Halloysite Clay Nanotubes for Controlled Release of Protective Agents

Yuri M. Lvov,[†,]* Dmitry G. Shchukin,[‡] Helmuth Möhwald,[‡] and Ronald R. Price[§]

[†]Institute for Micromanufacturing, Louisiana Tech University, Ruston, Louisiana, [‡]Max Planck Institute for Colloids and Interfaces, Golm, Germany, and [§]Glen Muir Technologies Inc., Stevensville, Maryland

ABSTRACT Halloysite aluminosilicate nanotubes with a 15 nm lumen, 50 nm external diameter, and length of 800 ± 300 nm have been developed as an entrapment system for loading, storage, and controlled release of anticorrosion agents and biocides. Fundamental research to enable the control of release rates from hours to months is being undertaken. By variation of internal fluidic properties, the formation of nanoshells over the nanotubes and by creation of smart caps at the tube ends it is possible to develop further means of controlling the rate of release. Anticorrosive halloysite coatings are in development and a self-healing approach has been developed for repair mechanisms through response activation to external impacts. In this Perspective, applications of halloysite as nanometer-scale containers are discussed, including the use of halloysite tubes as drug releasing agents, as biomimetic reaction vessels, and as additives in biocide and protective coatings. Halloysite nanotubes are available in thousands of tons, and remain sophisticated and novel natural nanomaterials which can be used for the loading of agents for metal and plastic anticorrosion and biocide protection.

*Address correspondence to ylvov@latech.edu.

There is an increasing amount of activity to produce multifunctional nanometer-scale containers and a growing demand for their use in sophisticated applications in the life and materials sciences. Ideally, such containers would be inexpensive materials with a simple means of fabrication, thus calling for simple synthetic methods (*i.e.*, self-assembly) or natural resources. Often, long, thin tubular systems are highly desirable, since for the same amount of cargo (compared to spherical capsules), they exhibit superior aero- and hydrodynamic properties and thus better processability. Moreover, one-dimensional systems possess unique electrical, optical, and magnetic properties. The ability to introduce well-defined and differing functionality to the inner and outer surfaces would also allow for their separate modification, for example, for varying hydrophobicity.

A substantial amount of the current research activity is devoted to carbon nanotubes. As for other tubule materials, there are also polymeric, metal, and metal oxide nanotubes. Polymeric nanotubes can be formed by self-assembly in some cases or templated by molecular sieves or cylindrical nanopores to form tubular structures.[1] Metal and metal oxide nanotubes are synthesized predominantly by a template method using polymeric or inorganic nanorods, which have to be prepared separately, as a template scaffold.[2] The disadvantage of these types of nanotubes is the employment of a template, which has to be removed after synthesis of the tubes, leading to low quantities of the product and time-consuming preparation procedures (including the preparation of the template itself).

Halloysite is an economically viable clay material that can be mined from deposits as a raw mineral. Halloysite ($Al_2Si_2O_5(OH)_4 \times nH_2O$) is a two-layered (1:1) aluminosilicate chemically similar to kaolin which exhibits a range of morphologies. One predominant form is a hollow tubular structure in the submicrometer range. The size of halloysite tubules varies from 500–1000 nm in length and 15–100 nm in inner diameter depending on the deposit (Figure 1). The neighboring alumina and silica layers, and their water of hydration, create a packing disorder causing them to curve and roll up, forming multilayer tubes. The reason flat kaolinite rolls into halloysite tubules remains unclear.[3] When $n = 2$ the clay is in the form of hydrated "halloysite-10 Å" with one layer of water molecules between multilayers. The "10 Å" designation indicates the spacing in the multilayer walls as the kaolinite plates roll up into a multiwalled cylinder. At $n = 0$, the structure is dehydrated "halloysite-7 Å" which may be obtained through an irreversible phase transition with loss of adsorbed water as the halloysite is heated to 90–150 °C (halloysite has an endothermic peak at 500–600 °C due to structural dehydroxylation and then it remains stable until approximately 1000 °C). There are between 15–20 aluminosilicate
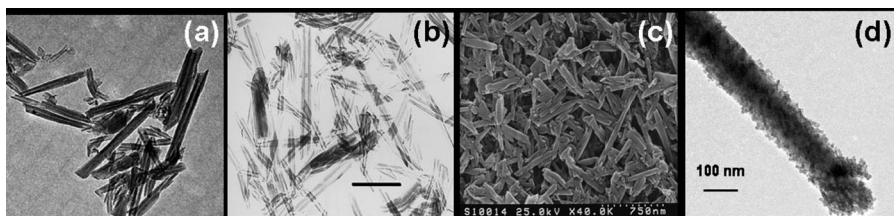

Figure 1. (a,b) TEM images of halloysite nanotubes dispersed in water. (c) SEM image of layer-by-layer nanocoating with (PEI/halloysite)[3] multilayer (top view), and (d) halloysite nanotube coated with PEI/PSS + (PEI/7 nm silica)[2] shell. Reprinted with permission from ref 10. Copyright 2002 Elsevier.

