EDITORIAL

A New Role for Autotrophic Methanogens?

For many years, wastewater engineers have known that the microbial communities in anaerobic digesters include autotrophic methanogens. These organisms live on the energy from the reaction $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$, obtaining the carbon dioxide and hydrogen from other organisms that contribute other steps of the digestion process. Our profession should do more to inform the participants in national and international debates over energy policy that these microbes could be part of significant changes in the way the world stores and transports energy.

On looking at the feed gases for these methanogens, one sees that there is no point in repeating here the reasons for alarm about global warming caused by carbon dioxide discharges into the atmosphere, which have prompted many discussions of how to reduce these discharges. For example, Service (*Science*, **305** [2004], 962) describes several current projects to confine CO_2 in geological formations. On the other hand, Lackner (*Science*, **300** [2003], 1677) reviews a variety of proposed methods for sequestration of carbon dioxide or carbonate compounds. He concludes that the best solution is to cause chemical reactions with vast quantities of minerals, producing insoluble solid materials that can be safely discharged into the environment as if they were natural rocks or gravel. He argues that this can be done in an economically acceptable way, but acknowledges that the costs would be substantial.

As for hydrogen, for many years advocates of a ''hydrogen economy'' (*e.g.*, Veziroglu, et al., eds., *Proceedings of the 11th World Hydrogen Energy Conference*, Schoen and Wetzel, Frankfurt, Germany, 1996; see also the more than twenty years of the *International Journal of Hydrogen Energy*) have performed economic analyses and carried out technological development and demonstration projects in support of their conviction that hydrogen should be used much more extensively than is presently the case, as a means of storing and transporting energy. Their enthusiasm is understandable when one focuses attention on the facts that the only waste from oxidizing hydrogen is water; that hydrogen can be used not only in combustion but in fuel cells; and that hydrogen is a more convenient and efficient form of energy storage than some other present or proposed technologies, such as rechargeable batteries and flywheels. In particular, using hydrogen fuel cells to power automobiles has seemed sufficiently attractive that the federal government of the United States has established a five-year, $1.7 billion project, called the FreedomCAR and Fuel Initiative, to develop and promote this technology (*Science*, **301** [2003], 315).

On the other hand, as variously noted by Service (*Science*, **305** [2004], 958), Keith and Farrell (*Science*, **301** [2003], 315), and Moy (*Science*, **301** [2003], 47), hydrogen has a number of disadvantages: low density, so that a large volume must be oxidized to produce a useful amount of energy; frequent leakage problems, despite currently established precautions; notably easy flammability; and the great expense of replacing existing fuel transportation, storage, and distribution systems by new equipment designed to handle hydrogen. Furthermore, Tromp, et al. (*Science*, **300** [2003], 1740) offer evidence that increased use of hydrogen would result in sufficient leakage to harm the stratosphere, including further reduction of the ozone layer. These considerations show why hopes for a far-reaching conversion to a hydrogen economy have so far not been fulfilled.

Methane evidently has advantages over hydrogen in being easier to store and transport safely; in having a higher energy density per unit volume at a given temperature and pressure; and in the existence of a vast installed infrastructure for handling natural gas, which is almost entirely methane. On the other hand, methane is not directly usable now in fuel cells (commercially available methane-fed systems actually perform a two-step process in which a reformer first extracts hydrogen from the methane, and then a fuel cell uses the hydrogen; research on cells directly fueled by hydrocarbons is still preliminary (Park, et al., *Nature*, **404** [2000], 265), and is a waste to make methane by autotrophic methanogenesis from hydrogen made from fossil methane. Thus, a nonfossil source of hydrogen would be needed for autotrophic methanogenesis to have a chance of providing a technical or economic benefit, thus excluding competition with a number of current or proposed uses of hydrogen.

However, a number of nonfossil sources of hydrogen exist, including electrolysis of water using electricity from any nonfossil source (such as nuclear, solar, wind, or hydroelectric), and chemical processes that directly use nonfossil heat (such as nuclear, solar, or geothermal) to drive the endothermic process of splitting water into hydrogen and oxygen. Furthermore, increasing use of nonfossil sources of energy is obviously desirable as one way to reduce carbon dioxide discharges. Also, Lackner, et al. (in Sakkestad, ed., *Proceedings of the 24th International Conference on Coal Utilization and Fuel Systems*, Coal Technology Association, Clearwater, Florida [1999], 885–896) describe methods that they believe to be technically feasible for collecting carbon dioxide from the atmosphere at an acceptable cost. If they are correct, then the components are in place for establishing systems that would be closed in the biosphere, splitting water and collecting atmospheric carbon dioxide for autotrophic methanogenesis, and releasing water and carbon dioxide when the methane is oxidized. Such systems would consume hydrogen close in time and space to its production, minimizing the risks and difficulties of handling it.

