PROFILE

Fathoming the Chemistry Of the Deep Blue Sea

In the distinguished career of ocean chemist Peter Brewer, his startling new research on carbon dioxide may make the most waves

MOSS LANDING, CALIFORNIA—Peter Brewer doesn't usually talk about windmills. His hot topic these days is carbon dioxide—specifically, how to store the greenhouse gas in the deep ocean. That tactic might slow the buildup of CO_2 in Earth's atmosphere, but many people are dead set against even testing it. They cite the dangers of perturbing the sea and the risks of harming wildlife. Some of their arguments puzzle Brewer, and that's where the windmills come in.

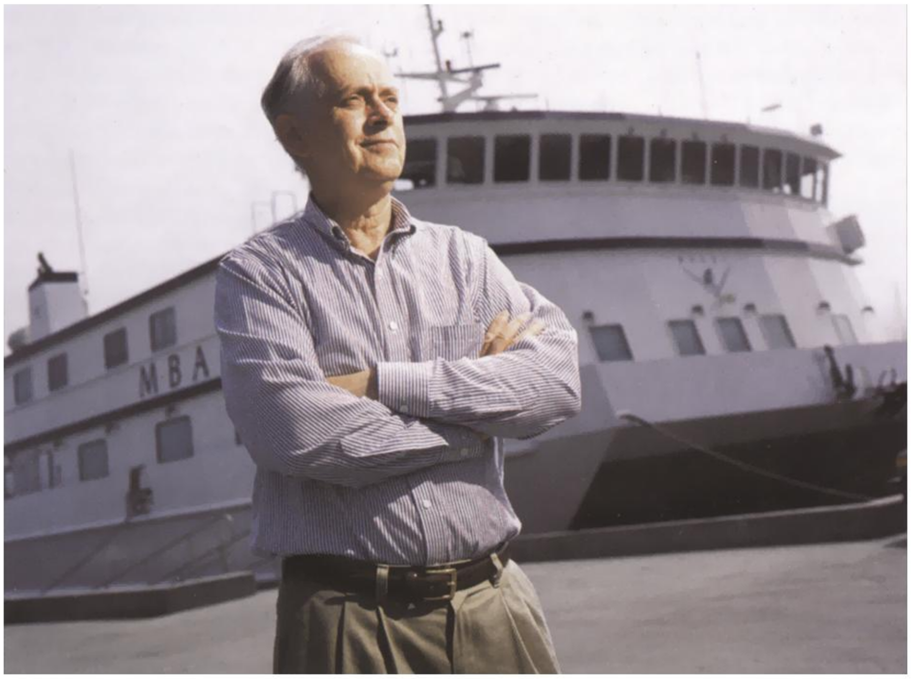
"People say, 'I vote for renewables,' but look at this," he says, displaying a recent column in the *San Francisco Chronicle*. Brewer supports green energy, but the column reminds him that no option is squeaky clean—not even wind power. "Wind turbines at Altamont Pass have killed 1025 birds, including 149 golden eagles," he says. "We have video of fish swimming up to a blob of liquid CO_2 on the sea floor and happily chowing down on worms, but if an eagle flies up to a windmill, it dies. If I'd killed 149 eagles, I'd have the world on my case."

The responsible thing, Brewer says, is to do both: Pursue alternatives to fossil fuels and try to squirrel away some of the CO_2 that nations will keep churning into the air. After all, he notes, the upper ocean already soaks up millions of tons of CO_2 each day, so a grand test of how the sea will respond is under way, like it or not. "We need to be levelheaded about this issue," he says. "Maybe the deep ocean is a better place for CO_2 than the atmosphere or the surface ocean, but we don't know yet. Until we ask the questions in an objective way, we won't get reasonable answers."

Brewer, age 60, is speaking in his impeccable office here at the Monterey Bay Aquarium Research Institute (MBARI). His windows overlook a sweeping beach and the ebbs and flows of what he calls "the greatest fluid on Earth." Pelicans soar past, momentarily obscuring the horizon. Over that horizon, beyond the Monterey Bay National Marine Sanctuary, lies a spot 3.6 kilometers deep where Brewer and his colleagues are conducting experiments unlike any others in the world.

At the crushing pressures on the ocean floor, CO_2 combines with seawater to form odd, semiliquid compounds called hydrates that should slowly dissolve into the abyss, segregating the gas from the atmospheric part of the global carbon cycle. On three cruises during June and July, the team set up the first controlled tests on the unpredictable nature of CO_2 hydrates. The sea-floor lab, erected by a remotely operated vehicle (ROV), included time-lapse cameras, pH probes, and several pens to observe the reactions of animals to the strange brew. The results, now being analyzed, should help shape the growing debate on whether society can handle its CO_2 problem by shoving some of it out of sight.

