Plankton Power

A system that takes advantage of the natural bacterial decomposition of biomass in the world's oceans and seas could not only produce biomethane to replace dwindling supplies of fossil fuels but also, by harnessing the absorptive powers of algae, remove carbon dioxide from the atmosphere.

By Mark E. Capron, P.E., M.ASCE

A report (*Carbon Dioxide Capture and Storage,* by B. Metz, O. Davidson, H. Coninik, M. Loos, and L. Meyer) issued in 2005 by the United Nations Intergovernmental Panel on Climate Change (IPCC) recommends that current annual greenhouse gas emissions be halved by the year 2050. Even if this goal is achieved, atmospheric carbon dioxide (CO_2) concentrations will exceed 500 parts per million (ppm) by volume, roughly double the peak concentrations of the last 650,000 years.

Achieving the IPCC goal of reducing emissions (but still increasing atmospheric concentrations) from 2005's 28 billion metric tons a year to 14 billion metric tons a year won't be easy. Figure 1 shows that replacing all the existing coal power plants in China, the United States, and India with nuclear, solar, wind, or hydroelectric plants would reduce fossil emissions by only 7 billion metric tons a year. This modest but expensive reduction in emissions presumes that the entire world would immediately cease adding new fossil-fueled power plants, motor vehicles, or home heating systems that emit carbon. The world needs to do more than modestly reduce emissions.

Table 1 lists some statistics and calculations on climate change. For example, most climate change solutions are land based, perhaps because most human endeavors are on land. However, 70 percent of the earth is covered with water, and climate change threatens both land and water. We cannot afford to ignore the 70 percent of the earth covered by water. Likewise, we cannot afford to ignore the solar power available there.

Because of our tremendous investment in fossil energy, we can expect the sequestration of CO_2 to be an important component of any strategy to reduce greenhouse gas emissions. Table 1 contrasts two potential carbon sequestering technologies by comparing the storage volume required to pull 200 ppm of CO_2 out of the atmosphere. The 200 ppm is roughly the amount that has been added by burning fossil fuels. While a significant amount of CO_2 could be placed in solution in deep underground aquifers, finding and establishing the suitability of aquifers on this scale would be expensive. In contrast, the earth crust thickness calculations in table 1 suggest that placing liquid CO_2 in the plentiful seafloor ooze could reduce the required storage volume by two orders of magnitude. Also, ocean digesters using plankton to produce pure CO_2 could be located directly above the seafloor sequestration areas.

In general, aquifers are mostly sand with water (or oil or natural gas) filling about 10 percent of the space between the grains of sand. As B. van der Meer explained in the paper "Carbon Dioxide Storage in Natural Gas Reservoirs (*Oil & Gas Science and Technology—Revue de l'IFP* 60, number 3 [2005]: 527–36), the ground temperature increases about 30°C with each kilometer of depth. The higher temperatures counteract the additional pressure from the depth, so the CO_2 (dissolved gas or, rarely, liquid) would be less dense and would tend to return to the earth's surface. Finding suitable aquifer sequestration volumes on the order of 100 m thick under 1 percent of the earth's land area would indeed be a formidable and expensive undertaking.

CO_2 is a liquid denser than seawater at depths below 3,000 m at typical deep ocean temperatures below 5°C. Except for dissolution, it is stable and would remain on the seafloor for millennia. It could be prevented from dissolving into seawater by covering it with seafloor ooze, injecting it into the seafloor, or encasing it. Liquid CO_2 has been found in seafloor ooze at the unexpectedly shallow depth

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Table 1 Select Statistics on Climate Change

