Examples of enabling technologies for the development of Nano-Based water treatment technologies

Introduction

This hand-out was developed for participants of the International Workshop on Nanotechnology, Water, and Development held on October 10 - 12, 2006 in Chennai, India. The hand-out provides examples of some enabling (or platform) technologies that may help with the affordability and scalability of nano-based community and household level point-of-use (POU) water treatment methods, such as those described in Meridian Institute's "Overview and Comparison of Conventional and Nano-Based Water Treatment Technologies" (http://www.merid.org/nano/watertechpaper/).

The hand-out describes production methods for carbon nanotubes, organic nanotubes, and halloysite nanotubes, as well as NanoFermentation™ and the Sol-Gel nanomaterial production processes. This hand-out is not intended to provide an exhaustive overview of technologies that enable nanotechnological innovation. It provides some examples of the types of enabling technologies that may help with the implementation of further technological advances.

Carbon Nanotube Mass Production Methods

Description of the Technology

The cost of carbon nanotubes is expected to decrease by a factor of 10 to 100 in the next 5 years due to new mass production technologies.[1] Chemical vapor deposition (CVD) and plasma torches are two of these technologies which are currently being used for commercial-scale production of carbon nanotubes.

Carbon nanotube synthesis using CVD involves depositing a catalyst solution on a substrate and then exposing the substrate to hydrocarbon gas in a furnace. The chemical reaction between the catalyst and the gas results in the growth of carbon nanotubes on the surface of the substrate. This method may be preferred for the fabrication of carbon nanotube membranes and thin films because it eliminates the step of attaching the nanotubes to a substrate.[2]

Examples of Production and Stage of Development

Examples of carbon nanotube producers include Thomas Swan & Co. Ltd. and Raymor Industries. Thomas Swan, based in the United Kingdom, launched a commercial-scale CVD manufacturing facility for high-purity single-walled carbon nanotubes in 2004. Thomas Swan is working on the scalability of its process and predicts that the price of single-walled carbon nanotubes will be measured in tens of dollars in the next few years.[3]

Raymor Industries recently began producing high-quality single-walled carbon nanotubes using its proprietary plasma-based continuous synthesis process.[4] Raymor's proprietary manufacturing process involves using a device called a microwave plasma torch to atomize methane and a molecular iron catalyst, after which the atoms are condensed in a furnace, resulting in the growth of single-walled carbon nanotubes. This process is considered highly energy efficient, using 200 kilowatt-hours for each

[1] Yuehe Lin, "Electrically Controlled Anion Exchange Based on Polypyrrole and Carbon Nanotubes Nanocomposite for Perchlorate Removal," *Environmental Science and Technology*, Vol. 40, No. 12, June 15, 2006, pp. 4004-4005.
[2] P.R. Poulsen, et al., "Single-Wall Carbon Nanotube Devices Prepared by Chemical Vapor Deposition," Niels Bohr University, Copenhagen, Denmark, pp. 1-3.
[3] Harry Swan, "Carbon Nanotube Manufacturing on a Commercial Scale - Ready for Mass-Markets," *The European Coatings Journal*, November 2004, <http://www.euronanotrade.com/index.php?option= content&task=view&id=385&Itemid=74>.
[4] "Raymor Begins Production of Single-Walled Carbon Nanotubes from High Capacity Production Unit," *Nanotchwire.com*, July 2, 2006, <http://www.nanotechwire.com/news.asp?nid=3460&ntid=133&pg=1>.

kilogram of carbon nanotubes produced.[5] Raymor's current production unit is able to produce 10 kilograms of carbon nanotubes per day and can be scaled up as demand grows. Raymor is currently working with a variety of manufacturers to integrate carbon nanotubes into products.[6]

Organic Nanotube Production Methods

Description of the Technology

Several research groups have developed mass production methods for fabricating organic nanotubes, which have a similar structure to carbon nanotubes but are made from various polymers and biomaterials.

Organic nanotubes are hollow cylindrical structures with diameters comparable to those of multi-walled carbon nanotubes. Organic nanotubes have better dispersibility in water and can encapsulate more functional substances than carbon nanotubes.

