DEVELOPMENT OF THE MINIATURE NEUTRON SPECTROMETER FOR THE LUNAR POLAR HYDROGEN MAPPER MISSION C. Hardgrove[1], S.T. West[1], L. E. Heffern[1], E. Johnson[2], J. Christian[2], R. Starr[3], T. Colaprete[4], [1]Arizona State University (School of Earth and Space Exploration, Tempe, AZ, LHeffern@asu.edu), [2]Radiation Monitoring Devices (Watertown, MA), [3]NASA Goddard Space Flight Center (Greenbelt, MD), [4]NASA Ames Research Center (Moffett Field, CA).

Mission: The Lunar Polar Hydrogen Mapper (LunaH-Map) is a 6U CubeSat selected for flight under NASA's Small, Innovative Missions for Planetary Exploration (SIMPLEx) program. LunaH-Map is manifested as a secondary payload on the Space Launch System (SLS) Exploration Mission 1 (EM-1). The LunaH-Map spacecraft is equipped with gimbaled solar arrays, 3 reaction wheels, a star tracker, an X-Band radio, a command and data handling system, power control system, neutron spectrometer array, and propulsion system [1, 2]. After deployment, LunaH-Map will use propulsion to perform a lunar flyby targeting L2 and will eventually be captured by the Moon within two months [3]. Upon lunar capture the spacecraft will spiral down to an elliptical low-altitude science orbit with perilune at the South Pole. During the science phase, a miniature neutron spectrometer (Mini-NS) will measure neutron counts about the perilune of each orbit to enable the mapping of hydrogen enrichments within permanently shadowed regions (PSRs) at spatial scales less than 15 km.

Background: Previous lunar missions have detected the presence of water/frost within PSRs and produced detailed maps of the extent of these regions and their stability [4, 5, 6]. There is substantial evidence for small-scale (< 10km) hydrogen enrichments within south pole lunar PSRs. In addition, several studies of Lunar Prospector Neutron Spectrometer (LP-NS) data have provided results that are consistent hydrogen enrichments within some PSRs, but not uniformly across all south pole PSRs [7, 8, 9]. Analysis of LP-NS data has also provided evidence of surface (non-buried) hydrogen enrichments in Shackleton crater at the Moon's south pole [10]. However, there remains uncertainty about the bulk (non-surficial/frost) abundance of these enrichments and whether these small-scale enrichments are pervasive throughout lunar south pole PSRs. Placing constraints on the bulk hydrogen abundance within PSRs will help point to specific processes and delivery sources for polar volatiles, and can help resolve mechanisms operating over long time scales (e.g. solar wind) from other, much shorter time scale delivery mechanisms (e.g. passing asteroids or comets) [11]. Small-scale bulk hydrogen abundance maps can also be correlated with other polar datasets (i.e. temperature) to help untangle the relationship between volatile distributions and other surface properties.

Previous work has shown that hydrogen enhancements of greater than 500 ppm at a spatial scale of 5 km should be sufficient in providing robust evidence for discerning hypotheses regarding transport processes of polar hydrogen enrichments [11]. In addition, pixon reconstructions of hydrogen abundance within Shackleton crater predict about 600 ppm [7]. Therefore, the Mini-NS is designed to detect bulk hydrogen abundances of approximately 600 ppm +/- 120. The orbit of the LunaH-Map spacecraft, and perilune altitude, will ultimately determine the spatial resolution of the Mini-NS. The current mission science phase achieves 282 orbits over two lunar days. The mean perilune altitude is designed to achieve between 10 to 15 km above terrain poleward of 85°S throughout the science phase, but will vary depending upon the final SLS EM-1 launch date and trajectory [3].

Miniature Neutron Spectrometer (Mini-NS): The Mini-NS is a Cs_2LiYCl_6:Ce (CLYC) based scintillation detector [13, 14]. CLYC is an elpasolite scintillator sensitive to both neutrons and gamma rays with the characteristic pulse shape of the ^{6}Li neutron capture reaction being used to distinguish the neutrons [14]. CLYC was selected because it can be manufactured in large boules, providing crystals of sufficient size to cover one face of the entire LunaH-map spacecraft. Other materials, like ^{3}He, were considered however the intrinsic efficiency of CLYC is greater for epithermal neutrons and CLYC could more readily maximize the surface area (and therefore, count rate) for the relatively short-duration science phase of the LunaH-Map mission.

The Mini-NS detector array consists of eight 4.0 x 6.3 x 2 cm CLYC crystals providing a total of 200 cm^2 detection area. Each crystal is mounted to a photomultiplier tube (PMT), resulting in eight modules. Four modules on either side of the detector are readout together, and each 4-module unit can operate independently. A thin Gd sheet is used to absorb thermal neutrons and covers the nadir, sides and back of the detector, providing a sensitivity to neutron energies greater than 0.4 eV. The size of the Mini-NS CLYC array was designed to achieve twice the epithermal count rates of the LP-NS. The detector dimensions are 25 x 10 x 8 cm, the mass is ~3.4kg, and the maximum power consumption is 22W.

$$R = \frac{C(w)}{C(0)} = \frac{1}{1+61w} \qquad (1)$$

$$f = (1 - R)/3 \qquad (2)$$

$$f = 1/\sqrt{N} \qquad (3)$$

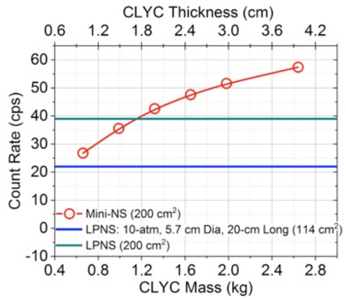

Figure 1: The thickness of the CLYC volumes was selected by comparison with the ^{3}He LP-NS detector. An epithermal count rate over twice that of LP-NS is achieved for 2cm thick CLYC crystals (200 cm^2 detector area).

