

they travel through the cathode to vaporize into a volume where the Na vapor pressure is much lower than it is on the anode side. Thus, the cathode design is subject to competing requirements to be thin enough to allow transport of sodium to the low-pressure side, yet thick enough to afford adequate electronic conductivity.

The concept underlying the development of the present mixed conducting electrode materials is the following: The constraint on the thickness of the cathode can be eased by incorporating Na⁺-ion-conducting material to facilitate transport of sodium through the cathode in ionic form. At the same time, by virtue of the electronically conducting material mixed with the ionically conducting material, reduction of Na⁺ ions to Na atoms can take place throughout the thickness of the cathode. The net effect is to reduce the diffusion and flow resistance to sodium through the electrode while reducing the electronic resistance by providing shorter conduction

paths for electrons. Reduced resistance to both sodium transport and electronic conductivity results in an increase in electric power output.

Previous research had shown that mixed-conducting electrodes to improve the performance of an AMTEC cell could be made from mixtures of Mo (an electronic conductor) and Na₂MoO₄ (an ionic conductor) or of W (an electronic conductor) and Na₂WO₄ (an ionic conductor). Unfortunately, electrodes made of these mixtures do not last long: the vapor pressures of Na₂MoO₄ and Na₂WO₄ are so high at the typical operating temperature of a sodium AMTEC cell (between 1,020 and 1,120 K) that these ionically conducting materials evaporate within a few hundred hours of operation.

The present mixed-conducting electrode materials are mixtures of Mo (as before, an electronic conductor) and Na_xTiO₂ (a conductor of both electrons and Na⁺ ions). Na_xTiO₂ can be formed by

exposing TiO₂ to Na vapor at a temperature >900 °C. Na_xTiO₂ is a mixture of Na-Ti-O compounds, all of which are electronically conducting by virtue of the conductivity of TiO₂, and ionically conducting toward Na⁺ ions. In an experiment, an electrode made from a mixture of equal weight proportions of Mo and TiO₂ was found to perform well at a temperature of 830 °C (1,103 K) for >1,000 hours, with no significant change in either electrode power or transport properties. Moreover, the performance of this electrode was found to equal or exceed the performance of the best previously known AMTEC electrode, which was made of RhW.

This work was done by Margaret Ryan, Roger Williams, Margie Homer, and Liana Lara of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].
NPO-20920

Process for Encapsulating Protein Crystals

Crystals can be grown in forms suitable for x-ray diffraction studies.

A process for growing protein crystals encapsulated within membranes has been invented. This process begins with the encapsulation of a nearly saturated aqueous protein solution inside semipermeable membranes to form microcapsules. The encapsulation is effected by use of special formulations of a dissolved protein and a surfactant in an aqueous first liquid phase, which is placed into contact with a second, immiscible liquid phase that contains one or more polymers that are insoluble in the first phase. The second phase becomes formed into the semipermeable membranes that surround microglobules of the first phase, thereby forming the microcapsules. Once formed, the microcapsules are then dehydrated osmotically by exposure to a concentrated salt or polymer solution. The dehydration forms supersaturated solutions inside the microcapsules, thereby enabling nucleation and growth of protein crystals inside the microcapsules.

By suitable formulation of the polymer or salt solution and of other physical and chemical parameters, one can control the rate of transport of water out of the microcapsules through the membranes and thereby create physicochemical conditions that favor the growth, within each microcapsule, of one or a few large crystals suitable for analysis by x-ray diffraction. The

membrane polymer can be formulated to consist of low-molecular-weight molecules that do not interfere with the x-ray diffraction analysis of the encapsulated crystals. During dehydration, an electrostatic field can be applied to exert additional control over the rate of dehydration.

This protein-crystal-encapsulation process is expected to constitute the basis of protein-growth experiments to be performed on the space shuttle and the International Space Station. As envisioned, the experiments would involve the exposure of immiscible liquids to each other in sequences of steps under microgravitational conditions. The experiments are expected to contribute to knowledge of the precise conditions under which protein crystals form. By enhancing the ability to grow crystals suitable for x-ray diffraction analysis, this knowledge can be expected to benefit not only the space program but also medicine and the pharmaceutical industry.

The prior art in osmotic dehydration for growing protein crystals involves the use of a small chamber in which a planar reverse-osmosis membrane is positioned between the mother liquor and a dehydrating salt solution. The prior art entails several disadvantages: (1) The nucleation and subsequent growth of protein crystals depend on

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increasing the concentration of precipitant and protein in the mother liquor; (2) there is no control over the effects of solute-driven convection on the surface of the crystal; (3) the crystals are not protected by any enclosure and thus are subject to physical damage as they are harvested and mounted; and (4) in some instances in the prior art, protein crystals have been protected by mounting them in aqueous gels, but this practice gives rise to the additional (as yet unsolved) problem of removing the gel material without adversely affecting the integrity of the protein crystals.