TABLE 1. Comparison of Halloysite and Carbon Nanotubes[4]

	halloysite nanotubes	carbon nanotubes
inner diameter/length	15 nm × *ca*. 1000 nm	2 nm × *ca*. 1000 nm
biocompatibility	biocompatible	toxic
price[a]	$4 per kg	$500 per kg
availability	thousand tons	grams

[a]Price is average for a number of companies.

layers rolled in the multilayer tubule walls with a layer spacing of 0.72 nm for the dehydrated halloysite. It was recommended by the AIPEA Nomenclature Committee to rename meta-halloysite (the dehydrated form) as "halloysite-7 Å," but for simplicity we will refer to it as halloysite.

From a technical perspective, the most interesting halloysite structures are cylinders with a very small inner diameter, and for loading/release studies one uses halloysite nanotubules with a diameter of 50 nm and a lumen of 15 nm.[4–6] The specific surface area of this halloysite is 65 m^2/g, pore volume is 1.3 mL/g, refractive index is 1.54, and specific gravity is 2.53 g/cm^3. For quicker release and higher loading efficiency, tubes of 50−100 nm lumen diameters may also be used. The outermost surface of the halloysite is relevant to silica, and the inner lumen surface may be compared to alumina. The surface ζ-potential of the halloysite falls between that of silica and alumina, indicating the predominance of silica properties on its exterior surface. Below pH 8.5 the tubule lumen has

> Halloysite is an economically viable clay material that can be mined from deposits as a raw mineral and is chemically similar to kaolin.

a positive inner surface, enabling loading of negative macromolecules and preventing their adsorption on the negatively charged outer surface.

It is interesting to compare halloysite with carbon nanotubes (Table 1). One can see that halloysite has some advantages in applications which require a biocompatible nanocontainer. In addition, halloysite clay is far less expensive, and the world supply is in excess of 50 000 tons per year. Therefore, a true mass-scale industrial application may be achieved in the near future.

Halloysite was found to be a viable and inexpensive nanoscale container for the encapsulation of biologically active molecules such as biocides and drugs, first demonstrated by Price *et al*.[4–6] Its physicochemical characterization as a novel drug delivery system has also been reported (for example, see refs 7−9). A strong surface charge on the halloysite tubules has been exploited for designing multilayers organized at the nanoscale using layer-by-layer (LbL) assembly.[10] The interior lumen of the halloysite has been used as an enzymatic nanoscale reactor.[11] The biocompatible nature of the halloysite was demonstrated when halloysite was used as a substrate for stem cell attachment and proliferation.[12]

An important development for halloysite applications has been shown for polymer loading, especially if one takes into account the possibility of tube orientation due to tension gradients in melted plastic. Halloysite is a hydrophilic material with a bulk contact angle with water of 10°. Therefore, to mix it with hydrophobic polymers re-

quires mediating molecules at the interface. These may be molecules with amphiphilic properties as was demonstrated for polypropylene loading.[13,14] A more radical approach could be modification of the halloysite SiO_2 surface with silane compounds. In our experiments, we have been able to achieve contact angles of 70° using this method. A range of metals including iron, copper, cobalt, permalloy, and nickel were utilized to form conductive and paramagnetic coatings on the halloysite clay.[15,16] These conductive small tubes may then be utilized in polymeric systems to form composites with interesting electromagnetic properties.

Other halloysite applications may include cosmetics, transdermal drug delivery systems, and bioimplants; delivery of herbicides, insecticides, and fungicides; and use in advanced ceramic materials and synthetic catalysts.[4,5] It is evident that halloysite is a promising biomaterial for dentistry and for bone tissue scaffolds.[8] We concentrate here on the description of halloysite as a tubular substrate for the entrapment and controlled release of functional species which may be used in coatings for oxidation and biofouling corrosion protection and demonstrate the promise of extensive applications.

