CALIBRATION OF THE HEND NEUTRON COUNTERS MOUNTED ON BOARD OF MARS ODYSSEY 2001 SPACECRAFT

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Abstract

The computation and calibration of the HEND detectors sensitivities were carried out in neutron energy range 0.2 – 15.3 MeV. The HEND (High Energy Neutron Detector) is the Russian instrument intended for search of planetary water that is mounted on the board of the "2001 Mars Odyssey" spacecraft. HEND is a set of the neutron detectors on the basic of ^{3}He proportional counters within different moderators for detection of epithermal, resonance and fast neutrons and the single-crystal high energy neutron spectrometer on the basis of stilbene detector. The calculation of the HEND detectors sensitivities depending on the neutron energy was done by the MCNP4C code taking into account the detailed geometry of the ready-assembled instrument. The calibration of the HEND was performed by the reference radioactive sources of neutrons and with the neutron beams of the electrostatic accelerator of ions. The reaction ^{7}Li(p, n)^{7}Be, d(D, n)^{3}He and T(d, n)^{4}He were used for obtaining of the quasimonoenergetic neutron beams. The calibration procedure of epithermal, resonance and fast neutron counters is described and the results of the experimental verification of the HEND sensitivity calculations are presented.

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Introduction

The exploration of Mars is associated with a fundamental problem of humanity evolutionary process. It is clear now that both planets, Earth and Mars, had practically the similar evolution during the early stages of their life. Therefore one of most important goal of exploration of Mars is the search for life on Mars now or any evidences of biological processes in the past. Mars has attracted more spacecraft exploration attempts than any other planets in the solar system. Of the 35 missions sent to Mars by three countries over 40 years. Two NASA's mission has achieved the great progress recently: "2001 Mars Odyssey" orbiter (2001) and Mars exploration rover "Spirit" (2004). The search for water is the NASA keystone strategy of the search for life. The "2001 Mars Odyssey" spacecraft is on the Mars orbit from 23 October 2001 and has on the board set of instruments for global exploration of elementary composition of Mars' surface and searching for water by methods of gamma ray and neutron spectroscopy. The "2001 Mars Odyssey" is the first spacecraft to make direct observations of the element hydrogen near and within the surface of Mars, and hydrogen provide the strongest evidence of water on or just under the Martian surface since it is one of the key elements within the water (ice) molecule. As a result of the detailed inspection of the planet from 2-hour circular orbit of approximately 400 kilometers altitude the considerable reservoirs of subsurface water (ice) was discovered at the polar cups, and that is most important, a little of water was found at the equatorial zone of the Mars. The first global map of water distribution was obtained by the scanning of the Mars' surface. The mission's science data collection will be continued for several more years. It is the greatest achievement in the modern science undoubtedly.

HEND detectors

In the structure of a complex of scientific equipments on the board of "2001 Mars Odyssey" are:

- GRS – Gamma-Ray Spectrometer with cooled detector of HPG, developed in the Lunar and Planetary Laboratory of the University of Arizona (USA);
- NS – Neutron Spectrometer for detection of thermal and epithermal neutrons, developed in Los Alamos National Laboratory (USA);
- HEND – High Energy Neutron Detector for detection of epithermal, resonance and fast neutrons, developed in Space Research Institute (Russia).

The main principle of the scanning of element hydrogen percentage on or just under the Mars' surface is measuring of the ratio of thermal and fast parts of neutron albedo spectrum. The secondary neutrons generated by high-energy galactic cosmic rays within the surface planetary layer with the thickness of 1-3 meters propagate out from the matter and interact with it. The appreciable content of hydrogen nuclei in the ground produces the change of the albedo neutron spectrum shape. The calculated neutron albedo spectra from the surface with different content of water are presented in Fig. 1 [1]. The other reliable evidence of the appreciable content of water is the observation of the strong gamma-line of 2 MeV due to hydrogen nuclei excitation in gamma spectrum from the surface.