World emissions of CO_2 from fossil fuels as of 2005	2.80×10^{10} metric tons per year
2005 world fossil energy production	1.16×10^{8} GWh
Earth's land surface area	1.50×10^{10} ha
Earth's water surface area	3.60×10^{10} ha
Mass of CO_2 from fossil fuels (approximately 200 ppm) in the atmosphere	1.0×10^{12} metric tons
Volume of underground aquifer (10 percent pore space) to reduce atmospheric CO_2 by 200 ppm with dissolved CO_2 at pressures of more than 50 atmospheres	1.7×10^{14} m³
Thickness of underground aquifer in order to contain the water with dissolved CO_2 under 1 percent of the earth's land surface area	110 m
Volume of liquid CO_2 to reduce atm CO_2 by 200 ppm in seafloor ooze below 3,000 m	1×10^{12} m³
Thickness of a layer containing the liquid CO_2 if it were spread under 1 percent of the earth's water surface area	0.28 m

Source: International Energy Annual 2005, U.S. Energy Information Administration.

of 1,400 m with 20 to 40 cm of sediment cover (F. Inagaki, M. Kuypers, U. Tsunogai, J. Ishibashi, K. Nakamura, T. Treude, S. Ohkubo, M. Nakaseama, K. Gena, H. Chiba, H. Hirayama, T. Nunoura, K. Takai, B. Jørgensen, K. Horikoshi, and A. Boetius, "Microbial Community in a Sediment-Hosted CO_2 Lake of the Southern Okinawa Trough Hydrothermal System," *Proceedings of the National Academy of Sciences* 103, number 38 [2006]: 14164–69). Microbial activity within centimeters of the liquid CO_2 there was typical of that in seafloor sediment.

Bacterial decomposition is a natural link in the carbon cycle. In water lacking oxygen, naturally occurring and ubiquitous bacteria convert organic matter into water, methane (CH_4), CO_2, and plant nutrients. Humans have employed "anaerobic digestion" for centuries. The process occurs naturally in swamps, in landfills, at wastewater treatment plants, and anywhere organic matter accumulates without oxygen. The digestion occurs at water temperatures ranging from 3°C to 40°C on microalgae, kelp, zooplankton, and fish waste.

A plankton ocean digester (POD) would harness this natural bacterial decomposition. Two issues have prevented the economic application of bacteria as a large-scale climate change solution. One is that anaerobic digestion containers are relatively expensive. But in view of the fact that a POD could inexpensively encompass a large volume, the rate of digestion and the density of the biomass within the container would have less of a bearing on its economic efficiency. The second issue is the cost of growing and harvesting the biomass. The POD's size and low cost open up new possibilities with regard to the biomass that could be grown and harvested and to the ways in which the harvesting could be carried out.

Anaerobic digestion of biomass offers the following advantages as a climate change solution:

- It produces both biomethane and CO_2 simultaneously at about a 6:4 volume ratio. This simultaneous production would, by using the biomethane in place of fossil fuels and sequestering the CO_2, make it possible to reduce atmospheric CO_2 concentrations to 250 to 270 ppm even with some continued use of fossil fuels.
- Ocean-scale algae farms and PODs would also provide platforms that could assist in studies of oceanology, ocean fauna, and ocean ecology.
- Pure biomethane is identical to natural gas. The future production of large volumes of biomethane would allow immediate investments in power plants and motor vehicles using natural gas without having to worry about using up natural supplies. Natural gas produces much less CO_2 per unit of energy. It is currently used in fuel cells, and it is also the current source of hydrogen. Thus a biomethane economy would be easier to achieve than a hydrogen economy.

- Anaerobic digestion is robust. Any type of organic matter, cellulose, or protein can be digested, the only exception being lignin. The feedstock is not limited to particular microalgae. Any plankton or kelp, giant reed, zooplankton, bacteria, or fish will be digested. Any ocean water temperature will work, although digestion slows near freezing.
- Algae farming, combined with anaerobic digestion, would be ecologically sustainable. While fossil fuels continue to be burned, the sustainability of the POD process would be limited by the volume of carbon that could be sequestered. However, the biomethane production could be scaled up to supplement other non-fossil-fueled energy technologies and thus eliminate fossil fuels in a completely sustainable way.
- The algae produce oxygen while capturing CO_2. Because fossil combustion captures oxygen, certain other CO_2 sequestering technologies would have the effect of slightly reducing atmospheric oxygen concentrations.
- The combined algae farm and POD system would produce and use no hazardous chemicals. (Pure methane, pure CO_2, and ammonia, while not healthy in high concentrations, occur naturally.)

