Nuclear fuel fragments released from the Fukushima Daiichi Nuclear Power Plant

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Ongoing decommissioning of the damaged reactors at Fukushima Daiichi Nuclear Power Plant (FDNPP) must address the most challenging issue: the removal of melted fuel. A first priority is to know the physical and chemical properties of the mixture of the melted fuel, *corium*, and structural materials, *debris*. We report, for the first time, the nano- to atomic-scale characteristics of the nano-scale fragments of nuclear fuels that were released from FDNPP.

Nano-fragments of an intrinsic U-phase were discovered closely associated with radioactive cesium-rich microparticles (CsMPs), which were found in paddy soils within ~4 km of the FDNPP. The thin foils of the samples were prepared using a focused ion-beam and observed using scanning transmission electron microscopy.

The nano-fragments of debris are either encapsulated by or attached to the CsMPs and occur in two different forms; (*i*) UO_{2+x} nanocrystals ~70 nm in size are embedded in a magnetite nanocrystal, ~400 nm in size. The structural relation indicates epitaxial growth of euhedral magnetite over previously crystallized UO_{2+x} nanocrystals that initially precipitated within the melted Fe-oxide. Further, trace amounts of fissionogenic Tc and Mo are distributed on the surface of magnetite. (*ii*) isometric $(U,Zr)O_{2+x}$ nanocrystals occur, ~200 nm in size. The U/(U+Zr) molar ratio ranges from 0.14-0.91. Also present are several pores, ~5 nm, within the nanocrystal, indicating the entrapment of vapors or fission gasses during crystallization. These results document the heterogeneous physical and chemical properties of debris at the nanoscale, reflecting the complex thermal processes during debris formation. The CsMPs are an important medium for the transport of debris fragments to the environment as a respirable fraction.