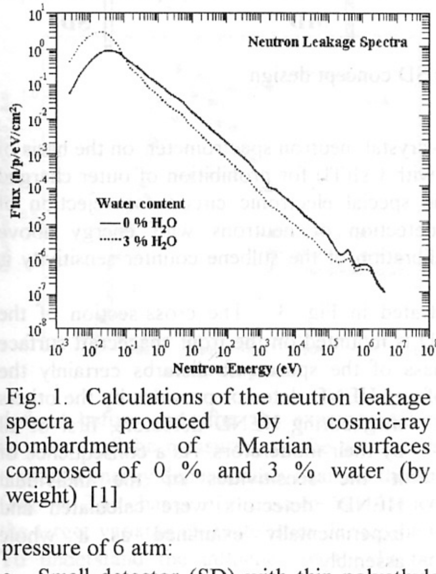

Fig. 1. Calculations of the neutron leakage spectra produced by cosmic-ray bombardment of Martian surfaces composed of 0 % and 3 % water (by weight) [1]

HEND combines into one instrument a set of five particles sensors and the electronic circuits. HEND includes three proportional neutron detectors based on the ^{3}He proportional neutron counter LND2517 with effective sizes ∅ 10.16×48.26 mm and pressure of 6 atm:

- Small detector (SD) with thin polyethylene moderator covered a cadmium screen of 0.5 mm thickness;
- Medium detector (MD) with medium polyethylene moderator inside a cadmium screen of 0.5 mm thickness;
- Large detector (LD) with thick polyethylene moderator with a cadmium screen of 0.5 mm thickness inside.

The designs of the detectors are presented in Fig. 2. The detectors are sensitive to different energy ranges of low-energy neutron spectrum. The data accumulation time from the counters could be vary from 12 s to 1 h by the digital command.

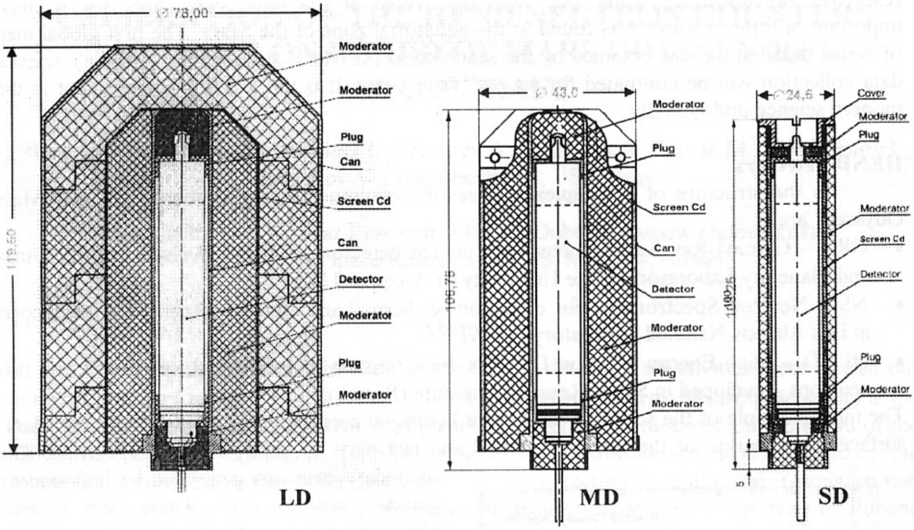

Fig. 2. The LD, MD and SD concept design

The high-energy detector of HEND is a single- crystal neutron spectrometer on the basis of stilbene detector surrounded by a veto-detector with CsI(Tl) for prohibition of outer charged particles registration. The spectrometer has the special electronic circuit for rejection of counts from gamma rays and intends for detection of neutrons with energy above approximately 1 MeV. The computation and calibration of the stilbene counter sensitivity is not the subject of the present paper.

The ready-assembled HEND is demonstrated in Fig. 3. The cross-section of the HEND assembly is about 25×30 cm^2. The HEND is mounted on the front spacecraft surface constantly aimed to Mars. Nevertheless the mass of the spacecraft disturbs certainly the neutrons field. The most influence on readings of any HEND detector provides by the others neighboring HEND detectors, first of all by their moderators. As a consequence of it the sensitivities of the individual HEND' detectors were calculated and experimentally examined as a whole assembly.