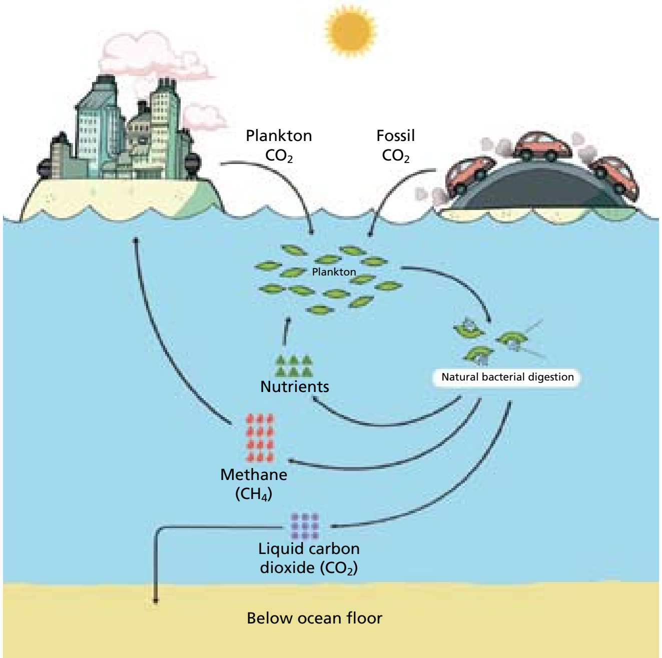
As figure 2 shows, the POD would be a sustainable link in cycles powered by the sun using water, plants, and bacteria. CO_2 present in the atmosphere from the combustion of fossil fuels is absorbed by algae. Thus the algae farm and POD could actually lower CO_2 levels.

The algae farm and POD could synergistically address the four crises described by M. Allsopp, R. Page, P. Johnston, and D. Santillo in *Oceans in Peril: Protecting Marine Biodiversity* (Washington, D.C.: Worldwatch Institute, 2007), namely, a loss of species diversity, fishery depletion, climate change (warming, acidity, rising sea levels, diminished ice caps), and pollution (nutrients, plastics, poisons, oil).

The algae farm and POD system could also create the ecosystem service areas discussed by P. Kareiva and M. Marvier in their article "Conservation for the People" (*Scientific American* [October 2007]: 50–57). An ecosystem service strategy is better than a "hot spot" approach for preserving biodiversity. Hot spot (a threatened area of high plant diversity) conservation often dispossesses local people. Ecosystem service, on the other hand, protects threatened ecosystems in a manner that benefits the people who depend on the ecosystem.

With anaerobic digestion, the container holds the nutrients that, together with sunlight, enable the algae to grow. No factory fertilizer is necessary. It is only necessary to recycle the nutrients to the water surface and add sunlight. Alternatively, if excess nutrients are causing "dead" zones, the nutrients should be sequestered or moved to areas where they can be useful.

POD Carbon and Nutrient Cycles



Courtesy of Mark E. Capron, P.E., M.ASCE, all

Ocean pressures harness the relatively high (10 times that of methane by weight) solubility of CO_2 to produce pure methane separate from pure CO_2. Then, ocean pressures and temperatures work with the phase change properties of CO_2 to effect the relatively low-energy conversion of the cool CO_2 gas (40 percent by volume of the mixture) to a nearly pure liquid. In contrast, capturing the CO_2 in the atmosphere (0.04 percent by volume) requires considerably more energy. The combustion of coal generates a hot exhaust that is 20 percent CO_2 by volume, and the combustion of methane generates a hot exhaust that is 8 percent CO_2 by volume.

