NEUTRON WELL-LOGGING PROFILES IN SLOPED THIN LAYER FORMATIONS SIMULATED BY MONTE CARLO METHOD

URSZULA WOŹNICKA[1], DOMINIK DWORAK[1], URSZULA WIĄCEK[1], TOMASZ ZORSKI[2]

1. Introduction

Neutron well-logging is one of the basic methods of well logging for porosity and lithology determination. A neutron source, placed in a borehole tool, creates a neutron field in the nearest environment – around the borehole. A neutron detector placed in the same tool at some distance from the source registers neutrons coming from that field. It gives information on some of the petrophysical parameters of rocks surrounding the borehole.

Descriptions of neutron fields and properties of neutron transport in matter have been strongly developed in reactor physics, both in the field of analytical and numerical methods. The same rules of neutron transport physics in various environments and the same mathematical methods can be used also for the description of neutron fields in geophysical applications.

Analytical description of the neutron fields can be done only for simple geometries, e.g. for the neutron field created by a point neutron source located in an infinite cylindrical borehole – surrounded by infinite and homogeneous rock medium. However, many interesting analytical solutions that are useful in the interpretation of neutron well-logging have been designed and applied in practice [1, 2]. More complex geometries – as, for instance, dipped thin layer formations crosscut by the cylindrical borehole – are not suitable for the analytical considerations.

Monte Carlo (MC) methods are continuously developed in the neutron transport domain. It is possible to reproduce, with very good accuracy, the real neutronic experiment, for example the neutron profiling in almost realistic measurement conditions. Monte Carlo simulations are a powerful tool supporting interpretation of neutron measurements in case of complex borehole geometries.

Advanced numerical software which can be implemented for a simulation of neutron well logging is the MCNP^{TM} code [3]. The program performs simulation of neutron transport in matter with the use of the Monte Carlo method. That possibility stems from the stochastic nature of neutron transport. Physical phenomena like neutron slowing down, scattering, and absorption processes are sampled from their probabilities and the whole history of the individual neutron transported from the source up to the final absorption can be followed. An advantage of this type of simulation is that all parameters such as porosity, elemental composition of rocks, tool construction, borehole filling and its diameter, etc. are known in advance, because they make up the input data for the

[1] URSZULA WOŹNICKA, DOMINIK DWORAK, URSZULA WIĄCEK
Henryk Niewodniczanski Institute of Nuclear Physics, Radzikowskiego 152 str., PL-31-342 Kraków, Poland.
Urszula.Woznicka@ifj.edu.pl, Dominik.Dworak@ifj.edu.pl, Urszula.Wiacek@ifj.edu.pl
[2] TOMASZ ZORSKI
AGH University of Science and Technology, Faculty of Geology, Geophysics and Environment Protection, Dept. of Geophysics, Al. A. Mickiewicza 39, PL-30-059 Kraków, Poland.
zorski@geol.agh.edu.pl

numerical calculations. This gives the possibility to examine the influence of each parameter of the medium individually on the response of the well-logging tool. An applicability of the MCNP code for nuclear geophysics is not limited to neutron well-logging tools. Very interesting results and solutions can be also obtained for neutron-gamma and gamma-gamma methods [4, 5].

The paper includes results of numerical calculations of neutron fields around the borehole and the corresponding response of the neutron-neutron well-logging tool on an example of the selected neutron well-logging tool (NNTE). Many neutron borehole profiles have been simulated for a wide range of asymmetric borehole–thin-layer geometries. The general model consists of an infinite rock, intersected by an infinite long borehole. A thin, flat rock layer of different lithology crosses that infinite rock under a certain angle to the borehole. To be close to reality the rock lithologies similar to those of the North-West Poland formations (shale sands) were chosen for the calculations. Numerous combinations of parameters – various porosities and thermal neutron absorption cross sections of the rocks as well as different layer thicknesses and slope angles – have been considered. The main goal of the research is to present the influence of an angle between a thin-layer and a borehole axis on the response of a neutron well-logging tool. Results are instantly useful for elaboration of the well-logging interpretation procedures for directional drillings, where the rock layers are usually sloped, or even highly inclined to the borehole axis.

