Neutron Probes for the Construction and Resource Utilization eXplorer (CRUX)

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Abstract

The Construction and Resource Utilization eXplorer (CRUX) project is developing a flexible integrated suite of instruments with data fusion software and an executive controller for *in situ* regolith resource assessment and characterization. CRUX includes two neutron detectors, the Surface Neutron Probe (SNeuP) and the Borehole Neutron Probe (BNeuP) to help locate and assess potential hydrogen-bearing deposits at the lunar poles and on Mars. Carried on a rover, SNeuP locates near-surface water (or other hydrogenous volatiles) in a lightweight (481 g) package. BNeuP determines the stratigraphy of hydrogenous subsurface layers to depths of 10 meters (or more if an integrated neutron source is used) while operating within a drill string segment. It weighs 517 g, and consumes 2.25 W. The instruments' heritage includes the Lunar Prospector neutron spectrometer and numerous programmatic space instrument applications at Los Alamos. We have tested the SNeuP and BNeuP prototypes and have demonstrated their ability to detect near-surface hydrogenous materials. In a lunar or Mars exploration application the instruments could be passive, sounding materials through the detection of neutrons produced by cosmic ray spallation in soils and ice. However, in terrestrial field tests we have used a neutron source to 'illuminate' surrounding materials and gauge the instruments' efficacy.

Introduction

There is evidence for enhanced hydrogen abundance at the lunar poles based on neutron measurements obtained during the Lunar Prospector mission, [*Feldman et al.*, 1998; 2001]. This hydrogen may be in the form of water ice and other volatiles in permanent shadowed cold traps. Successful lunar and planetary surface operations will depend critically on finding and exploiting such resources *in situ*. Therefore it is of prime importance to detect and assay beneficiable amounts of valuable resources such as water ice or other volatiles both before and during human exploration.

Neutron spectroscopy is an extremely robust technique for detecting and assessing hydrogenous compounds.

Galactic cosmic rays constantly impinge on the atmospheres or surfaces of planets, producing high-energy neutrons (~10 MeV) through nuclear reactions. The neutrons lose energy either by elastically or inelastically scattering in the planetary material or are absorbed by neutron capture reactions. An equilibrium neutron flux develops within the soil which is naturally divided into three energy populations: thermal neutrons (E = 0.01 – 0.4 eV), epithermal neutrons (E = 0.4 eV – 0.5 MeV) and fast neutrons (E ~ 0.5 – 10 MeV). For thermal neutrons the dominant reaction is neutron capture and for epithermal neutrons the dominant reaction is energy loss (moderation) from elastic and inelastic scattering. In the presence of hydrogen (e.g. hydrated minerals, water, hydrogen-bearing volatile species), elastic scattering is an extremely efficient energy loss mechanism for epithermal neutrons. The signature of enhanced hydrogen abundances is a large decrease (up to nearly two orders of magnitude) of the cosmic-ray induced epithermal neutron leakage flux.

The neutron detectors in SNeuP and BNeuP are gas proportional counters using the Helium-3 (n,p) reaction. One counter is clad in a thin layer of cadmium that absorbs all thermal neutrons below 0.4 eV, and serves as an epithermal neutron detector. The other counter is clad in tin but is otherwise identical and responds to neutrons of all energies. In this way the flux of thermal and epithermal neutrons are measured. The presence of hydrogenous materials in the soil leads to greater moderation and thermalization of energetic neutrons, and the resulting leakage flux of neutrons out of the soil depends strongly on the hydrogen concentration there. Thus, SNeuP provides rapid assessment of near-surface hydrogen content along a rover's traverse, while BNeuP offers a well-logging capability at a promising drill site.

