A Pulsed Neutron Gamma-Ray System for Mars Rover Missions

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Abstract—A Pulsed Neutron[1][2] Gamma-ray System (PNGS) can be used to determine the subsurface planetary geochemistry on rover missions to Mars and other planetary bodies. These data can be used to unravel the history of formation of biogenic materials, characterize the climate, explore the geology and characterize the radiation environment. We have performed feasibility studies for a Pulsed Neutron/Gamma-ray System (PNGS) to operate on a Mars Science Laboratory (MSL) type rover. It has been developed to meet the MSL rover mission constraints on mass and power limitations, temperature and radiation effects, and reliable operation for long periods of time.

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1. INTRODUCTION

The driving force behind the Mars Exploration Program is, ultimately, the search for evidence of past life on Mars. To achieve this goal, the current emphasis of the orbital and rover missions is identification of aqueous environments in which living organisms could have thrived. Our approach is to use geochemistry as a tool for understanding past Martian climate. We have performed feasibility studies for a Pulsed Neutron/Gamma-ray System (PNGS) suitable for use on a Mars rover that will measure subsurface geochemistry, density and stratification without the need for sample preparation, sample collection, or instrument deployment. Most importantly, this system will provide subsurface geochemical information without the need for mass-and power-intensive drilling operations and provide this information throughout the course of a rover traverse. The results based on the feasibility studies showed that the PNGS can provide insight into the past habitability of Mars by measuring H, C, and O, which record the history of water and carbon dioxide, and the biogenically important elements C, Ca, Mn, Cl, and P, which are required for life or concentrated by living organisms. A PNGS can determine H as well as the geochemistry of the rocks in which H occurs, distinguishing between hydrated minerals and subsurface water ice. Finally a PNGS can be used to measure major rock forming elements O, Mg, Al, Si, S, Ca, and Cl, allowing us to distinguish igneous and sedimentary rocks, the processes from which they formed originally, and the subsequent influences of chemical weathering and impact.

2. MARS EXPLORATION GOALS ADDRESSED BY PNGS

NASA's Mars Exploration Program is driven by the goals of understanding the biologic, climatic and geologic history of Mars, as well as preparing for future manned exploration. The PNGS system we have designed addresses some of the most fundamental issues within these four areas. First, life as we know it requires the presence of liquid water. In our search for past life on Mars, we must identify rocks and minerals deposited by water, which provide both evidence of environments amenable to past life and a record of the climate of Mars. These rocks and minerals are sedimentary in nature and can form either by the physical breakdown of the igneous rocks that dominate the surface of Mars (clastic sediments) or they can precipitate directly from water (chemical sediments), such as the sulfates and iron oxides identified by the Opportunity Rover in Meridiani Planum. A PNGS system can accomplish this goal through a range of measurements. Increasing Si abundances (as expressed by Fe/Si vs. K/Si (Fig. 1)) are a hallmark of clastic sedimentary rocks and record increasing abundances of the weathering-resistant mineral quartz. In contrast, chemical sedimentary rocks are often enriched in elements that dissolve readily in seawater, such as chlorine.

PNGS can be used to search for elements concentrated in minerals formed in biologically-active environments, including Mn-oxides (Mn), carbonates (Ca), sulfates (S) and salts (Cl). Concentrations of these elements, in excess of the nominal value in a landing site, would indicate areas of particular interest for biological prospecting.

In the search for regions that might host biogenic life, finding subsurface water—whether in the form of groundwater or, more likely, ground ice—is a key investigation in Mars surface exploration missions. PNGS is ideally suited for this investigation, with the ability to measure, for example, H/Si and H/Fe ratios in short time spans. The data from both the gamma-ray and neutron detector systems will be highly complementary in determining whether the H is in-ground ice or bound in hydrated minerals.

In addition to playing a key role in the search for extant life, the possibility of analyzing mid-latitude ground ice has profound implications for understanding the climatic history of Mars. PNGS can provide key elemental ratios that determine not only the abundance of subsurface H, but also the geologic and mineralogic context in which it occurs. This capability to deduce whether ground ice actually occurs in the mid-latitudes of Mars is critical to deciphering the current and past climate history of Mars, and is a first-order priority in the geochemical exploration of Mars.

