Non-destructive studies of fuel pellets and their cladding by spatially resolved neutron transmission spectroscopy at pulsed neutron sources

A.S. Tremsin[1], S.C. Vogel[2], M. Mocko[2], K.J. McClellan[2], D. Byler[2], A.S. Losko[2], M.A.M. Bourke[2], V. Yuan[2], R.O. Nelson[2], D.W. Brown[2], M. Okuniewski[3], W.B. Feller[4]

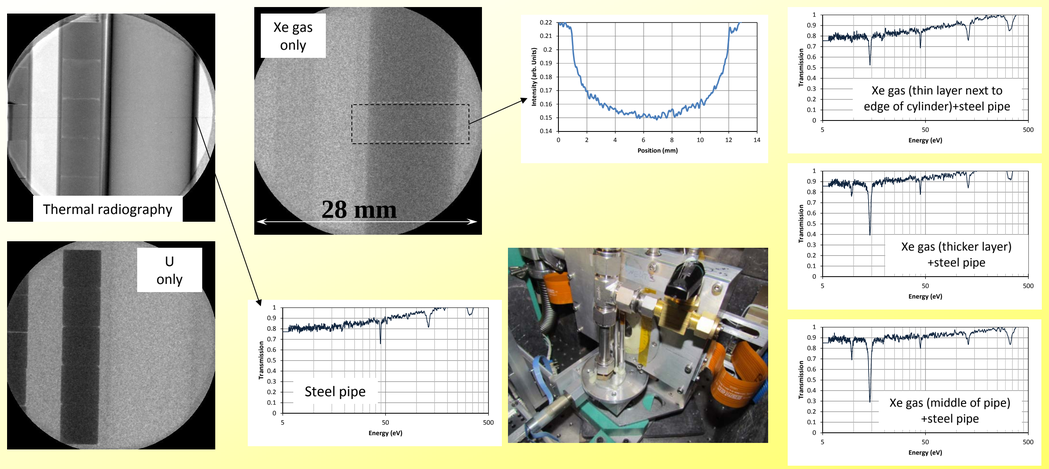
[1]University of California at Berkeley, Berkeley, CA 94720, USA; [2]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[3]Idaho National Laboratory, Idaho Falls, ID 83401, USA; [4]NOVA Scientific, Inc., 10 Picker Rd., Sturbridge, MA 01566, USA

Abstract

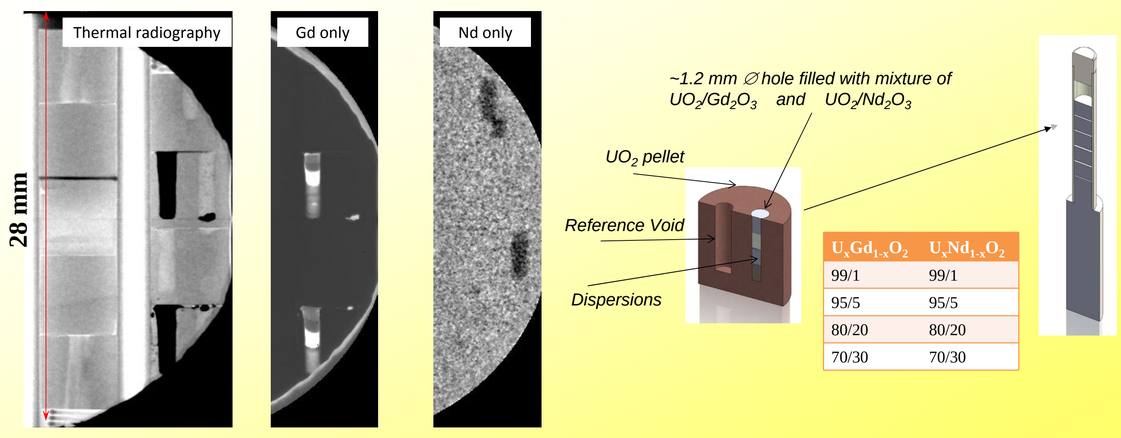
The unique combination of a narrow-pulse neutron source and fast time- and spatially-resolved neutron detection enables novel techniques for non-destructive studies in materials sciences and energy research. Spatially resolved neutron transmission spectroscopy can be performed simultaneously in a very wide range of neutron energies: from cold and thermal neutrons (~meV energies) revealing information on the crystallographic structure of the samples to epithermal neutrons (up to ~10 keV) enabling isotope-specific imaging and temperature mapping. Simultaneous detection of position and time (with <100 μm and 0.02-1 μs resolution, respectively) of individual neutrons in a wide range of energies of every neutron pulse is now possible with new detectors.