2. Numerical model of the thin layer formation and borehole

The geometry of the problem is presented in Figure 1. The geological formation consists of a thin flat rock layer of thickness 5 cm $\geq H \geq$ 50 cm surrounded by an infinite, other rock medium. These two different rock spaces (called further simply the "layer" and "surroundings") are represented in the calculations by two different rock models. All our rock models consist of the same rock matrix, and they can differ only in porosities, ϕ, and/or in thermal neutron absorption cross sections, Σ_a, as is explained below. The rock matrix, same for each rock model, has density equal to 2.63 g/cm^3 and its chemical composition is as follows:

	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	H_20	CO_2
mass %	72.5	7.0	2.0	7.5	1.8	1.2	8.0

This is the characteristic composition of the Carpathian Miocene formation in Poland. To define the particular rock models, the three different porosity values of that rock matrix were chosen: ϕ = 7.5, 20 or 45%, where the pores are completely filled with fresh water. It was further assumed that the Σ_a of the pure rock matrix may be equal to 15 c.u. or 40 c.u. To reach such Σ_a values a little amount of ^{10}B isotope (correspondingly 0.00163 % and 0.00663% by mass) was added to the rock matrix (at the SiO_2 expense). That small artificial supplement of the strong neutron absorber, ^{10}B, has an influence only on thermal neutron capture and does not change major remaining parameters of the formation. However, the effective Σ_{aeff} of each rock model of given porosity differs from the matrix Σ_a because of the presence of water filling the pore space. The Σ_{aeff} have been calculated applying $\Sigma_a(H_2O)$ = 22.24 c.u. Six different rock models, summarized in Table I, were built on the basis of the above assumptions. Each of these models can play a double role in the calculations – it can work as the thin layer or as the surroundings.

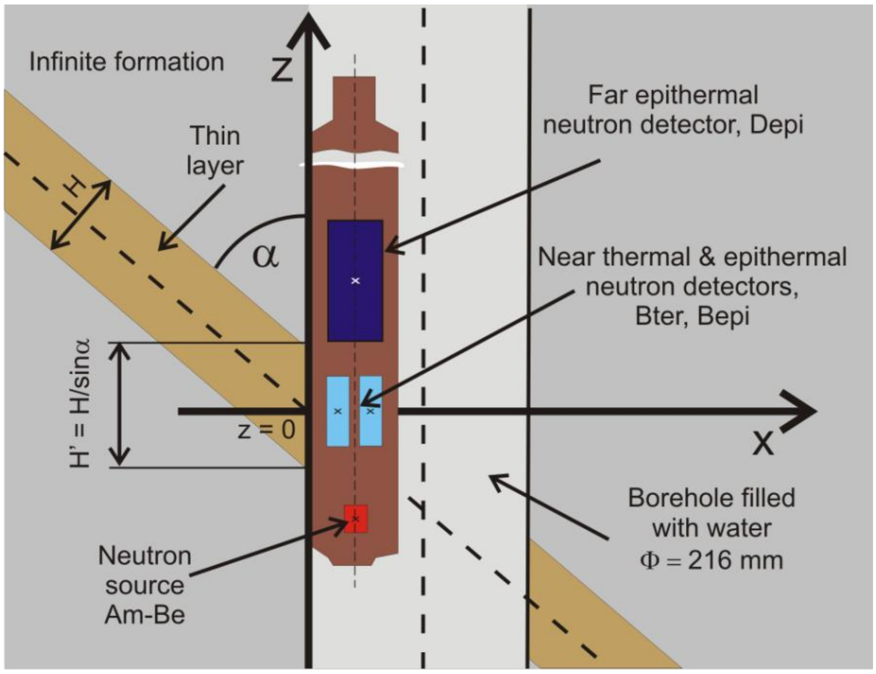

Figure 1. Formation – borehole geometry for MC modeling.

The borehole of diameter 216 mm, filled with the fresh water, intersects the whole formation - under an angle 15°≥α≥90° to the thin layer. In this way, our general model as shown in Figure 1 has seven changeable parameters: four of them describe the physical properties of the "thin layer and its surrounding medium" (two different ϕ and Σ_a), two others describe the "layer geometry" (H, α), and the last one (depth "z") gives the actual position of the NNTE tool relative to the thin layer.