PNGS aboard Martian rovers can provide a broad array of chemical information to address key geology issues. The surface of Mars is dominated by igneous rocks thought to range from primitive basalts to evolved, Si-rich andesites. The same elements that distinguish the maturity of sedimentary rocks can distinguish the extent of the evolution of igneous rocks on Mars. This use of multi-element plots to distinguish rocks of different origins was successfully applied to data from the Near Earth Asteroid Rendezvous (NEAR) mission [8]. In contrast to the low spatial resolution provided by orbital measurements, a rover-based PNGS provides details of the vertical and spatial heterogeneity of landing sites. Mars is geologically complex at spatial scales ranging from the microscopic to the hemispheric for a range of elements and minerals. Of greatest importance, the distribution of water plays a key role in deciphering the formation and modification of many primary rock types. These primary rock types are, in many places, obscured by regolith and the global dust that coats much of the planet. PNGS is particularly sensitive to Cl, which is heavily concentrated in the dust, providing a tool to identify those areas with the least global dust coverage. If such areas prove to be enriched in H, they become particularly attractive targets for biological prospecting. The gamma-ray spectrometer component of PNGS is uniquely suited to the detection these of naturally radioactive elements. The decay of long-lived U, K, and Th within rocks of all types contributes to the surface radiation environment. Evolved igneous lithologies, such as granites and andesites, contain enhanced abundances of these elements, providing another measure of the differentiation history of the Martian crust.

