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When Water Science Meets Water Technology

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IMAGINE TWO KINGDOMS, a large one surrounding a small one. A stockade encircles the smaller kingdom, the Kingdom of Water Science. Inside the walls, laboratories hum with excitement at new discoveries. Scientists send emails to their colleagues and publish in the journals that other Scientists read.

Every once in a while, the Scientists climb to the top of the walls to survey the kingdom that surrounds them. From the ramparts, they see its rolling hills, vast water resources, factories, and pollution. They worry whether the water will last — whether the pollution will eventually overwhelm the natural goodness of the water. They, in the self-contained Kingdom of Water Science, are utterly dependent on the surrounding land, and their work would seem pointless if they could not share what they learn with those outside.

To make sure their work reaches those who need it, the Scientists train eager apprentices. These acolytes struggle to make sense of the new words and elegant principles they must learn. When they have learned the rudiments of the language and principles, they are sent back out into the other kingdom — the Kingdom of Water Technology.

Carrying their boxes of textbooks, theses, and parchment degrees, the apprentices file through a single portcullis, a gate in the immense walls. Once outside, on the lush and fertile plain, a few turn and stare back at the intimidating walls. They hope they do not forget the hard-earned knowledge they have acquired. But, as is the way of the Kingdom of Water Technology, these apprentices soon discover that other things matter here. They must adjust their language and thoughts to the "Real World," as they now call it.

To translate their new discoveries into the arena of Technology, they find they need money — money for the large treatment plants that will keep rivers clean, money to clean up aquifers. They discover that money comes from government, and that politicians are a fractious lot, bickering over how to spend the money and wanting to ensure that none is wasted on "new ideas" that won't work. When the apprentices put their ideas before industry, they learn that industrial money and patience are in short supply, too.

For support, the apprentices — still eager to apply their knowledge — go to see colleagues who have worked in this Kingdom of Water Technology for years. They try to tell the old-timers about the latest discoveries. But the old-timers look up at the walls and shake their heads.

"Nothing worthwhile comes out of there. The Scientists aren't in touch with the Real World."

My presence here, I hope, is a sign that Scientists do come out. I am gratified to receive the Athalie Richardson Irvine Clarke Prize for Outstanding Achievement in Water Science and Technology because I see myself standing at the gate where Water Science meets Water Technology. I try to speed up the flow, so that all the valuable discoveries inside the walls reach those who work outside. And, I want information to flow in the other direction. Scientists need to be stimulated by the problems that need solving.

For the past 20 years, Dr. Rittmann has built a such an impressive body of research that, at present, he is among the most highly respected researchers in the field of water quality. His methods for cleaning up contaminated drinking water, wastewater, and groundwater, as well as his specialization in the biodegradation of common water contaminants, have earned him numerous honors.

Dr. Rittmann's strong commitment to the advancement of water research is indicated by his extensive involvement with numerous organizations, such as acting as former Chair of the National Research Council's Committee on In Situ *Bioremediation and as former President of the American Association of Environmental Engineering Professors. Currently, he is the John Evans Professor of Environmental Engineering at Northwestern University in Evanston, Illinois.*

As gate keeper, I (and others like me) do three things:

- Identify scientific concepts and tools for technology to use.
- Determine how technology can be developed from these new discoveries.
- Return to the scientific realm questions for fundamental research.

In my case, I also carry out fundamental research needed to answer these questions.

With information flowing rapidly in both directions, water technology should advance quickly. But, when I look at what should be a rapid two-way exchange, I see a bottleneck at the gate. I will give you two personal examples of this bottleneck and suggestions about what we can do to get things moving.

Biological Drinking Water Treatment

In 1984, Professor Vernon Snoeyink and I published an article in *Journal American Water Works Association* called, "Achieving Biologically Stable Drinking Water." This article described how biodegradable materials in drinking water (called biological instability) promote the growth of bacteria. When consumers turn on the tap, they detect taste, odor, or turbidity problems. This poor water quality is caused by the bacterial growth that occurs during distribution. Biological instability also accelerates corrosion, a big problem for water distributors.

The article pointed out that biofilm reactors can remove biological instability. In fact, European countries were already using biofilm systems to treat their water.

While water companies in Europe had used biofilm treatment for years, they did not understand exactly what made it work. They simply pumped water through riverbanks, sand beds, or gravel filters. They saw that the water did not create problems during distribution, and they began installing the new technology in their plants.

The Europeans still had no theoretical basis to help them design a system of the right size and type for the job at hand. The article that Snoeyink and I wrote provided the missing theoretical link.

It has taken nearly 10 years for the water industry in the United States to accept biofilm treatment — even though Europe was using it, and even though the science underlying the technology was laid out in 1984. In 1994, biofilm treatment is finally being used in the United States, in particular in Southern California. Why now? What opened the door for this new technology?

