The 2002 Clarke Prize Honoree

Harry F. Ridgway, Ph.D.

Research Director, Water Resources & Technology Department
Orange County Water District

For 25 years, Dr. Harry Ridgway has pioneered significant studies on membrane technology, particularly the discovery of the crucial role that microorganisms play in influencing the structure, function, and effectiveness of membrane materials used in purifying water and wastewater (the process is known as bio-fouling). He has also developed new methodologies to observe, measure, and quantify bacterial attachment to membranes under controlled conditions in the laboratory.

Because of his many accomplishments, nearly every membrane manufacturer in the world has worked directly with Dr. Ridgway to test and reformulate their newest and most advanced membrane materials to reduce the effects of biofouling. In addition, today's membrane processes are much more efficient and less costly due to research and developments made possible by his work.

Currently, Dr. Ridgway is building a database to determine the ability of membranes to reject organic contaminants of concern, such as pharmaceuticals, insecticides, and disinfection byproducts. His overall goal is to develop models that will help the water industry identify membranes that can remove target organic contaminants.

Dr. Ridgway received a Bachelor of Science degree with distinction in Microbiology/Chemistry from California State University San Diego in 1971 and a Ph.D. in Marine Microbiology from Scripps Institute of Oceanography at the University of California, San Diego, in 1976. He has been Research Director at the Orange County Water District in California since 1981.

THE 2002 CLARKE LECTURE

Membrane Research: The Quest for Pure Water in a New Millennium

HARRY F. RIDGWAY, PH.D.
Research Director, Water Resources & Technology Department
Orange County Water District

Water is H_2O:
Hydrogen two parts, oxygen one, but there is also a third thing that makes water and nobody knows what it is.

~ D.H. Lawrence (1885-1930), Pansies, *1929*

Earth's Water Report Card: Where We Stand

Water is among the simplest molecules known to man, consisting of just one oxygen and two hydrogen atoms bound by forces still incompletely understood. Because of its unique structure and curious behavior, water is able to form complex molecular aggregates capable of interacting with and solvating nearly any substance, leading in time to its complete dissolution. For this reason, water has been called the "universal solvent" and is required in a relatively pure form by virtually all forms of life on earth. Though the origin of water on earth remains a mystery (water-bearing meteorites and comets have been recently implicated), one thing is certain: the amount of water is, for all practical purposes, finite over our lifetimes and the supply of clean, safe drinking water is being rapidly outstripped by demand.

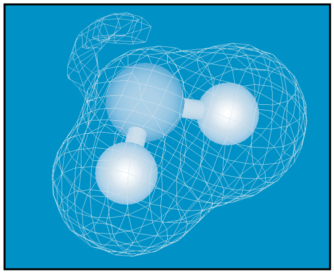
Most of us grew up in a modern society where we have learned to take clean water for granted – lots of it. Here are some interesting facts about water usage in America and much of the industrialized world:

- While usage varies from community to community and person to person, on average, Americans use 183 gallons of water per day for cooking, washing, flushing, and watering. The average family turns on the tap 70 to 100 times daily.

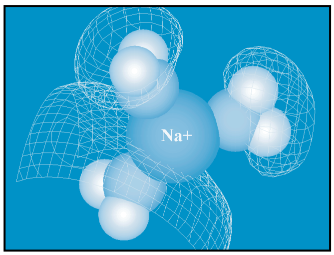
- About 74 percent of home water usage is in the bathroom, 21 percent for laundry and cleaning, and 5 percent for the kitchen. A typical clothes washer uses about 50 gallons of water and an automatic dishwasher uses 12 to 20 gallons. Flushing a toilet requires 2 to 7 gallons.

- A 10-minute shower or bath takes 25 to 50 gallons of water.

- It takes about 1,000 gallons of water to grow the wheat to make a 2-pound loaf of bread and about 120 gallons to produce one egg.



The H_2O molecule.



Three water molecules solvating a sodium ion (Na+).

- More than 1,400 gallons of water are needed to produce a meal of a quarter-pound hamburger, an order of fries, and a Coke.

- About 48,000 gallons of water are needed to produce the typical American Thanksgiving dinner for eight people.

