ACTIVE NEUTRON AND GAMMA-RAY MEASUREMENTS OF ICY PLANETARY SURFACES.

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Introduction: Gamma-ray and neutron spectrometers (GRNS) can be used to determine the hydrogen content and elemental abundances within the top ~tens of centimeters of planetary surfaces. Through the use of a DT (Deuterium-Tritium, 14.1 MeV) pulsed neutron generator (PNG), GRNS can more rapidly characterize planetary surface materials; this makes active GRNS useful for roving and landed missions [1, 2]. The first planetary active neutron investigation, the Dynamic Albedo of Neutrons, is returning significant scientific results from the surface of Mars [3, 4]; the recently selected Dragonfly mission to Saturn's Titan will also carry an active GRNS instrument (DraGNS) [5]. In addition, several other active neutron and gamma-ray instruments are in development [6, 7].

We investigated the response of an active GRNS system to analog materials relevant to planetary science missions such as basalt (volcanic, extrusive), granite (crustal, intrusive, high Th & K), iron blocks (meteorite falls), milorganite organic fertilizer (carbon-rich with >2wt% of N, P, S, & Fe), and polyethylene (ice, water, hydrated material simulant). These experiments contribute to a better understanding of the active GRNS data that will be collected on future landed missions to Mars, the Moon, Titan, and other planetary bodies.

Instruments & Experiment: Data with active GRNS instrumentation were acquired at the NASA Goddard Space Flight Center (GSFC) Goddard Geophysical and Astronomical Observatory (GGAO) outdoor test site to interrogate geologically relevant materials. Several GRNS detector materials (CLYC, HPGe, CeBr) were tested with both passive and active techniques on a rover/lander scale. By running the neutron generator in a pulsed mode (250 - 1000 Hz), we were able to study GRNS responses during and between pulses. We successfully constructed neutron die-away curves (i.e. bulk hydrogen abundance with depth distribution) as well as gamma-ray spectra (i.e. Fe, Si, Al, O, K, Th abundances) in both active and passive operational modes. In this study we build upon previous work that has demonstrated the scintillator material Cs_2YLiCl_6:Ce (CLYC) is capable of discriminating both neutrons and gamma-rays based on differences in the shape of the scintillator light-pulse, with the $^6Li(n,\alpha)t$ reaction allowing for detection of neutrons [6, 8].

The NASA GSFC GGAO is equipped with a commercial Thermo MF Physics Model MP320 DT neutron generator capable of producing up to 10^8 neutrons per second with a frequency range from 250 to 1000 Hz, resulting in pulse times of 50 - 200 μs. Experiments were performed at the GGAO in summer of 2019 using the Colombia River basalt monument and granite monument with varying amounts of polyethylene, fertilizer, basalt, granite, and iron blocks layered on top of and within the monument [7]. Altering the amount of polyethylene in layers serves as a proxy for varying the H content (reported as water-equivalent-hydrogen (WEH)) content with depth on a planetary surface.

High-hydrogen environments: Hydrogen is an efficient neutron moderator; neutron moderators shift the population of fast (high-energy) neutrons towards thermal (low) energies. In H-rich environments, fast neutrons emitted by the PNG are moderated to lower energies, resulting in a higher amounts of thermal neutrons scattered back to the GRNS after each pulse. The shape and magnitude of the neutron die-away curve changes dramatically as H increases from 0 to 25 wt.% WEH and in this work we use a combination of polyethylene blocks and fertilizer to vary the amount of WEH within this range of abundances [1]. Using CLYC on the GGAO basalt monument and polyethylene

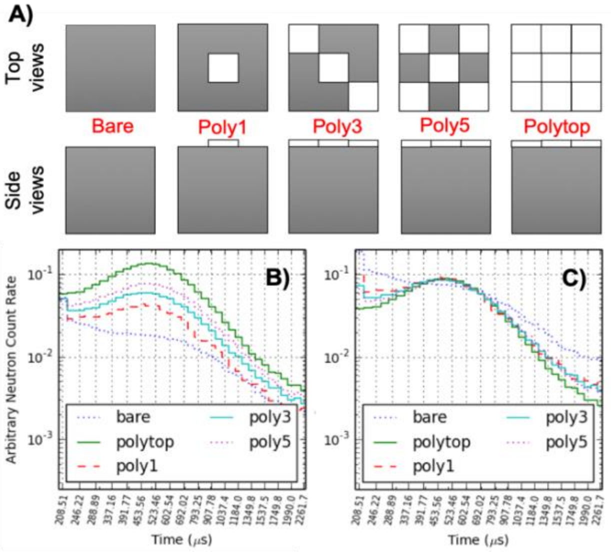

Figure 1: A) Polyethylene testing configurations; B) neutron die-away curves normalized to the PNG output pulse (0 – 200 μs); C) neutron die-away curves normalized within the thermal neutron peak region (330 – 900 μs), according to methods of [4, 9].

