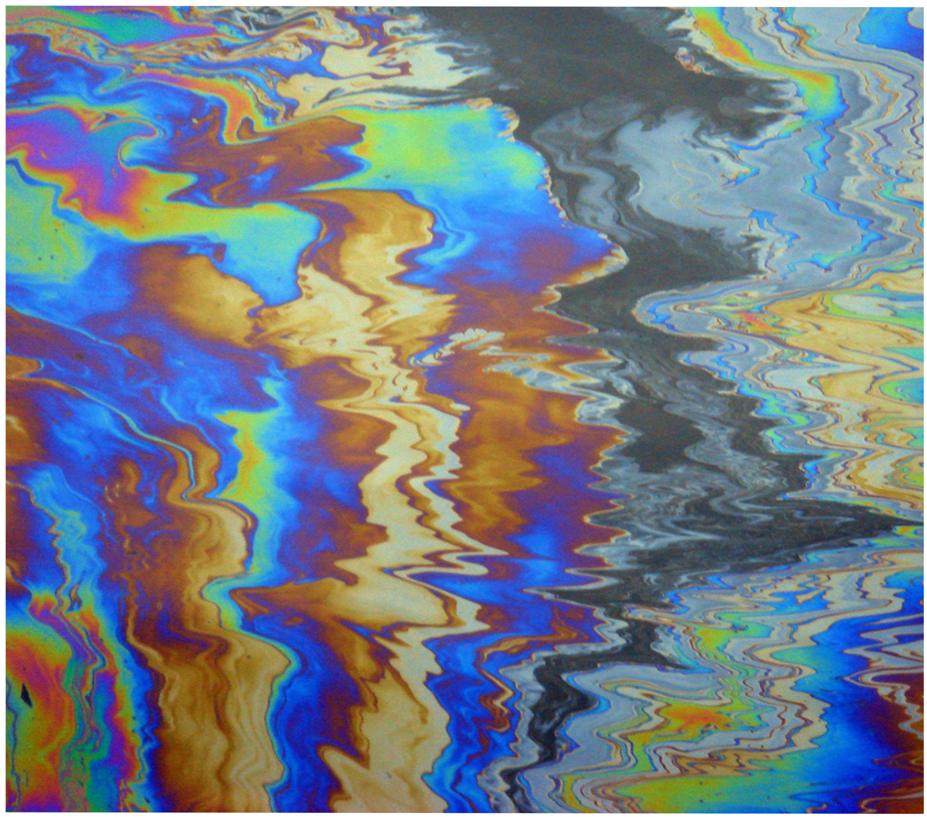
Murky Waters: Two Princeton Professors' Research into Water Purification Methods

BY CLARE MARTIN '21

In November 2015, the Environmental Protection Agency advised citizens of Hoosick Falls, NY to abstain from drinking or cooking with water from the village's water supply due to dangerous levels of perfluorooctanoic acid (PFOA),[1] a chemical found in consumer products, such as non-stick pans and stain-repellent clothing.[2] In January 2016, the city of Flint, Michigan began receiving federal aid for its lead contamination crisis.[3] These instances of water contamination are just a few examples of the issues facing the United States when it comes to improving water quality. According to a 2010 report published by the Environmental Working Group (EWG), 35 U.S. cities' water supplies contain the probable human carcinogen, chromium-6, and a 2016 study conducted by researchers at Harvard University revealed dangerous levels of a family of carcinogenic industrial chemicals in 33 states' drinking water.[4]



New Jersey is not immune to the water pollution issues plaguing the nation. A recent study published by EWG, which analyzed data collected from 2010 to 2015 on the presence of toxic chemicals in 48,712 U.S. water utilities, found that the prevalence of PFOA in New Jersey exceeded that in any other state.[5] Twenty-five utilities serving 1.6 million people reported concentrations of PFOA above health guidelines of 1 part per trillion (ppt), as defined by EWG.[2,5]

Normally, water destined for human consumption undergoes a five-step purification process at a water-treatment plant. Untreated water coming from either groundwater or a reservoir is first screened for large contaminants, such as wood or fish.[6] Next it is coagulated, resulting in the deposit of sediment at the bottom of a tank.[7] The water stream then passes through a series of finer filters that separate out smaller solid particles and some microbes.[7] Finally, the water is disinfected by the addition of chlorine, which kills any remaining microbes, and stored before distribution to homes and businesses.[7] This process, however, is limited in that filters require regular cleaning to prevent the accumulation of solids that may clog filters. The maintenance of filters is an added cost that a filter-free process can avert.