Loading and Sustained Release. To entrap hydrophilic molecules, halloysite is mixed as a dry powder with a saturated solution of a chosen active agent in water, ethanol, acetone, or another solvent and then exposed to high vacuum. For highly soluble materials, one can slow down the release rate by blending them with viscous polymeric materials compatible with the active agent (*e.g.*, polyvinyl pyrrolidone). Materials with low melting points may be loaded in liquid form (*e.g.*, khellin).[4] Halloysite nanotubules have been used for entrapment and the subsequent release of different drugs: Nifedipine (antianginal), Furosemide (antihypertension), and Dexamethasone (corti-
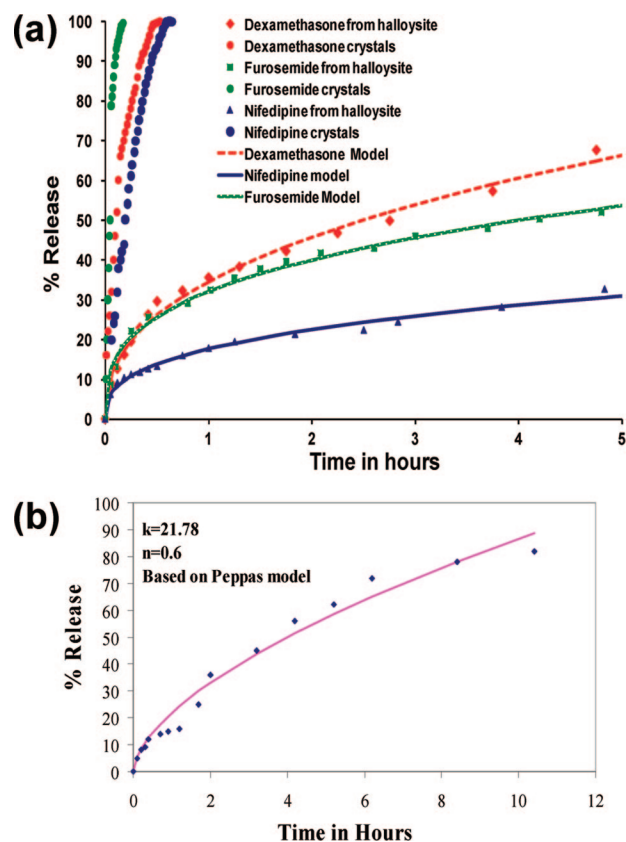
Figure 2. Release curves from halloysite in water in comparison with release from non/encapsulated crystals, pH 7: (a) dexamethasone, furosemide, and nifedipine.[9] Reprinted with permission from ref 4. Copyright 2007 Wiley-VCH Verlag GmbH & Co. KGaA. (b) Anticorrosion agent benzotriazole with the curve fit based on Peppas model of the release.[9]

costeroid).[9] The release profiles of drugs and the corrosion inhibitor benzotriazole from halloysite in comparison to that of the microcrystals are shown in Figure 2a,b.[9] It is evident that the release from the halloysite tubules takes 50−100 times longer than that from the microcrystals. In all the release curves an initial burst is observed within 10 min followed by a prolonged 8−10 h release. Previously, we were able to achieve a linear four hour release of nicotinamide adenine dinucleotide (NAD) from halloysite by increasing the viscosity of the loading solvent. We assume that linear release may be due to the higher loading of macromolecules inside the halloysite tubule giving a nanopore controlled release. No macromolecules were inserted between halloysite clay layers in the roll, and it was confirmed by the preserved 7.2 Å packing X-ray reflection. The amount of ex-

ogenous active agent is difficult to determine. We cannot exclude some of the active agents being attached to the outer surface of the halloysite, especially in natural gap-defects on the cylinder surface at the end of the rolled clay sheet (it is a natural pocket on the tubule surface). The typical 5−10% initial release burst observed may be related to dissolution of this material. Halloysite is a biocompatible material but because of the aluminosilicate chemistry should not biodegrade. Therefore, its usage in medicine may be restricted to oral dosing, dermal application, or dental uses or associated with medical implants.

