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Pulsed neutron generator system for astrobiological and geochemical exploration of planetary bodies

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Abstract

A pulsed neutron/gamma-ray detection system for use on rovers to survey the elemental concentrations of Martian and Lunar surface and subsurface materials is evaluated. A robotic survey system combining a pulsed neutron generator (PNG) and detectors (gamma ray and neutron) can measure the major constituents to a depth of about 30 cm. *Scanning mode* measurements can give the major elemental concentrations while the rover is moving; *analyzing mode* measurements can give a detailed elemental analysis of the adjacent material when the rover is stationary. A detailed map of the subsurface elemental concentrations will provide invaluable information relevant to some of the most fundamental astrobiological questions including the presence of water, biogenic activity, life habitability and deposition processes.

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1. Introduction

The analysis of the characteristic neutron and gamma-ray spectra induced by energetic neutrons is one of the most powerful methods for in situ chemical analysis of heterogeneous materials. Orbital and in situ measurements of the gamma-ray and neutron emission spectra induced by cosmic rays have been used to determine the chemical composition of the near-Earth asteroid 433 Eros by the NEAR probe [1]. Recently, gamma-ray/neutron spectrometer results from the Mars Odyssey Orbiter indicate an abundance of ice, likely embedded in or interlayered with the geologic strata [2].

However, cosmic ray induced gamma-ray and neutron spectra require long acquisition times and are not well suited for detailed evaluation of planetary or lunar near surface materials using rovers. Other potential sources of neutrons for geochemical measurements on extraterrestrial bodies include (α, n) reactions (e.g. ^{241}AmBe), spontaneous fission isotopes (e.g. ^{252}Cf), radioactive power generators (RTGs) and pulsed D–T fusion neutron generators (PNGs). The main considerations for neutron source selection for planetary exploration are launch safety, energy spectra of the emitted neutrons, neutron yield, mass, volume, power requirements and switchability, ability to turn the source on and off. Furthermore, it is important that the neutron source does not emit gamma rays itself to avoid having interference with the measurements. The ability to switch off the neutron source is highly desirable both for launch safety reasons as well as to avoid activation of the craft and detection equipment during the mission flight time. The ^{252}Cf source and RTGs can not be turned off; switchable (α, n) reaction based sources are possible but have not been commercially developed; whereas, PNGs are easily switchable since they only produce neutrons when the ion source is on and the high voltage is applied. Also, miniature, low power PNGs are commercially available and are routinely used for geochemical logging in the hostile oilfield environment.

PNGs have other significant advantages for geochemical survey applications on extraterrestrial bodies. The concentration measurements of the very important elements, C and O, are most easily accomplished by detecting the gamma rays following inelastic scattering of high-energy neutrons. The threshold for the C and O inelastic reactions are 4.8 and 6.4 MeV, respectively. All the neutrons generated by the D–T reactions in the PNGs are in the range 13.4–14.7 MeV whereas the other neutron sources only have a small percentage of neutrons above 6 MeV as shown in Fig. 1.

A thorough knowledge of the neutron source emission spectrum is very important for extracting the maximum information from measured gamma-ray and neutron spectra. The data inversion process involves calculating or measuring the system response to the all the elements of interest and then "fitting" these elemental signatures to the observed data. Much of the system response information is acquired by computational methods for which the source emission characteristics must be known. PNGs are unique compared to other neutron sources since the neutrons are emitted with a well-known distribution in a very narrow energy band.

PNGs that operate at constant high voltage with a pulsed ion source also have the very valuable characteristic that the neutron flux can be switched on and off in less than one microsecond and the neutron output duty cycle can be any value from 1% to 100%. The cycle frequency can be as high as 2×10^4 Hz. Thus, a neutron on–off sequence can be generated that allows the maximum elemental information to be extracted from the complex, neutron induced gamma-ray and neutron spectra. For example, gamma rays from inelastic neutron interactions are detected while the PNG is on, gamma rays from neutron capture interactions are detected in the 1–1000 μs time interval just after the neutron pulse is turned off, and gamma rays from the neutron activation of the surrounding materials are detected in the time interval after the capture gamma rays have gone to zero and before the start of the next neutron pulse.