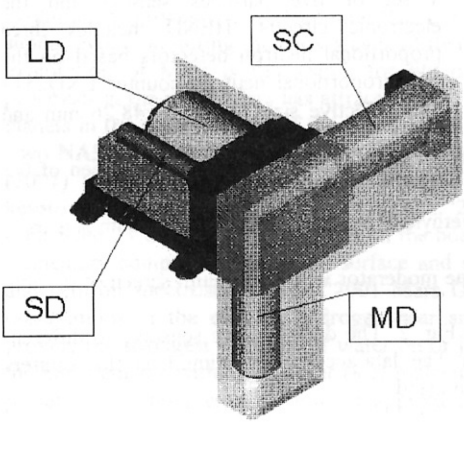

Fig. 3. The ready-assembled HEND

Three patterns of HEND took part in the calibration procedure: FU1, FU2 (the flight patterns) and KDI (development type). All instruments were made identically, but the small differences in their sensitivity existed nevertheless.

Neutron sources for the HEND testing

The physical calibrations of the HEND counters were performed in Joint Institute for Nuclear Research. Two types of neutron reference sources were used:

- electrostatic accelerator of ions (EG-5) with thin lithium, deuterium and tritium targets;
- reference radioactive source of neutrons (^{252}Cf).

In case of lithium target, the protons were accelerated to energies of 2 – 2.8 MeV and the reaction ^{7}Li(p, n)^{7}Be with the threshold of 1881 keV was used for receiving of the quasimonoenergetic neutrons in energy region 0.2 – 1.0 MeV. At proton energies lower than 1,921 MeV there are two branches of neutrons emitting in forward direction, so in our experiments the lowest proton energy was 2,000 MeV. Corresponding neutron energy at 0° is equal to 0,23 MeV. Starting from the proton energy 2,373 MeV ^{7}Li(p, nγ)^{7}Be* reaction comes into play, but even at highest proton energy used in our experiments – 2.707 MeV, it gives admixture of 4% of neutrons with energy 0,5 MeV to the main branch with energy 1,003 MeV. The detailed review of this reaction was made in [2] and neutron energies, yields and angular distributions were calculated with laboratory differential cross sections compiled in [3]. The method of calculations offered in [4] was used to calculate neutron yields. The experimental testing of the neutron fluxes and energy dispersions at place of the HEND counters arrangement was carried out as well.

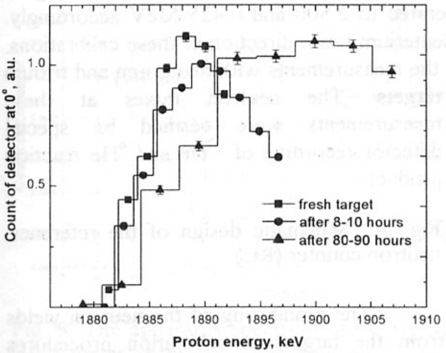

Fig. 4. Neutron detector counts vs proton energy near the threshold of ^{7}Li(p,n)^{7}Be reaction. Target thickness is determined as the corresponding curve FWHM

The neutron-producing target was prepared by the natural lithium evaporation on the copper backing plate. The proton's energy was stabilized with the accuracy of 0.1%. The target thickness changed from 5 keV to 10 keV during the experimental run. The exact thickness of the target were defined before and after the experimental runs by means of the measuring of the neutron yield – proton energy dependencies near the threshold (Fig. 4). The change of the curves is evidence of the target variable characteristics during the run. To understand the influence of the Li target thickness on neutron yield one need look at the neutron yield vs proton energy dependence (Fig. 5). The highest variation of neutron yield takes place in proton energy range 2.1 – 2.3 MeV. The estimation at this proton energy and at the target thickness change from 5 to 10 keV gives 0.9 % decreasing of the neutron yield to the end of the experimental run. For other proton energies the neutron yield variations owing to this effect are smaller.

