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SIMULATION OF NEUTRON TRANSPORT FOR THE PURPOSE OF NEUTRON FILTERS OPTIMIZATION IN THE PULSED NEUTRON LOGGING APPARATUS

Kosarev V. E., Goncharova G. S., Platov B. V. , Rakaev I. M. and Kosareva L. R.
Kazan Federal University, Institute of Geology and Petroleum Technologies, Tatarstan, Russia
E-Mail: Victor.Kosarev@kpfu.ru

ABSTRACT

Numerical modeling of thermal neutron filters, which are an integral part of the apparatus of pulsed neutron logging (PNL), has been carried out. Many models of filters were created. The neutrons slowing down and absorption processes in filters was analyzed. Optimum structure and dimensions of neutron filters was offered.

Keywords: pulsed neutron logging (PNL), slowing down, absorption of neutrons, nylon, paraffin, cadmium, neutron filters.

INTRODUCTION

When operating and drilling oil and gas wells there is a permanent need to address a variety of tasks necessary to select the exploitation mode of reservoir. A leading role in this belongs to the geophysical well-logging methods. One of such methods for the evaluation of reservoir saturation and reservoir properties is pulsed neutron logging (PNL). However during the measurements of PNL, logs are significantly influenced by noises. Thus, neutrons passing directly from the source to the detector can substantially influence the resulting values. In order to prevent such incidents, special neutron absorbing filters are placed between the neutron source and the detectors.

The goal of this research work is a study of the neutron filter influence to the weakening of neutron flux between the fast neutron source and the detectors as well as selection of the optimum size and material for the filter. The most widely distributed materials with good retarding and high absorption properties are considered.

DESIGN FEATURES OF PULSED NEUTRON LOGGING TOOLS

The apparatus of PNL includes a source of fast neutrons (so called “neutron generator”) [1] and a set of thermal and epithermal neutron detectors, which form near and far detectors 0. The measurement cycle includes: rock treatment with the fast neutrons emitted from the generator and registration of the amount of thermal and epithermal neutrons on the near and far detectors. In order to prevent passage of neutrons directly from the source to the detector zone, special neutron absorbing and moderating filters are placed between these construction units. In the capacity of the filters in the designing of the apparatus substances are used with a high hydrogen content (paraffin, nylon, etc.), as well as materials with high neutron capture cross section (cadmium, gadolinium, etc.) 0. The key properties of the considered materials are presented in Table-1.

Table-1. Key properties of most commonly used neutron moderators and absorbers.

Characteristics	Nylon	Paraffin	Cadmium	Gadolinium
Chemical formula	$C_{12}H_{22}N_2O_2$	$C_{22}H_{52}$	Cd	Gd
Density, g/cm^3	1.14	0.93	8.65	7.9
Melting point, Degrees C	220	44-56	321	1313
Neutron capture cross section Σ 0, barn	33.9	27.6	2520	48 890

It should be mentioned that nylon is more stable at high temperatures than paraffin. As regards absorbers, the gadolinium has almost 20 times bigger neutron capture cross section compared with the cadmium.

MODELS OF THE NEUTRON FILTERS

In our case due to the high cost of the neutron generators and detectors, construction of a physical model was impossible. However, authors had used a widespread approach in world practice for such cases - the mathematical modeling and numerical simulations of the experiment. Software built on the Monte Carlo method is currently being used (MCNP, Geant4, etc.) 0, 0. The modeling process is to track the position of each elementary particle (in this case - a neutron), which left the source from its "birth" to extinction. In this research, for performing calculations, features of the package Geant4 were used. It represents a set of dynamic libraries which was written using the C++ programming language. In this case the process of model creating consists of providing the geometry description and the medium properties, listing the elementary particles detectors, etc. in the form of a predefined set of classes. During the research, calculation of the particles movement in the simulated environment and their registration was carried out at each predetermined point in time.

To carry out this research three types of mathematical models were created (Figure-1).