PNGs that are operated with a *pulsed high-voltage supply* either have pileup gamma rays that cannot be analyzed by the detector and/or have too long a duty cycle between pulses where neither inelastic nor capture gamma rays are present.

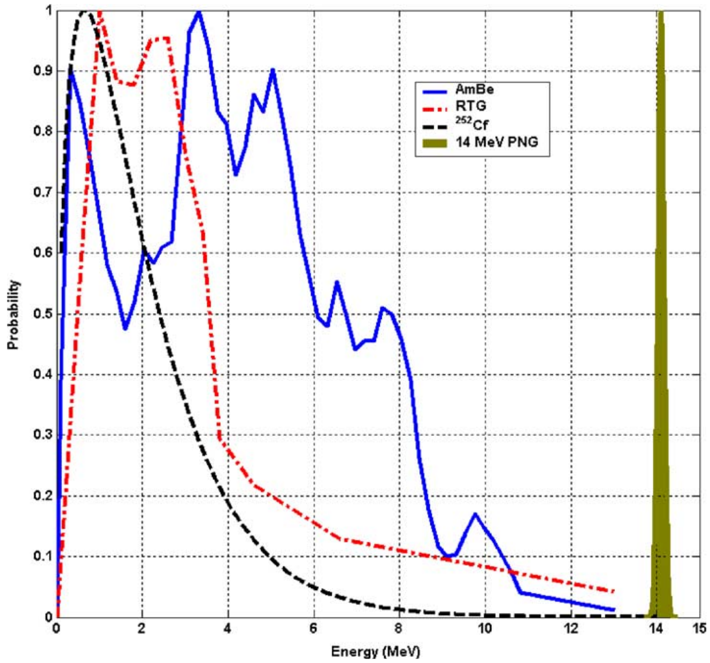

Fig. 1. The source spectra for AmBe [4], RTG [5] and ^{252}Cf [6] isotopic neutron sources are shown. Note that the spectra for (α, n) sources can vary significantly in details especially below 2 MeV, depending on the homogeneity of the target and α emitter mixture and the thickness of the capsule. The emitted neutron energy from D–T reaction is almost mono-energetic with average neutron energy of 14.4 MeV.

Thus, PNGs that are operated with a constant high voltage and a pulsed ion source are the only practical designs for geochemical logging. In an optimal design, the count rate is set by the pulse rate of the generator.

The slowing down time for the 14 MeV neutrons is a strong function of the amount of hydrogen present in the surrounding materials. A Martian or Lunar Rover with a PNG and gamma-ray and neutron detectors will have the capability of surveying for the major near surface geochemistry when moving and of analyzing for the elemental fractions and geochemistry of a small area in much more detail when at rest.

2. Description of the instrumentation package

The instrumentation package evaluated for planetary rover applications has a PNG with a pulsed ion source and gamma-ray and neutron detectors mounted much like that of an oilfield geochemical logging tool. Such instruments have been routinely used for oil and gas exploration applications for the last few decades. These oilfield tools are used for subsurface formation elemental measurements, geochemical analysis and behind casing fluid analysis at depths up to 9000 m, in temperatures ranging from −40 °C to beyond +200 °C, and on drill collars where shocks exceed 250 g for hundreds of hours.

In addition, to the ruggedness of the environment and the difficult operating conditions, the borehole-logging tool must be as small in diameter as possible in order to enter an oil well through the production tubing (typically less than 5.0 cm) and must be low power since the power must be delivered to the tool by a cable up to 9000 m long. PNGs operating under typical conditions used in the oilfield require about 15 W for outputs of 1×10^8 n/s with life-time on the order of a thousand hours. Less power is required for lower average neutron fluxes. The total mass of the complete instrumentation package including the detectors is expected to be about 8.0 kg.

The neutron detectors proposed for the system are widely used, rugged ^{3}He detectors. Such detectors have been successfully flown on many previous NASA missions. A ^{3}He detector surrounded with a layer of Cd is used to detect epithermal neutrons since Cd has large absorption cross-section at thermal energies. An unshielded ^{3}He detector is used for thermal neutron detection. Also, a rover instrumentation system will have a neutron monitor mounted next to PNG to monitor the source neutron output.