Based on the data in tables 1 and 2, 4 percent of the earth's water surface would make it possible to grow enough algae to sequester fossil CO_2 emissions equal to 50 percent of the amount emitted in 2005. Moreover, the biomethane produced would be sufficient to meet 60 percent of the world's energy needs as of 2005. In contrast, growing trees to sequester all of the 2005 CO_2 emissions would require 50 percent of the earth's land surface, would only be practicable with abundant supplies of freshwater, and could be undone by droughts or fires.

The prediction of algae production per unit area is based on U.S. National Renewable Energy Laboratory (NREL) demonstrations (J. Sheehan, T. Dunahay, J. Benemann, and P. Roessler, *A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae* [July 1998]) that produced biodiesel from algae in the 1990s. The authors recorded algae growth rates in grams per square meter per

Table 2 Anaerobic Digester Gas Production

Algae ash-free dry production	5 g/m²/d
Algae ash-free dry production	18 metric tons/ha per year
Algae volatile solids production	16 metric tons/ha per year
Anaerobic digestion methane from kelp	0.4 SCM/kg
Methane production from algae	6,570 SCM/ha per year
CO_2 production from algae	9 metric tons/ha per year

day, ash-free dry weight, and weight percentage of lipid (oil) content. Growing algae for biodiesel is more difficult than growing indiscriminate organic matter because the ubiquitous low-lipid algae and bacteria displace the high-lipid algae.

In a December 2007 e-mail, Eric Jarvis of the NREL made the following suggestion: "A very good level of productivity would be 50 g/m²/day in an open pond system—the theoretical maximum is something around 100 g/m²/day. In real-world algal cultures, getting 10–20 is more realistic."

Table 2 is based on an interpolation of indiscriminate algae growth of 5 gm/m²/day, half the NREL low end, in order to allow for a more ecologically sustainable operation in open water. The prediction for gas production here is based on *Anaerobic Digestion of Biomass* (New York City: Elsevier Applied Science Publishers, 1987), wherein D.P. Chynoweth and R. Isaacson tabulate gas production during anaerobic digestion per unit of biomass volatile solids content. Volatile solid measurement is not the same as ash-free dry weight. Ash-free dry weight includes lignin, which is not anaerobically digested. Sea kelp, as Chynoweth and Isaacson note, contains 6 percent lignin. Table 2 assumes volatile solids are 90 percent of ash-free dry weight.

Chynoweth and Isaacson's table 5.5 indicates experimental methane yields for sea kelp ranging from 0.2 to 0.37 standard cubic meter (SCM) per kilogram of volatile solids. Figure 9.2 in that work indicates that 0.37 SCM per kilogram of volatile solids is achieved at 70 days of detention and 0.45 SCM per kilogram of volatile solids is achieved at 200 days. Figure 5.5 there gives the methane to CO_2 ratio expected from different feedstocks. Algae and bacteria produce about 60 percent methane. Fats produce a higher proportion of methane, while proteins and carbohydrates produce a lower proportion.

Three revenue streams for large anaerobic digesters would be available at any lake, sea, or ocean location. They are the first three numbered in table 3, a projection of incomes from a 10,000 ha plankton farm and associated POD. The first and largest stream is from the sale of biomethane to replace fossil natural gas at \$7/GJ (\$0.70/therm). Natural gas costs have been above \$10/GJ, but the 2005 IPCC report cited above mentions a range of \$2.60/GJ to \$4.40/GJ as a cost that would be competitive with coal.