Water that does not originate from a reservoir, but rather, from sewers—known as wastewater[7]—must also undergo a purification process before it is directed to a reservoir from which potable water may be derived. The three-stage process involves the separation of large solid particles from water (primary treatment), the addition of bacteria to degrade organic compounds (secondary treatment), and the removal of specific contaminants, such as nitrogen or phosphorus, and the disinfection of water through addition of chlorine (tertiary treatment).[8,9] Yet normal nitrification via ammonium oxidation during secondary

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treatment requires the aeration of water, an expensive step, to provide aerobic bacteria access to oxygen.[10] At the disinfection stage, certain organic compounds that enter the water table due to human activity, such as PFOA, can evade removal.[5]

Mechanical and Aerospace Engineering Professor Howard Stone and Civil and Environmental Engineering Professor Peter Jaffe are currently researching ways to improve the treatment of water for drinking and the treatment of wastewater that enters lakes and rivers.

CHEMICAL WATER PURIFICATION

According to Stone, the invention of a chemical purification system involving CO_2 rather than a physical filter serendipitously emerged as an "outgrowth of another project." About four years ago, a colleague in industry, Patrick Warren, approached Stone to discuss the role of ions in manipulating particles in porous materials.

For several years, Stone's lab group collaborated with Warren on better understanding this physical process. The group included then postdoctoral researchers Sangwoo Shin and Orest Shardt, who co-led authorship of the resulting paper published this past spring, "Membraneless water filtration using CO_2."[11] Their project began with an analysis of the chemical gradients that ordinary salts, such as sodium chloride and potassium chloride, induce in water. These gradients, Stone explains, can cause small particles called "colloidal" materials to move. Colloids are heterogeneous mixtures of particles between 1 and 1000 nanometers in size;[12] they cannot easily be separated by filtration,[12] necessitating an alternative method of purification.

From the research on colloid behavior in static systems, systems in which there is no fluid flow, Shin and Shardt realized that if it were possible to create ion gradients in water using salts, then it was also possible to do so by dissolving gas, like CO_2. This technique could be applied in a flow situation, such as the removal of particles from water. When CO_2 dissolves in water, a portion of the CO_2 reacts to form carbonic acid, H_2CO_3, which dissociates into a proton, H^+, and a bicarbonate anion, HCO_3^-. The ions begin moving through water at different speeds because of the difference in their sizes, and this movement establishes an electric field.[13] Particles introduced into the stream of ionized water are attracted to either the region of positive electric field or the region of negative electric field, thus allowing the separation of the stream into two: one containing the waste particles and another containing the purified water.[13] Exposure of the water stream to air allows the removal and recycling of CO_2 for subsequent purification.[13] In addition to circumventing the costliness of filter replacement, this system is at least 1,000 times more energy efficient than conventional filtration methods.[13]

Although Stone envisions the practical applications of his lab's proposed system in the future, the popularity of filtration systems in industry may pose a barrier to the invention's takeoff. "People I've talked to in industry suggest that one use of the kind of technology we're working on, if we were to ever advance it further, might be to put it upstream of a filter to reduce the particulate stress on a filter," he says, acknowledging that "it's unlikely they're ever going to take a filter out of a system." While the system currently targets the filtration stage of water purification, Stone hopes that his lab's invention could eventually remove bacteria from water to mitigate stress on the disinfection stage of water purification.