Conventional organic nanotube production methods are time-intensive and involve multiple steps. They also require about 20,000 liters of organic solvent per kilogram of nanotubes produced and several days of drying time. New production methods are being developed to improve the production of organic nanotubes.

Examples of Production and Stage of Development

Japan's National Institute of Advanced Industrial Science and Technology (AIST) recently developed a mass production method for producing a variety of amphiphilic organic nanotubes that uses less than one thousandth of the solvent used in conventional techniques and requires only a few hours for drying. AIST's production method synthesizes amphiphilic organic nanotubes through the self-assembly of hydrophilic and hydrophobic saccharide and peptide parts in an organic solvent such as ethanol. Using this method, the nanotubes assemble in a single step, resulting in high yields in a short period of time. This method also required 10 liters of solvent for the production of a kilogram of nanotubes and several hours for drying. AIST is now working on advancing their organic nanotubes for adsorption, encapsulation, and slow release functions, which could have applications in filtration and biological and heavy metal remediation.[7]

Purdue University in the U.S. is also developing mass-producible organic nanotubes called "rosette nanotubes," which are made from components of DNA. These rosette nanotubes are self-assembled in water when supermacrocycles, which are rings of atoms made from the guanine, cytosine, and amino acids, stack on top of one another to form a hollow tube. This fabrication method is also single-step, resulting in the potential for high-yield, and scalable using conventional industrial processes. Researchers from Purdue have predicted that a small-scale industrial plant could produce about 500 kilograms of these nanotubes per month.[8] Purdue is currently working on several biomedical projects involving the use of rosette nanotubes for bone and tissue regeneration.[9]

Halloysite Nanotube Production Method

Description of the Technology

Halloysite is naturally formed clay that can be mined from a number of regions. Halloysite particles are nanoscale and naturally tube-shaped, making them a potential alternative to manmade carbon nanotubes.[10]

Because the concentrations and physical properties of the nanotubes can vary between different clays, some companies are developing nanotube extraction methods. Methods are also being developed for functionalizing the nanotubes, integrating them directly into specific materials and applications, combining them with polymers to make nanocomposite materials, or producing them as a dry powder of colloidal nanotube suspensions for use as an intermediate product.[11]

Example of Production and Stage of Development

NaturalNano, Inc. in the U.S. is developing several separation and production processes for halloysite nanotubes.[12] NaturalNano currently has collaborative agreements with several research organizations and universities to develop products containing their

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[5] O. Smiljanic (Raymor Industries), "Novel, Industrial Scale Production of Single Wall Carbon Nanotubes Using Plasma," presentation at the 2006 NSTI Nanotechnology Conference and Trade Show, Boston, MA, May 9, 2006.

[6] "Raymor."

[7] "Successful Development of Massive Synthesis of White Organic Nanotubes," AIST, July 20, 2006, <http://www.aist.go.jp/aist_e/latest_research/2006/20060807/20060807.html>.

[8] Chhavi Sachdev, "DNA parts make versatile nanotubes," *Technology Review News*, June 6, 2001, <http://www.trnmag.com/Stories/060601/DNA_parts_make_versatile_nanotubes_060601.html>.

[9] "Self-assembling 'nanotubes' offer promise for future artificial joints," *Purdue News*, April 9, 2004, <http://www.purdue.edu/UNS/html4ever/2004/040409.Webster.rosette.html>.

[10] Michael Kanellos, "Future nanotech tools made from clay," *CNET News*, October 26, 2005, <http://news.com.com/Future+nanotech+tools+made+from+clay/2100-11390_3-5914034.html>.

[11] "Amended Annual Report," US Securities and Exchange Commission filing, June 26, 2006, pp. 3, 11.