The optimal detector for gamma-ray spectroscopy measurements has high efficiency, excellent resolution, a broad temperature operating range and is resistance to radiation damage. Unfortunately, there is no gamma-ray detector that simultaneously satisfies all these criteria. Alternative detectors include scintillators, i.e. NaI, BGO, CsI and semi-conductors, i.e. HpGe detectors. While scintillators offer high efficiency and resistance to temperature, they suffer from poor energy resolution. On the other hand, germanium detectors offer excellent resolution, which is important for nuclide identification and hence signal processing, but need cooling and suffer from radiation damage when exposed to high-energy neutrons. Of course, MCNP [7] modeling can be carried out for any detector or detector combination; however, the results reported here were calculated using a CsI scintillation gamma-ray detector.

3. Results

The instrumentation package used for the MCNP modeling studies reported here consists of a PNG, thermal and epithermal neutron detectors (2.5 D × 10 H cm), and a CsI gamma-ray detector (5.0 D × 7.5 H cm). The neutron detectors are placed between PNG and the CsI detector. The package is placed on the surface of the soil assuming that the instrument will be mounted on one of the arms of the rover. The soil used for the MCNP modeling has the composition found with the MARS Pathfinder APXS instrument [3].

For this configuration, the epithermal neutron detector response for homogeneous soil with

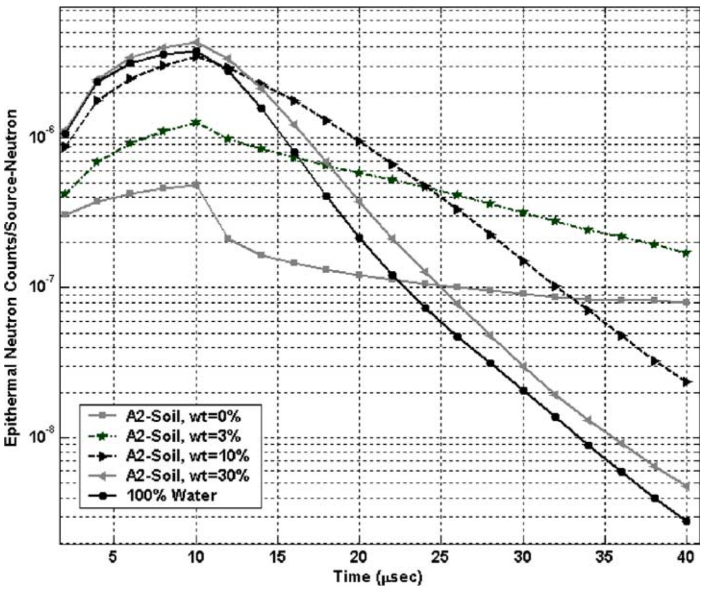

Fig. 2. Epithermal neutron detector time dependent response for varying water content in soil [3]. The count rate per acquisition time interval is obtained by multiplying by the neutron source output.

varying water content is shown in Fig. 2. The time dependent response is particularly sensitive to the water content. In addition, the decay curve will provide extra information with regard to proper-

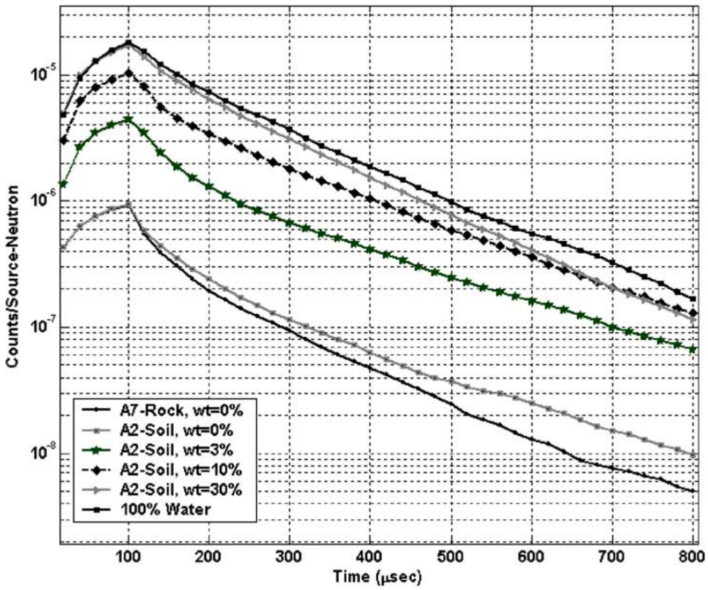

Fig. 3. Thermal neutron detector time detector response for varying water content in soil [3]. The count rate per acquisition time interval is obtained by multiplying by the neutron source output.