Table I. Parameters of rock models used in MC calculations

Rock model	ϕ [%]	Σ_a [c.u.]	$\Sigma_{a\ eff}$ [c.u.]	ρ_{vol} g/cm^3]
Miocen-1 (M-1)	7.5	15	15.54	2.508
Miocen-2 (M-2)	7.5	40	38.67	2.508
Miocen-3 (M-3)	20.0	15	16.45	2.304
Miocen-4 (M-4)	20.0	40	36.45	2.304
Miocen-5 (M-5)	45.0	15	18.26	1.897
Miocen-6 (M-6)	45.0	40	32.01	1.897

The NNTE well-logging tool (Neutron–Neutron–Thermal–Epithermal) is a neutron tool equipped with an Am-Be neutron source and a set of three detectors: two near detectors (thermal, Bter, and epithermal, Bepi) and one remote detector (epithermal, Depi). The two epithermal detectors create a compensate dual-detector tool which is low sensitive to the borehole impact and to the neutron absorption properties of the medium. The near Bter detector is sensitive to hydrogen content and the Σ_{aeff} of the environment. The detailed numerical model of the NNTE tool has been created and validated in benchmark experiments [6].

3. The MCNP calculations and results.

A detailed description of the MCNP simulations is included in [8]. The responses of each detector have been calculated for the infinite homogeneous media – corresponding to the rock models from M-1 to M-6. The results are included in Table II. The original MCNP results give an average number of neutrons absorbed in a unit of the detector volume, per one neutron emitted from the source. Using the calibration procedure for the NNTE tool [6], these raw data have been recalculated to clearer units [count/s]. The detector responses obtained for the infinite media show the wide range of variability. Some of trends in the profile curves can also be visible. Let us consider the thin layer of the M-6 model surrounded by the infinite medium M-1: the Bter detector counts ~944 count/s when the neutron tool goes through the M-1 rock model and next the negative anomaly is created (with the minimum value ~400 count/s) when it goes through the M-6 layer. The actual shape and size of the anomaly depends mainly on the thickness *H* of the thin layer, angle α, porosity ϕ, and $\Sigma_{a\ eff}$. In some cases the size of the anomaly does not reach the count rate of the respective infinite medium (see e.g. Figure 2, Detector Bepi, *H* = 15 cm).

Table II. Numerical results of the detector responses in infinite rock models

Rock model	Bter [count/s]	σ(Bter) [count/s]	Bepi [count/s]	σ(Bepi) [count/s]	Depi [count/s]	σ(Depi) [count/s]
M-1	943.99	2.55	298.60	0.90	169.17	1.05
M-2	741.82	2.08	297.39	0.89	164.43	1.04
M-3	719.61	2.23	224.36	0.79	95.55	0.84
M-4	560.44	1.91	224.14	0.78	93.52	0.83
M-5	484.04	1.89	166.81	0.70	60.72	0.76
M-6	400.20	1.68	166.69	0.70	59.94	0.76

The examples of calculated profiles are presented in Figure 2. The thin layer (M-2 rock model: low porosity and high $\Sigma_{a\ eff}$) is surrounded by the rock model M-5 (high porosity and low $\Sigma_{a\ eff}$). The profiles registered by near detectors are presented: on the left for thickness of the thin layer *H* = 15 cm, and on the right for *H* = 50 cm. The slope angle α varies from 90° up to 30° (*H* = 50 cm) and 15° (*H* = 15 cm). The zero value on the depth axis marks the point when the centre of the detector is situated opposite the intersection of borehole and layer symmetry lines. The anomalies registered by the remote Depi detector has a similar course as for the near Bepi detector. The straight vertical lines mark the responses of the detectors in infinite rock models M-2 and M-5, respectively.