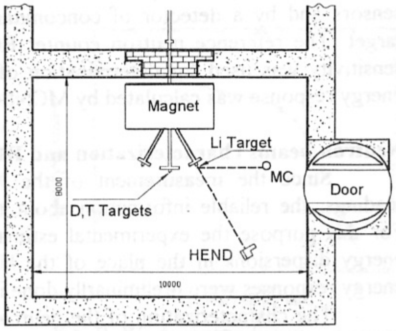

Fig. 6. EG-5 experimental hall plan view. MC – the comparative neutron counter for monitoring of the neutron yield from the target

The layout of the accelerator experimental hall arrangement is shown in Fig. 6. The HEND assembly was placed at 0^0 to the proton beam direction at the testing. The angular ranges that HEND overlaps vs distance of testing was ± 15^0 maximum. The energy dispersion of the neutrons crossing the HEND surface was caused by the some effects: uniformity of the target and its degradation because of burning, proton's energy losses on the target thickness, neutron interactions with materials of backing plate, target holder and others details near the target, stability of the proton's energy, the angular resolution of the measurement and so on. The HEND counter readings contain as well the contribution from multiscattered background neutrons resulting from the small dimensions of the accelerator experimental hall and presence of surrounding equipments.

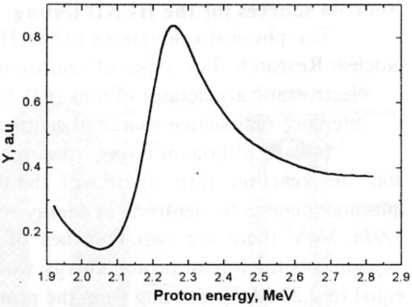

Fig. 5. Neutron yield from the thin ^{7}Li target in ^{7}Li(p,n)^{7}Be reaction at 0° averaged over 0.214 sr solid angle

The d(D, n)^{3}He and d(T, n)^{4}He reactions were used for the HEND calibration at higher neutron energy. The deuterium ions were accelerated to 2.500 and 0.425 MeV accordingly. The HEND assembly was placed at 42^0 to the deuterium beam direction at these calibrations. The neutron energies were 5,1 and 15,3 MeV in the measurements with deuterium and tritium targets. The neutron fluxes at these measurements were verified by special detector recording of ^{3}He and ^{4}He reaction products.

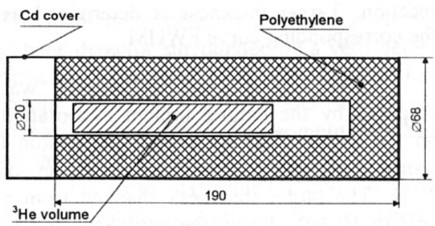

Fig. 7. Schematic design of the reference neutron counter (RC)

The monitoring of the neutron yields from the targets at calibration procedures was carried out by a comparative neutron counter placed aside from the HEND, beam current sensors and by a detector of concomitant alpha-particles in measurements with the tritium target. The reference neutron counter RC (Fig. 7) with well known energy dependence of sensitivity was used for determination of the neutron flux through the HEND assembly. Its energy response was calculated by MCNP4C code.

Neutron beams characterization and RC testing

Since the measurement of the HEND detectors sensitivities is based on the RC readings, the reliable information about the neutron beam characteristics has been required. For this purpose the experimental estimations of the average neutron energies, the neutron energy dispersions in the place of the HEND assembly arrangement and testing of the RC energy responses were preliminarily done in the energy range 0,2-1,0 MeV.

The characterization of the neutrons crossing the HEND surface was carried out with the high-pressure ^{3}He filled counter (RS-P4-0810-204) [5]. The precise determination of the ^{3}He content within the counter was done at the IBR-2 diffraction scattering neutron beam with energy 0.06 eV. The pressure of the ^{3}He was found out equal to 10 atm (the density of ^{3}He at 20° C – $1.2079 \cdot 10^{-3}$ g·cm^{-3}). The counter was placed in the HEND position. The counter was entirely covered the cadmium shell in order to suppress the scattered neutron background. The ORTEC base amplifier with 3 μs time constant was used for the signal amplification. The apparatus pulse-height spectrum of the ^{3}He gaseous proportional counter irradiated with the thermal neutrons has the peak corresponding to the sum of the energies of the $n + {}^3He \rightarrow p + {}^3H + 0.764\ MeV$ capture reaction products. In this case the apparatus peak resolution and its position are defined by the proper characteristics of the counter and electronics only. The neutron spectrometry with ^{3}He counter is based on this peak shift measurement at the various neutron energies. The energy calibration of the analyzer scale must be done for these measurements. Furthermore, the neutron energy dispersion results in the widening of the peak in comparison with the resolution of the thermal neutron peak. It gives the possibility to estimate the energy dispersion of the neutrons from the target. Owing to the peak asymmetry the closest estimation realizes by the examination of the right slopes of the peaks. The details of these measurements have been described in [6]. The testing has been done for the four values of the average neutron energy – 229.8; 489.7; 868.0 and 973.4 keV, that corresponds the proton energies 2,00; 2.24; 2,60 and 2.707 MeV. The apparatus spectra from nearly thermal neutrons and from 489.7 keV neutrons are shown in Fig. 8 for example.