Revenues 2, 3, and 4 all derive from a \$30 per metric ton value on global warming gas avoidance or sequestration. The economist Bjorn Lomborg makes the case in his book *Cool It: The Skeptical Environmentalist's Guide to Global Warming* (New York City: Knopf Publishing Group, 2007) for spending on other worthy humanitarian endeavors, suggesting, "We should tax CO_2 at the economically correct level of about two dollars per ton, or maximally fourteen dollars per ton." A figure of \$14 per ton would equate to \$0.14 per gallon (\$0.04/L) of gasoline. The IPCC report found carbon

Table 3 Revenues for Algae Farm and Plankton Ocean Digester

Plankton, microalgae, or macroalgae farm size	10,000 ha
Unit value of methane as fuel	\$7/GJ
Unit value of CO_2 sequestered	\$30/metric ton
1) Value of methane fuel (with 40 percent used up in production)	\$9.8 million per year
2) Value of biomethane displacing CO_2 from coal production	\$1.2 million per year
3) Value of CO_2 sequestered directly	\$2.6 million per year
4) Value of methane capture from dead zones (limited to areas producing uncaptured methane)	\$6.5 million per year
Total value available	\$20 million per year

capture and storage would add \$0.01 to 0.05 per kilowatt-hour of electricity (equivalent to \$100 to \$500 per metric ton of CO_2). Also note that Lomborg makes a strong case for research. A simple carbon credit trading system would need a mechanism for counting research as a "credit."

Revenue 2 is the smallest. It derives from the use of POD-generated biomethane in place of coal. Coal emissions of CO_2 from electricity production have been put at 100 kg/MWh.

Sequestering the CO_2 produced directly from the POD provides revenue 3.

Revenue 4, dead zone methane capture, is limited to the roughly 20 Mha of dead zones worldwide. The Gulf of Mexico's dead zone (2 Mha) is caused by nutrients from the Mississippi River. Nutrients cause excessive algal growth. The dead algae sink and are digested by bacteria. After the bacteria have consumed the dissolved oxygen, anaerobic digestion continues, producing methane and CO_2. As a greenhouse gas, methane is 20 times more potent than CO_2. If the algae were harvested for the pod, the value for eliminating methane emissions would, according to the Chic-Climate Exchange, be 18.25 times the value for eliminating CO_2 emissions.

Although not shown in table 3, there would also be revenue incidental to harvesting the fish attracted to a floating kelp forest or algae farm. This income should be on the order of \$125 million for a 10,000 ha forest. The sale of fish would help defray the cost of harvesting the kelp to place in the POD. However, fish harvesting would only be carried out in an area encompassing 6 Mha. If the area were extended, world demand for fish would not be high enough to absorb the extra catch.

Where algae are harvested to remove a nuisance or excess nutrients, recycling the nuisance into energy could produce a tipping fee revenue.

An Excel spreadsheet model of the POD process is available (e-mail MarkCapron@PODenergy.org) for "what if" simulations. The model postulates a relatively inexpensive digestion container sized for the algae from a 10,000 ha farm. It would cost between \$1 million and \$8 million delivered to the site. An installed cost of \$20 million with a life of four years would mean a capital cost of \$5 million per year for the POD. The process shown in figure 3 is thus much less complex and expensive than it first appears. When operating without a dead zone or fish harvesting, about \$9 million a year remains after POD purchase for growing, harvesting, and conveying feedstock; sequestering CO_2; recycling nutrients; transporting methane; and other expenses.

The model assumes that 40 percent of the methane would be expended in the entire operation, from the growing of biomass through the delivery of gases or liquids to their final destinations. That represents the continuous use of 34 MW for operations. Wind or wave energy may be more cost effective owing to its ready availability. Energy would also be available from the dissolved and compressed gases. Only about 1 MW would be needed to compress the pure gaseous CO_2 to a liquid should dissolution of CO_2 hinder direct production of liquid.

If the biomass were plankton harvested as a 3 percent solids slurry with a 180-day detention time, the POD would contain up to 3 million m^3 of feedstock slurry. Harvesting would be at the rate of 17,000 m^3 per day of liquid slurry, or 0.2 m^3/s. If the POD were located near the center of the farm, the feedstock would traverse a distance of up to 6 km. Similar liquid volumes containing nutrients generated in the POD would be recycled and distributed over distances that also could reach 6 km.