"The sense is that [ocean sequestration] is technologically feasible and that it's effective for hundreds of years if it's deep enough," says climate modeler Ken Caldeira of Lawrence Livermore National Laboratory in Livermore, California. "The big question, and the potential showstopper, is biological impact. Those kinds of experiments are really important, and without Peter they wouldn't be done."



Go west. Peter Brewer stands before the *Western Flyer*, MBARI's $22 million ship.

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Liverpool to Woods Hole

Probing the sea hardly crossed Brewer's mind when he was growing up in Ulverston, a market town in northwestern England. The young Brewer loved walking and exploring nature, but moving vehicles were another story. "I couldn't go 10 miles [16 km] in a car without throwing up," he recalls. "I'm amazed I ended up on a ship." But he did, thanks to ocean chemist John Riley of the University of Liverpool. In his senior year as an unhappy chemistry major, Brewer talked to Riley about ocean sciences. "All of a sudden, life seemed to get better," he says.

His expeditions as a doctoral student at Liverpool were whoppers: two 9-month voyages on the Indian Ocean in 1963–64 as part of an international team. "I was graduate student slave labor, and it was immensely tedious. We did thousands of measurements by hand," he says. The final data, taken in the Red Sea, exposed a deep pool of hot and salty brines. Brewer's first paper, published with co-workers in *Nature*, described what others later identified as the world's first hydrothermal vents.

The tedium Brewer experienced on those first cruises led to his lifelong focus on building automated instruments to study the ocean and to nail data beyond doubt. "He has pushed the community to be meticulously accurate in its measurements," says oceanographer Mary Scranton of the State University of New York, Stony Brook, one of Brewer's students. "He forced people to worry about the analytical details and to make sure their answers were right to the fifth decimal place."

Brewer's research on the Red Sea brines caught the attention of John Hunt, chemistry chair at the Woods Hole Oceanographic Institution (WHOI) in Massachusetts. Hunt recruited Brewer, who crossed the pond in 1967 with his wife, Hilary. "Our plan was to go for 2 years," Brewer says. Instead, it became two dozen years as his career took off.

The highlight of Brewer's first decade at WHOI was his work on the Geochemical Ocean Sections Program. On several cruises in the 1970s, researchers derived pictures of 3D circulation patterns in the ocean basins. Their tracers were carbon-14, tritium, radium, and other radioactive isotopes. Brewer became an expert on the chemistry of suspended particles and the ocean's carbon cycle. However, researchers were at an impasse about how to sort the marine CO_2 signal into its various sources and fates.

During a chat with new WHOI director John Steele in 1978, Brewer volunteered to try to identify the imprint of CO_2 in the ocean from the burning of fossil fuels. He devised equations that separated out the biological influences on oceanic CO_2, leaving behind a clean, inorganic signal from fossil fuels. His paper caused an uproar. "The calculation was so simple that it raised suspicion," he recalls. But his method has survived the test of time with few modifications.

The carbon work led to Brewer's primary legacy: the Joint Global Ocean Flux Study (JGOFS). Brewer drove the early stages of this sweeping program, which gave researchers their first global view of carbon flux to the deep ocean and other cycles that link climate to the biogeochemistry of the sea. "JGOFS needed a strong person to move it into the international arena," says Steele. "Peter took that step when it wasn't at all obvious what it would mean for the rest of his career. But it became one of the dominant elements of marine science in the last decade."

A billionaire calls

Unbeknownst to Brewer, another marine force was emerging at the same time. It was MBARI, conceived by the sheer will of engineer David Packard.

Packard, co-founder of Hewlett-Packard Corp., established MBARI in 1987. "He wanted to make an experimental attack on the deep ocean with a world-class lab, the best ship, and the best ROV," Brewer says. It took time to overcome growing pains, including a culture clash between scientists and engineers and turnover among directors. When the MBARI board coaxed a résumé from Brewer in 1990, Packard called him 2 days later. They clicked, and Brewer crossed the continent in 1991 as the new director.

Brewer steered the creation of MBARI's three key assets by 1996: its waterfront lab and office building, the twin-hulled *Western Flyer* research vessel, and the ROV *Tiburon*, which can dive to a depth of 4 kilometers. All told, those big-ticket items cost $52 million, funded by the David and Lucile Packard Foundation. Brewer also broadened the institute's reach beyond Monterey Bay and its dramatic canyon.

