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MArs Neutron Energy Spectrometer (MANES): an instrument for the Mars 2003 Lander

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Abstract

We describe the instrument design and detector development for MANES which has been selected to fly on the Mars 2003 Lander. Section 1 explains the need for the spectrometer in determining the increased risk of carcinogenesis for astronauts. Section 2 presents the instrument design including an outline drawing, a cross-sectional view and a detailed block diagram. Sections 3 and 4 describe the low and high energy detector components of the spectrometer and present responses to monoenergetic neutron beams. Sections 5 and 6 explain the design approaches to charged particle discrimination and instrument transfer function modeling.

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1. Introduction

High energy charged particles of extra-galactic, galactic and solar origin collide with spacecraft structures in Earth orbit outside the atmosphere and in interplanetary travel beyond the Earth's magnetosphere. These primaries create a number of secondary particles inside the structures that can produce a significant ionizing radiation environment. This radiation is a threat to long-term inhabitants or travelers for space missions and produces an increased risk of cancer and DNA damage. The primary high energy cosmic rays and trapped protons collide with common spacecraft materials such as aluminum and silicon and create secondary particles inside structures that are mostly protons and neutrons. Charged protons are readily detected and instruments are already in existence for this task. Neutrons are electrically neutral and therefore, much more difficult to measure and detect. These neutrons are reported to contribute 30–60% [1] of the dose inside space structures and cannot be ignored. Currently there is no compact, portable and real time neutron detector instrumentation available for use inside spacecraft or on planetary surfaces where astronauts will live and work.

Present neutron detection systems use gas tube proportional counters for the monitoring of low energy (0.025 eV–1 MeV) neutrons. However, for higher energies the detector systems are quite large and massive and often employ passive detection methods which must be recycled and read out after the fact. Physically large neutron diffraction tables are used for accelerator experiments. Emulsions are flown on the Space Shuttle and returned to Earth for analysis. The NASA Ames aircraft uses an instrument built with Bonner spheres which are large spheres of polyethylene moderator some tens of centimeters in diameter with a photodiode in the center and weighing 1500 pounds.

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Table 1
Recommended radiation weighting factors for equivalent dose calculations in humans for different particle types and energy ranges

Radiation Component	Weighting Factor ICRP
X-rays, gamma rays, electrons, positrons, muons	1
Neutrons with energy < 10 keV	5
Neutrons 10–100 keV	10
Neutrons 100 keV–2 MeV	20
Neutrons > 20 MeV	10
Protons > 2 MeV	5
Alphas, fission fragments, nonrelativistic heavy nuclei	5
	20

The Martian atmosphere has an areal density of only 37 g/cm^2 of mostly carbon dioxide molecules. This shallow atmosphere presents fewer mean free path lengths to the bombarding cosmic rays and solar particles. Therefore, the secondary neutrons present at the surface of Mars will have undergone fewer generations of collisions and have higher energies. Albedo neutrons from the surface of the planet will also contribute to the radiation environment. The greater threat to humans on Mars occurs when the neutrons of higher mean energy transverse the thin, dry Martian atmosphere and encounter the water in the tissue of the astronaut's body. Body water, being hydrogenous, efficiently moderates the high energy neutrons as they penetrate deeply into the astronaut, consequently depositing greater radiation doses near and in blood forming organs than would be experienced on Earth. Humans on Mars will be exposed to an increased risk of cancer particularly in organs like the liver and the spleen. A second significant threat is the possibility of a very high energy heavy ion or neutron causing a DNA double strand break in a single strike.

The energy bins designated in the Table 1 by the radiation protection commission have guided us in the emphasis for our spectrometer. In particular, the high efficiency of the neutron capture reaction at lower neutron energies, where weighting factors are higher, motivated us to select a ^{3}He proportional counter gas tube in this region. Likewise, silicon solid-state detectors with their large density of scattering centers were investigated for energies greater than several MeV in the energy region where weighting factors are smaller but fluence data is lacking.

2. MANES instrument design

MArs Neutron Energy Spectrometer (MANES) was proposed in response to A0 99-HEDS-01 for additional payloads to fly on the Mars 2003 Lander. The proposal was submitted in August 1999 and was selected for the definition phase in November 1999. The MANES instrument is partitioned into two channels—the low energy spectrometer (LES) and the high energy spectrometer (HES)—which are mounted to a central housing containing the electronics to operate the instrument and provide the spacecraft interface. An outline drawing of MANES is shown in Fig. 1, with a cross-section of the instrument given in Fig. 2.