In contrast, the encapsulation of protein crystals in semipermeable membranes in the present process does not involve the use of gel, yet it creates closed environments that favor the growth of the crystals under prescribed conditions of controlled dehydration and protects the crystals against harsh environments that could otherwise damage the crystals.

In the present protein-crystal-encapsulation process, the microcapsules are spherical. The entire outer surface of the membrane of a microcapsule is accessible for osmotic dewatering as well as for and infiltration by hydrogen or hydroxyl ions. Such infiltration can be utilized to change the pH levels within microcapsules to favor or enhance protein saturation and subse-

quent crystal growth. The increase (relative to the prior art) in interfacial surface area occasioned by the transition from planar membranes to spherical microcapsules makes it possible to change conditions more rapidly throughout the mother liquor surrounding the crystal(s), thereby promot-

ing the formation of more ordered and more nearly perfect crystals.

This work was done by Dennis R. Morrison of Johnson Space Center and Benjamin Mosier of the Institute for Research, Inc. Further information is contained in a TSP [see page 1].

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, Johnson Space Center, (281) 483-0837. Refer to MSC-22936.

Lightweight, Self-Deployable Wheels

Compacted, frozen wheels are deployed by heating above T_g .

Ultra-lightweight, self-deployable wheels made of polymer foams have been demonstrated. These wheels are an addition to the roster of cold hibernated elastic memory (CHEM) structural applications. Intended originally for use on nanorovers (very small planetary-exploration robotic vehicles), CHEM wheels could also be used for many commercial applications, such as in toys.

The CHEM concept was reported in "Cold Hibernated Elastic Memory (CHEM) Expandable Structures" (NPO-20394), *NASA Tech Briefs*, Vol. 23, No. 2 (February 1999), page 56. To recapitulate: A CHEM structure is fabricated from a shape-memory polymer (SMP) foam. The structure is compressed to a very small volume while in its rubbery state above its glass-transition temperature (T_g). Once compressed, the structure can be cooled below T_g to its glassy state. As long as the temperature remains $<T_g$ the structure remains com-

pacted (in a cold hibernated state), even when the external compressive forces are removed. When the structure is subsequently heated above T_g , it returns to the rubbery state, in which a combination of elasticity and the SMP effect cause it to expand (deploy) to its original size and shape. Once thus deployed, the CHEM structure can be rigidified by cooling below T_g to the glassy state. The structure could be subsequently reheated above T_g and recompact. The compaction/deployment/rigidification cycle could be repeated as many times as needed.

SMPs with T_g s ranging from -100 to almost $+100$ °C are available. Hence, it should be possible to select SMPs with T_g s suitable for CHEM structures for a variety of potential terrestrial and outer-space applications. During an investigation directed toward extending the CHEM concept to wheels, several wheel designs for a proto-

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type nanorover were evaluated. CHEM models of the designs were fabricated and assessed by subjecting the models to a CHEM processing cycle. All wheels recovered completely after the cycle, and a wheel design with the fastest deployment was selected for the nanorover. Full-scale wheels were fabricated and assembled on two-wheeled prototype nanorover. Finally, the compacted wheels were successfully deployed at 80 °C and subsequently rigidified, both at room temperature in the terrestrial atmosphere and at a lower temperature and pressure chosen to simulate the Mars atmosphere.

*This work was done by Artur Chmielewski, Witold Sokolowski, and Peter Rand of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].
NPO-21225*

Grease-Resistant O Rings for Joints in Solid Rocket Motors

There is a continuing effort to develop improved O rings for sealing joints in solid-fuel rocket motors. Following an approach based on the lessons learned in the explosion of the space shuttle *Challenger*, investigators have been seeking O-ring materials that exhibit adequate resilience for effective sealing over a broad temperature range: What are desired are O rings that expand far and fast enough to maintain seals, even when metal sealing surfaces at a joint move slightly away from each other shortly after ignition and the motor was exposed to cold

weather before ignition. Other qualities desired of the improved O rings include adequate resistance to ablation by hot rocket gases and resistance to swelling when exposed to hydrocarbon-based greases used to protect some motor components against corrosion. Five rubber formulations — two based on a fluorosilicone polymer and three based on copolymers of epichlorohydrin with ethylene oxide — were tested as candidate O-ring materials. Of these, one of the epichlorohydrin/ethylene oxide formulations was found to offer the

closest to the desired combination of properties and was selected for further evaluation.

*This work was done by Albert R. Harvey and Harold Feldman (deceased) of Thiokol Propulsion for Marshall Space Flight Center. To obtain a copy of the report, "Resilient, Hydrocarbon Base Grease Resistant O-ring Seals for Solid Rocket Motor Applications," please contact the company at (435) 863-4123.
MFS-31643*