NUCLEAR SPECTROSCOPY FOR GEOCHEMICAL ASSAY IN HUMAN EXPLORATION OF THE LUNAR SURFACE AND POLES. T. S. J. Gabriel[1], C. Hardgrove[1], I. Jun[2], M. Litvak[3] [1]School of Earth and Space Exploration, Arizona State University (781 E Terrace Mall, ISTB4, Room 795, Tempe, AZ 85287-6004; Travis.Gabriel@asu.edu), [2]Jet Propulsion Laboratory, [3]Space Science Institute (IKI) Moscow

Introduction: Neutron and gamma-ray spectrometers have been deployed extensively for the purposes of exploration geology on Earth, as they provide geochemical assay for both volatile (e.g. H) and major rock-forming elements (Na, Mg, Al, Si, Fe, etc.). These instruments rely on the interaction of high-energy particles that penetrate much deeper than photon or x-ray based instruments (tens of centimeters to a meter depth). The sensitivity to planetary volatiles at depth makes them ideally suited for sensing subsurface water-ice deposits potentially present in permanently shadowed regions on the Moon and their heritage in drilling applications makes them ideal for probing the regolith composition at depths beyond a meter.

Surface-based spectrometers provide geochemical assay of the subsurface with a sensing footprint that is considerably smaller (~tens of cm) than orbital spectrometers (tens to hundreds of km), making them more relevant to the geologic spacial scales of human and rover traverses. From a human exploration standpoint, these instruments are simple to operate (*e.g.* they have no pointing requirements) and have already been successfully been deployed in remote operations on the surface of Mars. We present the case for landed nuclear spectrometers in future human exploration missions to the Moon, operational considerations, and lessons learned from current deployments. We also present one such instrument based on a set of space heritage hardware for future lunar surface exploration.

Nuclear Spectroscopy for Lunar Geochemistry: Neutron and gamma-ray spectrometers play unique, yet complementary roles in producing geochemical assay critical for open lunar science questions and resource assessment. In *passive* mode, nuclear spectrometers measure neutrons and gamma-rays leaking from the subsurface that were generated through the interaction of Galactic Cosmic Rays (GCRs) with the regolith. Neutron spectrometers are particularly sensitive to the subsurface abundance of H, due to neutron scattering interactions, as well as the abundance of neutron absorbing elements (*e.g.* Fe, Ti, K, Gd, and Sm for the Moon [*e.g.* 1]). Gamma-ray spectrometers measure characteristic gamma-rays due to interactions with atoms of a range of major rock forming elements (Fe, Mg, Si, etc.), but can also constrain the abundance of radionucleides (e.g. K and Th) through the analysis of characteristic gamma-rays produced by natural decay. The identification of these elements at lunar landing sites is critical in providing ground-truth elemental composition, which complements the comparatively large sensing area (tens of kilometers) from orbital measurements [*e.g.* 2]. The identification of these elements is necessary to map compositionally distinct rocks, including those rich in potassium (K), Rare Earth Elements, and phosphorous (KREEP), which is a distinct geochemical unit linked to the last dregs of the hypothesized lunar magma ocean [3]. Silicic volcanic rocks, which have been examined from orbit and are intimately linked to the late stages of lunar volcanism [4], can also be identified and mapped using nuclear spectroscopy. The abundance of neutron absorbing elements, as determined by a gamma-ray spectrometer, can also be used to inform the analysis of neutron spectrometer data to obtain a more accurate assessment of volatile (H) content. Thus, the combination of neutron and gamma-ray instruments in a single instrument package increases the science return through complementary analysis. Nuclear instruments can also be low power, reducing mission requirements considerably.

In *active* mode, a neutron generator produces discrete pulses of high-energy neutrons that penetrate the subsurface, which produces low-energy neutrons and gamma-rays that are detected by the spectrometers. Active instruments provide comparatively quick geochemical assay (on the order of minutes) compared to passive measurements (on the order of hours to days), but either configuration can be deployed on a rover or lander platform. Moreover, by measuring the return of neutrons and gamma-rays as a function of time after a generator pulse, additional geochemical information is provided through analysis of the time-resolved spectra. Nevertheless, the presence of a neutron generator in a human exploration environment requires special considerations; in particular, astronauts must maintain distance from the instrument while the neutron generator is powered on. Otherwise, the generator poses no radiation risk when powered off (passive mode).