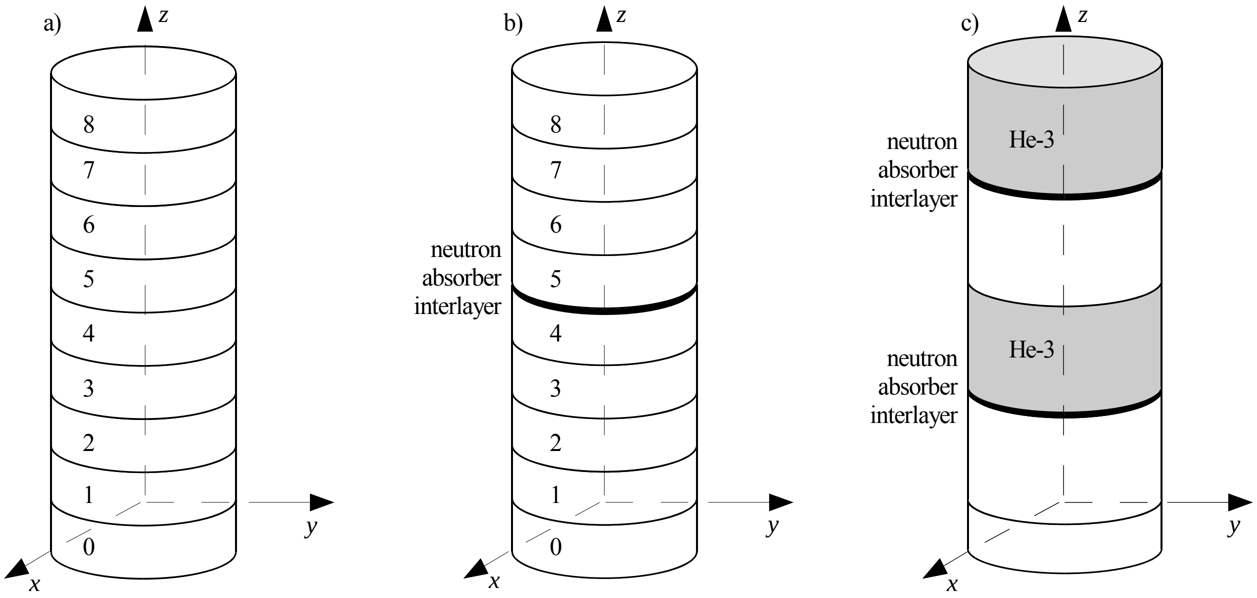

Figure-1. Neutron filter models: a) set of cylinders composed from substances with high neutron slow-down cross section; b) same, but with the addition of a thin layer made from high neutron capture cross section material; c) same as in point «b», but part of the cylinders are filled with He^3 to simulate neutron detectors.

Each model consists of a set of cylinders with a diameter of 10 cm (3.94 inches). The cylindrical form of the model is conditioned by the interior of the well logging tool. The neutron source was placed at the point with coordinates (0, 0, 0), located between the zero and the first cylinder. The composition and the properties were set individually for each cylinder. In the first case, all the cylinders were filled with the substance with a high cross section of neutron moderation (paraffin or nylon). In the second case, a thin (1 mm or 0.04 inches) layer with anomalous absorbing properties (cadmium or gadolinium) was located in the middle of the model at different distances from the source. In the first and second case, the height of each cylinder was 2.5 cm (0.98 inches). All cylinders, starting with the first, acted as detectors. In the third case a prototype of a pulsed neutron logging tool was used. In this case part of the cylinders (with a height of 10 cm or 3.94 inches) was filled with He^3 in order to model the neutron detectors. Decelerating filters with a height of 5 or 10 cm (1.97 or 3.94 inches) were located between the neutron generator and the first detector, as well as between the two detectors. The medium outside the cylinders was assumed to be absolutely absorbing. It means that all neutrons passing through the side border were ignored. During simulation, neutrons that have passed inside the cylinder volume were counted. As a result of the simulation, the decrease of quantity of neutrons with time was calculated for each of the cylinders.