I would only be flattering myself if I thought that the driving force came from people reading my papers on biofilm treatment. The real impetus in this case, as always, comes from the Kingdom of Water Technology — the Real World.

The most important push came from government regulations. The United States Environmental Protection Agency (EPA) is changing its regulations and beginning to place stricter limits on concentrations of disinfection byproducts, such as the trihalomethane chloroform. To meet the new standards, water utilities must reduce the amount of chlorine added to water because chlorine reacts with natural organic matter to form trihalomethanes and a range of other chlorine-containing molecules. As utilities make this change, they are finding out that the principal benefit of high residual chlorine was to suppress microbial growth otherwise spurred by biological instability.

Now that water companies can no longer meet EPA targets by adding large doses of chlorine, they need to look for another way to stop microbial growth. They are beginning to think more favorably about biofilm treatment as one stage in the treatment process.

In biofilm treatment, water passes through a bed of rocks, gravel, sand, or activated carbon. Soon, microorganisms attach to the surfaces and biodegrade compounds, causing biological instability. Otherwise, the biological instability goes straight into the distribution system, creating quality problems at the consumer's tap.

The biofilm process uses biodegradation reactions that occur naturally, such as in a stream bed. The biofilm process simply allows the natural biodegradation reaction to occur in a small controlled reactor instead of during distribution, where it creates water-quality problems.

Southern California has a particularly pressing need for biofilm treatment. Population increases in the arid West are forcing utilities and municipalities to exploit low-quality sources. Raw waters from sources such as the Colorado River, California Water Project, and some aquifers are high in undesirable components, including dissolved organic carbon (DOC), color, and biological instability.

To make this low-quality source acceptable to consumers, water companies are using ozone treatment. Ozone disinfects and removes color, along with other benefits. But it also generates even more easy-to-biodegrade organic material. When ozone treatment is used, biofilm technology is essential to keep biological instability from causing problems.

Fortunately, biofilm science and water technology "met" about 10 years ago. Although the 1984 article and subsequent works could not drive interest in biofilm treatment, they are part of the two-way exchange at the gate. Today, we understand the scientific basis for the process. We know that a technological solution works. Now we have the tools to provide safe and aesthetically pleasing drinking water without creating problems from disinfection byproducts or bacterial growth.

Characteristics of Water Science and Technology in America

Despite the recent enthusiasm for biofilm treatment of drinking water, I wonder why it took a decade for the technology to appear in treatment plants — and, we are just at the beginning. Why did it take 10 years for the water industry to take a serious look at this new technology?

In contrast, innovations in electronics, communications, computers, automobiles, and health care bombard the marketplace. Companies are on the lookout for new technologies. Innovation makes these industries thrive.

Why the bottleneck in the water industry? Without question, we in the water industry have many of the ingredients necessary for rapid innovation.

The Kingdom of Water Technology has pressing needs, always the parent of invention. For example, we know water distributors must produce biologically stable drinking water without heavy chlorination. We need to clean up contaminated groundwater and rid our water sources of hazardous chemicals. To supply increasing demand in arid regions, we need to improve wastewater reuse.

Fortunately, the Kingdom of Water Science has helped provide the "people resources" to find answers to our most pressing needs. We have a pool of well-educated and motivated professionals eager to solve challenging problems.

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We have the most sophisticated and productive network of researchers in the world; students, post-doctoral associates, and visiting scholars flock to our universities and other research laboratories to receive the most advanced technical experience available. We produce the greatest number of technical papers. And, our educational system provides the best balance of scientific fundamentals and technical practice.

In spite of these ingredients, innovation in our field is slow. This paradox spurred me to consider characteristics of the Water Science and Technology arena that slow down innovation. What structural "bottlenecks" keep innovations from reaching the marketplace in a timely manner?

Four things make innovation slower than in some other fields:

- A "messy" system.
- Insufficient capital accumulation.
- No high-value product.
- Inadequate attention to intellectual capital.

First, Water Science and Technology are "messy" because they operate in the natural environment. Environmental systems deal with complicated mixtures of organic and inorganic molecules, microorganisms, and debris created and mixed together by nature, not by us. We have limited control over what enters our systems for treatment. Our raw materials frequently keep changing their temperature, concentrations, and makeup. Unlike chemical engineers, automotive engineers, or electrical engineers, water engineers cannot specify their raw materials or work in clean, sterile factories.

The result of all this natural messiness is that water scientists and engineers must spend much of their efforts in "detective" work, trying to characterize what is coming down the pipe. Furthermore, they must design and operate highly robust systems that can tolerate unexpected changes and still deliver a good product. All this messiness may make water science appear less elegant. Certainly, messiness makes technological innovation more difficult than it is for "cleaner" systems.