Modeled Mini-NS Epithermal Count Rates: A dry lunar count rate, $C(0)$, was derived using MCNP6. The model uses a GCR spectrum with ϕ=300, a lunar FAN surface composition, a model of the Mini-NS and a complete LunaH-Map spacecraft (to account for neutrons moderated within the chassis and components). The count rate, $C(w)$, was then determined using the relationship in (1), where w represents the hydrogen concentration. Several models with varying thicknesses of CLYC were used to determine the optimal detector sizing (**Figure 1**).

Preliminary Sensitivity in Regions of Low Repeat Coverage: We derive expected count rates from (1) and count rate reductions using (2) for various hydrogen enrichments that may be observed by the Mini-NS. The 3-σ total counts required to observe a given enrichment are also derived using (2) and (3), where f is the fractional uncertainty in counts. Using the approximate perilune velocity of 2 km/s, we derive a sensitivity to hydrogen (< 300 ppm) based on the total counts observed for a single flyby from an altitude of 10 km (**Figure 2**). A more detailed preliminary treatment of the Mini-NS sensitivities to hydrogen enrichments is presented in [16], which includes binning and mapping of enrichments using the expected science phase ground tracks. At latitudes poleward of ~85°S, multiple passes over a given mapping region will be achieved within the two month science phase, however, equatorward of ~85°S cross-track distances will increase such that a single flyby is a reasonable approximation of the hydrogen sensitivity.

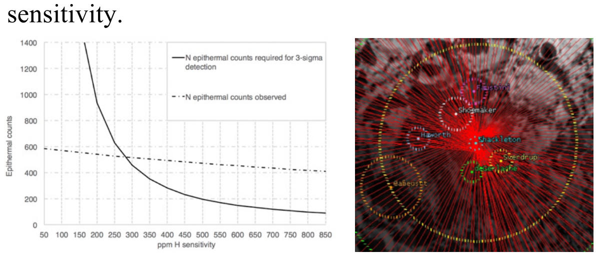

Figure 2: (*left*) The required total epithermal counts required to discriminate a given abundance of hydrogen from surrounding dry regolith, per the methods described in [12]. (*right*) LunaH-Map science phase ground tracks [3] with craters of interest labeled. Yellow circle at ~85S denotes orbital altitudes >12km.

Path to Flight: As part of the LunaH-Map flight program, the Mini-NS Preliminary Design Review was held in June of 2016. A Critical Design Review was held in June of 2017 and the delivery of the flight unit to ASU is scheduled for early 2018. The Mini-NS review board includes members of the LP-NS, Dawn GRaND and Resource Prospector instrument teams. To date, several modules of the Mini-NS have undergone and passed vibration (GEVS) and thermal cycling (-30 to +60 C) tests. The flight unit will undergo proto-qualification vibration testing at NASA Ames Research Center and thermal cycling at Los Alamos National Laboratory (LANL) in summer of 2018. The Mini-NS will be calibrated with moderated Cf-252 and deuterated spheres in the Neutron Free In-Air (NFIA) facility at LANL. The energy-angle response in 3-axis will be determined along with temperature corrections during thermal cycling using NFIA calibrated neutron sources. An engineering development unit (EDU), populated with four CLYC crystals and one PMT, has also been constructed for fit checks, interface testing and preliminary measurements at ASU (**Figure 3**). Characterization of the Mini-NS EDU, signal processing and digital board are underway at ASU and RMD.

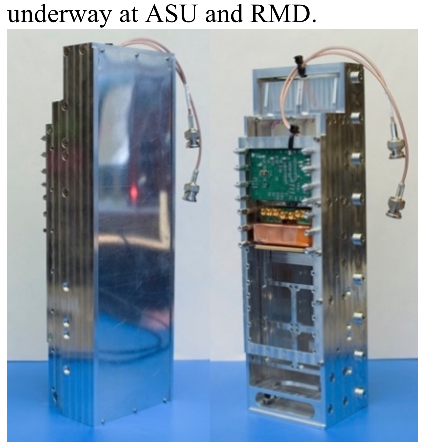

Figure 3: The Mini-NS EDU is simplified version of the flight unit with four CLYC modules populated and one PMT.

References:

[1] Hardgrove C., et al., LPSC (2016) #2654 [2] Babuscia, A. et al. IEEE Aerospace Conference 4.0607. (2017) [3] Genova, A. L. and Dunham, D. W. 27th AAS/AIAA Space Flight Mechanics Meeting 17-456. (2017) [4] Feldman, W. C. et al. Science, 281 1496. (1998) [5] Mitrofanov, I. G. et al. Science, 330 483. (2010) [6] Colaprete, A. et al. Science, 330 463. (2010) [7] R.C. Elphic, et al., Geophys. Res. Lett. 34 (2007) [8] V.R. Eke, et al, Icarus 200 (2009) [9] L.F.A. Teodoro, et al, Geophys. Res. Lett. 37 (2010) [10] R.S. Miller, et al., Icarus 233 (2014) [11] M.A. Siegler, et al., LPSC (2015) #2675 [12] Lawrence D., et al. Acta Astronautica 115 (2015) [13] Glodo, J. et al. IEEE Nuclear Sci. Symposium Conf. pp. 959-962. (2007) [14] Johnson, E. et al. Exploration Science Forum NESF2016-073. (2013) [15] West S.T., et al., LPSC (2017) #2909.