DEPENDENCE OF THE NEUTRON FLUX DECELERATION ON FILTER MATERIAL

In the capacity of the neutron moderator materials two substances with high hydrogen content, widely used in the apparatus of PNL, were tested: nylon (caprolon) $C_{12}H_{22}N_2O_2$ and paraffin $C_{22}H_{52}$. Figure-2 presents neutron amount distribution in the nylon and paraffin filters. The X-axis shows the time values that have passed after neutron emission. On the Y-axis the distance from the neutron generator to the middle of each cylinder is shown. Isolines show the number of neutrons recorded at each predetermined time.

During the analysis of the decay curves of the quantity of neutrons, wellbore and formation components are traditionally considered 0 (Figure-3). Several methods exist for approximation of such curves as sum of two exponential functions. The approximation is used to determine the average life of thermal neutrons in the well and in the formation. The formation component is primarily used in order to evaluate the layer porosity and saturation. The easiest way for determination of the formation component is to discard that part of the data that is located in the low time zone and identification of the component which describes right part. The influence of borehole components tends to be substantial up to 400-600 microseconds, depending on the type of fluid present in the borehole. During the creation of neutron filters one of the most important tasks is minimization of the amount of neutrons passing directly from the source to the detector at times exceeding 400 µs.

As can be seen in Figure-2 the decrease of the neutrons amount in the nylon is noticeably higher than in paraffin. Thus, for further simulations nylon was chosen as a filter material. However, it should be mentioned that even in the nylon filter there is a significant flow of «direct» neutrons (going directly from the source to the detectors). In fact this flow forms background noise during registration in the well. By this means at the time of 400 µs the neutron flow with an approximate size of 10^2 was registered. That kind of neutron flow can lead to substantial inaccuracy in the evaluation of the formation component. As seen on the figure increasing the filter length results in a decrease of neutron flux. However, from the viewpoint of construction of borehole devices such elongation is not always possible.

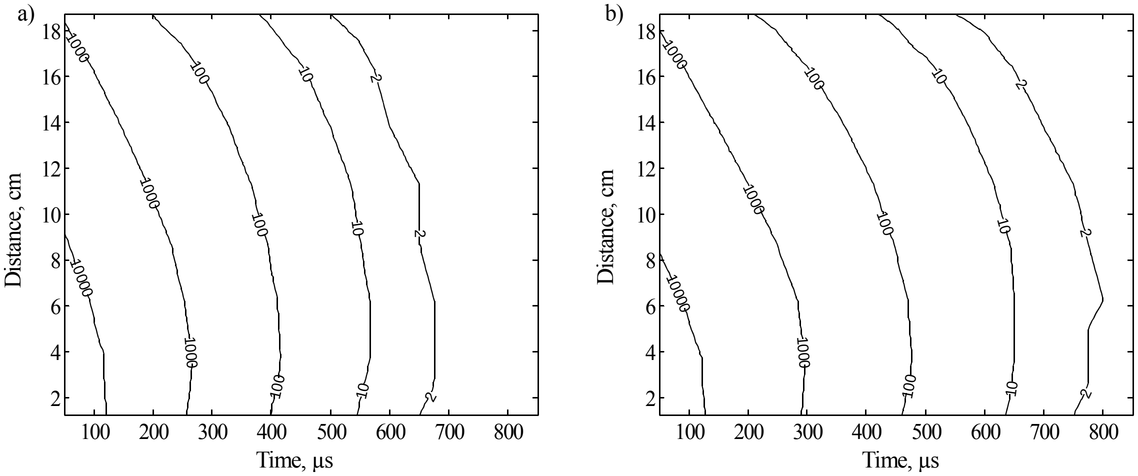

Figure-2. Distribution of neutron amount in the nylon (a) and paraffin (b) filters.

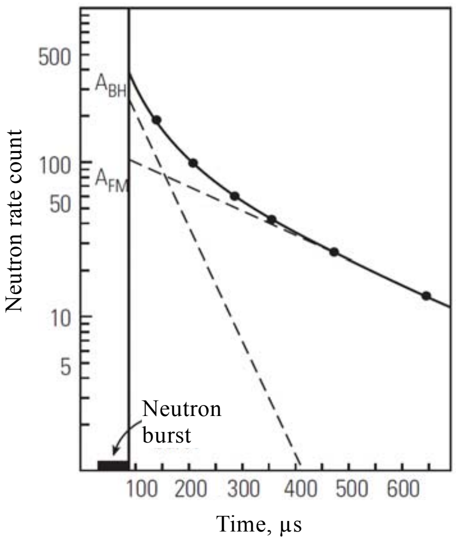

Figure-3. Example of thermal neutron decay depending on time 0. A_{BH} – borehole component; A_{FM} – formation component.

