Dual-Energy Neutron Tomography of Water in Rock
using the Argonne IPNS

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ABSTRACT

In dual-energy hydrogen imaging, the increase in hydrogen neutron cross-section at subthermal neutron energies is used to enhance the imaging of small amounts of hydrogen against a background of other absorbing materials by subtracting a tomographic image obtained for higher energy neutrons from that obtained for subthermal neutrons (picking energies such that the other absorbing materials have nearly the same cross-sections at both energies). This technique was used to provide dual-energy imaging of water in tuffaceous rock, with the goal being to track water flow through porous rock for site risk analysis of permanent disposal of radwaste. A feasibility experiment was conducted at the IPNS facility with coarse spatial resolution, yielding promising results.

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ABSTRACT. In dual-energy hydrogen imaging, the increase in hydrogen neutron cross-section at subthermal neutron energies is used to enhance the imaging of small amounts of hydrogen against a background of other absorbing materials by subtracting a tomographic image obtained for higher energy neutrons from that obtained for subthermal neutrons (picking energies such that the other absorbing materials have nearly the same cross-sections at both energies). This technique was used to provide dual-energy imaging of water in tuffaceous rock, with the goal being to track water flow through porous rock for site risk analysis of permanent disposal of radwaste. A feasibility experiment was conducted at the IPNS facility with coarse spatial resolution, yielding promising results.

1. Introduction

In multiple-energy neutron tomography, specific nuclides are imaged or their images are enhanced by using the differences in cross-section variation with neutron energy of the nuclides present, by either subtracting tomographic images or by producing several different sets of radiographs at different neutron energies, often by simultaneously distinguishing different neutron energies during one exposure. Use of a pulsed accelerator and active neutron detectors time-gated to the beam allows simultaneous selection of desired neutron energies by flight-time measurement. In this manner, resonance radiography has been performed at the NIST electron linac from 1 to 40 eV [1] and at the Argonne IPNS (Intense Pulsed Neutron Source) from 0.3 to 10 eV [2], in which separate images are formed at discrete resonance energies where there are strong increases in neutron absorption for nuclides of interest (actinides, rare earths, and fission products for Z > 40, at these energies). Images of each nuclide are unfolded from the resonance patterns.

A related technique is dual-energy hydrogen imaging, in which the increase in hydrogen neutron cross-section at subthermal neutron energies is used to enhance the imaging of small amounts of hydrogen against a background of other absorbing materials by subtracting a tomographic image obtained for higher energy neutrons from that obtained for subthermal neutrons (picking energies such that the other absorbing materials have nearly the same cross-sections at both energies). This is a candidate technique for imaging water in tuffaceous rock, with the goal being to track water flow through porous rock for site risk analysis of permanent disposal of radwaste at Yucca Mountain, Nevada.

Yucca Mountain is being studied as a potential site for the underground high-level nuclear waste repository. Flow of groundwater through cracks and pores of the underlying tuffaceous rock will affect the geological barrier. And experimental data on water distribution in tuff is also needed to support modeling studies for estimating the potential risk to the human population. In experiments undertaken to assess possible methods to image water in tuff, nuclear magnetic resonance tomography failed to provide viable images [3], using a conventional spin echo technique. Water tracers are needed in electromagnetic geotomography to improve contrast, because the contrast for detecting water in cracks of tuff is lower than in granite (because of the higher porosity in tuff). Preliminary testing with high-frequency electromagnetic geotomography
provided low spatial resolution. A more sensitive technique is needed, preferably one that does not require tracers and that images water without artifacts from cracks and pores in the tuff.

2. Tuff Cross-section Measurement

Transmission tomography using low-energy neutrons appears to be a promising alternative technique because of the much higher absorption of these neutrons by water (due to its hydrogen content) compared to tuff (which is primarily SiO₂). Contrast and sensitivity to water can be improved and artifacts due to cracks and density changes in the tuffaceous rock can be greatly reduced if two neutron energies can be found for which water absorption is substantially different in value while the tuff absorption remains approximately the same. The transmission tomograph taken from data using one of the neutron energies can be subtracted from the tomograph taken from data at the other energy, in principle yielding a tomograph showing an image of the water only.

The Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory, shown in Fig. 1, is an ideal instrument for such measurements. At IPNS, 30 intense pulses of 500 MeV protons per second strike a U target, where spallation produces fast neutrons that are moderated to low energies. Peak thermal flux is about $4 \times 10^{14}$ n/cm². By time-gating neutron detectors to the pulses and measuring moderator flight time, a group of neutron energies can be selected for each measurement. Within the energy range of effective IPNS neutron flux intensity, the absorption coefficient for water is 8.5 cm⁻¹ at 15 meV and 4.5 cm⁻¹ at 85 meV, while the absorption coefficient of fully dense tuff is approximately 0.37 cm⁻¹ independent of energy in the range 10-100 meV.

A feasibility experiment was conducted at the IPNS facility, using the GPPD (General Purpose Powder Diffractometer) beam station, which is about 20 m from the U target, as a matter of convenience. As shown in Fig. 2, a cylindrical tuff sample 7 cm in diameter was placed on a stage that can be rotated or translated by stepping motors programmed by a PC and triggered by an external logic signal. For each orientation/position combination, neutrons were collected at 15 and 85 meV in a $^3$He proportional counter having a 1 to 2 mm opening. An upstream monitor was used to normalize the data. Measurements were taken at 4 scan positions across the tuff sample for each of 3 angular views. The sample contained a relatively large crack upon which water had been dripped, as seen in Fig. 3.

3. Data Analysis

Coarse-resolution tomographic reconstructions were performed at the two energies, using a standard convolution algorithm [4]. In the reconstructions, the darker regions indicating the strongest absorption are consistent with expected presence of water in the crack, particularly at the outer rim. The image obtained by subtracting the reconstruction at 85 meV from that at 15 meV displays an enhancement of the water distribution, and absorption differences due to rock boundaries are nearly invisible, as shown in Fig. 4 (the tuff sample is rotated approximately 180 degrees in Fig. 4 as compared to Fig. 3). The data acquired from the 12 spectra (3 rotations, 4 scan positions at each angle) were smoothed over a 32-pixel array in the reconstructions.

The subtractive tomographic reconstruction is reasonably representative, considering the coarse spatial resolution. Approximately 20% of the neutrons penetrated the dry 7-cm diameter tuff sample, sufficient transmission to carry out neutron tomography with samples of significant size.
at substantially better spatial resolution [5]. This technique can be extended to other fluid distribution imaging problems (if the fluid does not contain hydrogen, a tracer might be used).

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5. References


Fig. 1. Diagram of Argonne IPNS facility.
Fig. 2. IPNS setup for dual-energy imaging of water in tuff.
Fig. 3. Approximate sketch of tuff cross-section.

Fig. 4. Subtractive dual-energy reconstruction of tuff cross-section (rotated approximately 180 degrees from sketch in Fig. 3).