- 1,800 gallons of water are needed to produce the cotton in one pair of jeans and 400 gallons to produce the cotton in a shirt.

- It takes 39,000 gallons of water to produce the average domestic auto, including tires.

- Producing an average-size Sunday newspaper requires about 150 gallons of water.

- To meet current domestic, farming, and commercial demands for water, about 800,000 wells are drilled each year in the United States (approximately 100 per hour).

Most Americans have been led to believe that water is a renewable resource that will always be available; however, the facts dictate otherwise. Indeed, pessimists among us can look around and claim with some credibility that earth's fresh water supplies are in serious trouble. As stewards of our planet's precious natural resources, we have amassed a rather poor record of achievement. Today, nearly 2 billion people – almost one-third of the world's population – do not have adequate access to safe drinking water and reliable sanitation systems. Children are at the greatest risk, with more than four perishing each minute due mostly to water tainted with pathogenic microorganisms, such as cholera and typhoid. The World Bank estimates that by 2025, more than 48 countries will experience severe water stress or scarcity and the number of people adversely affected will exceed 1.4 billion, the majority in the least developed countries. By 2035, an estimated 3 billion people will be living in severely water stressed countries. Today, the United States and the world face major threats to their water supplies through a host of what many consider intractable problems, including:

- The uncontrolled depletion (i.e., mining) of our potable water aquifers at unprecedented rates.

- Widespread chemical contamination of our rivers, lakes, estuaries, and oceans from urban and agricultural runoff, industrial effluent, untreated wastewater, and acid rain.

- Pollution by known and emerging waterborne pathogens from untreated water or, more recently, by purposeful introduction in times of war.

- Desertification through persistent drought and massive overgrazing in many parts of the United States and the world.

Recent U.S. intelligence reports indicate that water, not energy or food, will become the major resource problem in the United States and the world by the year 2015.

The unregulated building of dams on many of the world's major river systems will lead to serious environmental degradation and international disputes, possibly even wars, over water rights. For example, Egypt currently imports more than 97 percent of its water supplies from other neighboring countries, some of whom represent political and economic rivals, at best. By 2025, the stress on water supplies will become further exacerbated by continued population growth and global climate change, placing billions of people at risk. Studies by the United States Environmental Protection Agency, the American Water Works Association, and the Association of Metropolitan Water Agencies indicate that our water and wastewater delivery infrastructure is becoming obsolete or decaying at an alarming rate, with estimated infrastructure renewal costs of approximately $1 trillion, an amount that is prohibitively expensive even for most nations.

Pollution along a Santa Ana River tributary in Southern California.

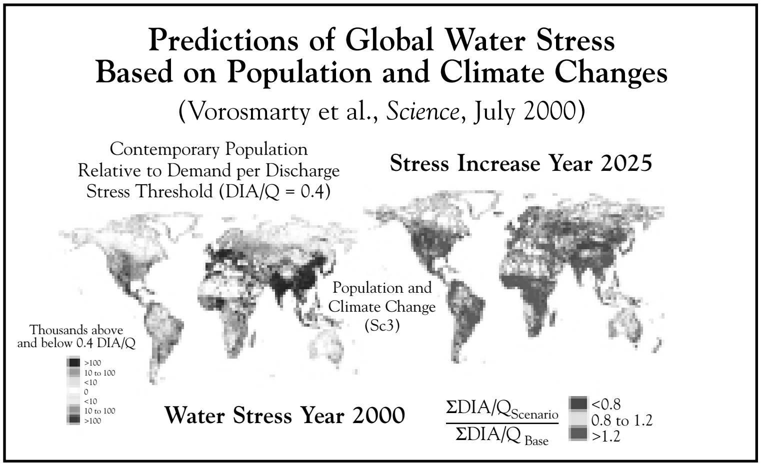
In a 1993 *National Geographic* article, Michael Parfit captured the essence and gravity of the current state of affairs: "People have long been convinced that with bulldozers and concrete we can control water and adapt it to our ways. We have changed water to our benefit in many cases, but we have also messed it up. The changes have often been drastic. We've turned rivers into lakes, deserts into alfalfa fields, aquifers into waste

"The crisis of our diminishing water resources is just as severe (if less obviously immediate) as any wartime crisis we have ever faced. Our survival is just as much at stake as it was at the time of Pearl Harbor, or the Argonne, or Gettysburg, or Saratoga."