The loading of enzymes is of special interest because of their biocatalytic activity.[11] A typical protein globule diameter is 2−8 nm which is close to the 15-nm lumen opening. Thus, 2−20 protein globules can fit into the total cross-sectional

area of the inner core. The behavior of large molecules in such narrow nanochannels has not been described yet. A probable irreversible adsorption of protein monolayers on the lumen surface can make analysis especially complicated. We have studied the entrapment and release properties of globular proteins with different diameters and surface charge: insulin, pepsin, urease, myoglobin, hemoglobin, albumin, glucose oxidase, and catalase.[2] As expected, the rate of protein release from halloysite tubes was slower compared to lower molecular weight drugs referred previously, and the release time reached 140 h for insulin (to achieve 80% release). Generally, release for negatively charged proteins was longer than for positively charged ones (*e.g.*, for anionic at pH 7 catalase, 150 h; for cationic albumin, 10 h) which may be related to the positive surface charge of the tube lumen.[4]

Biomimetic Nanoreactor. The biomimetic synthesis of inorganic composites is a rapidly developing research area lying at the nexus of chemistry, biology, medicine, and materials science. Biomineralization is one of the most promising methods of forming hybrid inorganic/organic nanomaterials, which often display unique and desirable morphological, structural, and chemical properties. Halloysite tubules were employed as hollow enzymatic nanoreactors for this purpose. The reaction of urease-catalyzed deposition of $CaCO_3$ from an aqueous solution containing $CaCl_2$ and urea was realized as a model reaction to demonstrate the possibility of conducting a biomineralization process inside the nanotube.[11] The negative charge of urease enhanced its adsorption inside the positively charged halloysite lumen. After the enzyme-catalyzed inorganic synthesis, $CaCO_3$ was synthesized exclusively inside the hollow tubular lumen. It has been elucidated that the urease-catalyzed hydrolysis of urea resulted in the formation of precipitated CO_3^{2-} ions. The synthesized

CaCO$_3$ completely fills the inner halloysite lumen and exhibits the metastable vaterite phase. This "enzymatic" approach may be utilized either for loading the interior of halloysite with different compounds or with bioactive material.

Shell/Stopper Assembly. A LbL self-assembly method was used for formation of organized polyelectrolyte nanoshells on halloysite tubes.[4] In this process, a polycation solution is added to the suspension of colloidal particles, and after adsorption saturation the particles are separated from free polycations in solution. Then, a polyanion layer is deposited. In the same manner, one can deposit any number of polyelectrolyte layers and charged nanoparticles in the shell. Figure 1c shows such nanotube encapsulation in a multilayer polyelectrolyte shell.[4] An assembly of polyelectrolyte nanoshells on halloysite changes its surface properties and forms stoppers at the lumen openings. In addition, the permeability of the polyelectrolyte shell can be varied by its composition and number of layers. By varying the pH, the shell permeability was changed to increase or decrease the release rate. This is especially important for enhanced release in the vicinity of corrosion spots where the pH is increased (up to pH 9−10). This approach was used for a triggered release *via* opening/closing of LbL stoppers at the halloysite ends.[17]

Tubule−Polycation Multilayer. The assembly of anionic halloysite in organized multilayers through the alternate adsorption of linear polycations *via* a LbL technique has been

> Halloysite tubules have been employed as hollow enzymatic nanoreactors for biomimetic synthesis.
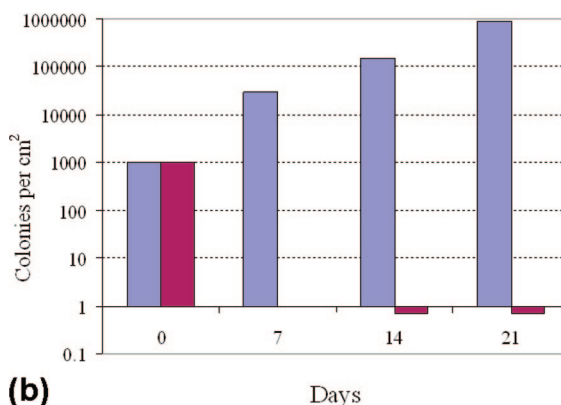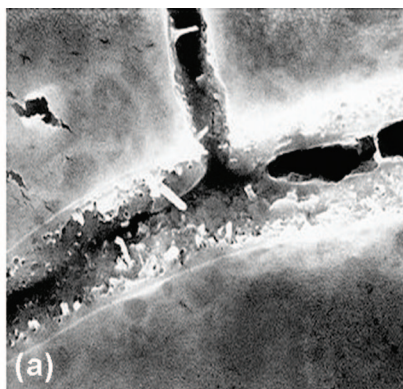
Figure 3. (a) SEM image of cracks in a dry layer of paint with inclusion of halloysite nanotubules containing an antifouling agent. (b) Mold growth inhibition: number of colonies *vs* days (blue, untreated; purple, treated growth media).[4] Reprinted with permission from ref 4. Copyright 2007 Wiley-VCH GmbH & Co. KGaA.