blocks in a variety of configurations shown in **Figure 1A**, we generated a set of neutron die-away curves for low to high amounts of H. Qualitatively, we confirm that the shape of the neutron die-away curve changes significantly for low amounts of H (~0 to 6 wt.% WEH in top 2” layer). However, for high amounts of H ($\gtrapprox$10 wt.% WEH in top 2” layer) the normalized curves are no longer distinguishable between measurements (**Figure 1C** – poly1 through 3 and polytop). At high H abundance, the total magnitude of the thermal neutron die-away curve is the main indicator of H content. In the absence of information about the neutron output of the PNG, the shape of the thermal neutron die-away curve can be used to determine H abundance, however, normalized curves require additional counting statistics and longer integration times to statistically separate from one another (**Fig. 1 C**). This work demonstrates that in high-H environments (~10 wt.% WEH or more), the shape of the neutron die-away curve does not significantly change and is more representative of the abundance of neutron absorbing elements [10].

Neutron die-away curves have been used determine burial depth of H [3, 4]; to test this in high-H environments we buried a large amount of H under varying amounts of milorganite fertilizer and constructed neutron die-away curves, shown in **Figure 2**. We observed both a suppression of neutrons and an expected shift in time for the returning thermal neutron peak using a thin layer (2”) of fertilizer on top of a stack of polyethylene blocks. However, for large amounts of fertilizer we observed more of a peak broadening in time, rather than a peak shift, this is presumably due to some H existing within the fertilizer. We observed a suppression of the total thermal neutron output for both thicknesses of fertilizer.

Implications for future missions: Neutron die-away curves can be used to inform near-surface H content as well as compositional information (e.g. neutron absorbers) in high-H environments. This work demonstrates that for GRNS with a PNG, the integrated thermal neutron albedo (w/out timing) can be used to estimate the H abundance, however, additional information about the near-surface neutron absorbing elements could be gained through analysis of the neutron die-away curve. Due to the reduced effect on curve shape at high H, it is important to monitor the neutron output of the PNG for determination of bulk H content. This would additionally enable more robust reduction of raw neutron die-away data without requiring normalization.

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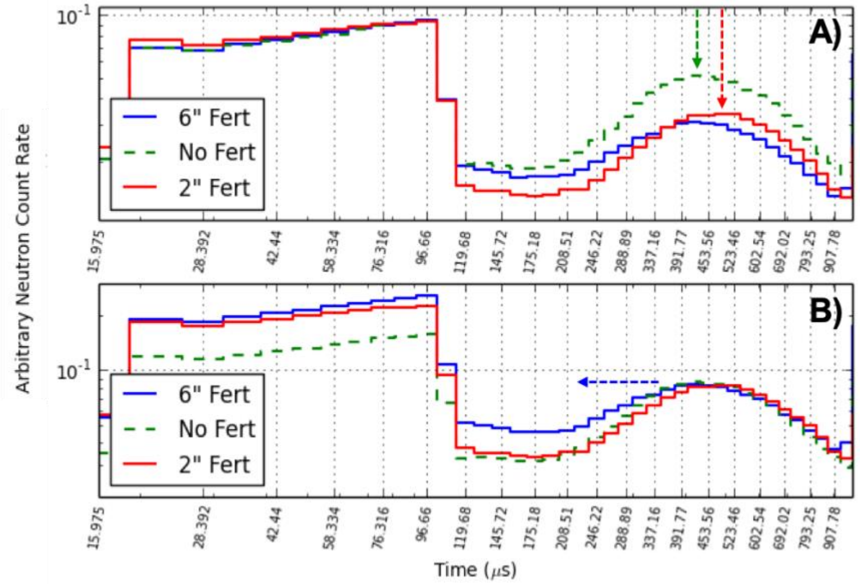

Figure 2: Neutron die-away measurements using 2" (red solid line) and 6" (blue solid line) thick layers of fertilizer over large amounts of polyethylene (green dashed line). Changes in neutron die-away peak shape are indicated by the dashed arrows. The total neutron die-away curve is shown in A) as normalized to the PNG pulse output and in B) as normalized to the thermal neutron peak region.

[9] Sanin, A. B., et al. NIM:A, vol. 789, (2015), pp. 114 – 127;[10] Kerner et al., JGR-Planets (*submitted*)