Current Surface-Deployed Spectrometers: There currently exists only one neutron spectrometer deployed on a planetary surface:

Dynamic Albedo of Neutrons. The Mars Science Laboratory Curiosity Rover has a neutron spectrometer that can operate in both active and passive mode, complementing the array of other onboard geochemical instruments. Since landing, the Dynamic Albedo of Neutrons (DAN) instrument has operated successfully on the surface of Mars for over 7 years [5]. DAN analysis has determined the water content of sedimentary rocks and unconsolidated materials throughout the rover traverse [*e.g.* 6], as well as in targeted campaigns [*e.g.* 7], including those at dunes [8] and water-rich fracture features [9]. DAN has also been used for strategic rover traverse planning; in one instance, the neutron spectrometers detected silicic rocks due to their low Fe composition (*i.e.* low neutron absorption cross section). This lead to an extensive investigation at a location called Marias Pass [10] and the eventual identification of a silicic volcanic sediment source in a drilled sample [11]. Importantly, the DAN instrument has provided ground-truth measurements at the scale of human exploration traverses, which complements and informs orbital maps of elemental abundances that have a resolution of tens to hundreds of km [*e.g.* 12].

Future Lunar Surface Spectrometers: We present a nuclear spectroscopy instrument package that includes both neutron and gamma-ray spectrometers: the Moon rAdiation, Neutron, and Gamma Observer (MANGO). The He^3 neutron spectrometer on MANGO is based on the space-qualified heritage of DAN and the spectrometer developed for the European Space Agency (ESA) ExoMars mission: the Autonomous Detector of Radiation and Neutrons Onboard Rover at Mars (ADRON-RM/EM) [13]. MANGO also features a $CeBr_3$ gamma-ray spectrometer that is a close analog to the spectrometer developed for the BepiColombo mission *en route* to Mercury. The neutron and gamma-ray units are also slated to fly onboard future landed missions at the Lunar poles by Roscosmos [*e.g.* 14].

Several aspects of the MANGO instrument lend it to be well-suited for operation in a human exploration scenario on the Moon. MANGO's $CeBr_3$ gamma-ray spectrometer can be operated at non-cryogenic temperatures, reducing the overall complexity and thus relaxing operational constraints. Importantly, MANGO can also be operated in both active and passive mode; the former reduces integration times considerably (see Table 1). This configuration allows for complete flexibility to rapidly evolving mission architectures and operational requirements that vary from mission to mission depending on the landing site of interest or tactical decision making during an ongoing mission. The modular design of MANGO has also allowed for the inclusion of a Liulin-type dosimeter [15], with heritage from several flight missions: the International Space Station, Photon and Bion satellites, Chandrayaan-1 mission to the Moon, Phobos-Grunt mission, rockets, balloons, aircrafts, etc. The dosimeter package monitors dose, dose rate, flux, and Linear Energy Transfer (LET) spectra of space charged particles [15], effectively providing a complete assessment of the near-surface radiation environment.

		Integration Time [hr]	
Element	**Precision [wt%]**	**Passive**	**Active**
Fe	1.0	7	5
Si	0.5	<15	1.5
Al	1.0	<10	0.6
Na	0.1	>168 (> 1wk)	6.5
Mg	0.5	<168 (<1 wk)	2.1
Ca	1.0	37	35
K	0.05	1	*
Th	1e-6 (1 ppm)	2	*

Table 1: Preliminary integration times to achieve a given precision for landed passive and active nuclear spectroscopy measurements of lunar regolith.
* Quantity determined in passive mode only.

Conclusions: Neutron and gamma-ray spectrometers provide bulk geochemical abundances for a range of species relevant to open lunar science questions. For example, neutron spectrometers can detect the presence of H-rich materials (buried water ice) at depth that may not be detected with other photon or x-ray based instruments. Gamma-ray spectrometers provide geochemical assay, allowing for the identification of KREEP-rich and silica-rich rocks, including those that may be buried as well. These local-scale compositional measurements are necessary in providing ground truth to regional scale geochemical maps derived from orbital spectrometers. Given the opportunity for active and passive measurements and the lack of pointing requirements, nuclear instruments are particularly flexible in a human exploration operational environment.

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