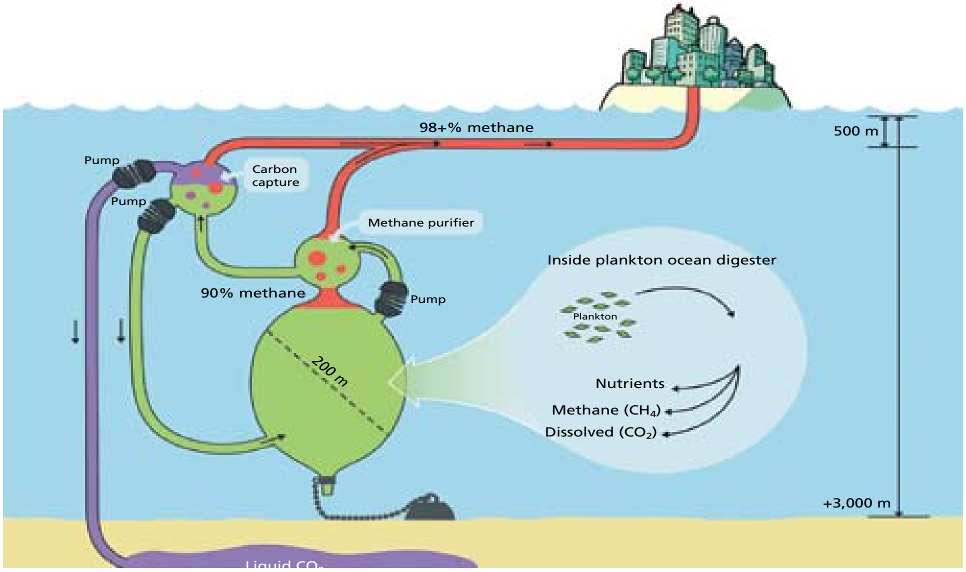
In figure 3, the main digesting container has been filled with a feedstock slurry that contains CO_2 from the previous batch of slurry. Bacteria convert the feedstock into gases and nutrients. The methane purifier removes any remaining CO_2, which saturates the slurry. The CO_2 comes out of solution as a liquid in the carbon capture unit, which has a lower pressure and may be warmer. The slurry returning to the main chamber becomes less saturated as pressure increases and temperature decreases.

A bench test optimized with the use of video would use pressure vessels with windows, interior wipers, and light. One could photograph the bubbles of CO_2 gas or the liquid CO_2 rising through the bottom layer and the liquid CO_2 gathering between the water and the methane gas. The bottom layer would be a brown slurry of decaying algae in water. With presaturation of the slurry, the middle layer would be liquid CO_2. The top layer would be mostly methane gas with some CO_2 gas. The CO_2 and methane might supersaturate the slurry and suddenly come out of solution as a liquid or gas with vibration or if the pressure or temperature were to change. It is also possible that the low pH resulting from high CO_2 concentrations might inhibit methane production.

Bench tests will help establish which of the many anaerobic digestion processes are most economically viable for each POD location. Different POD sites will have different temperatures, CO_2 concentrations, detention times, feedstocks, bacteria strains, et cetera.

In scaling up operations to lakes and seas, it would first be necessary to find a body of water where excess algae are already harvested. For example, California's Salton Sea Authority harvests algae when funds are available. When harvesting does not take place, bacteria digesting the dead algae use up the dissolved oxygen, and thousands of dead fish wash up on the beach. There are many bodies of water with excess nutrients and existing algae harvesting operations. Dead zones are even more plentiful, and there it would be appropriate to fund algae harvesting with a tax on upstream fertilizer use. At any such site, a lake-size POD of the type shown in figure 4 could be deployed.

The ideal lake would have excess nutrients and excess algae that are routinely blown or carried by surface cur-



POD Operation as a Batch Process

rents toward the digester. The digester should be close to an onshore generator (internal combustion engine, gas turbine, fuel cell) that in turn should be close to a facility that is using more electric power and heat than are produced by the generator. Owing to electrical distribution costs, the avoided costs for utility energy are significantly more than what a utility will pay for electricity.