The second factor I see is a lack of capital accumulation within the environmental field, particularly in the United States. We have a large number of consulting firms and small, specialized vendors of environmental equipment and services. In the United States, we do not have a

Kurita or *Hitachi*, as in Japan; a *Societe Lyonnaise des Eaux*, as in France; or a *Daewoo*, as in Korea. These companies command large financial resources and integrated research, development, design, and operation. To make rapid progress towards innovation in the water business, a country or firm needs to invest major financial resources and be able to coordinate the ever-necessary meeting of Water Science and Water Technology. The country or firm needs to apply fundamental research to practice and stimulate research with feedback from practice.

Unlike the automobile, electronics, or health-care sectors, the water industry does not provide a high-value product, the third factor affecting the pace of innovation. Even our most precious commodity — safe drinking water from the tap — is priced at bargain prices, just a few dollars per thousand gallons.

Why are unit costs low? One reason is that our society will not allow the cost of something so essential as water to be unaffordable for a significant fraction of its citizens. The key to affordability has been a low unit price, and water engineers have been remarkably clever at finding ways to mass produce treated water at low prices.

While a great triumph of technical skill, the success at mass producing a low-cost product leads to a serious long-term problem: insufficient investment. Large capital resources are needed to ensure that new challenges are met in a timely and reliable manner. Our emphasis on keeping yesterday's price low is one cause of today's dilemma — insufficient capital accumulation.

The fourth factor in the slow pace of innovation is that too little attention is given to developing the intellectual capital that allows Water Science and Water Technology to meet, particularly in the most critical early stages of development. This is not a problem unique to the United States, but Americans seem less aware that a problem exists.

One of the ironies of my career is that the results of my research and publications in the area of biofilm processes are recognized and, more importantly, directly applied much more enthusiastically in Japan than they are in my home country.

I have many experiences that illustrate the Japanese enthusiasm for developing intellectual capital. A few years ago, I was visited by a busload of Japanese engineers. They were on a discovery mission to the United States to learn about new research and applications of biological treatment. I was one stop on their travel itinerary. I will never forget this visit. At the end of our discussions and laboratory tour, all 15 Japanese crowded around me in my office, which wasn't that big, to take a photograph documenting that they all had met with me. I think they need these photographs to get their travel-expense reimbursement. This photo opportunity reminds me of them seeking sources of new information, asking questions, taking notes, and getting pictures.

I have a steady flow of requests from abroad to place visitors in my laboratory. Visitors want to stay for a month, 6 months, 1 year, or 2 years to learn in-depth the concepts and tools we use in making water science meet water technology.

A critical piece of information is that these visitors come with full funding from their government or a private firm. Within the past couple years, requests have come from Japan, Korea, France, Spain, Switzerland, Germany, and Canada. Similar requests from the United States are minimal. This difference suggests that at least some of our competitors from abroad are more willing to invest in the intellectual capital needed to make Water Science meet Water Technology.

In Situ Bioremediation: When Does It Work?

During the past year, I completed my tenure as Chair of the Committee on *In Situ* Bioremediation for the National Research Council (NRC). The committee's findings are published in *In Situ Bioremediation: When Does It Work?*, a book available from the National Academy Press in Washington, D.C. The committee's work represents another outstanding example of making Water Science meet Water Technology.

Despite having great potential for being a cost-effective and low-risk method for cleaning up groundwater and soils contaminated with organic chemicals, *in situ* bioremediation has been applied in only a small fraction of site remediations. Why is it that a technology that promises to cut cleanup costs by a factor of 10 or more is not implemented with greater enthusiasm? Once again, why is innovation so slow? When we began our NRC study, we identified two reasons.

First, most of the key decision-makers do not understand the microbiological and engineering bases for bioremediation. Most hydrologists, engineers, regulators, and business managers are ignorant of and, therefore, leery of processes involving unseeable microbes having unpronounceable Latinate names and carrying out esoteric-sounding reactions. Likewise, microbiologists are baffled by engineering, geology, and regulations.

Second, the bioremediation business had taken on an unsavory reputation, one associated more often with "snake oil salesmen" than with solid microbiological and engineering principles. But, there are microbiological and engineering principles underlying *in situ* bioremediation. In fact, one dilemma is that there are too many principles. Even experts in one aspect of bioremediation cannot easily "catch up" on all the important principles.

The NRC study I chaired was focused directly on the gate where Water Science meets Water Technology. To clear the bottleneck, we had to connect the practice of bioremediation with its underlying principles. We needed to establish sustained and substantive communication between the leaders from both Kingdoms. We had to focus that communication on the most important issue. And, we needed to tell the right people about our conclusions.

The Committee on *In Situ* Bioremediation included 14 experts from all phases of science and technology: scientific research in several disciplines, including engineering, field remediation, government regulation, and user clients. Meeting intensively for a week, we forced science and technology to meet. Through this "gatekeeping" process, we came to a clear consensus concerning the questions that were our charge:

- Can *in situ* bioremediation work?
- If so, can its success be evaluated?
- What guidelines are necessary for designing and carrying out an evaluation?