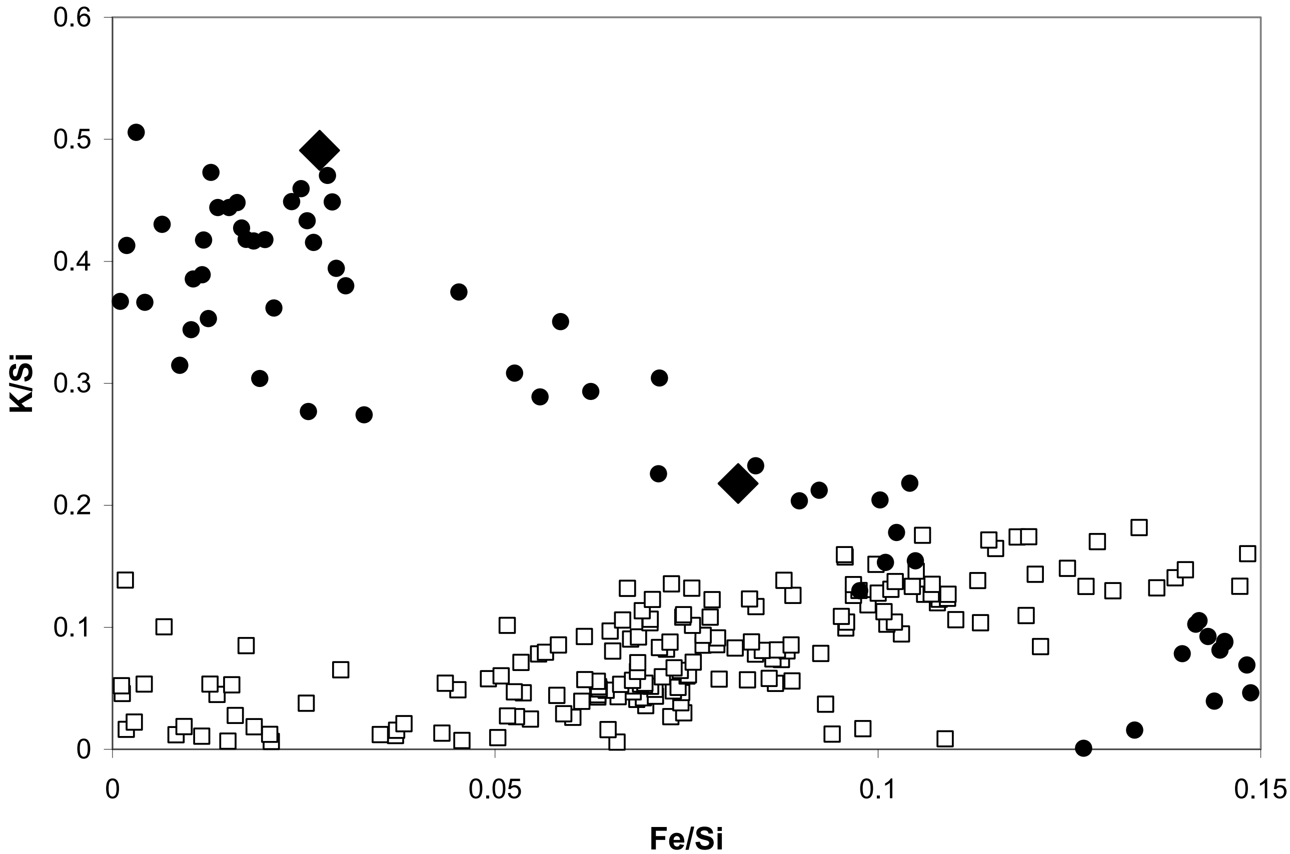

Figure 1 - The elemental ratios Fe/Si and K/Si distinguish terrestrial igneous (filled circles) and sedimentary (open squares) rocks and trace the extent of differentiation or mechanical weathering. Igneous rocks trend to lower Fe/Si and higher K/Si values with increasing differentiation, while physical weathering of these rocks produces sedimentary rocks with low Fe/Si and K/Si values. Orbital geochemical data for Mars (solid diamonds) imply different igneous rock types on the surface.

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3. The PNGS Method

Neutrons emitted by generators create gamma rays that can be separated by time-after-neutron-creation into three classes, 1) inelastic, 2) capture and 3) activation gamma rays.

The inelastic gamma rays are generated by fast neutron-nucleus inelastic interactions with the surrounding material. The inelastic gamma rays are emitted within 10^{-9} seconds of the parent neutron creation. C and O have very distinct inelastic gamma ray signatures.

The capture gamma rays are generated after the fast neutrons have lost energy to become thermalized and then captured by nuclei in the surrounding material. Nuclei that capture the thermal neutrons are usually in an excited state that promptly decays to the ground with emission of characteristic capture gamma rays. The capture gamma rays come during a period of 10^{-9} to 10^{-3} seconds after neutron creation in the generator. H, Cl, Si, Ca, S, Fe, Ti and Gd can be assayed by their capture gamma-ray signatures.

The activation gamma rays come from radioactive nuclei that are created either by the Fast neutron or the Thermal neutron interactions. Activation gamma rays from these short-lived radionuclides can be acquired after the neutron generator has been off for more than 10^{-3} seconds. Elements that can often be assayed from activation gamma rays are Al, Na, and Cu.

Finally, the natural radioactive elements K, U, and Th can be measured during the period when the activation gamma rays are measured.

Using a pulsed neutron generator, the gamma-ray measurements can be divided into three time periods during and in between the pulses: measurements made during the neutron pulse when the inelastic gamma rays dominate the spectrum; measurements made just after the pulse ends and for a period of time before the thermal neutrons have essentially died away when the capture gamma rays dominate the spectrum; and finally after the thermal flux has significantly diminished to the beginning of the next pulse when the activation, nature activity and background gamma rays dominate the spectrum.

The epithermal and thermal neutron die away is measured as a function of time in between the neutron pulses. Time resolution on the order of microseconds is used. There are two time periods of interest, first when the epithermal neutrons dominate the spectrum and then when the thermal neutrons dominate the spectrum. The slowing down times strongly depends on the hydrogen content of the sample. These times can range from tens to hundreds of microseconds.

A number of factors must be considered in the design of an experiment using the PNGS approach. These include: both gamma-ray and neutron detectors, neutron generator geometry; the magnitude of the neutron flux and pulse width per pulse; pulse rate; neutron generator life time; shielding between the neutron generator and detectors if necessary; cosmic ray shielding for the gamma-ray detector; and finally minimizing the cosmic-ray primary and secondary activation of the materials near the measurement system.

Cosmic rays can interact with the gamma-ray detectors to produce a significant background especially above ~3 MeV. Active shielding can be used to reduce this background component [9]. The detector also can be activated by cosmic-ray primary and secondary interactions, producing a background of internally emitted gamma rays. This background component may be identified and eliminated with timing circuitry. Cosmic rays interacting in the surface of the planet will produce neutrons by spallation interactions and gamma rays will be produced by inelastic scatter, and capture (both prompt and delayed processes). Epithermal, and thermal neutrons will be a continuous source of background for the PNGS measurement. Methods for dealing with these backgrounds will be discussed below.

The geometric configuration has to be chosen so that the gamma ray and neutron detectors view a significant solid angle of the irradiated surface. The generator source neutrons must be shielded or at least be a sufficient distance away to prevent neutrons from the generator saturating the gamma ray and neutron detectors. Furthermore, the neutron flux per pulse must be adjusted so that detector saturation will not occur for the given configuration and still produce gamma rays with neutron induced and scattered fluxes above the level produced by the cosmic ray induced fluxes. Finally the geometry must be chosen to fit the constraints of the rover vehicle mission and design. In the next section we describe such a design for the Mars Science Lander (MSL) mission.