~ Jim Wright, U.S. Representative, The Coming Water Famine, *1966*

dumps. We've even changed the chemistry of rain. It's not just a crisis; we've undermined the foundation of life."

Given the sobering prospects for sustaining the supply and quality of earth's fresh water supplies, there is more than a little truth in the statement that never in the history of the world have the demands for rapid progress in water science and technology been greater, the need more critical, and the risks so high. Yet, the notion of a quick fix for such daunting and far-reaching problems seem almost unimaginable and wholly incompatible with the sluggish pace of scientific and social progress. This is especially true of progress in water purification and restoration (recycling) technologies, which nowadays require the successful integration of multiple scientific disciplines, such as biotechnology, chemistry, physics, engineering, computer science, and materials science.

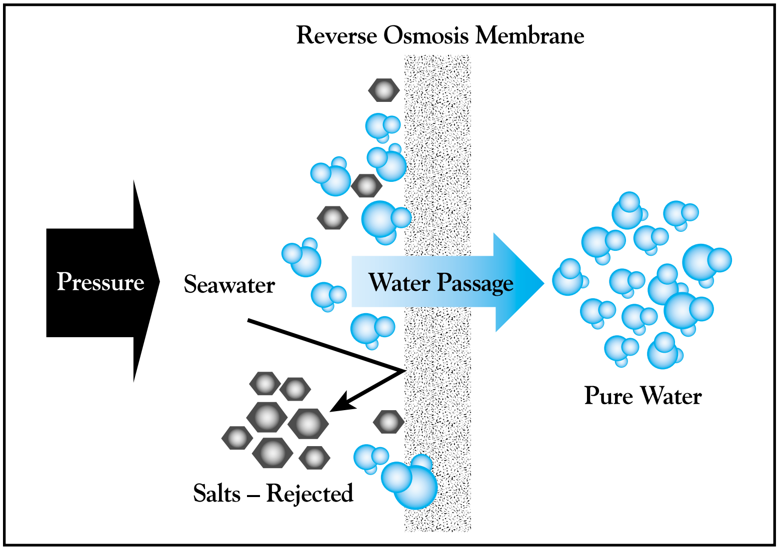


Predicted water stress for the world.

The Way Forward: A Crucial Role for Research

What must we do to avert a global water crisis? First of all, I believe that whatever course of action we embark upon will not be easy, and things could get worse, perhaps much worse, before they get better. At the most basic level, we need better water conservation methods, better management and protection of our world's natural resources, and more reasonable and sustainable global population growth. Additionally, we must pursue a vigorous, coordinated, and sustained mission of research and discovery aimed at understanding and coping with the most fundamental aspects of our global water issues.

While significant progress has been made in recent decades, there is still much that is unknown concerning how best to purify water and manage earth's water resources. For example, many questions remain concerning how waterborne microbial pathogens survive and are disseminated in the environment. Indeed, the vast majority of microbes, pathogenic or otherwise, that inhabit the hydrosphere still remain unclassified, and we are unable to grow them in the laboratory. Although disinfection and filtration technologies have improved in recent times, no one has yet devised the perfect treatment system for all applications, and we have only a rudimentary understanding of how these



The concept of reverse osmosis, in which the normal osmotic flow of water across a permselective membrane is reversed by applied pressure.

processes work on a molecular level. I believe that without such understanding, new scientific progress and technological innovation could be severely hampered in the future.

Throughout the ages, scientific research (often aided by a healthy dose of serendipity) has been the foundation of mankind's quest for pure water. Every major technological improvement in water treatment, from the earliest recorded inventions of filtration and disinfection by pre-Egyptian cultures more than 5,000 years ago to the discovery of modern semipermeable desalination membranes in the early 1960s, has been grounded in research spurred on by critical human needs.