Our proof-of-principle experiments conducted at LANSCE demonstrate the **unique capability of energy resolved neutron imaging providing the isotope specific imaging of fuel elements through resonance transmission analysis simultaneously with the crystallographic structure of cladding through Bragg edge imaging, as well as imaging of defects in the fuel element, such as cracks and voids through neutron radiography. We demonstrate spectroscopic imaging of Urania with W, Nd, Gd inclusions and Xe and Kr gases within steel container overlapping with Urania pellets.**

Xe gas (90 psi pressure) imaged in a steel pipe together with Urania pellets

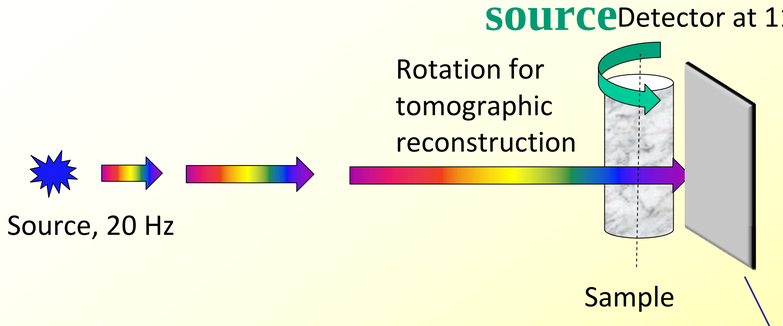


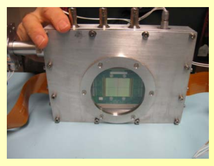
Nd, Gd inclusions within Urania of various concentration



$U_xGd_{1-x}O_2$	$U_xNd_{1-x}O_2$
99/1	99/1
95/5	95/5
80/20	80/20
70/30	70/30

Energy resolved transmission imaging at pulsed neutron source





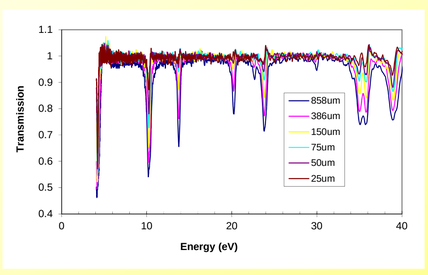
Active area with 2x2 Timepix chips (28x28 mm²)

Fast parallel readout (x32) allowing ~1200 frames per second and ~300 us dead time

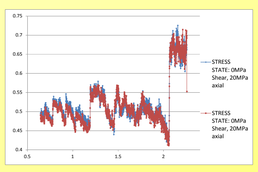
Multiple Bragg edges and resonances measured at the same time.

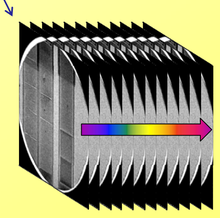
For a given area of the image:

Resonances: transmission spectra of Ta foils. Sharp resonances are observed at specific energies



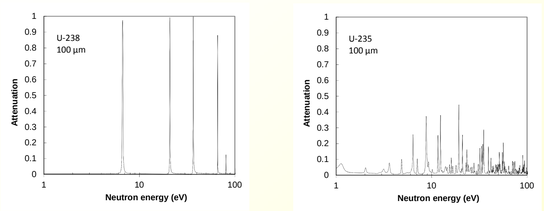
Bragg edges: transmission spectra, steel





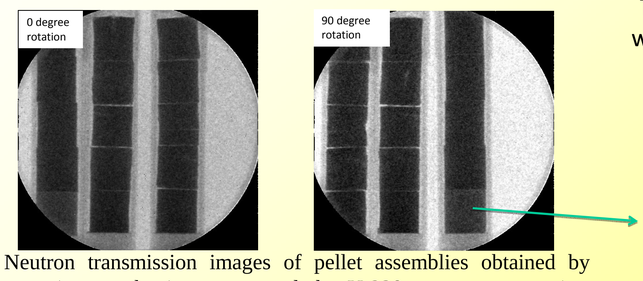
Measured stack of images, each corresponds to a particular energy E with resolution ΔE/E ~0.5%

Isotope specific imaging through resonance transmission analysis



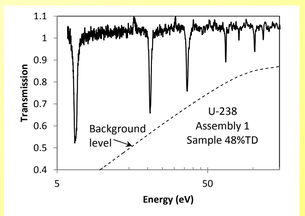
Theoretical attenuation of different U isotopes

