II matrix cracking. Failure initiation is determined using a failure criterion, and the evolution of these ISVs is controlled by a set of traction-separation laws. The traction separation laws are postulated such that the area under the curves is equal to the fracture toughness of the material associated with the corresponding failure mechanism. A characteristic finite element length is used to transform the traction-separation laws into stress-strain laws. The ISV evolution equations are derived in a thermodynamically consistent manner by invoking the stationary principle on the total work of the system with respect to each ISV.

A novel feature is the inclusion of both pre-peak damage and appropriately scaled, post-peak strain softening failure. Also, the characteristic elements used in the failure degradation scheme are calculated using the element nodal coordinates, rather than simply the square root of the area of the element.

This work was done by Evan J. Pineda of Glenn Research Center and Anthony M. Waas of the University of Michigan. Further information is contained in a TSP (see page 1).

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steven Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-18954-1

High-Performance, Low-Temperature-Operating, Long-Lifetime Aerospace Lubricants

John H. Glenn Research Center, Cleveland, Ohio

The synthesis and characterization of six new ionic liquids, with fluoroether moeties on the imidazolium ring, each with vapor pressures shown to be $<10^{-7}$ Torr at 25 °C, have been demonstrated. Thermal stability of the ionic liquids up to 250 °C was demonstrated. The ionic liquids had no measurable influence upon viscosity upon addition to perfluoropolyether (PFPE) base fluids. They also had no measureable influence upon corrosion on steel substrates upon addition to base fluids. In general, 13 to 34% lower COFs (coefficients of friction), and 30 to 80% higher OK load of base fluids upon addition of the ionic liquids was shown.

The compound consists of a 1,3-disubstituted imidazolium cation. The substituents comprise perfluoroether groups. A bis(trifluoromethanesulfonyl)imide anion counterbalances the charge. The fluorinated groups are intended to enhance dispersion of the ionic liquid in the PFPE base fluid. The presence of weak Van der Waals forces associated with fluorine atoms will limit interaction of the substituents on adjacent ions. The longer interionic distances will reduce the heat of melting and viscosity, and will increase dispersion capabilities.

This work was done by Bryan Bergeron, David Skyler, Kyle Roberts, and Amy Stevens of Physical Sciences, Inc. for Glenn Research Center. Further information is contained in a TSP (see page 1).

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steven Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-19039-1.

Carbon Nanotube Microarrays Grown on Nanoflake Substrates

This process creates materials comprised predominantly of single-walled carbon nanotubes.

Lyndon B. Johnson Space Center, Houston, Texas

This innovation consists of a new composition of matter where single-walled carbon nanotubes (SWNTs) are grown in aligned arrays from nanostructured flakes that are coated in Fe catalyst. This method of growth of aligned SWNTs, which can yield well over 400 percent SWNT mass per unit substrate mass, exceeds current yields for entangled SWNT growth. In addition, processing can be performed with minimal wet etching treatments, leaving aligned SWNTs with superior properties over those that exist in entangled mats.

The alignment of the nanotubes is similar to that achieved in vertically aligned nanotubes, which are called “carpets.” Because these flakes are grown in a state where they are airborne in a reactor, these flakes, after growing SWNTs, are termed “flying carpets.”

These flakes are created in a roll-to-roll evaporator system, where three subsequent evaporations are performed on a 100-ft (≈30-m) roll of Mylar. The first layer is composed of a water-soluble “release layer,” which can be a material such as NaCl. After depositing NaCl, the second layer involves 40 nm of supporting layer material — either Al_2O_3 or MgO. The thickness of the layer can be tuned to synthesize flakes that are larger or smaller than those obtained with a 40-nm deposition.

Finally, the third layer consists of a thin Fe catalyst layer with a thickness of 0.5 nm. The thickness of this layer ultimately determines the diameter of SWNT growth, and a layer that is too thick will result in the growth of multi-walled carbon nanotubes instead of single-wall nanotubes. However, between a thickness of 0.5 nm to 1 nm, single-walled carbon nanotubes are known to be the primary constituent. After this three-layer deposition process, the Mylar is rolled through a bath of water, which allows catalyst-coated flakes to detach from the Mylar. The flakes are then collected and dried. The method described here for making such flakes is analogous to that which is used to make birefringent ink that is coated on U.S. currency.

After deposition, the growth is carried out in a hot-filament chemical vapor deposition apparatus. A tungsten hot filament placed in the flow of H_2 at a temperature greater than 1,600 °C creates atomic hydrogen, which serves to reduce the Fe catalyst into a metallic state. The catalyst can now precipitate SWNTs in the presence of growth gases. The gasses used for the experiments reported are C_2H_2, H_2O, and H_2, at rates of 2, 2, and 400 standard cubic centimeters per minute (sccm), respectively.

In order to retain the flakes, a cage is constructed by spot welding stainless steel or copper mesh to form an enclosed area, in which the flakes are placed prior to growth. This allows growth gases and atomic hydrogen to reach the flakes, but does not allow the flakes, which rapidly nucleate SWNTs, to escape from the cage.