How does scientific inquiry work and why should we depend on it now? Writing in the journal *Science* in 1964, John Platt made the compelling and widely influential claim that the surest way to explore the unknown and make advancements in the most efficient way possible was through the application of what he called "strong inference" (SI). Briefly, Platt defined SI as a series of logical steps that included:

- Identifying alternative (multiple) hypotheses to explain the initial observation.
- Designing critical experiments to, as nearly as possible, exclude one or more of the hypotheses.
- Carrying out the experiment(s) to get decisive results.
- Reiterating the procedure by formulating sub-hypotheses to refine the possibilities that remain.

To explain what he meant by SI, Platt invoked the metaphor of climbing a tree.

At each fork, there are alternative choices (hypotheses) that diverge in different directions. A test (experiment) is performed at each junction to eliminate one or more of the possible choices (e.g., a test to determine which branches can support the climber's weight). New tests are then designed and performed (e.g., which branch leads to the left or to the right) until all alternatives but one are ruled out.

Such a process of scientific inquiry may at first appear slow and even cumbersome, and Platt's remarks are not without controversy; however, the consequences of making wrong choices based on an absence of experimentation or insight can be devastating. On the other hand, the application of SI (or some version of it) has allowed many fields of science and technology to progress with remarkable speed and stunning achievements. Good examples include the recent advancements of molecular biology and biotechnology, space exploration, and the earth sciences (e.g., plate tectonics).

> *"Better a cruel truth than a comfortable delusion."*
> *~ Edward Abbey*

I believe a path of basic and applied scientific research and discovery is our best (and perhaps only) hope at this critical juncture to assure the future of earth's precious water resources; however, to navigate this path successfully will require one other essential ingredient — the will to do so. Our public and private institutions (and the insightful individuals who support them) must be willing to galvanize new support for education and provide the kind of environment that fosters creativity and scientific inquiry. We must not shy away from new or disturbing ideas and retreat to the imagined safety that ignorance provides.

The World's First Desalination Membranes: A Journey of Research and Discovery

Among the most fascinating and powerful discoveries in the field of water science and technology was the development of the world's first desalination membranes. This path to discovery was paved with both pure science and a series of chance occurrences that, together, resulted in one of the most far-reaching and beneficial technological innovations of our time. The idea of making a membrane or some other device that could efficiently separate the salts from seawater and produce pure drinking water was an age-old dream of humans. While studying plant cells between 1824 and 1830, Henri Dutrochet discovered and named the phenomenon of osmosis, which is the passage (diffusion) of water through a semi-permeable (permselective) membrane in response to a solute concentration gradient. The term "permselective" refers to the fact that the membrane is preferentially permeable to water while dissolved salts are held back (i.e., rejected). The osmotic transport of water across a permselective membrane is driven, in large part, by the universal tendency of matter to become chaotic.

Whereas Aristotle (384 to 322 BC) described kidney anatomy, it was not until the late 1800s and early twentieth century that kidney function was understood in general terms. Through osmosis and active transport, the specialized membranes (nephrons) of our kidneys remove urea, salts, and other waste products from the bloodstream, and some believed it might be possible to someday develop technology to emulate such a process. The laws of diffusion and the theoretical framework necessary to carry out membrane-based separations were largely

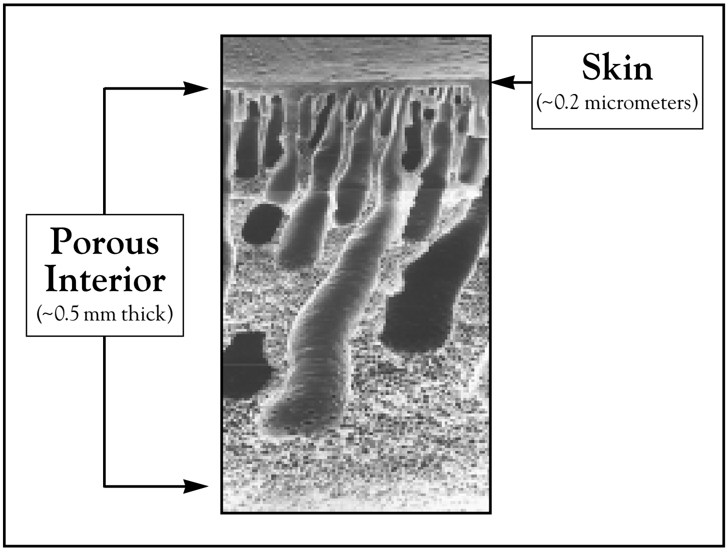


Image courtesy of Bob Riley, Separation Systems, Inc.