SNeuP and BNeuP Description and Function

The Surface Neutron Probe (SNeuP) derives from the HYDRA neutron spectrometer, a remote sensing tool for locating hydrogenous materials. It is sensitive to such materials within about 70 cm of the surface, if cosmic rays are the primary neutron-generating source. The instrument is currently under development through a NASA Mars Instrument Development Program grant, with one system fabricated and tested, and a second in development. SNeuP's heritage includes the Lunar Prospector neutron spectrometer, programmatic neutron detectors, and the Mars Odyssey neutron spectrometer. The HYDRA Version 2 unit is shown in Figure 1. HYDRA consists of a sensor module (right) and a data module (left),

Figure 1. HYDRA Neutron Spectrometer Version 2.0.

connected by a cable harness that carries power to the sensor module and signal back to the data module. For a lander/rover application the entire instrument weighs 481 g, and consumes 1.84 W. HYDRA senses the presence of hydrogenous materials by measuring variations in the thermal and epithermal neutron fluxes. Neutrons are captured by ^{3}He nuclei in the proportional counters to produce a proton and a triton with a combined energy of 764 keV. Interaction of these products with the gas in the tube provides a characteristic charge pulse that is amplified, threshold discriminated and measured. The instrument communicates via an RS232 serial link with a laptop PC running Labview.

For the planetary surface prospecting application, rover speed (~10-50 mm/s), dwell time at a geophysical site (>100 sec), and instrument height (<100 cm) drive the detector size and sensitivity. The important parameter is "effective dwell time" over a parcel the size of the SNeuP detection footprint, which for a 1-meter instrument height is ~1 m diameter. Horizontal resolution could be improved by locating the SNeuP instrument closer to the surface. The epithermal neutron count rates decrease with increasing water abundance because more and more neutrons effectively become trapped and thermalized in the hydrogen-rich materials, and fewer emerge as a measurable epithermal leakage flux above the surface.

The Borehole Neutron Probe (BNeuP) is based on the D-HYDRA drill-integrated neutron spectrometer. D-HYDRA is a borehole/well-logging tool for locating hydrogenous materials down hole. It is sensitive to such materials within about 10 meters depth, and within several tens of centimeters of the borehole if cosmic rays are the primary neutron-generating source. The instrument is currently under development in a partnership between Los Alamos National Laboratory and Honeybee Robotics under a NASA Mars Instrument Development Program grant, with one system completed and under test. BNeuP's heritage includes the HYDRA surface neutron spectrometer and the Lunar Prospector neutron spectrometer, as well as programmatic neutron detectors, and the Mars Odyssey neutron spectrometer.

The D-HYDRA prototype unit is shown in Figure 2. D-HYDRA consists of detectors housed with high voltage power supply and front-end electronics, coupled to a peripheral interface controller (PIC) and controller area network (CAN) serial communications bus. The entire instrument weighs 517 g, consumes 2.25 W, and is inserted into a Honeybee drill string segment. D-HYDRA senses the presence of hydrogenous materials by measuring variations in the thermal and epithermal neutron fluxes using gas proportional counter tubes, in exactly the same way as the HYDRA instrument.

Neutron Probe Testing

We used a Californium-252 neutron source in testing to provide a signal for the HYDRA detectors because galactic

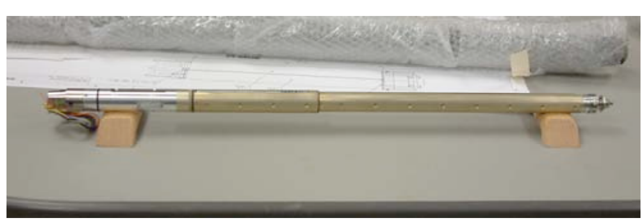

Figure 2. D-HYDRA Drill-Integrated Neutron Spectrometer.

cosmic rays do not reach the Earth's surface. In this case the leakage flux behaves differently than for a cosmic ray source. Energetic source neutrons enter the soil, scatter and are moderated by the hydrogen nearest the surface. Hydrogen-rich materials tend to have a higher neutron "albedo," moderating the fast neutrons but permitting these moderated neutrons to leak out of the hydrogen-rich layer if not buried too deeply. The result is an *increase* of thermal and, to a lesser degree, epithermal neutron fluxes above hydrogenous deposits. This has been observed and simulated in our HYDRA field tests.