STUDY OF THE NEUTRON ABSORBERS

Another way of decreasing the number of «direct» neutrons is the addition of a substance with a high rate of neutron capture cross section between the source and detectors. This type of model (Figure-1, b) was constructed in the second step of the research. Usage of the substance with anomalous neutron capture cross section is capable for minimizing neutron amount near the detector. Thereby it decreases «direct» neutron flux. In terms of PNL apparatus design that kind of absorber is placed in the form of a thin plate immediately prior to the detectors.

At the initial stage of the filter simulation, absorbing qualities of the absorber interlayers were being studied. Figure-4 shows the distribution of the neutron flux in the nylon filter with the 1 mm (0.04 inches) thick cadmium interlayer at the distance of 10 cm (3.94 inches) from thermal neutron source (with the energy 1 eV). It can be clearly seen that after the cadmium interlayer neutron flux is absent. Obviously, 1 mm (0.04 inches) thick cadmium layer is enough for absorbing all the thermal neutrons passing through the interlayer.

However in modern borehole instrumentation the initial energy of the neutrons is 14.1 MeV. Figure-5 presents the distribution of the neutron flux in the nylon filter with the 1 mm (0.04 inches) thick cadmium interlayer at the 5cm, 10 cm and 15cm (1.97, 3.94 and 5.91 inches) distances from the fast neutron source. Results show that the cadmium interlayer actively absorbs the thermal neutrons in its nearest environment.

The difference in macroscopic capture cross section of thermal neutrons in the cadmium and gadolinium (Table-1) is significant. In that case with the usage of these two elements in numerical simulations of the absorber interlayer was done. For this purpose two neutron filter models with the absorber interlayer at the distance of 10 cm (3.94 inches) from the fast neutron source were calculated (Figure-1, b). Figure-6 represents the comparison of neutron amount depending on the distance to the fast neutron source. The represented dependences show that cadmium interlayer absorbs all the thermal neutrons. Replacing cadmium with gadolinium has no influence on the reducing of neutron amount above the thin plate. At the same time, usage of the cadmium will substantially increase the cost of the filter.

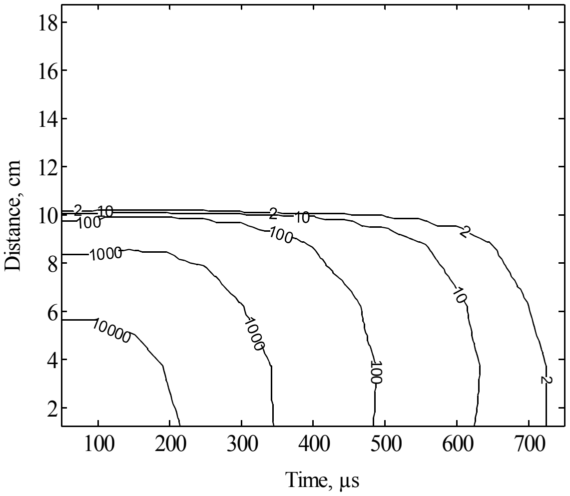

Figure-4. Distribution of the neutron flux in the nylon filter with the 1 mm (0.04 inches) thick cadmium interlayer at the distance of 10 cm (3.94 inches) from thermal neutron source. Energy of the neutron source is 1eV.