Electron micrograph showing the structure of the Loeb-Sourirajan reverse osmosis membrane. Note the "skin" region that is responsible for the membrane's permselective qualities.

established in the later half of the nineteenth Century and early 1900s. Yet, the notion of a practical desalination membrane continued to elude scientists and engineers of the time.

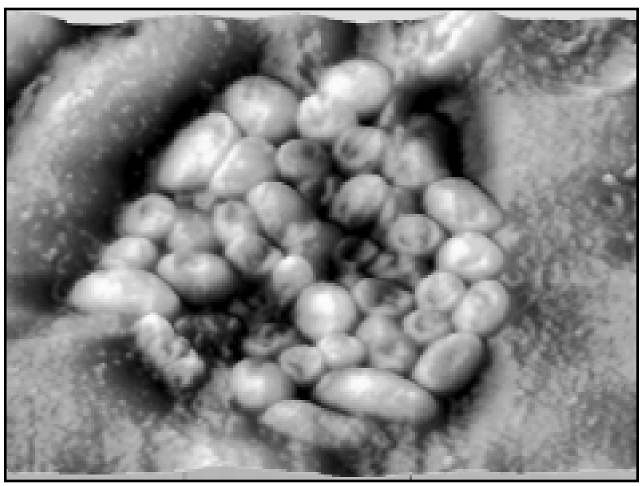
Shortly after World War II, some scientists and government officials began to speculate that a looming water crisis lay ahead for America. In response to this concern, the Office of Saline Water was established to facilitate the identification and exploration of novel water desalination technologies. The Office of Saline Water, and later the Office of Water Research and Technology, poured more than $100 million into basic and applied research on new water treatment and desalination technologies with the dream of exploiting the world's oceans to produce an unending supply of safe potable water at a reasonable cost. Research and experimentation was already underway by this time, involving multistage distillation processes and methods based on cyclical freezing and thawing of water to remove the salts; however, these approaches required water to undergo a state change (i.e., liquid water at ambient temperatures had to be either heated and vaporized or frozen solid) and such state changes were expensive to carry out because they require much energy. The real breakthrough came in the mid-1950s when Charles E. Reid and his students at the University of Florida discovered what came to be known as reverse osmosis (RO), a process in which the normal osmotic flow of water across a semipermeable membrane is reversed by an applied pressure. No state change was needed in the RO process, making it an inherently less expensive desalting technology. Today, RO is the preferred technology for water purification and desalination around the world, and the water community is now — to a significant degree — dependent on this process.

Reid's early membranes were, however, too thick and operated too slowly to be of any practical value, and he and his colleagues eventually abandoned their research. Subsequently, Henry Mahon and coworkers at Dow Chemical Company began making cellulose acetate (CA) fibers in the late 1950s in hopes of improving the water production of the early Reid-type membranes; however, it was not until late 1959 that Sidney Loeb and Srinivasa Sourirajan, working in a research laboratory at the University of

California, Los Angeles, created a practical RO membrane. These new CA membranes, which quickly came to be known as Loeb-Sourirajan membranes, had water flows that were more than 10 times greater than the original Reid and Dow membranes and opened the door to commercialization of the process. Harry Lonsdale, Ulrich Merten, Bob Riley, and others working at General Atomic in San Diego, California, ardently studied the structure and function of the new membranes and made many fundamental discoveries concerning how they worked and how to improve them. They discovered that the Loeb-Sourirajan membranes worked so efficiently because they possessed an exceptionally thin "skin" where the actual water transport and desalination took place.

With these early discoveries and breakthroughs, commercial membrane manufacturing companies sprang up almost overnight, and the new RO membrane technology was quickly put to the test of desalinating seawater and brackish water around the world. In the mid 1970s, John Cadotte discovered how to make more effective multilayered polyamide RO membranes, now called thin-film composite (TFC) membranes, which have since largely supplanted the first CA membranes.