performed.[10,12] As polycations, poly(ethyleneimine) or poly(allylamine) have been used. The tubules in the layer are not parallel, but randomly oriented, and the layer density is rather low (Figure 1d). We have obtained the density of halloysite/PEI multilayers as $\rho = 0.48 \pm 0.08$ g/cm^3. This is less than the density of water and demonstrates that there is no water in the voids between the halloysite tubules in the dry film. Taking the halloysite density as 2.53 g/cm^3 one may calculate that 25% of the sample volume is occupied by halloysite and 75% of the sample is air (or may be filled with liquid). We foresee a possibility of assembly of oriented nanotubes in multilayers. Multilayer deposition of halloysite is possible not only on large solid surfaces but on soft biological surfaces such as wood or cotton cellulose microfibers and on medical implants. This coating allows a drastic increase of the porosity of fibers and materials made from them (*e.g.,* paper and textile) and can be loaded with functional materials (such as antiperspirant or self-cleaning agents).

Bioprotection. One of the first applications of halloysite as a nanocontainer was a coating with antifouling properties where a marine biocide was loaded into the halloysite which was then mixed with paint for ships. Mildewcides also are capable of sustained activity (Figure 3). As an antifouling biocide, we have studied iodobutylpropyl carbonate (IBPC), and its release curves were similar to those described earlier for drug release.[4] Inclusion of the halloysite as a nanoclay in coatings may be aided by the SiO$_2$ surface chemistry, allowing for a range of surface treatments. Common quaternary surfactants, as well as functional silanes, may render the clay easily wet by common polymers. Unlike platy clays, halloysite does not need exfoliation prior to
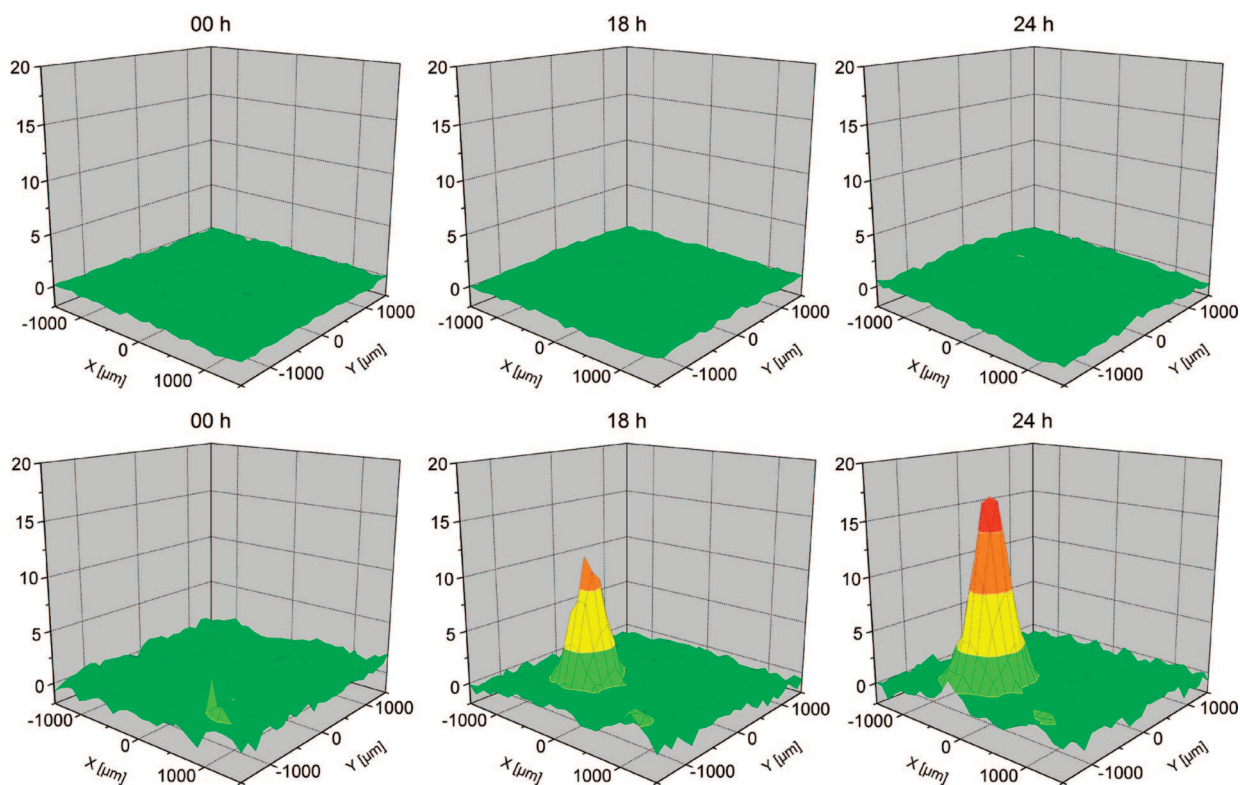
Figure 4. Current density measurements using the scanning vibrating electrode technique. The *Z*-axis represents the current density in μA/cm² and the scanned area is 3 × 3 mm². The samples were observed over 0, 18, and 24 h in aqueous 0.1 M NaCl. (top) Aluminum Al_2CuMg alloy coated with ZrO_x−SiO_x sol−gel mixed with benzotriazole-loaded halloysite at 0.01 wt %, and (bottom) sol−gel coating without halloysite addition showing development of a corrosion defect. Both samples were scratched to provide artificial defects and to demonstrate self-healing ability of a ZrO_x−SiO_x sol−gel mixed with benzotriazole-loaded halloysite.