As shown in figure 4, the first step would be to unroll the container. Next, the container would be filled with a slurry of harvested algae. Particular types of bacteria might be added in this step. In the next step, the gas is harvested. The last step, harvesting the nutrients while preparing the container for another batch cycle, is not shown in the figure.

PODs could be economically producing biomethane today in lakes or small seas where algae are already harvested for nutrient control. However, answers to a number of questions are needed for economic ocean-scale operations. While many of the questions below could be answered with bench tests, some will require a gradual expansion of operations from lake scale to ocean scale:

1) What feedstocks (microalgae, floating kelp forests, typical plankton) are best for particular areas of the world? How will the feedstock be grown and harvested with minimal expenditure of energy, labor, and capital? What is the relationship between harvesting energy and the solids percentage of the feedstock? Surface wave forces taper to zero at water depths below about a wavelength. While that is about 100 m in the ocean, it can be less than 5 m in smaller bodies of water. A deep POD would avoid wave forces, but how well would feedstock growing and harvesting operations survive storms?
2) Will the naturally occurring bacteria be sufficiently plentiful and optimal in performance? The algae and plankton gathered on the ocean surface might not have many of the methane-producing bacteria adapted to depths exceeding 500 m with unusually high levels of dissolved CO_2.
3) What are the relationships between gas production, methane fraction, incidental hydrogen sulfide production, time, feedstock volume, feedstock type, feedstock solids concentration, feedstock detention time, bacteria selection, bacteria management, pressure, temperature, CO_2 concentration, moisture content, agitation, and hydrate formation? Relatively little anaerobic digestion research has been carried out at typical ocean pressures and temperatures. At one atmosphere, water saturates with CO_2 at 1,500 ppm. At 50 atmospheres, water saturates with CO_2 at 60,000 ppm. Advances in bacteria storage (for example, anaerobic versions of In-Pipe, produced by the In-Pipe Technology Company, of Wheaton, Illinois, and of BioAmp, produced by Ecobionics, of Irving, Texas) may be applied for more uniform gas production.
4) What are the relationships between sediment properties, depth below water surface, sediment cover depth, temperature, seismic shaking, and the rate at which liquid CO_2 dissipates? Would liquid CO_2 with a hydrate, plastic, or sediment skin be stable for millennia?
5) How much methane escapes to the atmosphere from excess nutrient dead zones? If the dead zone were revived with POD operations, what methane capture credit would be appropriate?
6) In a POD, at what rate would methane and CO_2 come out of or go into solution depending on pressure, temperature, other dissolved gas concentrations, the presence of liquid CO_2, and the presence of hydrates?
7) How will digested nutrients be transferred from the POD to the water surface for optimum algae and plankton growth? Most of the nitrogen will be in the form of ammonium, high concentrations of *(continued on page 75)*

(continued from page 57) which are toxic to aquatic animals. Bacteria will convert the ammonium into nitrate while consuming oxygen and alkalinity. Algae will consume the nitrate while using sunlight to convert dissolved CO_2 into oxygen.

Deploying PODs and algae farms for biomethane production would pay dividends in a number of other areas as well:

- New vitality: Live algae add oxygen to water, while dead algae remove oxygen as they decompose. Eutrophication is the process whereby a body of water becomes enriched in dissolved nutrients (such as nitrates and phosphates from human wastes or terrestrial farming) that stimulate the growth of aquatic plant life, usually resulting in the depletion of dissolved oxygen. The algae growing in such a body of water could become POD feedstock, and the nutrients could be safely recycled on land for use in agriculture or landscaping. Lake bottom nutrients might also be pushed to the surface to speed algal growth and further clean the lake. A moderately eutrophied lake of about 1,000 ha could feed a 5,000 m^3 digester. The water-supported digester would be collapsible so that it could be rotated among several lakes.
- Benefits of algae farming: In addition to furnishing food for fish and promoting species diversity, the endeavor would provide a renewable source of methane and would effect carbon sequestration. Nutrient recycling would follow an initial dose of nutrients, which could be from deep water. A floating kelp forest could provide fish habitat and kelp for the POD operation.
- Biodiesel production: In near-shore applications, the POD could provide a rich source of CO_2 for algal biodiesel growth. Such growth is easier to control with a rich (better than about 10 percent) CO_2 source because ambient air (about 400 ppm CO_2) has other algae and harmful bacteria. The CO_2 from the digester gas and methane combustion (for