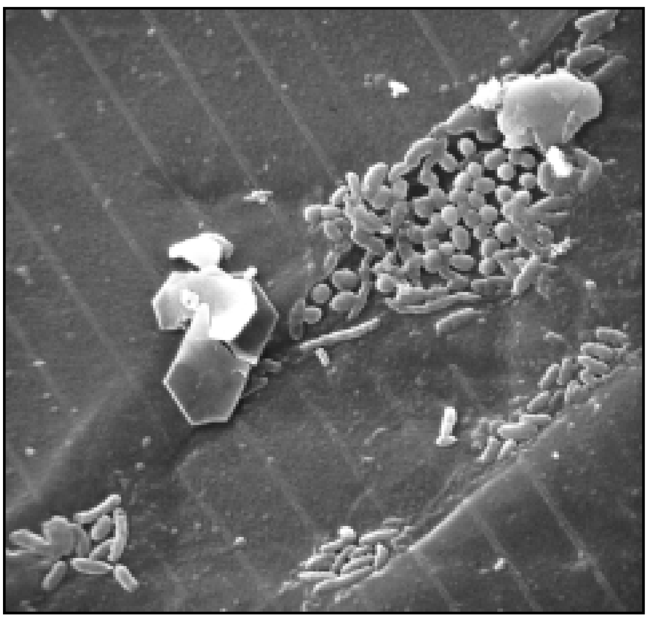
Even with the stunning early successes of RO technology, problems began to emerge as field data poured in. One of the most serious problems occurred when suspended particles (colloids) and other substances in the feedwater accumulated on the surfaces of the RO membranes, effectively plugging them. New studies were embarked upon in the late 1970s to better understand this phenomenon. Harvey Winters at Fairleigh Dickinson University in Teaneck, New Jersey, was among the first to recognize that bacteria could firmly attach themselves to glass coupons placed in the feedwater supplying RO systems. The bacteria formed a kind of gel-like layer (called a biofilm), which is now widely recognized as one of the most serious issues with modern membrane systems. The process of bacterial attachment and biofilm growth at a solid-liquid interface is referred to as biofouling. Working first at the University of California, Irvine in the late 1970s, then at Water Factory 21 in Fountain Valley, California, in the early 1980s, my coworkers and I reported that certain feedwater microbes could attach irreversibly to CA and polyamide RO membranes, leading to a rapid decline in performance. These initial findings stimulated intensive research into the mechanisms of cellular attachment and what could be done to prevent it. The problem was



Courtesy of Jana Safarik, Orange County Water District

Beginnings of a biofilm. Bacteria are seen in the atomic force microscope attached to the surface of a reverse osmosis membrane.

similar in some respects to a disease process in which a pathogenic bacterium or virus infects a host organism, causing illness. Just as we use antibiotics to cure microbial infections, many new chemical agents, some with biocidal activities, were tested to see if they could prevent RO membrane biofouling. At the same time, novel methods were devised to study how the bacteria attached to the synthetic membranes and why. This work led to yet new control strategies in which the surfaces of the RO membrane materials themselves are chemically modified in an effort to retard or prevent bacterial attachment and biofilm formation. Such research efforts actively continue today in many laboratories throughout the world. Practically all new membrane materials are now routinely tested for their biofouling tendencies.



An early reverse osmosis membrane biofilm of rod-shaped bacteria.

We have now entered a new and exciting era of exploration concerning the role of microbial life forms on the surfaces of desalination membranes and other materials of industrial or biomedical importance. Who knows where this line of inquiry will ultimately lead and what technological innovations will occur as a result? Already, some have envisioned new possibilities and have designed "biofiltration" systems to treat polluted water, incorporating both synthetic separation membranes and beneficial microbes in the same device to both filter the water and biodegrade pollutants.

The discovery of the first functional RO membrane to its commercialization into a practical and profitable global technology took less than a decade. Now, some 40 years hence, membrane-based water purifications arguably represent the most important and promising technologies we have for sustaining the world's potable water reserves. Even with its stunning success, membranes alone will likely be insufficient to solve all of our global water needs in the decades ahead.