The report begins by describing the scientific bases for bioremediation. For example, the report describes how the main agents for bioremediation are bacteria, roughly 1 micrometer (μm) in size. Through chemical reactions, the bacteria transform organic contaminants into innocuous products.

Most below-ground contaminants are not dissolved in water, but trapped in the soil — a long-term source of contamination to the water. The report describes how bacteria, attached to soil, biochemically transform the contaminants that have dissolved into the water. When the numbers of bacteria are large enough, they can transform the contaminant as fast as it leaves the source of contamination.

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The key is that conditions must be right for the bacteria to thrive. Bacteria, like humans, need to eat and breathe. While bacteria do not use mouths, some "eat" the contaminants we wish to eliminate. Although bacteria do not use lungs, they "breathe" oxygen or another molecule that serves the same purpose. Eating and breathing generate energy that the bacteria use to grow and sustain themselves. They then can do our work — destroying hazardous chemicals.

In addition to eating and breathing, bacteria also need to avoid stress. A pH too far from neutral or the presence of toxic materials are stressors that can inhibit bacterial growth and their ability to do the work of detoxification.

If all of the conditions to encourage bacteria are not present at a cleanup site, engineers can alter conditions to make the environment more favorable for the bacteria.

The report explains the technologies currently used to perform *in situ* bioremediation. I will not go into details, but will highlight one extremely valuable distinction coming from our meeting of science and technology.

The report explicitly recognizes that *in situ* bioremediation can be carried out in two distinct ways having two different goals. *Engineered bioremediation* adds food and oxygen to the subsurface, speeds up biodegradation, and makes the trapped source disappear quickly. With *intrinsic bioremediation*, on the other hand, the goal is to contain the source of contamination. We simply use microorganisms that are already in the ground to prevent the dissolved contaminant from going very far. Intrinsic bioremediation does not make the contamination disappear faster, but prevents the contaminants from coming into contact with people.

The most important "take home lesson" in the book is our strategy for evaluating bioremediation. Field sites are complex. Measuring contamination levels below ground is difficult. Detecting whether or not microbial activity is occurring is also difficult. How can we be sure bioremediation is successful?

The Committee agreed that three kinds of evidence point to a successful remediation:

- Documentation from field samples that the contaminant is being removed.
- Documentation from laboratory studies or peer-reviewed literature that the contaminant has the potential to be biotransformed under the conditions expected at the field site.
- Several pieces of evidence from field samples demonstrating that the potential for biotransformation is actually realized in the field.

Surprising as it may seem in retrospect, evaluation protocols used prior to the NRC book seldom included the third type of evidence — the use of field samples to prove that microorganisms are the cause of contaminant cleanup. Since regulators require field evidence before they accept any remediation scheme, application of the evaluation strategy is crucial. The report provides scientifically based guidelines that recognize the realities of field sites. This meeting of Water Science and Water Technology should speed the use of *in situ* bioremediation.

What Now?

Making Water Science meet Water Technology is the surest way for us to create innovative processes that are reliable, cost-effective, and quickly put into practice. How can we help the two-way exchange at the gate between Water Science and Water Technology go as rapidly as possible?

Based on my own experiences, I believe that the most important factor for making Water Science meet Water Technology is that the gate become a focus for attention and resources. Getting leaders from Water Technology to work closely and continually with experts from Water Science does not come for free. Here are some specific ideas.

First, I am greatly encouraged by the recent development of industry-supported research organizations, including the National Water Research Institute, American Water Works Association Research Foundation, and Water Environment Federation Research Foundation. Bringing industry resources directly into the research-funding arena goes a long way towards providing financial capital for the science half of the equation. Furthermore, industry may be more inclined to use the fruits of research if it helps define and fund the research.

On a second front, Americans need to scout the rest of the developed world for good ideas. Perhaps organizations like the National Water Research Institute or EPA would sponsor high-level discovery missions to Japan and Europe. The Japanese are not the only ones who can send busloads of technical experts armed with cameras and notebooks. America is not the center of the world when it comes to all aspects of water science and technology. We can learn plenty from the experience and ideas of others. We should be alert and eager to adapt the ideas of others to our own needs.

Third, perhaps the water industry should shift its emphasis towards product quality and away from low pricing. Prices for water services need to include investments that ensure the processes we use today and tomorrow are founded on the best scientific and technological knowledge available.

Finally, we need to invest in those activities that allow us to provide a high-quality service today and to respond effectively to the next generation of challenges. It is at the gate between the two Kingdoms where we most need to work together. Opening the heavy door at the portcullis is hard work. It requires pushing or pulling from both sides. Only when the door is opened and kept open does Water Science meet Water Technology.

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