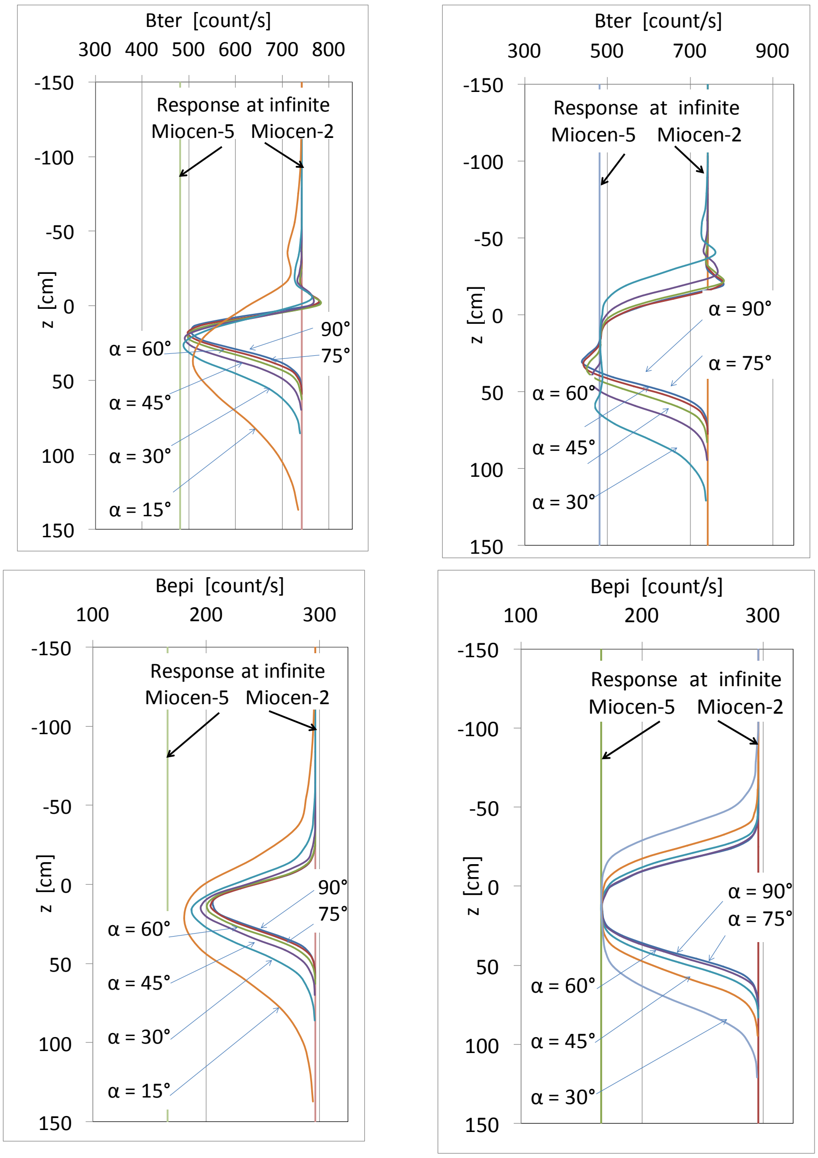

Figure 2. Neutron profiles modeled by m-c simulations for Bter and Bepi detectors for different slope angles, α, for Miocen-5 thin layer: left: H = 15 cm, right: H = 50 cm thickness. The layer is surrounded by Miocen-2 rock model. Description of the z axis - as in Fig. 1.

The change in the slope angle α causes changes in the shape of anomalies; the width is growing and the slope of the anomalies decreases. The slope of the anomaly becomes asymmetric for the Bter response. This results both from the strong asymmetry of the formation–layer geometry and from the presence of tool asymmetry (location of the source–detector system in relation to the rock formation). The strong differences between the neutronic properties of both rock models (M-2 and M-5) can create disturbances on the boundary layer.

4. Conclusions

The presented selected results of the MC simulations of the neutron tool in the complex borehole–thin layer formation geometry show the capabilities of numerical modeling of neutron transport processes. The announced series of profiles are used as the input data to the next considerations associated with the elaboration of the new interpretation procedures of well logging profiles in sloped thin layer formations. As is shown in *Figure 2*, starting from the $\alpha \leq 45°$ the obtained well logging profiles require different interpretation procedures than the simple, symmetrical borehole–formation geometry, that means geometry with $\alpha = 90°$.

The numerical simulation method as presented above can be also useful for optimization of the construction of neutron well logging tools, e.g. optimization of source–detector distances as well as the design of proper shielding layers protecting detectors from the direct source radiation and from scattered radiation originated from the borehole fluids.

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