This work was done by Howard K. Schmidt, Robert H. Hauge, Cary Pint, and Sean Pheasant of Rice University for Johnson Space Center. For further information, contact the JSC Innovation Partnerships Office at (281) 483-3809.

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

Rice University
Office of Technology Transfer MS 705
P.O. Box 1892
Houston, TX 77251-1892
Phone No.: (713) 348-6188
E-Mail: techtran@rice.edu

Refer to MSC-24500-1, volume and number of this NASA Tech Briefs *issue, and the page number.*

Differential Muon Tomography to Continuously Monitor Changes in the Composition of Subsurface Fluids

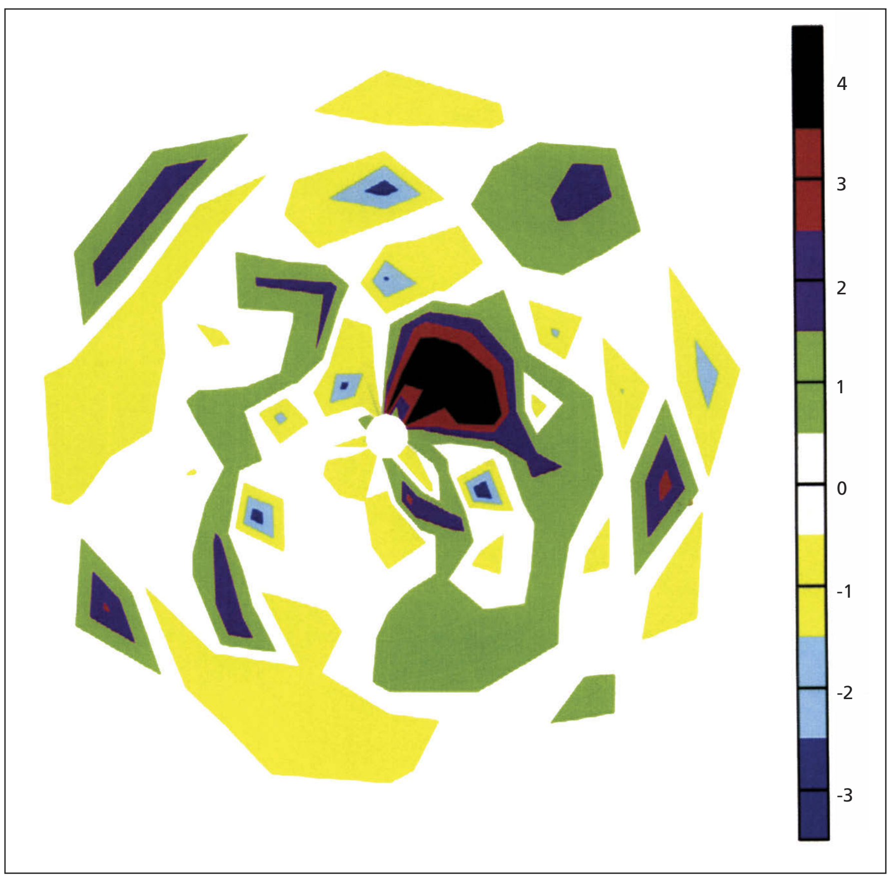
This innovation enables tracking of carbon storage or enhanced oil recovery in subsurface reservoir projects.

NASA's Jet Propulsion Laboratory, Pasadena, California

Muon tomography has been used to seek hidden chambers in Egyptian pyramids and image subsurface features in volcanoes. It seemed likely that it could be used to image injected, supercritical carbon dioxide as it is emplaced in porous geological structures being used for carbon sequestration, and also to check on subsequent leakage. It should work equally well in any other application where there are two fluids of different densities, such as water and oil, or carbon dioxide and heavy oil in oil reservoirs.

Continuous monitoring of movement of oil and/or flood fluid during enhanced oil recovery activities for managing injection is important for economic reasons. Checking on leakage for geological carbon storage is essential both for safety and for economic purposes. Current technology (for example, repeat 3D seismic surveys) is expensive and episodic. Muons are generated by high-energy cosmic rays resulting from supernova explosions, and interact with gas molecules in the atmosphere. This innovation has produced a theoretical model of muon attenuation in the thickness of rock above and within a typical sandstone reservoir at a depth of between 1.00 and 1.25 km. Because this first simulation was focused on carbon sequestration, the innovators chose depths sufficient for the pressure there to ensure that the carbon dioxide would be supercritical.

This innovation demonstrates for the first time the feasibility of using the natural cosmic-ray muon flux to generate continuous tomographic images of carbon dioxide in a storage site. The muon flux is attenuated to an extent dependent on, amongst other things, the density of the materials through which it passes. The density of supercritical carbon dioxide is only three quarters that of the brine in the reservoir that it displaces. The first realistic simulations indicate



A contour plot of the **Muon Intensity Change** due to CO_2 injection into the reservoir over a period of one year, expressed as standard deviations from the initial value.