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:

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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

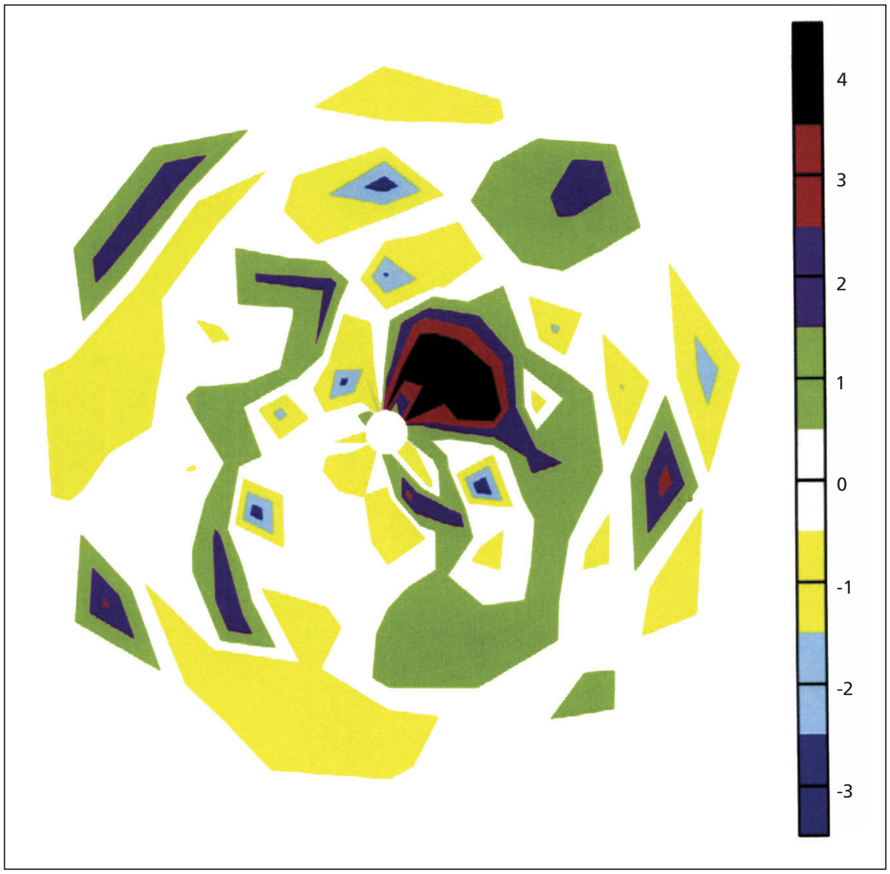
This innovation enables tracking of carbon storage or enhanced oil recovery in subsurface reservoir projects.

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.

that changes as small as 0.4% in the storage site bulk density could be detected (equivalent to 7% of the porosity, in this specific case). The initial muon flux is effectively constant at the surface of the Earth. Sensitivity of the method would be decreased with increasing depth. However, sensitivity can be improved by emplacing a greater array of particle detectors at the base of the reservoir.

This work was done by Max Coleman of Caltech; Vitaly A. Kudryavtsev, Neil J. Spooner, and Cora Fung of University of Sheffield; and Jon Gluyas of University of Durham for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). *NPO-48328*