The Future of Membrane Science and Technology

Today, we humans face a tall order. We are challenged with meeting an unprecedented and rapidly expanding global demand for safe, pure water. Echoing the sentiments of John Platt and others like him, it seems to me that focused, sustained, and scientifically sound research is the least expensive and fastest way to meet this monumental challenge. It is hard to predict what the next breakthroughs will be or where they will occur. But returning to the example of membranes, the "holy grail" and mantra of the clever membranologists of today seems to be this: to develop an inexpensive, non-fouling, highly durable, osmotic separations barrier (membrane) that can efficiently desalinate and purify water using minimal energy. The new membranes must also be "intelligent" in the sense that they must automatically respond to adverse physico-chemical conditions in the feedwater (e.g., a sudden increase in the concentration of a specific chemical pollutant or microbial contaminant) and then optimize their behavior accordingly (e.g., by increasing their own rejection for the contaminants in question). The membranes of the future should also remove or inactivate pathogenic microorganisms and viruses. They will likely possess specific water and solute gates to allow the selective passage of only certain kinds of beneficial substances (e.g., water, iron, or other trace nutrients) while disallowing the transport of harmful contaminants, such as toxins and carcinogens. The membranes themselves may have the capability of "sensing" harmful chemical pollutants or microbial contagions as they contact special recognition (receptor) sites engineered into the membrane surfaces. Finally, as the fields of biotechnology, nanotechnology, and materials science begin to merge, the membranes of tomorrow will increasingly resemble biological membranes in their complexity and functionality.

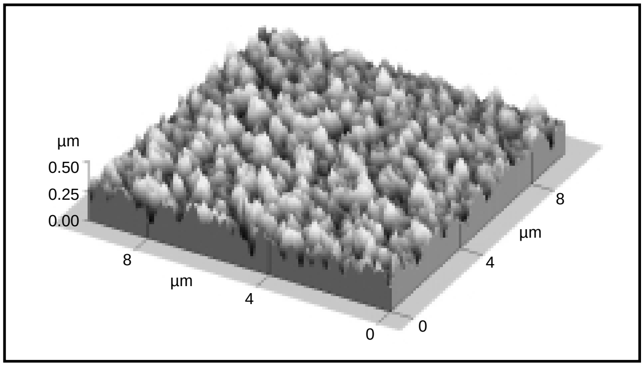
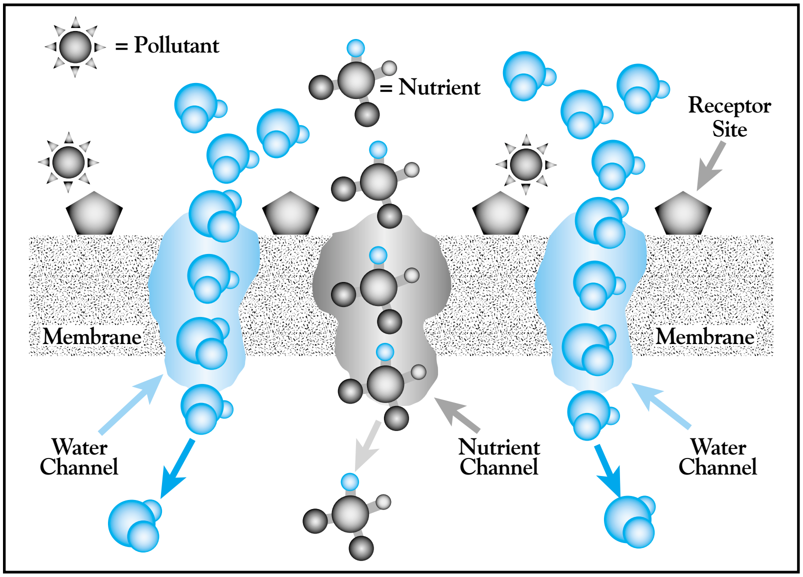


Image courtesy of Jana Safarik, Orange County Water District

A modern thin-film composite membrane with a modified surface to retard biofouling, as seen in the atomic force microscope.

Will We Make It in Time?