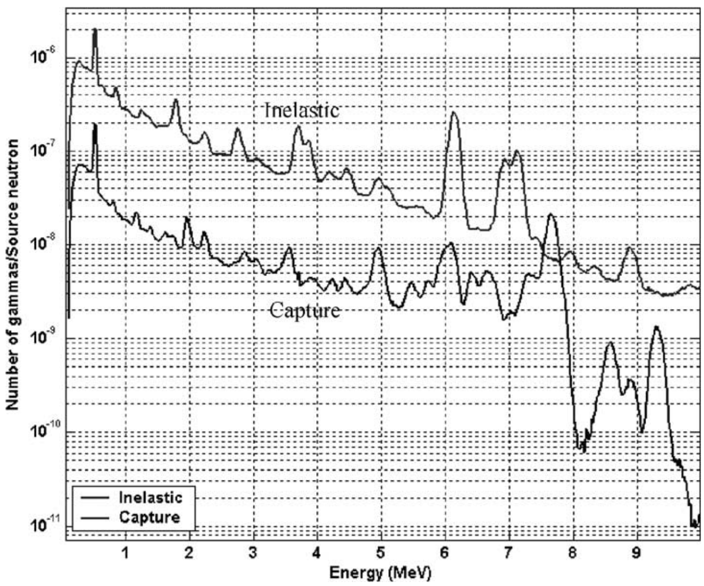

Fig. 4. The CsI gamma-ray detector response for a soil sample with the APXS instrument composition [3] + 3% water. The capability of turning the source on and off for a given pulse width allows recording inelastic and capture spectra separately. The resolution of the CsI detector was 8.5%.

ties of the subsurface since the slope is proportional to the slowing down length of the media.

The thermal neutron detector response for varying water content in soil is shown in Fig. 3. Here, the slope of the decay curve is proportional to the capture cross-section of the media, which is not only proportional to density but also to hydrogen and absorber content, i.e. chlorine content, of the media. Furthermore, thermal neutron decay time measurements can be performed using PNG as a neutron source and the gamma-ray detector to detect neutron capture. The slope of the decay curve is again proportional to the capture cross-section of the media.

The CsI gamma-ray detector response for a soil sample with the APXS instrument composition [3] + 3% water is shown in Fig. 4. Due to the timing scheme, the burst can be turned on and off automatically, which allows recording inelastic and capture spectra separately. This is especially beneficial when scintillators with poor energy resolutions are used, the interpretation and signal processing becomes much easier since inelastic and capture gammas can be separated. Every element has characteristic inelastic, capture and activation gamma-ray signatures and the resulting gamma-ray spectra are the fractional supposition of all the characteristic elemental spectra.

4. Conclusions and future work

The initial modeling results for a PNG and neutron/gamma-ray spectrometer system for planetary and lunar rover surveys are presented and the modeling results show the considerable analyzing power of such instruments.

The PNG system is complimentary to the APXS spectrometer used on the Mars Pathfinder, which has a very shallow sensitivity depth. The PNG spectrometer instrument easily detects H, C, O and other major constituents over a large volume of the surrounding material since 14.4 MeV neutrons are deeply penetrating and many of the resulting gamma rays are high energy. Neutron activated, gamma-ray spectroscopy is the only technique available that can determine the in situ fractional concentrations of H, C and O in the subsurface region.

Further MCNP modeling will be directed at determining the sensitivity of different instrument configurations to the critical elements as defined by the scientific objectives for planetary and lunar missions. Also, in situ measurements with a borehole-logging tool mounted near the surface or dragged along the surface on a carrier will be used to benchmark the MCNP modeling results and demonstrate the instrument capabilities.

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