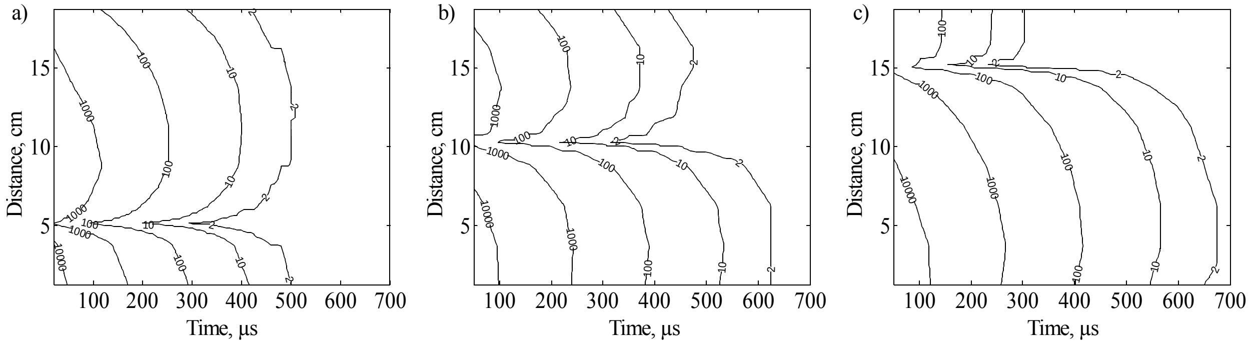

Figure-5. Distribution of the neutron flux in the nylon filter with the cadmium interlayer at different distances from neutron source (14.1 MeV). Cadmium interlayer is situated at the distance of: a) 5 cm (1.97 inches); b) 10 cm (3.94 inches); c) 15 cm (5.91 inches).

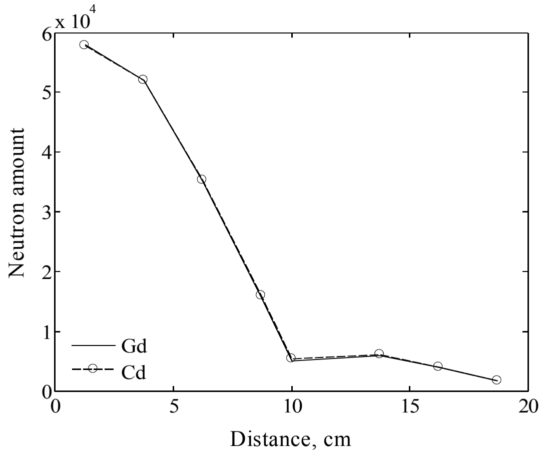

Figure-6. Dependence of thermal neutrons amount on the distance to the fast neutron source. Absorber interlayer (1mm thickness - 0.04 inches) located at 10cm (3.94 inches) distance from the source.

This stage of simulation has shown that increasing the filter length results in a decrease of neutron flux level behind the absorber plate. However the amount of those neutrons still remains substantial. This kind of picture can be seen according to following reasons. Neutrons emitted from the source have significant energy. Part of those neutrons loses their energy (slow down) during the interaction with hydrogen nuclei near the source. Another part flies much further; moreover some of the neutrons reach beyond the outskirts of the absorber plate and pass through it without interaction. It is known 0 that cadmium and gadolinium have essentially big values of the neutron capture cross section for the particles with the energy range prior to 10 eV. Neutrons with high energy can fly through the absorber plate and slowdown to the thermal energies in the second part of the filter.

NEUTRON FLUX CALCULATION IN A DUAL-PROBE MODEL OF THE PNL APPARATUS

In the PNL tools gas filled neutron detectors are used for registration of thermal and epithermal neutrons. They are located at different distances from the source. For simulation of the dual-probe apparatus two models were created. Part of the cylinders were filled with He^3 (Figure-7, a). In the first model (Figure-7, b) thickness of the nylon filter under the He^3 detectors was 10 cm (3.94 inches), in the second model (Figure-7, c) - 5 cm (1.97 inches). In both cases the height of the He^3 detectors is equal to 10 cm (3.94 inches). During the experiments a 1 mm (0.04 inches) thick cadmium plate was placed under each detector.