BIOLOGICAL WATER PURIFICATION

In addition to the chemical purification research taking place on campus, biological methods of water purification are currently under development in Jaffe's lab. According to Jaffe, while examining how nitrogen runoff from agricultural lands affects the "cycling of iron and indirectly the retention of various trace metal pollutants" in river wetlands at the Assunpink Wildlife Management Area a few years ago, his lab discovered that the bacterial strain Acidimicrobiaceae bacterium A6 can oxidize ammonium under iron-reducing conditions. During this anaerobic process, which is controlled by a pathway called Feammox, ammonium consumed from water reacts with iron to produce nitrite in the presence of an enzyme. However, due to the co-metabolic nature of this enzyme, a portion of it is lost to other metabolic processes within the bacterium.

Jaffe's lab seeks to harness the unspecific nature of this enzyme to promote the conversion of toxic substances other than ammonium, such as trichloroethylene (TCE)—a commonly used manufacturing solvent and suspect carcinogen[10,14]—to digestible forms. When TCE is present, the bacterium's enzyme inserts an oxygen atom into some of the TCE molecules rather than the ammonium molecules. TCE then "steals" some of the Feammox enzyme that the bacterium expended energy to produce. The resulting spontaneous breakdown of TCE epoxide molecules into innocuous carbon products inconveniences the bacterium but is a boon to humans. Other anthropogenic contaminants Jaffe and his lab intend for the Feammox pathway to target are uranium and arsenic, elements that occur naturally in soil but are mobilized to enter the water table through human activity, such as mining. In the case of uranium, the bacterium does not digest the element, but rather, converts soluble uranium hexavalent to insoluble uranium dioxide, which may then be harvested out of water.

The next step in Jaffe's research is determining how to produce the Acidimicrobiaceae bacterium A6 in large quantities—10^9 cells per cubic centimeter of water—for injection into an environmental contamination site, a process called bioaugmentation.[10] If this is successful, many questions will follow. To what degree is bioaugmentation possible? Does bioaugmentation effectively reduce the concentration of water pollutants? What is the range of contaminants possible for degradation?

WATER POLLUTION AT PRINCETON

Investment in water purification methods extends beyond Princeton's research labs, as the university uses various water purification methods, such as sand filters, carbon filters, softeners, a reverse-osmosis system, and demineralizing systems, to filter water on campus.

Caroline Savage, the Campus as Lab Manager of Princeton's Office of Sustainability, explains that Princeton University Facilities are "monitoring a few key locations at various points along our watershed to assess what type and what quantity of pollutants our watershed might contain, and to what extent Princeton University is contributing to that pollution." Although the study is in its nascency, the preliminary results appear promising. "Phosphorus and nitrogen are higher than we would like for them to be, but not at alarming levels, and occasionally Total Suspended Solids [solids in water that can be caught in a filter][15] have also been higher than we'd like, but those are the only 'pollutants' we're seeing as a result of this study," she explains over email.

The findings of the EWG study do not surprise Jaffe, who views the pollutant stress on New Jersey's waters as a side effect of the state's density. "A lot of stuff falls on roads that then washes off into streams. People put a lot of products on their lawns that wash into streams," he says.

Jaffe believes the real concern lies with new contaminants that lack regulation and careful appraisal by researchers. "[I]t is possible that there may be something in our drinking water and in other states and locations, too, that we are not fully aware of, that we haven't done all the toxicological studies [on], and therefore it's not yet regulated," he says.

ASSESSING WATER QUALITY IN THE FUTURE

Looking toward the future of their research projects, Stone and Jaffe cite their main research obstacle as translating methods perfected in the lab to the real environment. Stone explains that the challenge of scaling up models and systems is a challenge "present throughout science and engineering." In the case of his lab's method of CO_2 water filtration, Stone concedes that his lab did not investigate the effect of CO_2 and water with salts or other chemicals on the separation of particles into a waste stream. In future studies, "how those other chemicals will affect this process is a question that we would have to answer."

Similarly, Jaffe explained that shifting from mere theory of the Feammox pathway to administering the bacterium to water systems will be the subject of further study in years to come. "It becomes often the big jump," he adds, "that we can do something in test tubes in the lab, but can we go through the field and still control the process? That is the hard thing where many things fall apart."

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