use. In addition, unlike common nanoclays, the functionality of the halloysite as a controlled delivery system or as a conductive filler expands the range of polymeric applications, permitting greater variability in product design. The unique feature of halloysite tubules are chemically different outermost and innermost surfaces, which allows for separate chemical modification. Halloysite admixing to hydrophobic media (such as oil-based paint or polypropylene) requires mediator molecules to match halloysite surface properties with properties of the bulk plastic. Some results on halloysite admixing to plastics have been demonstrated and 30−50% increase in loaded polymer tensile strength was observed.[13,14]

Food additions, fertilizers, oil well anticlogging treatments, sustained drug release, plastic fillers, specific ion adsorbent, and even hydrogen storage are all possible applications based on loading of functional molecules into the halloysite lumen and their slow release.[4] Other perspective applications include templating nanoparticle surfaces, cosmetics, the delivery of herbicides, insecticides, fungicides, and antimicrobials, and use in advanced ceramic materials, bioimplants, transdermal drug delivery systems, synthetic catalytic materials, and molecular sieves.

Corrosion Protection. Corrosion of metals is one of the main destruction processes resulting in huge economic losses, especially in aerospace, automotive, construction, and the petroleum industries. Recent achievements in surface science open a new avenue for the fabrication of coatings with active anticorrosion properties through the integration of nanoscale containers (carriers) loaded with the inhibitor or other active compound into existing "passive" protective films thus designing completely new coating systems based on the "passive" matrix/"active" container structure. The main idea here is to develop nanoscale containers, which can be sensitive to external (*e.g.*, mechanical damage) or internal (*e.g.*, pH changes) corrosion triggers.[18] If the local environment undergoes changes or if the corrosion process initiates on the metal surface, the nanocontainers should release encapsulated inhibitor directly into the damaged area, thus achieving self-healing. Because of the possibility of loading the inner volume of halloysite materials with inhibiting agents and controlled-release behavior, halloysites can be successfully employed as inhibitor-loaded nanoscale containers in a new generation of self-healing anticorrosion coatings. Halloysite nanotubes were loaded with the corrosion inhibitor benzotriazole, which is soluble in water, and then incorporated into ZrO_2−SiO_2

sol−gel coating deposited onto aerospace AA2024 aluminum alloy.[17] Halloysites were distributed in the sol−gel coating without aggregation or accumulation on the surface of the film or on the coating-metal interface.