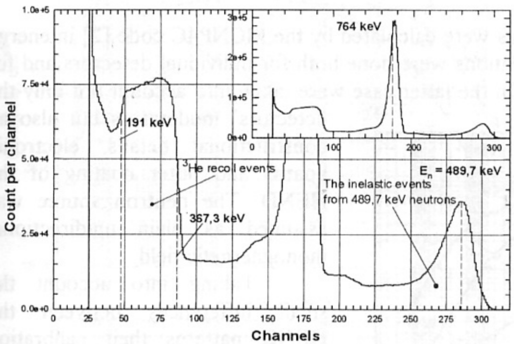

Fig. 8. The apparatus spectrum of the high-pressure ^{3}He counter from 489.7 keV neutrons

The energy dispersions have been found equal to 6.3; 26.8; 58.8 and 73.4 keV accordingly. The knowledge of the ^{3}He(n,p)^{3}H capture reaction cross-sections (ENDF60) for these neutron energies allowed to calculate the neutron flux values in the HEND position and to carried out the comparison of the calculated and measured responses of the RC. This comparison is presented in Fig. 9. The results of the RC testing gave confidence to the reliability of the RC sensitivity calculation in the whole energy region.

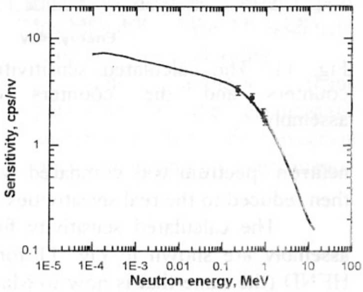

Fig. 9. RC response function (points – experimental data, curve – spline fit of calculation.

HAND detectors calibration procedure

The appreciable level of multiscattered neutrons background was observed in the place of the HAND arrangement. It was experimentally established that the background gradient is small and its level can be assumed as constant in vicinity of the measurement place. Thus, the readings of any HEND detector at distance R from the target can be defined as a first approximation by following:

$$N/N_M = a/R^2 + b,$$

where N and N_M are the count rates of the individual HEND detector (in the assembly) and the neutron monitor (MC). The others HEND detectors influence on this detector readings as square R was accepted at that. Every measurement of individual HEND detector sensitivity was done at several distances from the target (from 0.5 to 3 m) and the values of parameters a and b were determined then by the best fitting procedure for a set of data measured at different distances. The value b was presumed as the detector readings owing to the background in the measurement place. The fitting result of one of the measurement with lithium target is presented for example in Fig. 10.

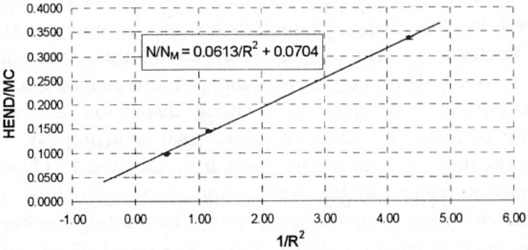

Fig. 10. The neutron background measurement

The HEND detectors sensitivities at some neutron energies between 0.2 and 15.3 MeV were determined then as the ratio of their readings without background contribution to the neutron fluxes measured by the RC counter.

Results and discussion

The SD, MD and LD sensitivities were calculated by the MCNP4C code [2] in energy range from 10^{-8} to 20 MeV. The calculations were done both for individual detectors and for real geometry of the HEND assembly. In the latter case were taken into account not only the detectors' moderators but also all constructional details, electronic boards and outer coating of the HEND. The neutron source was assumed as plain unidirectional monoenergetic field.