MSL mission power, weight and volume constraints are such that the neutron generator flight systems are limited to about 10^8 neutrons/sec. Pulse widths of 10's of microseconds and 10^5 neutrons per pulse are needed in order to measure the inelastic gamma-ray flux during the pulse without saturating the detectors. This then sets the neutrons/pulse and repetition rates for the experiment. Depending on the expected hydrogen content the timing widow for the prompt capture and activation/background windows can be set. Again there will only be a few events per pulse that can be measured. At this rate the measured inelastic, prompt capture, activation/background gamma-ray fluxes, and neutron die away fluxes will be above the cosmic ray induced background. Significantly higher fluxes per pulse and significantly lower pulse rates will greatly limit the effectiveness of a PNGS based experiment.

A major source of background will be the excitation of the materials in the rover structure and the instrument itself. Care must be taken in selecting materials in the PNGS to minimize interferences with important surface elemental measurements. The interference from the materials in the rover can only be controlled by proper placement of the PNGS on the rover although there is limited space available for instrument accommodation.

Finally, the lifetime of operation of the neutron generator must be greater than a thousand hours without significant degradation of its operation. Such neutron generators are now available. [1].

4. PNGS DESIGN AND SENSITIVITY

In order to demonstrate the feasibility of including a PNGS on a Mars rover mission, a detailed design study has been completed using the specifications and constraints imposed by the Mars Science Laboratory (MSL) program. The mass constraint was determined considering that the total mass available for scientific instrumentation was set at ~50 kg. Assuming that four other instruments may have to be accommodated, it was assumed that about 20% of the allotment could be used for the PNGS system. Furthermore, the system would have to be designed to fit into the instrument bay of the MSL Rover. As a result of this study, it was found that the PNGS instrument could be constructed for the weight shown in Table 1a. The power needed is detailed in Table 1.b, and with instrument power management, it can operate within mission constraints. Figure 2 shows a possible configuration for a PNGS aboard the MSL rover. The gamma ray and neutron detectors are 50 cm from the neutron generator source and both the detectors and the generator are 75 cm above the surface. Mars geochemical models have been developed using information derived from Martian meteorite studies and results obtained from measurements made by the Pathfinder Sojourner mission [10]. Monte Carlo simulations of the PNGS operation and response have been carried out, and the results indicate that a PNGS experiment for subsurface geochemical exploration can be designed within the MSL mission constraints and achieve many of the mission's major scientific objectives.

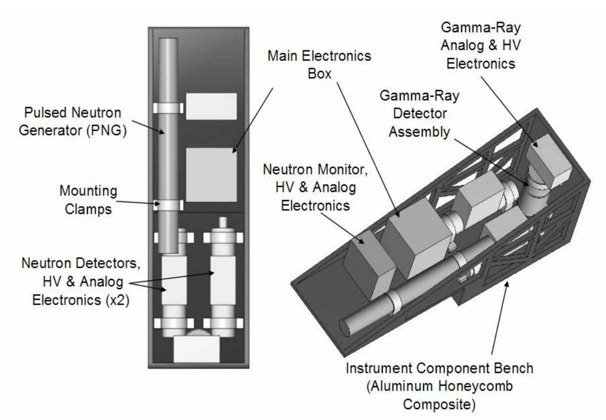

Figure 2 – Possible Configuration of the PNGS Instrument on a Mars Science Laboratory Rover

The PNGS detection sensitivity is different for each element of interest. Calculated results were obtained using the Monte Carlo code (MCNPX [11]) with representative model soil and rock compositions. The composition of the rover, while not known in any detail, is assumed to be made of materials that have the same elemental composition as those of interest on Mars (e.g., Al, Fe, C, H). Two model compositions were used: one for uniform soil [10] with 3% H_2O, the other for a basaltic rock composition. The assumed compositions are shown in Table 2. Actual measurements on Mars would probably be some combination of rock and soil with some H_2O concentration. One measure of sensitivity is the uncertainty that can be obtained for a given counting time. The results are shown in Table 2 for an assumed counting time of 30 minutes. For other counting times, the statistical uncertainties vary as the square root of the time. Calculations for the PNGS were done with and without the rover contribution to the total gamma ray signal. For the rover case, it was assumed that the rover contribution to the total signal could be measured or calculated independently and removed from the total gamma ray signal. For comparison, the expected sensitivity for a gamma signal due only to galactic cosmic rays (GCR) without any rover contribution is also shown in Table 2. For natural radioactivity from K, Th, and U the calculations were done assuming the measurements were done without the PNGS and are shown in Table 2.