Probably one of the most important questions raised by this prospect is whether using autotrophic methanogenesis could promote the development of nonfossil sources of energy by allowing them to be located further from where their output is consumed. For example, the region with the highest potential in the world for wind energy development may be in the mountains of southern Chile, the only land area exposed to the winds long known to seafarers as ‘‘the roaring forties’’ (*e.g.*, in Balmeceda, Chile (Novacek, *Smithsonian*, Dec. [2001], 101–102). To the author’s knowledge, no one has tried to develop wind generators in this region because it is too far from major cities or industrial centers for conventional electric transmission lines to carry the power at an acceptable cost. It seems reasonable to ask whether storing and transporting the energy as methane would make it economically feasible to use this resource. The same point applies to the abundant geothermal energy available in a few places with more or less continuous volcanic activity, such as the area around the Kilauea volcano in Hawaii, or Mt. Etna in Sicily, or others.

More generally, the potential for storing and transmitting energy as methane may offer an opportunity for rethinking current assumptions about using nuclear energy. The electric power industry has operated for many years on the assumption that nuclear power plants must be located as close as possible to the cities they serve. Thus, in the United States, it is necessary for newly manufactured nuclear fuel rods to be transported over highways or railroads for hundreds or even thousands of miles to reach the many plants that serve widely dispersed major population centers. If the nuclear industry had successfully implemented plans made several decades ago for reprocessing used fuel to recover unconsumed U^{235}, and Pu^{239} newly bred from U^{238}, much more transportation would have been necessary, with much more dangerously radioactive materials. Questions of transportation safety and security are among the reasons, though not the only ones, why plans for reprocessing and breeding have now been abandoned. If it becomes feasible to use nuclear energy (as heat or as electricity or both) to provide the feed gases for autotrophic methanogenesis, so that the energy is stored and transported as methane, then a time may come when nuclear plants can be sited farther from the consumers of their output and closer to fuel processing facilities, or perhaps even to build large integrated nuclear energy centers that provide onsite reprocessing without long-distance transportation of nuclear fuel materials, and make it easier to have elaborate security measures against theft, attack, sabotage, or accidents. These possibilities for nonfossil plants to produce hydrogen have not been considered in analyses of the economics of energy in the future and there are many other topics that will need to be investigated to form a complete picture of what autotrophic methanogens can contribute. For example, the reaction formula above shows that, compared to directly using the hydrogen for fuel, methanogenesis has the disadvantage that only one-half the hydrogen supply goes into methane and the rest is used in producing water. On the other hand, a study conducted at the Argonne National Laboratory in Illinois concluded that “. . . creating the infrastructure needed to fuel 40% of America’s cars [with hydrogen] would cost a staggering $500 billion or more” (*Science*, **305** [2004], 960). Turner’s work (*Science*, **305** [2004], 972) suggests that it will be a challenging task to assess the relative benefits of saving such expenditures compared to accepting the costs of making the extra hydrogen needed by methanogens.

In a widely reported and somewhat controversial (*Science*, **300** [2003], 581) analysis, Hoffert et al. (*Science*, **298** [2002], 981) provide a detailed argument that major additional research expenditures are needed to find ways to meet the world’s energy needs while stabilizing the atmospheric level of carbon dioxide. As Hoffert’s eighteen co-authors included a wide range of expertise in physics, power engineering, economics, atmospheric science, and space technology, but no one likely to be familiar with waste microbiology, it is not surprising that autotrophic methanogenesis was not included among the many technologies that they discussed. Neither was it mentioned in the recent special section about hydrogen (*Science*, **305** [2004], 917, 957–976). Let us hope that this editorial is a first step toward remedying this oversight. It would indeed be a striking turn of history if a crucial contribution toward solving the world’s energy troubles were provided by the humble methanogen.

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