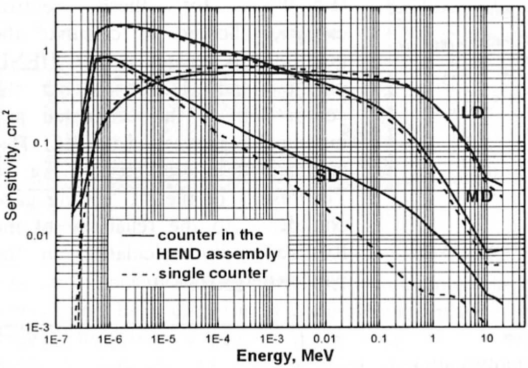

Fig. 11. The calculated sensitivities of the single counters and the counters in the HEND assembly

Taking into account the small differences between the HEND patterns their calibration with reference ^{252}Cf source was done. The calibrations with reference ^{252}Cf source were carried out within a big dwelling at a height of 4 m above a floor and the neutron background level was negligible. The calculated response of every detector type (as an assembly) to the ^{252}Cf source neutron spectrum was compared with the real response and the calculated sensitivities were then reduced to the real sensitivities.

The calculated sensitivity functions for individual detectors and for detectors as an assembly are shown in Fig. 11 for the case of normally irradiation of the front panel the HEND (the same that is now to Mars). As would be expected the SD feels the worst-possible influence from neighbouring material, particularly in high-energy range.

The comparisons of the calculated and experimental sensitivities of the detectors as an assembly for FU1, FU2 and KDI are shown in Fig. 12-14 as well. The total experimental errors correspond to 95 % of confidence intervals on the neutron energies and the detector

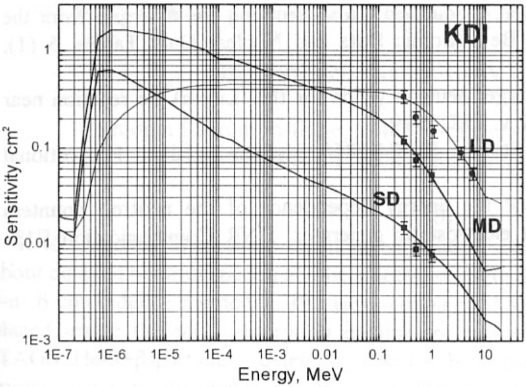

Fig. 12. The experimental testing of the counter sensitivities for the KDI pattern of the HEND

sensitivities. Apparently the quite satisfactory agreement of the calculated functions with calibration data in spite of very complicated geometry of calculation and proper individual distinctions between the patterns of the instruments. The HEND sensitivity functions were used at

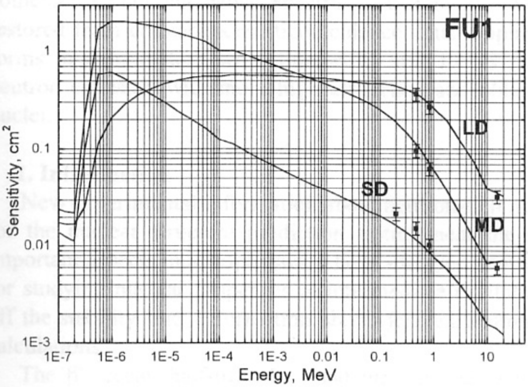

Fig. 13. The experimental testing of the counter sensitivities for the FU1 pattern of the HEND

processing of the data from the Martian orbit and the variation of the HEND detector readings allowed building up the planetary map of water distribution. The map obtaining by the HEND is in a good agreement with the map obtaining by the American instruments for search of water

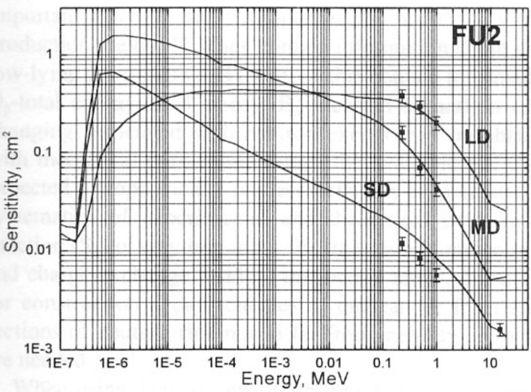

Fig. 14. The experimental testing of the counter sensitivities for the FU2 pattern of the HEND

and the data from both instruments are essentially supplemented each other.

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