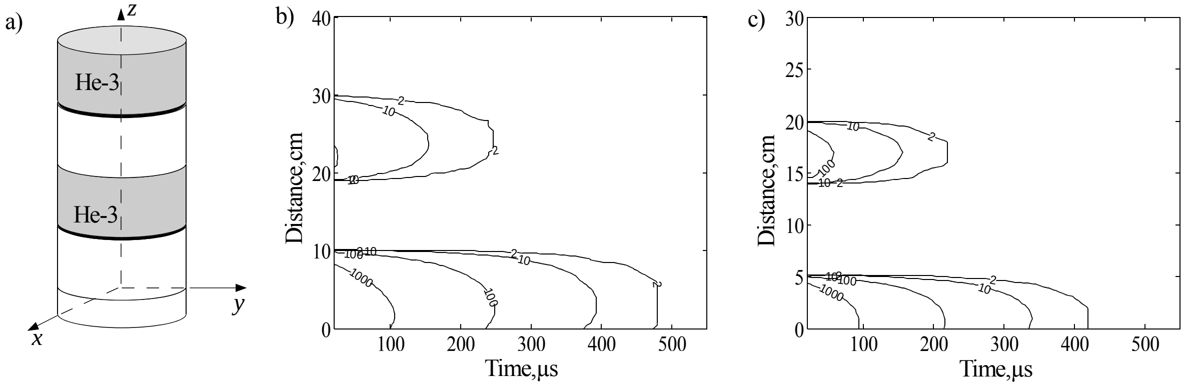

Figure-7. Model of PNL probes (a); distribution of the neutron amount in the model at different thickness of nylon filters 10 cm (b) and 5 cm (c).

The figure shows that inside the filters neutrons are present, whereas in the zone of the helium detectors neutron counts are absent. Moreover, a bigger amount of neutrons was registered in the top filter with respect to the lower one. This figure is typical for both types of PNL tool models. On the second model (Figure-7, c) neutron counts in both of the filters are lower than in the first model.

That kind of neutron distribution in the models can be explained as follows. As in the case considered in the previous section, in consequence of high hydrogen content in the nylon, part of the neutrons slowdown in close proximity to the source (in the first filter under the near detector). Other neutrons pass through the detector zone without any interactions with the helium and reach the second detector where the pattern repeats. Obviously the second filter is reached by a lower number of neutrons (Figure-7). In addition to the above, the thicker the filter, the higher the quantity of neutrons slowing down in it and then diffusing during the substantial period of time. However it doesn't mean that the size of the filter should be reduced or that the filter should be completely excluded from PNL apparatus. Absence of a moderator layer between the generator and detectors can lead to the registration of too big a number of neutrons and as a consequence to an overflow of neutron counts in the detectors at the initial time intervals (first tens of microseconds). This can be explained by the combined interaction of two factors. Firstly it is a significant quantity of neutrons emitted by the source. Secondly, in spite of the comparatively low values of interaction cross section with the He^3 (for about 3 barns [4]) in the zone of high energies, neutron interaction is not equal to zero.

During the carrying out of this numerical experiment authors concluded that the length of the thermal neutron filter should be within 5 to 10 cm (1.97 - 3.94 inches). It is essential to add a 1mm (0.04 inches) thick cadmium plate after the filter. In case of absence of the cadmium interlayer, length of the moderating filter should be increased, if allowed by the size of the constructed apparatus.

CONCLUSIONS

For the apparatus of PNL the numerical simulation of various neutron filter configurations was done. Usually composition of filters includes a layer of the substance with high slowing-down cross section for fast neutrons and a layer of a substance with high thermal neutron capture cross section. It appears that nylon is the most appropriate material for PNL apparatus in the considered set of neutron moderator materials. Nylon filter length should be about 5-10 cm (1.97-3.94 inches), if it is added after the layer of material with high thermal neutron capture cross-section. Otherwise the length of the nylon should be increased (as a minimum to 15 cm-5.91 inches). However, from the viewpoint of construction of borehole devices such elongation is not always possible. In the capacity of thermal neutron absorber material, usage of the cadmium is recommended. For absorption of all thermal neutrons in the filter, 1mm (0.04 inches) thick cadmium plate is enough. Replacing cadmium with gadolinium is inappropriate, as it leads to a substantial increase in the cost of the filter without increasing of it's the absorption properties.

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