The MANES instrument will have a mass of less than 5 kg and measure the Martian neutron spectrum over a large energy range. The daytime energy consumption will be less than 25 W h. The night time energy will be 17 W h in survival mode. The temperature range of the MANES instrument is −55°C to 46°C. To achieve these objectives, our specific aims for the Mars 2003 Lander MANES instrument are as follows:

(1) Measure the fluence energy spectra for neutrons on the surface of Mars over an energy range from

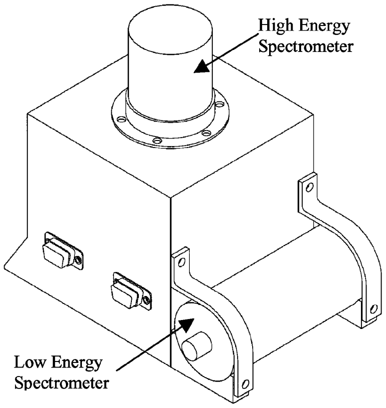

Fig. 1. Box level view of the MANES instrument.

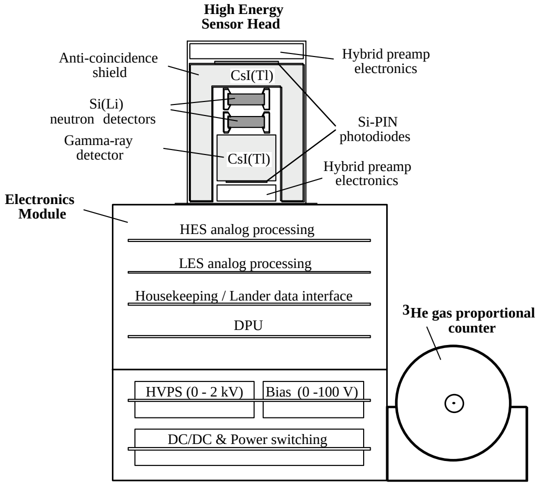

Fig. 2. Cut away drawing showing the high energy sensor head, the low energy tube and the electronics module.

100 keV to 50 MeV with a goal of 20 keV to 100 MeV with an energy resolution of 10% or better.

(2) Monitor the time variations in the neutron environment over the Mars 2003 mission life (a minimum of 90 Martian Sols). Compare and contrast differences between day and night spectra (diurnal variation) and effects of the solar cycle.

(3) Measure the fluence ratio of protons to alpha particles and heavy ions for the incident charged particles. Compare the results with those from the MARIE instrument on the Mars 2001 mission.

(4) Measure the gamma ray fluence spectra emanating from the surface of Mars from 0.1 to 10 MeV with an energy resolution of 10% to determine the significance of its contribution to dose and dose equivalent. Use prompt gamma lines produced in neutron capture and inelastic reactions for the same elements to identify neutron albedo sources and depth in soil.

(5) Compare the measured neutron spectra to the models that propagate the incident cosmic ray spectrum through the Martian atmosphere and the reflected particle spectrum through the planetary surface layers.

(6) Obtain theoretical descriptors of carcinogenesis as a function of particle type, energy, and time.

(7) Use mechanistic models to extrapolate results to those for radiation environments, doses, and dose-rates of concern for space exploration.

(8) From the experimental results, calculate the dose, dose rate, dose equivalent and dose equivalent rate to be expected by astronauts on Mars.

With these aims in mind the instrument was designed to occupy volume AP2 on the Mars 2003 Lander. Fig. 1 shows a box level view of the instrument which occupies an envelope of $18 \times 18 \times 15$ cm. Fig. 2 shows a cut away view and highlights the high energy spectrometer. Fig. 3 is a detailed block diagram of the MANES instrument.

The volume of data will consist of several energy spectra of a few kilo bytes each which are stored continuously until a request for download. A minimum of 60 h of operating time is required for a statistically significant number of counts up to 50 MeV. To study the diurnal variation 120 h are required.

3. Low energy spectrometer (LES)

Neutrons in the energy range from 100 keV or less to 8 MeV will be measured by the LES. The proposed LES will consist of one ^{3}He proportional counter tube. The tube will operate in a full $^3\mathrm{He(n,p)}^3\mathrm{H}$ neutron absorption reaction mode and in an elastic neutron scattering and ^{3}He recoil mode. In full absorption mode the neutrons react with ^{3}He to produce protons and tritons, which are easily detected charged particles. The basic reaction is

$$^3\mathrm{He} + {}^1\mathrm{n} \rightarrow {}^3\mathrm{H} + {}^1\mathrm{p}$$

with an energy release $Q = 0.764$ MeV plus the energy of the incident neutron [2]. Energy deposition spectra for this type of detector will have a peak at 0.764 MeV. This peak corresponds to the energy associated with epithermal neutrons (those with little energy compared to that released in the reaction). The omnipresent epithermal peak provides continuous calibration of energy scale. Modeling and extensive beam facility testing will provide necessary corrections for tube efficiency (Fig. 4).