Table 1.a

INSTUMENT SYSTEM	**WEIGHT (kg)**
Pulse Neutron Generator	4,10
Neutron Detector	3.52
Gamma Ray Detector	3.15
Total	10.77

Estimated Weight for a Mars Science Laboratory System

Table 1.b

Component	**Avg. Power**
1 Main Electronics Box	12.1 Watts
1 Neutron Generator Electronics	+14.6 Watts
1 Gamma Ray Detector	0.75 Watt
2 Neutron Detectors	1.5 Watts
1 Neutron Monitor	0.75 Watts
4 HVPS	1.3 Watts
Heaters	5 Watts
Instrument Total:	35.9 Watts

Estimated Power for a Mars Science Laboratory System

Table 2 Sensitivity Calculations

2.a Expected Uncertainties (%) for 30 Minutes Counting Time for Soil with 3% H2O

		PNG Source*		**GCR Source**
Element-Mode	**Soil Composition**	**Without Rover**	**With Rover Removed**	**Without Rover**
H-capture	0.27%	21%	31%	48%
O-inelastic	46.6%	0.6%	0.6%	14%
C-inelastic	0.06%	4.7%	14%	>100%
Si-inelastic	19.4%	0.9%	1.2%	5%
Si-capture	19.4%	19%	27%	32%
Fe-capture	15.6%	2.8%	3.5%	10%
Cl-capture	0.53%	13%	19%	24%
Mn-capture	0.4%	15%	22%	90%
Ti-capture	0.66%	30%	44%	>100%
Ca-capture	4.6%	48%	72%	>100%

S-capture	2.7%	59%	85%	>100%
Mg-capture	5.1%	>100%	>100%	>100%

2.b Expected Uncertainties (%) for 30 Minutes Counting Time for Basalt Rock

		PNG Source*		
Element-Mode	**Basalt Composition**	**Without Rover**	**With Rover Removed**	**GCR Source Without Rover**
H-capture	0.0%	--	--	--
O-inelastic	43.5%	0.5%	0.6%	10%
C-inelastic	0.0%	--	--	--
Si-inelastic	24.4%	0.6%	0.8%	11%
Si-capture	24.4%	27%	38%	45%
Fe-capture	6.8%	8%	12%	37%
Cl-capture	0.0%	--	--	--
Mn-capture	0.4%	70%	>100%	>100%
Ti-capture	0.1%	>100%	>100%	>100%
Ca-capture	7.8%	65%	86%	> 100%
S-capture	0.0%		--	
Mg-capture	4.5%	>100%	>100%	>100%

*PNG Source characteristics: 10^5 neutrons per pulse, 10^3 pulses per second.

2.c Expected Uncertainties (%) for 30 Minutes Counting Time for Natural Radioactivity

	Soil with 3% H2O		**Basalt Rock**	
	Composition	**Uncertainty**	**Composition**	**Uncertainty**
K^{40}	0.5%	4%	0.3%	70%
Th^{232}	0.3 ppm	70%	0.6 ppm	35%
U^{238}	0.08 ppm	>100%	0.15 ppm	60%

5. CONCLUSIONS

PNGS can be used to determine the subsurface planetary geochemistry on rover missions to Mars and other planetary bodies. These data can be used to unravel the history of formation of biogenic materials, characterize the climate, explore the geology and characterize the radiation environment. With PNGS, measurements can be made of an array of geochemically diagnostic elements, with meter-scale spatial resolution down to depths as great as 20-30 cm. No other instrument with this capability has ever flown on a landed or rover mission to any planetary body. Our studies have shown that such a system can be flown on a rover of the type proposed for the Mars Science Laboratory within the power, weight, volume and lifetime constraints of such a mission.

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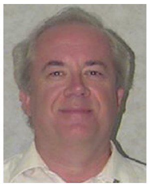

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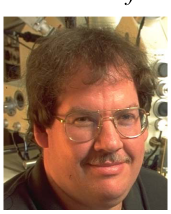

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