Figure 3 shows the HYDRA/SNeuP test setup at the Army Corps of Engineers Cold Regions Research Engineering Laboratory (CRREL) in Hanover, New Hampshire. In October of 2005 we tested HYDRA's ability to detect near-surface deposits of 3- and 10-wt% H_2O in this facility. Deposits with diameters of 25, 50, and 100 cm were buried at depths of 30, 15, 5 and 0 cm. The soil used in the test was silica-rich with a minor contribution from micaceous minerals. When dried the soil moisture content was 0.1 wt% H_2O, and the hydrous mineral contribution was equal to 0.39 wt% H_2O. The entire setup was cooled to -40º C for the tests, and a stepper-motor-driven sled carried the HYDRA instrument and neutron source across the test box, as shown in Figure 3.

Figure 3. HYDRA/SNeuP test setup at the Cold Regions Research Engineering Laboratory (CRREL). (Left) Construction of buried ice-bearing deposits in otherwise dry soil. (Right) Final configuration with motorized sled apparatus for performing traverses at -40º C.

By compiling the traverses (15 in all), we can bin the count rate data spatially and create a map of the HeSn (thermal + epithermal) neutron count rates. This is shown in the top panel of Figure 4. Spatial smoothing using a Gaussian filter with a 26-cm full-width at half-maximum spread helps improve signal fidelity, as can be seen in the lower panel of Figure 4. The 30-cm deep deposits are marginally detectable because the intervening 30-cm of 0.5-wt% H_2O 'dry' material attenuates the deposit's signal (e-folding length is ~13 cm). In a realistic lunar surface scenario, in which cosmic rays generate the neutrons and the overburden has much less than 0.5 wt% H_2O, depth sensitivity of 70 cm or more can be achieved.

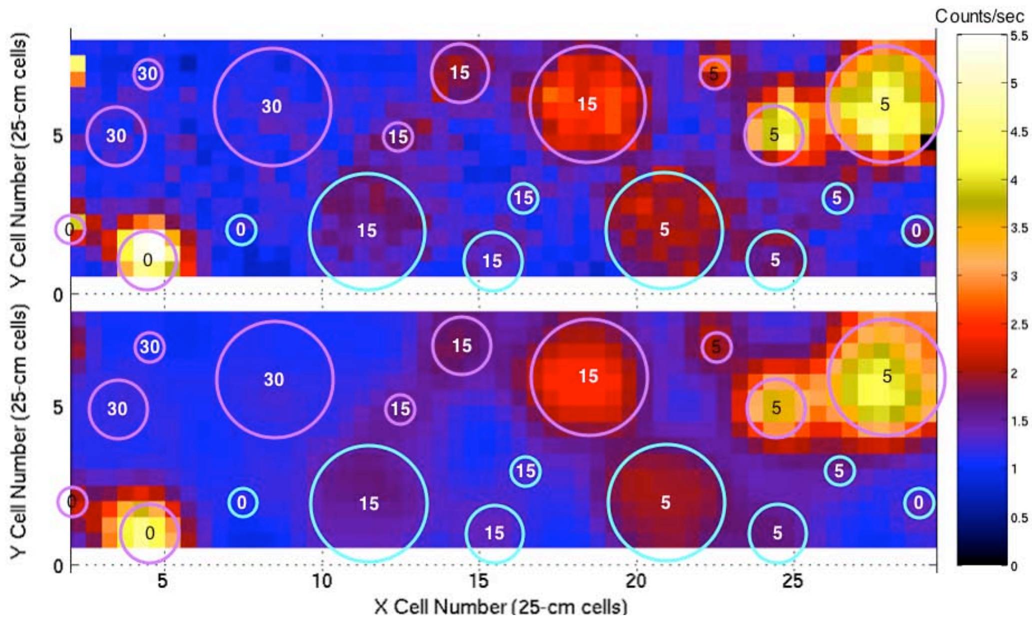

Figure 4. (Top) HeSn (thermal+epithermal) count rates binned in 12.5 cm square bins. (Bottom) HeSn count rates binned and smoothed using a gaussian with a 26-cm full-width at half-maximum. Icy deposit outlines are superimposed; numbers indicate depth of burial. Data from CRREL testing, 3-7 October, 2005.