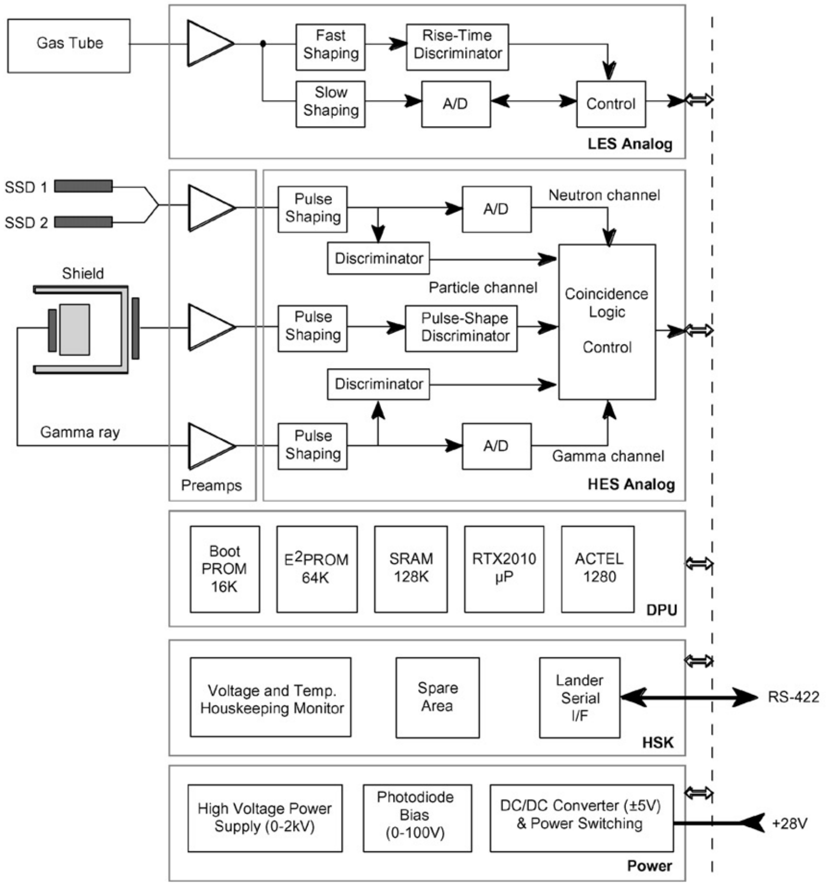

Fig. 3. Detailed block diagram of the MANES instrument.

4. High energy spectrometer (HES)

A thick lithium drifted silicon surface barrier detector determines the presence of neutrons greater than 5 MeV by elastic and inelastic neutron–silicon interactions that produce charged particles. Charged silicon recoils (elastic reaction) and secondary particles such as protons, alpha particles and residual nuclei (inelastic reactions) deposit charge in the detector. This charge is subsequently collected and measured by standard pulse height techniques. Thicker detectors offer increased efficiency for neutron detection by containing a greater number of possible interaction sites for the neutron, and consequently presenting a greater fraction of the mean free path to incident neutrons. This fact is especially important as the neutron energy increases to tens of MeV.

The efficiency of the 5 mm thick detector exposed to mono-energetic neutron beams in experiments at the Columbia University Radiological Research Accelerator Facility (RARAF) is shown in Fig. 5. The measured efficiency is about 5% in the interval from 5.89 to 18.5 MeV. The agreement between our data and the DOE and NASA models [3–5] indicates that we can achieve efficient detection ($> 3\%$) of neutrons with energy up to 50–100 MeV.

5. Background and charged particle discrimination

The HES silicon detector is sensitive to primary incident charged particles and uncharged gamma rays

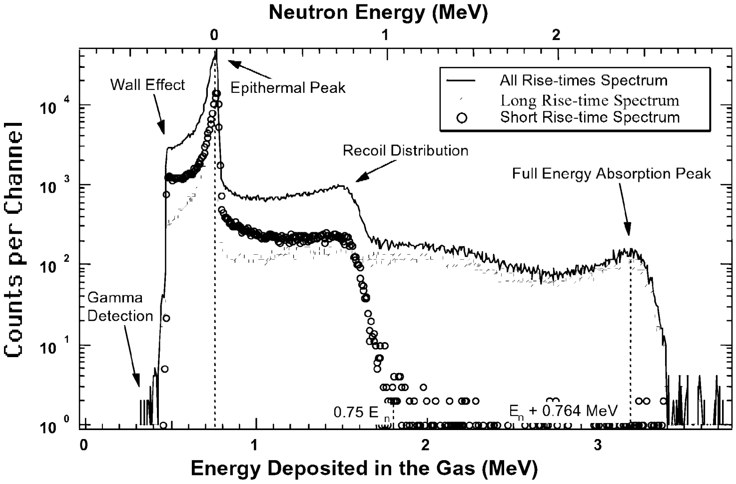

Fig. 4. Pulse height spectra for different rise-times of a mono-energetic 2.46 MeV neutron beam at the Columbia RARAF source. The ^{3}He(n, n)^{3}He elastic recoil reaction produces short rise-time pulses while the ^{3}He(n, p)^{3}H absorption reaction produces long rise-time pulses. Pulse-rise-time is used to discriminate between the two effects. The full-width at half-maximum of the epithermal peak is indicative of the detector resolution. The width of the absorption peak is due mainly to the energy spread in the incident neutron beam.