Figure 2b shows a release curve for the anticorrosion agent benzotriazole. In refs 17 and 18 it was demonstrated that such sustained benzotriazole release is efficient for corrosion protection. Materials loaded in halloysite nanotubes are protected from leaching or other potential environmental hazards and may be released on demand in needed rates. The addition of inhibitor-loaded halloysites to the coating matrix at 0.01 wt % does not reduce the initial barrier properties of the sol−gel coating. Moreover, the anticorrosion efficiency was increased and a self-healing effect was demonstrated. Figure 4 panels a and b present spatially resolved corrosion current density measurements near artificial defects made in ZrO_x−SiO_x sol−gel coating (a) with and (b) without benzotriazole-loaded halloysite. The coating without halloysite addition shows the development of a corrosion defect during immersion in NaCl solution. On the other hand, the sample coated with thin sol−gel film doped by benzotriazole-loaded halloysite exhibits no evidence of corrosion current and corrosion propagation during the immersion in a corrosive NaCl solution. This fact demonstrates the possibility of using halloysites as nanoscale containers for self-healing anticorrosion coatings. The function of inhibitor-doped halloysites is to keep and provide slow release of the inhibitor blocking the initial corrosion processes and healing microscale defects in the coating. The halloysites prevent the interaction of the inhibitor with the sol−gel matrix and, thereby, deactivation of the inhibitor. Admixing of halloysite to oil-based coatings and plastics needs to tune the surface hydrophobization which may be

Halloysites are cheap, abundantly available, and durable, with high mechanical strength and biocompatible. However, they are not yet well studied with regard to the chemistry of the inner and outer surface and the possibilities of liquids inside the nanoscale volumes, which is most important for controlled encapsulation and release.

achieved through siloxane or with surface-active molecule treatment.

As discussed above, there are many unsolved problems in halloysite research and development. Toward improving halloysite tube-loading, researchers are performing nanofluidic experiments with little established theory for this. It is likely that many solvent characteristics in 15 nm channels are different from the bulk ones. Deviation of physicochemical characteristics (viscosity, pH, salt concentration) inside the lumen are also expected and need to be analyzed. Mechanical properties of single tubes have not yet been analyzed. Formation of controllable stoppers at the end of the tube is another challenge in the development of nanotube halloysite containers.

Among the possible applications of halloysite nanotubes, we emphasize the following as the highest level of priority and applicability: (1) controlled release of anticorrosion agents; (2) sustained release of herbicides, insecticides, fungicides, and antimicrobials; (3) paint loaded with antifouling properties (marine biocides and antimolding agents); (4) sustained release of drugs (cosmetics, dermatology), fertilizers, food additives, and fragrance; (5) plastic fillers for strength enforcement and protection (*e.g.,* radiation or ultraviolet stability); (6) templating nanoparticle synthesis (rodlike); (7) radiowave absorbing coating with metal-

lized halloysite tubes; (8) catalytic materials and molecular sieves; (9) specific ion adsorbent (heavy metal ions); (10) encapsulation of hydrogen storage materials; (11) use in advanced ceramic materials and bioimplants.

These applications will profit from the fact that halloysites are cheap, abundantly available, and durable, with high mechanical strength and biocompatible. However, they are not yet well studied with regard to the chemistry of the inner and outer surface and the possibilities of liquids inside the nanoscale volumes, which is most important for controlled encapsulation and release. Also their mechanical properties and their interaction with organic materials need further study and control to arrive at stable, active fillers in composites. These tubes are especially attractive because of the different chemistry of the inner and outer surface and of their tunable inner diameter. This makes them ideal models for nanofluidics, an upcoming field of high impact in science and technology. Aluminosilicates are not toxic and allow for a range of applications areas. Like carbon nanotubes, halloysite tubes can be rendered conductive by coating with conductive polymers or may be metallized using electrolyzed deposition techniques developed for the silicon chip industry. When used for mechanical re-enforcement it is possible to fill them with active agents

that may permit the production of smart materials that are responsive to chemical, thermal, or mechanical perturbations. Lowering the costs for nanomaterials will open a number of applications that will likely remain outside the realm of carbon nanotubes or other synthetic structures due to cost considerations. Halloysite is also a "green" material and because it is a natural product will not add risk to the environment as other nanomaterials may have the potential to do.