For D-HYDRA testing, we used a drill-integrated Cf-252 neutron source to provide a signal for the detectors. Again, the leakage flux behaves differently than with a cosmic ray source because the nearly point source 'illuminates' the nearby materials as it travels down the borehole. The source neutrons enter the surrounding materials, scatter and are moderated by any nearby hydrogen. The moderated neutrons leak out of the hydrogen-rich layer, resulting in an enhancement of both thermal and epithermal neutron fluxes at the detector. The source holder in D-HYDRA is located some 18 cm above the sensors, creating a slight offset to the measurements as the source "illuminates" most brightly the materials above the sensors.

The CRREL cold room facility used for HYDRA testing also housed an experimental borehole setup for D-HYDRA testing in October of 2005. The left panel of Figure 5 shows a photo of the 2-meter tall borehole enclosure during construction. Alternating layers of wet and dry soil were built from the bottom up. The instrument was raised and lowered through the layers by a stepper motor/cable arrangement. As with the HYDRA test, the facility was maintained at -40 C. The right panel of Figure 5 is a schematic diagram of the layered materials in the enclosure. As in the HYDRA/SNeuP testing, the material between layers has 0.5 wt% H_2O. The layering specifications are in Table 1.

Figure 6 shows data from the CRREL borehole test of D-HYDRA. The instrument responds to the enhanced hydrogen abundance in 10- and 20-cm thick

