

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 moieties 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 ( $\approx 30$ -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  $\text{Al}_2\text{O}_3$  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.