Packard's death in 1996 was one factor in Brewer's decision to step down as director. "The death of a billionaire is a traumatic experience," he says. "There was internal strife. After five-and-a-half years, I'd shot off most of my silver bullets." Brewer's management style also caused friction, some oceanographers say. "Peter can be fairly opinionated, and as a result he is not beloved by everyone in the community," one comments. Still, that's not what matters to most researchers. "He has not gone out of his way to be best friends with colleagues, but few would argue with his intellectual integrity and his desire to come up with the right answer," says Scranton.

Nothing's fishy. This Pacific grenadier seemed oblivious to blobs of liquid CO_2 on the sea floor near Monterey Bay last month. Researchers have set up tests to look for more subtle effects on deep-sea life.

CREDIT: COURTESY OF JIM BARRY AND PETER BREWER/MBARI

Indeed, Brewer's standing is evident in "Ocean Sciences at the Millennium," a report issued in May by the National Science Foundation. NSF convened a "decadal committee" of marine scientists and asked Brewer to co-chair it with Ted Moore of the University of Michigan, Ann Arbor. The report, which resounds with Brewer's forthrightness, calls upon NSF and the community to move toward technologically advanced and agile observing platforms to capture the variability of the ocean environment.

Brewer echoes NASA Administrator Dan Goldin when he discusses the report. "We need to have smaller, faster, smarter observing systems that we can deploy to capture complex events," he says. "The old strategy of doing it by brute force has got to yield to more sophisticated ways of measurement and scientific observation. I feel very strongly about that."

Gases under pressure

Brewer's recent work on greenhouse gases in the deep sea is anything but brute. At first he was fascinated by the properties of gas hydrates—high-pressure, low-temperature phases that behave as liquids with icy skins. However, it became clear that the research meant far more than playing with eerie liquid forms of methane or CO_2.

Grim forecasts of accelerating fossil fuel use had led some scientists to ponder the viability of capturing CO_2 in power plant exhaust and pumping it to the sea floor. Italian chemical engineer Cesare Marchetti first raised the notion in 1977, and a few teams worked on models or lab studies in high-pressure vessels, but no one had data from the ocean. Then, a report from the U.S. President's Council of Advisors on Science and Technology in 1997 mentioned sequestration via CO_2 hydrates. That caught the eye of Brewer and his colleagues, including geologist Franklin Orr of Stanford University.

The weird chemistry of the deep ocean was made plain by Brewer's team 2 years ago (*Science*, 7 May 1999, p. 943). That paper—and an accompanying video—showed the unearthly sight of CO_2 hydrates bubbling over the top of a beaker at a depth of 3650 meters and rolling along the sea floor like tumbleweeds. The CO_2 sucked in seawater more voraciously than anyone had thought, and the icy hydrate skin appeared surprisingly impervious. In one striking sequence, a deep-dwelling fish swam up to the transparent blob.

"That little video clip, which he has shown around the world, has had a tremendous impact," says Steele. Adds MBARI oceanographer Ed Peltzer: "If we didn't have this on videotape, I don't think we could convince anybody that we saw it. The images were startling and totally unexpected."

For the latest missions, MBARI engineers developed a new system for the ROV that injects not just a few liters of liquid CO_2, but about 50 liters. That's about as much CO_2 as the United States churns into the air for each citizen, every day. The scientists have just started analyzing the latest oddities, but they can't hide their excitement. One image shows a "frost heave" rising within a corral filled with liquid CO_2—the first evidence that hydrates can penetrate into sediments. Another shows a pH electrode plunging deep into a hydrate blob without breaking the skin, like a finger pushing into a water-filled balloon.

No one can hazard a guess about what all this means for deep-sea sequestration of CO_2. The biological impacts, Caldeira's "potential showstopper," are still unknown. Nearby fishes have shown no ill effects to date, save for one that swam into a CO_2 plume and fell asleep. "From what we've observed so far, it looks pretty good," Brewer says.

However, MBARI biological oceanographer Jim Barry is concerned about potential sublethal effects, such as slower growth rates or inability to reproduce. "There are reasons to suspect that deep-water organisms may be more sensitive to pH changes or CO_2 changes in comparison to shallow-water organisms," he says. To try to discern such effects, Barry placed sea cucumbers and sea urchins into corrals containing CO_2 for about 3 weeks, while others went into control corrals. He'll use genetic analysis to search for impacts.

Beyond biology, policy-makers will weigh many sequestration pros and cons. Not least among them are economics, technological capability, and public acceptance. Brewer hopes his team's data will help keep those discussions on track.