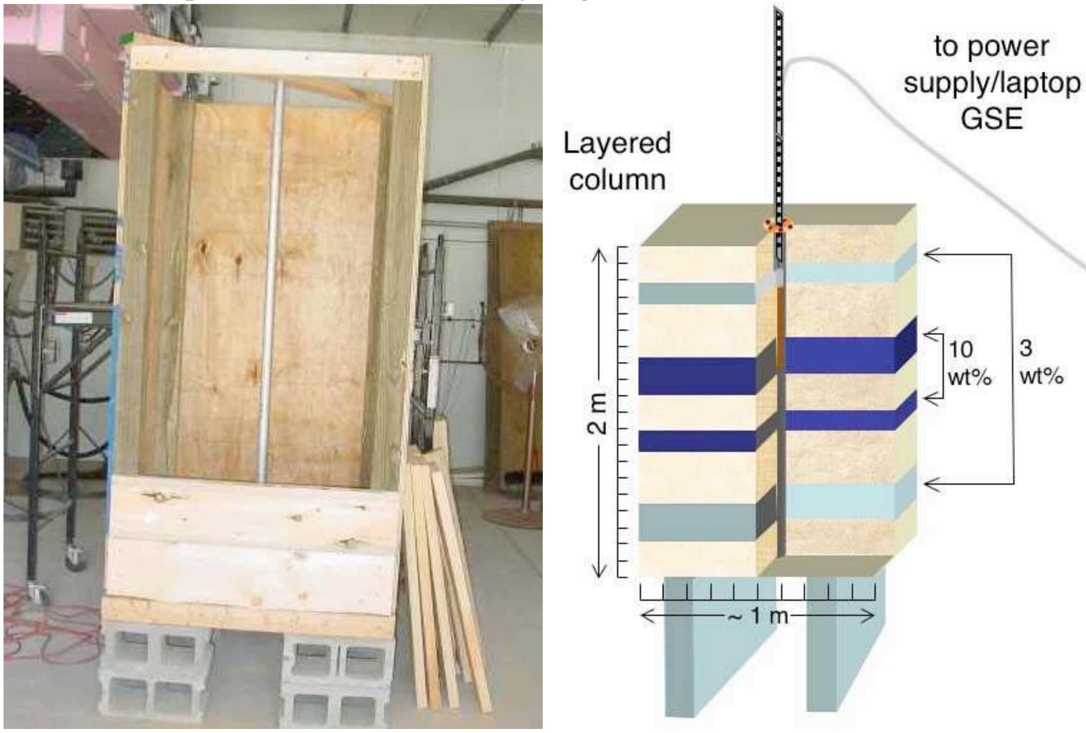

Figure 5. (Left) The D-HYDRA/BNeuP borehole test setup during construction at CRREL. The borehole tube is at the center. (Right) Schematic showing borehole stratigraphy, comprised of alternating wet (3 and 10 wt% H_2O) and dry (0.5 wt% H_2O) layers.

layers of 3- and 10-wt% H_2O soil (vertical cyan and purple bars, respectively). Enhancements in thermal and epithermal neutron count rates are seen at the 'ice layers.' The asymmetry in count rate enhancements is due to the source being located 18 cm 'above' the detectors. The peak counting rates are seen when the detectors are

Table 1. Layer H_2O wt%

	Burial Depth			
	20 cm	60 cm	120 cm	160 cm
Layer Thickness	10 cm	20 cm	10 cm	20 cm
Water content	3 wt%	10 wt%	10 wt%	3 wt%

in the middle of a wet layer and the neutron source is above the layer. When the source itself is in a wet layer and the detectors are below, elevated count rates are seen because more of the source neutrons are being moderated and thermalized in the layer. These additional neutrons leak out and are detected. The resulting full-width, half-maximum response is roughly 35 cm

Conclusions

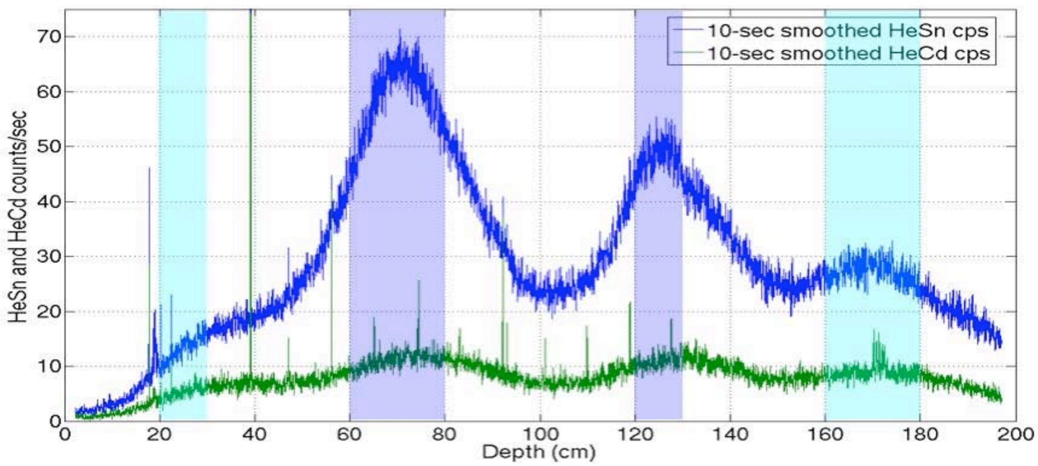

Figure 6. Running 10-sec averages of D-HYDRA count rates in the HeCd epithermal (green) and HeSn thermal+epithermal (blue) energy ranges versus depth for the test depicted in Figure 5. Data from CRREL on October 12, 2005.

For CRUX's lunar and planetary surface operations mission objectives, the two neutron probes serve as a primary means of quickly prospecting for and assaying hydrogenous resources. SNeuP is a remote surveying tool for locating and assessing near-surface, accessible hydrogen-bearing materials while on a roving platform; BNeuP assesses the stratigraphic column of buried hydrogenous materials at a particular site

The instruments perform as expected, providing both localization and an assessment of "ore value," in terms of total hydrogen present. The neutron probes complement other *in situ* and remote sensing techniques in providing comprehensive situational awareness for mapping and decision making, both for surface operations and for drilling.

Acknowledgments

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