REFERENCES AND NOTES

1. Iyoda, M.; Hasegawa, M.; Enozawa, H. Self-Assembly and Nanostcture Formation of Multifunctional Organic *p*-Donors. *Chem. Lett.* **2007**, *36*, 1402–1407.
2. Chen, X.; Mao, S. Synthesis of Titanium Dioxide Nanomaterials. *J. Nanosci. Nanotechnol.* **2006**, *6*, 906–925.
3. Joussein, E.; Pitit, S.; Churchman, J.; Theng, B.; Righi, D.; Delvaux, B. Halloysite Clay Minerals-A Reviewer. *Clay Miner.* **2005**, *40*, 383–426.
4. Lvov, Y.; Price, R. Halloysite Nanotubules, a Novel Substrate for the Controlled Delivery of Bioactive Molecules. In *Bio-Inorganic Hybrid Nanomaterials*; Ruiz-Hitzky, E., Ariga, K., Lvov, Y., Eds.; Wiley: London, Berlin, 2007; Chapter 12, pp 419– 441.
5. (a) Price, R., Gaber, B. Controlled Release of Active Agents Using Inorganic Tubules. U.S. Patent 5,651,976. (b) Price, R. Sustained Delivery of Active Compounds from Tubules with Rational Control. U.S. Patent 5,705,191. (c) Price, R. Method of Controlled Release and Controlled Release Microstructures. U.S. Patent 6,280,759. (d) Price, R. Efficient Method for Subsurface Treatment, Including Squeeze Treatment. U.S. Patent 6,401,816. (e) Redlinger, M.; Corkery, R. Cosmetic Skincare Applications Employing Mineral Derived Tubules for Controlled Release. U.S. Patent 2007/0202061.
6. Price, R.; Gaber, B.; Lvov, Y. *In-vitro* Release Characteristics of Tetracycline, Khellin, and Nicotinamide Adenine Dinucleotide from Halloysite: A Cylindrical Mineral for Delivery of Biologically Active Agents. *J. Microencapsulation* **2001**, *18*, 713–723.
7. Levis, S.; Deasy, P. Use of Coated Microtubular Halloysite for the Sustained Release of Diltiazem Hydrochloride and Propranolol Hydrochloride. *Int. J. Pharm.* **2003**, *253*, 145–157.
8. Kelly, H.; Deasy, P.; Ziaka, E.; Claffey, N. Formulation and Preliminary *in Vivo* Dog Studies of a Novel Drug Delivery System for the Treatment of Periodontitis. *Int. J. Pharm.* **2004**, *274*, 167–183.
9. Veerabadran, N.; Price, R.; Lvov, Y. Clay Nanotubules for Drug Encapsulation and Sustained Release. *Nano J.* **2007**, *v.2*, 215–222.
10. Lvov, Y.; Price, R.; Gaber, B.; Ichinose, I. Thin Film Nanofabrication *via* Layer-by-Layer Adsorption of Tubule Halloysite, Spherical Silica, and Proteins. *Colloids and Surfaces: Engineering* **2002**, *198*, 375–382.
11. Shchukin, D.; Price, R.; Sukhorukov, G.; Lvov, Y. Biomimetic Synthesis of Vaterite in the Interior of Clay Nanotubules. *Small* **2005**, *1*, 510–513.
12. Kommireddy, D.; Sriram, S.; Lvov, Y.; Mill, D. Layer-by-Layer Assembled Nanoparticle Thin Films - A New Surface Modification Approach for Stem Cell Attachment. *Biomaterials* **2006**, *27*, 4296–4303.
13. Du, M.; Gao, D.; Jia, D. Thermal Stability and Flame Retardant Effect of Halloysite Nanotubes on Poly(propylene). *Eur. Polym. J.* **2006**, *42*, 1362–1369.
14. Liu, M.; Guo, B.; Du, M.; Cai, X.; Jia, D. Properties of Halloysite Nanotube-Epoxy Resin Hybrids and the Interfacial Reactions in the Systems. *Nanotechnology* **2007**, *18*, 455703.
15. Fu, Y.; Zhang, L.; Zheng, J. In-situ Deposition of Pd Nanoparticles on Tubular Halloysite Template for Initial Metallization. *J. Nanosci. Nanotechnol.* **2005**, *5*, 558–564.
16. Kilislioglu, A.; Bilgin, B. Adsorption of Uranium (U-YI) from Aqueous Solutions on Halloysite Clay. *Radiochimica Acta J.* **2002**, *90*, 155–160.
17. Shchukin, D.; Möhwald, H. Surface-Engineered Nanocontainers for Entrapment of Corrosion Inhibitors. *Adv. Funct. Mater* **2007**, *17*, 1451–1458.
18. Shchukin, D.; Zheludkevich, M.; Yasakau, K.; Lamaka, S.; Ferreira, M. G. S.; Möhwald, H. H. LbL Nanocontainers for Self-Healing Corrosion Protection. *Adv. Mater.* **2006**, *18*, 1672–1678.