure, which reduces overall energy consumption. The drawback is the extra cost of the additional pumps and membranes needed to produce the same amount of fresh water. One innovation that provides similar benefits to staging without the additional cost is called closed-circuit RO, which recirculates the salty stream and slowly pressurizes it as it concentrates.

The average electricity bill for industrial users in the US in 2014 was about 7 cents/kWh_e, so the 3–4 kWh_e/m^3 energy budget of a large-scale RO plant corresponds to an outlay of 21–28 cents/m^3. The total cost to operate such plants is in the range of 60–80 cents/m^3, roughly half that of a typical residential water bill.

A good portion of the difference between the total cost and the energy cost is due to the membranes themselves. Nowadays researchers are working to develop membranes that do a better job of letting water through and keeping salt out. Success would mean that smaller membranes in more compact, less expensive systems could produce the same quantity of fresh water as current systems produce.

Zeolites (a particular class of minerals) and various en-



Reverse osmosis: Plant, principle, prospects. **(a)** The Barcelona, Spain, seawater desalination plant was inaugurated in 2009. **(b)** When salt water (green) and fresh water (blue) are separated by a semipermeable membrane that lets only fresh water through, water moves from the fresh volume to the salty one in a process called osmosis (left). Once the pressure P in the salty volume reaches the so-called osmotic pressure π (center), the system achieves equilibrium. If pressure is applied to the salty region so that $P > \pi$ (right), fresh water will be forced out of the salty volume; that process is desalination by reverse osmosis. **(c)** Water permeability A and salt permeability B characterize membrane performance. Here the permeabilities are given relative to those for a typical commercial seawater (sw) membrane. Membranes in current use tend to fall along the red line. According to simulations, nanoporous graphene membranes and other ultrapermeable materials may achieve water permeabilities up to 1000 times greater than that of commercial seawater membranes. (Salt permeabilities for such membranes have not yet been simulated.)

gineered materials such as carbon nanotubes and nanoporous graphene are defining new types of ultrapermeable membranes that have the potential for much greater water permeability than conventional thin-film composites. In many cases, the goal is to tune the size of the subnanometer pores to create a molecular sieve. The idea is backed by intuitive physics: Ions in solution are surrounded by a solvation shell, a sphere of water molecules that orients around the ion as a consequence of the water's polarity. That surrounding water sphere effectively increases the size of the solvated ion to about double the 0.3-nm size of a single water molecule. A properly sized pore, then, should admit water but reject the effectively larger, solvated ions. In reality, however, ultrapermeable membranes likely rely on a combination of factors beyond sized-based solute exclusion to achieve the desired separation; those include charge-based rejection, functionalized groups that interact chemically with specific solutes, and geometric barriers that inhibit salt passage.

A design trade-off

A significant drawback of many ultrapermeable membranes is that they, like conventional membranes, do not perfectly block salt passage. In particular, because the ultrapermeable materials allow water to pass so much more readily than salt, a layer of salt starts to build up against the membrane surface as water is squeezed out of the feed. That buildup, or concentration polarization, contributes to salt flux across the membrane. The higher the rate at which water leaves the salty stream, the higher the concentration of salt at the membrane surface and the higher the salt flux. On the other hand, a higher water flux also means less time to produce a given amount of fresh water and thus less time for salt to pass through. So the high water flux associated with ultrapermeable membranes leads to a trade-off; ultimately, the design of the RO system and the salt permeability of the membrane combine to determine salt rejection.

One membrane material that may demonstrate extraordinary water permeability and high salt rejection is nanoporous graphene. As shown in panel c of the figure, molecular dynamics simulations have predicted that nanoporous graphene membranes can achieve water permeabilities three orders of magnitude above conventional thin-film composite membranes. Real-world membranes may not achieve such high water permeabilities, or they may be limited by concentration polarization. But even tripling the water permeability of current state-of-the-art membranes could reduce the membrane cost by nearly 50%.

With drastic reductions in energy consumption to near the thermodynamic limit and advanced membranes that can purify water at several times the rate of conventional membranes, desalination is taking its place among the most efficient industrial technologies. As current research further hones energy and cost improvements, desalination will increasingly contribute to the solutions of local and global water-scarcity problems.

Additional resources

▶ M. Elimelech, W. A. Phillip, "The future of seawater desalination: Energy, technology, and the environment," *Science* **333**, 712 (2011).
▶ M. M. Pendergast, E. M. V. Hoek, "A review of water treatment membrane nanotechnologies," *Energy Environ. Sci.* **4**, 1946 (2011).
▶ T. Humplik et al., "Nanostructured materials for water desalination," *Nanotechnology* **22**, 292001 (2011). ■