[12] "NaturalNano 2005 Annual Report," NaturalNano, Rochester, NY, 2006, p. 5.

halloysite nanotubes. NaturalNano recently filed a patent application for a new halloysite production method that eliminates the need for exfoliation, an expensive and time-intensive process in which layers of the clay are chemically separated.[13] Carbon nanotubes produced in labs can vary in price, but average at around US$250 per gram. NaturalNano purchases halloysite clay by the ton and estimates that the price of finished halloysite nanotubes will range from US$3.50 to US$20 per pound, depending on whether they are functionalized or not.[14]

NanoFermentation™

Description of the Technology

Oak Ridge National Laboratory (ORNL) has developed a method called NanoFermentation™ for creating metal and mixed metal oxide nanoparticles by using the natural metabolic processes of metal-reducing bacteria, a breakthrough that could facilitate cost-effective commercial-scale nanopowder production.

NanoFermentation™ uses metal-reducing bacteria that are naturally found in a variety of anaerobic environments such as the ocean floor, lake sediments, and subsurface geological structures.[15] NanoFermentation™ can be done at room temperature using conventional equipment. [16] Metal compounds are fed to the bacteria, which are cultured in a large fermenter, and harvested in the form of single nanoscale crystals.[17] The amount of nanoparticles produced is very large compared to the size of the cell culture. Also, the nanoparticles are produced outside the cell and can be collected without damaging the cell culture. A single cell culture can be reused for different metal compositions as well. The nanoparticles produced through NanoFermentation™ are extremely pure and homogenous.[18]

Stage of Development

NanoFermentation™ has thus far been used to produce iron, cobalt, nickel, chromium, manganese, and zinc metal oxides, as well as metal oxides from rare earths and uranium. The highest priority application of NanoFermentation™ is the production of nanoscale magnetic ferrites, which can be used for a variety of materials, including adsorbents. ORNL is now scaling the process to larger, pilot-scale batches and developing ways to create additional types of compositions. Additionally, ORNL has recently been contacted by an undisclosed client interested in integrating NanoFermentation™-produced nanomaterials into their proprietary water purification device. [19]

Sol-Gel

Description of the Technology

Sol-Gel Technologies Ltd. in Israel developed Sol-Gel, a versatile, simple, and inexpensive process for fabricating a range of ceramic and glass materials, including nanopowders, nanoporous membranes, thin films, coatings, and porous aerogels.

The sol-gel process begins with the preparation of a "sol," which is a colloidal suspension of inorganic metal salts or metal organic compounds. The sol is then cast into a mold to create a wet "gel" that can be converted into ceramic and glass materials through a variety of processes. Ceramic nanofibers can be directly spun from the sol, ceramic nanopowders can be formed through precipitation, spraying, and emulsion methods, and dense ceramics can be formed by heat-treating the wet gel.[20] Temperature variations, reagents, solvents, and catalysts can also be used to customize that material' surface texture, pore size, and shape. The sol-gel process can be conducted under room temperature and normal atmospheric pressure.[21]

Stage of Development

The sol-gel process is currently being used to fabricate a variety of nanomaterials, including nanoparticles, membranes, and porous substrates used in water treatment technologies. [22]

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[13] "NaturalNano Files Nanocomposite Patent for Wide Range of Uses in Polymers and Plastics Industries," *BusinessWire*, September 12, 2006, <http://home.businesswire.com/portal/site/google/index.jsp?ndmViewId=news_view&newsId=20060912005567&newsLang=en>.
[14] Kanellos.
[15] Robert J. Lauf, "NanoFermentation™: A bioprocess for manufacturing inorganic nanomaterials," The NanoTechnology Group, Inc., June 5, 2006, <http://www.thenanotechnologygroup.org/index.cfm?Content=88&PressID=1392>.
[16] "ORNL scientists noted for nanotech," nanotechwire.com, July 23, 2006, <http://www.nanotechwire.com/ news.asp?nid=3532&pg=14>.
[17] "NanoFermentation: Bacteria Create Magnetic Powders," *ORNL Technology Transfer and Economic Development Newsletter*, Summer 2005, p. 3, <http://www.ornl.gov/adm/tted/newsletters/ttednews_insert_sum05.pdf>.
[18] Lauf.
[19] Lauf.
[20] "Sol-Gel Technology," Chemat Technology, Inc., <http://www.chemat.com/html/solgel.html>.
[21] "Technology – Nanoengineering Solutions," Sol-Gel Technologies, <http://www.sol-gel.com/technology.html>.
[22] "Technology."