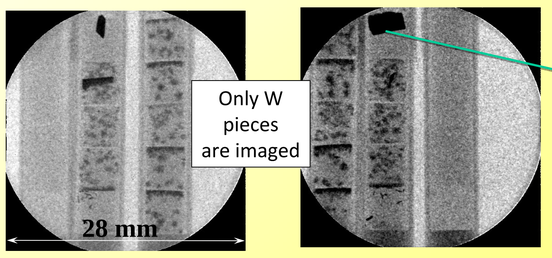
Mockup fuel rodlets imaged in the experiment

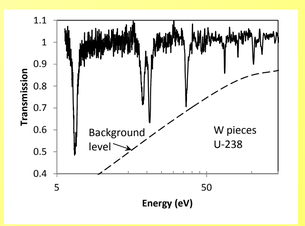


Neutron transmission images of pellet assemblies obtained by summing up the images around the U-238 resonance energies: 6.41 to 6.9 eV; 20.51 to 21.28 eV; and 36.22 to 37.67 eV.

Transmission spectra measured within the samples: U-238 and W and U-238 only.

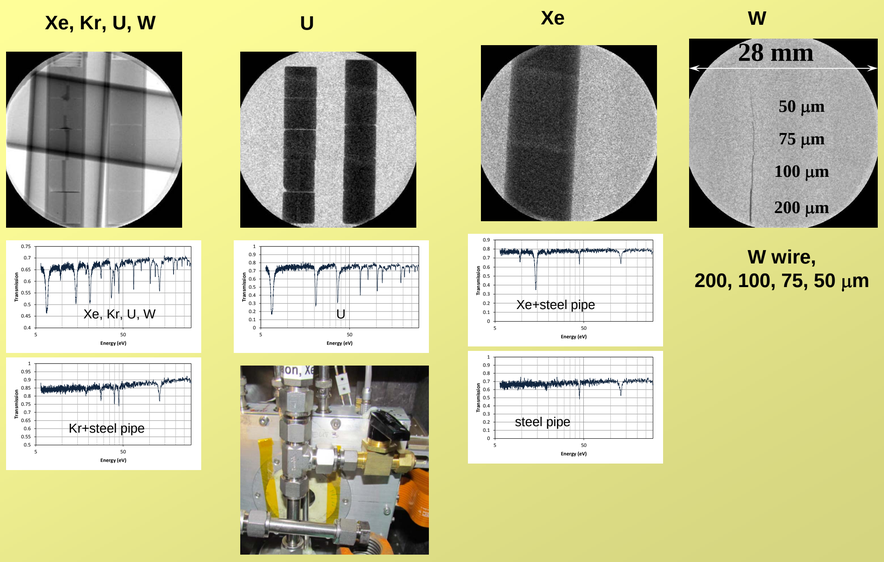






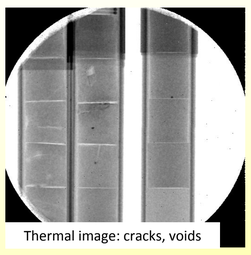
Same as above except for W energies of 17.57 to 19.74 eV

Individual elements are exclusively imaged simultaneously



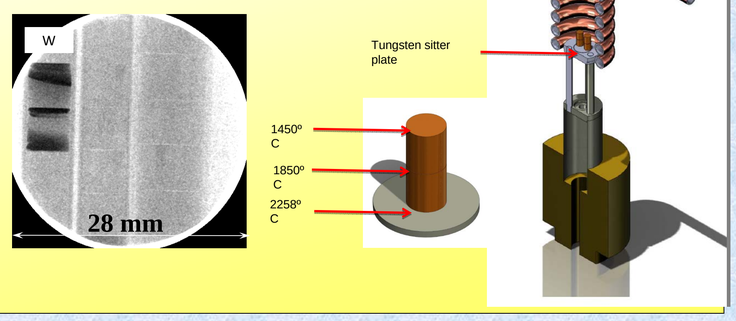
W wire, 200, 100, 75, 50 μm

Cracks and W inclusions in the pellets



Thermal image: cracks, voids

Thermal neutron radiography of fuel pin assemblies. No epithermal neutrons are included in those images. Variation of pellet density in right assembly is clearly seen on the bottom sample (48%TD). The voids and cracks in the pellets are clearly visible in the left and middle samples. This radiography can be taken simultaneously with resonance and Bragg edge transmission images.



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Contacts: ast@ssl.berkeley.edu Tel: (510) 642 4554