"I suspect most CO_2 probably will be disposed of underground, because it's been done and people are comfortable with that idea," Brewer says. "But we shouldn't exclude the ocean from our thinking. We're already putting 25 million tons of CO_2 into the surface ocean every day through the atmospheric loop. Why is the deep ocean any different? It's a much larger place, and it's far more benign."

Brewer draws guidance from the words of a Japanese student, who spoke at a Kyoto workshop on the ethics of CO_2 disposal. " 'Proceed with caution, and have the courage to stop if necessary,' " he says. "I like that."

–ROBERT IRION

MATHEMATICS

Randomly Distributed Slices of π

Mathematicians slowly circle in on a proof that π's unpredictable digits really are as random as they seem

The digits of π dance about so unpredictably that scientists and statisticians have long used them as a handy stand-in for randomly generated numbers in applications from designing clinical trials to performing numerical simulations. But surprisingly, mathematicians have been completely at sea when they try to prove that the digits of π (or of any other important irrational number for that matter) are indeed randomly distributed. When a number's digits are randomly distributed, you have no information about what any given digit will be even when you know the previous one. Now two mathematicians have taken a large step toward proving π's randomness, perhaps opening the door to a solution of a centuries-old conundrum.

The problem has been around for some 900 years, says Richard Crandall, a computational mathematician at Reed College in Portland, Oregon. But mathematicians have precious little to show for their centuries of work, according to David Bailey, a mathematician at Lawrence Berkeley National Laboratory in California. "It is basically a blank," he says. "It's embarrassing."

The degree of embarrassment is hard to imagine. The overwhelming majority of numbers have digits that are truly random when expressed in a given base—a property called normality. In a normal number, any string appears exactly as often as you'd expect it to—in base 10, the digit 1 appears a tenth of the time, for example, and the string 111 appears 1/1000 of the time. But even though normal numbers are everywhere, and almost all numbers are normal, mathematicians have failed to prove the normality of even a single number other than a handful of oddballs carefully constructed for the purpose. "As far as the naturally occurring constants of math are concerned, like π, the square root of 2, log 2, and [natural] log 10, there are basically no results," says Bailey.

Now Bailey and Crandall have breathed new life into the randomness problem by building on a discovery that flabbergasted the math world 5 years ago. In 1996, Bailey, along with two mathematicians at Simon Fraser University in Vancouver, Canada, Peter Borwein and Simon Plouffe, came up with an algorithm for calculating any digit of π without having to calculate all the digits that precede it—unlike every other known π recipe. If you want to know, say, the 289th digit of π, plug 289 into the formula, dubbed BBP. Out will pop a number between 0 and 1. This number, converted back into base 16, reveals the digit you're after. "It was a pleasant surprise," says Jonathan Borwein (Peter's brother, also a mathematician at Simon Fraser).

The formula looked as if it might help mathematicians solve the centuries-old conundrum of the randomness of π's digits. "If you can stick your hand down into the digits that way, then it's strong evidence that the numbers are independent," adds Jonathan Borwein. This thought struck Bailey when he came up with the BBP formula. "My immediate reaction was, 'Oh my God, this might allow us to work on the normality of π,' " he says. "I was consumed with this."

Bailey and Crandall have now made a hypothesis that formulas such as BBP (except for particularly boring ones) will spit out values that skitter chaotically between 0 and 1 for different digits that get plugged in. If true, this chaotic motion ensures that the output of the BBP formula would be essentially random for any given digit that is plugged in. This, in turn, would mean that π's digits are also random. As the two mathematicians report in the summer 2001 issue of *Experimental Mathematics*, if the hypothesis is true, it would prove not only π's randomness, but also that of other constants that have BBP-type formulas, such as the natural log of 2.

Although their hypothesis is as yet unproven, it has restated the ancient problem in a new language. Instead of attacking the problem with the mathematical tools of older disciplines such as number theory or measure theory, Bailey and Crandall's hypothesis turns the normality of π into a problem of chaotic dynamics—the sort of discipline that attracts applied mathematicians, computer scientists, and even cryptographers.

Jonathan Borwein hopes that this insight will finally allow mathematicians to prove that π's digits are random. "Whenever you recast an old problem in a new language, there's hope that the new language will provide a new impetus," he says. "It can open up better avenues for looking at these things."

But even Crandall himself expects a mere "10% chance of a partial solution" to the hypothesis in the next decade. For mathematicians, apparently, π is not a piece of cake.

–CHARLES SEIFE