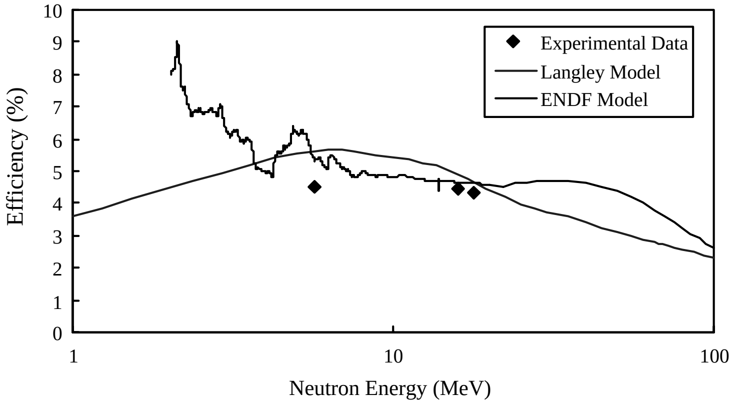

Fig. 5. Five millimeter Si(Li) detector efficiency as a function of energy from modeling compared to RARAF experiments [3–5]. This agreement indicates that MANES can efficiently measure neutron fluence to 50–100 MeV.

as well as neutrons. To separate the desired neutrons from the other incident radiation requires an anti-coincidence shield that surrounds the bulk silicon detector. This shield will be made of cesium iodide, which scintillates in the presence of charged particles. Light detected from the anti-coincidence material by photodiodes will be used to veto any signal subsequently detected in the inner silicon detector. The anti-coincidence shield will be in the form of a cup surrounding most of the silicon detector with a separate CsI plug shielding the remaining side. Electrical leads to the silicon detector through the anti-coincidence shield will be routed in a labyrinth fashion to eliminate any channeling of primary charged particles past the shield to the silicon. The design of the cup is based on that used in the Near Earth Asteroid Rendezvous (NEAR) X-ray and Gamma Ray Spectrometer. Minimizing the escapes is important since even inside a large spacecraft structure or on the surface of Mars, the primary charged particles dominate the secondary neutrons at high energies.

The anti-coincidence cup will include a CsI plug to measure gamma ray flux as a function of energy. This data will be used to subtract the gamma ray background from the flight data, but will also give additional information on the neutron albedo radiation environment of the Martian surface.

6. Instrument modeling

Data from LES must be converted from counts data to neutron fluence data. The first step in the conversion process is to apply the energy calibration to change channel number to energy for each spectrum. LES provides absorption and recoil count data which must be transformed to neutron flux. Absorption data is normalized by multiplying the count data for each channel by the efficiency of the tube for that energy bin. Recoil data must be unfolded to give incident neutron spectra as a function of energy. The end data product for the LES spectrometer is a series of time tagged low energy neutron spectra.

HES measures energy deposited in silicon detectors by secondary particles produced in nuclear reactions, not the incident neutron energy itself. The energy of any single neutron cannot be recovered from the deposited energy. However, the processes which create secondary particles are well known, and the probability of depositing a given amount of energy from a reaction are also well known as a function of neutron energy. Given these probabilities, it is possible to estimate, or unfold, the incident neutron energy spectrum from the energy deposition spectrum.

The HES data conversion takes essentially the same steps as that for the recoil LES spectrum, except that the response function is different and the inversion process involves solving a matrix equation for the incident neutron spectrum. As with the LES data, the first step in the conversion process is to apply the energy calibration. The second step is to use the response functions for the solid-state detector determined through modeling and experiment to calculate the best-fit or most probable incident neutron spectrum from the count data. The final data product for HES is a series of time-tagged high energy neutron spectrum.

The secondary scintillator detectors will produce an array of count data for gamma rays and number of counts for protons, alphas, and heavier ions. The gamma ray count data will be converted to an energy spectrum by applying the energy calibration factors and then multiplying the count data in each bin by the efficiency of the detector for that bin. The count data for protons, alphas, and heavier ions will be adjusted to account for the relative efficiency of each particle type in the scintillation detector, and then used to calculate relative abundances of these particles. The final data products for the secondary detectors will be time-tagged gamma ray energy spectra and charged particle abundance ratios.

7. Status

The 2003 Mars Lander was cancelled in November 2000 as part of the NASA restructuring of the Mars exploration program.

Acknowledgements

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