Thanks to funding institutions like the National Water Research Institute and the Joan Irvine Smith & Athalie Richardson Irvine Clarke Foundation, which foster a positive environment for research and innovation, new scientific discoveries are happening at an unprecedented pace. Many of these discoveries are small ones that never make the evening news, but they are nevertheless essential to pave the way for the more visible breakthroughs that we all hear or read about from time to time; therefore, I remain guardedly optimistic regarding the future of the world's water supplies. Yet, our success as one member of an exceedingly complex and interdependent web of life is by no means guaranteed, and it is still possible for us to fail. There have always been strong social forces that discourage missions of discovery or seek to undermine the development and dissemination of new ideas and technologies, labeling them as dangerous or unnatural. It is questionable whether the current levels and patterns of global population growth are sustainable. Certainly, there must be limits beyond which no amount of technology can save us. We simply may be too late. But I do not think so. Human history is replete with examples of ingenious individuals



"Intelligent" water purification membranes of the future will resemble biological systems.

who have made far-reaching changes for the greater good. The discovery of RO membranes represents just one example. There are new breakthroughs every day, but we must remain patient and vigilant and we must nurture the kind of environment that fosters creative thinking, scientific discovery, and technological innovation. Now is the time that we must act; we cannot afford to wait a moment longer to begin to invest in the future of our planet and our children.

Thank You

It is difficult for me to express how deeply moved I am by those of you who have so kindly and unselfishly recommended me for the 2002 Clarke Water Prize. Receiving this recognition for my humble contributions to water science and technology over the past two or more decades means more to me than I am able to express in words alone. Feeble as this attempt might be, I wish to extend my heart-felt gratitude to all of my dedicated friends and colleagues in the water sciences – it is you who deserve this recognition. No matter what we endeavor to accomplish, none of us functions in a vacuum, and we are all forever indebted to those who have paved the way before us. It is with this thought that I want to thank a number of friends who have intersected my life and who have taught me what is important and true.

I shall begin with a true genius and eternal skeptic, Don Phipps, who regularly and convincingly demonstrates to me the depths of my ignorance. I want to thank Jana Safarik for reminding me that some of my really wild ideas should remain just that; Grisel Rodriguez and Menu Leddy, who demonstrate every day that science advances though diligence, perseverance, and being happy even in dark times; Tom Knoell for being my running partner and biopolitical mentor for so many years; Ken Ishida for simply being the superb scientist and critical thinker that he is (he has few equals and has set the bar high); Richard Bold for his wit and humor, without which the world would be the worse off. I include these people as part of my family and wish the best for them.

To my friend Hans-Curt Flemming, I offer special thanks, for he remains the magician whose powers

I envy and that I aspire to. I am also indebted to my dear friends Greg Robinson, Bob Riley, Gabriela Schaule, Randall Skelton, Roy Wolfe, Donna Ferguson, Dierdre Sims, Jim and Paul Van Huan, Dave Butler, and Mauri-Lynn Heller, who have always been there for me when the chips were down. I fear that I shall never be able to fully repay them for all they have given me.

I must also mention Andrew Lichtman, Barb Heatherly, and Debbie Van Huan who, on many a run together along the Santa Ana River, kindly shared their life-affirming wisdom and philosophy for the betterment of my soul. Helene Baribeau, Paul Philips, Paul Burns, Ron Doggett, and Chuck Pendleton constitute the gangly crew and kindred spirits that gave me the wings to truly fly and, for this, I am forever in their debt. I want to thank my family (Suzanne and Jim), who keep me grounded, and my late parents, who gave me the wisdom and courage to pursue what I love. I wish to thank my mentors and my heroes, Beatrice Kelly, Ralph and Lanna Lewin, Ken Nealson, Melvin Simon, Michael Silverman, and Betty Olson for so tolerantly leading this stray horse to water even if he did not always drink.

I must also extend my sincerest appreciation and gratitude to the past and present Board members and dedicated staff of the Orange County Water District. Besides so graciously tolerating my presence among them, it was their vision and conviction that helped shape a vibrant and challenging research environment that allowed new and unproven ideas to flourish. A greater and more forward-looking organization would be hard to find.

Most of all, I wish to express my thanks to the Joan Irvine Smith & Athalie Richardson Irvine Clarke Foundation for its gracious and visionary support of the Clarke Water Prize and for acknowledging the critical importance of water for one and all.

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