(continued from page 75) example, from on-site electricity generation) could boost oil-bearing algae production and nutrient uptake. After harvesting the algal oil for biodiesel, the remaining algae could be digested for methane production.

- Dust control: Lakes and seas are drying up in many places around the world, filling the air with unhealthy dust. For example, the Salton Sea and the Dead Sea are drying up; both now lie below sea level and require a substantial expenditure of resources for restoration and continued viability. Proposals have been made for somehow connecting these seas to the ocean. Farming algae for both POD methane and biodiesel production could offset the expense of saving such seas and lakes. The POD could also remove the nutrients that pollute the lake or sea.
- Ocean gyre revival: An ocean gyre is an area of inward-spiraling surface currents. Gyres accumulate floating plastic trash. An area in the North Pacific twice the size of Texas is now a huge repository for floating plastic. The income from operating PODs and algae farms in a gyre may provide the incentive to recycle or dispose of the plastic trash.
- Desalination: The POD may share components with a seawater desalting process in that seawater is used to produce gas hydrates. In a gas hydrate, water molecules surround a gas molecule, typically six or eight water molecules for each gas molecule. Both methane and CO_2 form hydrates at the temperatures and pressures of the deep ocean. When the hydrate is deconstructed, the remaining water has less salt than the water that formed the hydrate. The hydrates (also known as clathrates) are solids. Some hydrates are lighter than water; some are denser. The "leftover" water could have a higher salt concentration and be denser than seawater. The water with higher salinity or the hydrate might be suitable as a high-density substance that could share containers with—and sink—the liquid CO_2 produced by the POD. Hydrate formation is exothermic, and the heat released may improve the efficiency of the CO_2 removal chamber. Moreover, endothermic hydrate deconstruction may aid with converting CO_2 from gas to liquid.
- Wastewater: Mike MacCracken, Ph.D., the chief scientist for the Climate Institute, of Washington, D.C., has suggested using lake-size PODs in developing countries for inexpensive waste treatment and energy production. If the developing country currently has wastes (human, animal, plant) that are generating methane, developed countries could obtain carbon credits by funding facilities to capture that methane.

Much research and development will be required if PODs with biomass harvesting are to be deployed in the world's oceans in a way that is economically justifiable. The effort is worthwhile because the triple benefits of energy production with simultaneous carbon sequestration and nutrient recycling offset the risk. Further offsetting risk is the opportunity to address other ecological and economic issues with synergistic projects.

PODs can sustainably lower atmospheric CO_2 concentrations, even with continued use of fossil fuel. For example, harvesting algae from 4 percent of the earth's water surface would be sufficient to sequester 50 percent of the fossil CO_2 emissions generated by the world in 2005 while simultaneously producing enough biomethane to meet 60 percent of the world's energy needs as of 2005. ■

Mark E. Capron, P.E., M.ASCE, of Oxnard, California, developed the plankton ocean digester concept on the basis of his background in ocean engineering at the Naval Civil Engineering Laboratory when it was in Port Hueneme, California, and the wastewater experience he has gained as a senior engineer for the Ventura Regional Sanitation District, in Ventura, California. This article provides the details of a poster he presented in January of this year at the Eighth National Conference on Science, Policy, and the Environment ("Climate Change: Science and Solutions"), organized by the National Council for Science and the Environment and held in Washington, D.C.