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DEVELOPMENT OF MULTISECTOR PULSED NEUTRON LOGGING TOOL CONSTRUCTIONAL PARTS

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Abstract

This paper focuses on the results of mathematical modeling aimed to construct multisector pulsed neutron logging (PNL) tool, which can be used to locate the cracks that are formed during hydraulic fracturing operations. This project resulted in a model of multisector PNL tool containing 6 detectors placed in such a way that they are equidistant from the source.

This paper also presents:a. optimal collimation design providingdetection of neutronsfrom specific formations;b. model allowingto assess the quality of collimation in multisector logging tools; c. optimal detector configuration for the multisector PNL tool.

The project results have also shown the possibility of increasing the number of registered thermal neutronsby introducing special constructional parts into the PNL tool design, allowing to changedirection of the neutron flux from the source into the area adjacent to detection units.

Consequently,special constructional parts for the multisector PNL toolwere modeled to increase thenumber of neutrons recorded and determine the azimuth of the hydraulic fractures.

Keywords: Pulsed neutron log, Neutron moderation, Neutron absorption, Neutron collimation, Hydraulic fracturing.

Introduction

At present it is difficult even to imagine oil and gas field development without the use of enhanced recovery methods. Hydraulic fracturing (or just ‘fracking’), being one of the most popular and effective techniques,canaid the production by increasingessentially the flow rates. Despite the fact that hydrofrackingis well-studied [1] (this method was first introduced in the 1940s, and the first hydraulic fracturing operation was carried out in 1948) and highly developed technically, not every hydrofrackingoperation turns out to be successful.

Given the high cost of hydrofracing operations, thisis a particularly topical factor, since it ultimately affects production rates and company profit.

Success in this case depends not only on the technology and materials used, but also on quality control methods applied at every stage of the operation.

Basic geophysical monitoring techniques are: thermal logging, cross-dipole acoustic logging, gamma-ray spectral logging, pulsed neutron logging (PNL) [1, 2].

1. Model of Multisector PNL Tool

The possibility of determining fracturing location using a PNL tool and thermal neutron absorbing materials is shown in [3].

Tracer proppant with a large neutron capture cross-section (i.e. containing Gd_2O_3, B_4C, etc.) [3] is used for quality control in hydraulic fracturing operations. Consequently, physical (neutron) properties of the fracture are very different from the properties of surrounding rock mass.

Let's now take a look at a pulse neutron logging (PNL) tool. It includes a fast neutron source (so-called “neutron generator”) [4] and a set of thermal (or epithermal) neutron-sensing devices, forming the so-called near (ND) and far (FD) detectors [5]. Each measurement cycle includes irradiation of the rock mass with fast neutrons generated by the source and then registration of thermal (or epithermal) neutrons at the near and far detectors. In order to prevent neutrons from flowing directly from the source to the detectors, special filters are used to slow the neutrons down or absorb them. Filters are often made of nylon, which is characterized by high hydrogen content [6].

Mathematical modeling and numerical simulation [7] are the most widely used approaches. They imply software tools which are based on Monte Carlo method (Geant [8], MCNP [9], and others). The modeling process itself involves tracking the position of each elementary particle (i.e. neutron) from its “birth” to itsextinction.

To create a neutron log tool with an azimuthal resolution, a detecting block allowingto record the signal from the various segments (sectors) of the rock mass has to be used. This project presents a model of a neutron log tool consisting of 6 gas-filled thermal neutron detectors with 20 mm diameter and 120 mm height arranged circumferentially inside the tool. It is obvious that the same approach may be used to model a log tool containing, for example, spectral gamma-ray detectors.

Figure 1 shows a mathematical model of the PNL tool inside a well, where: 1 – rock mass; 2 – portland cement; 3 – casing column; 4 – fresh water; 5 –far detector (60 cm); 6 – near detector (30 cm); 7 – neutron filter (nylon+Cd); 8 –

14.1 MeV neutron source; 9 –log tool case, 10 – fracture with a proppant. Figure 1a represents a vertical section of the PNL tool; Figure 1b represents a lateral section of the tool, near the detector.

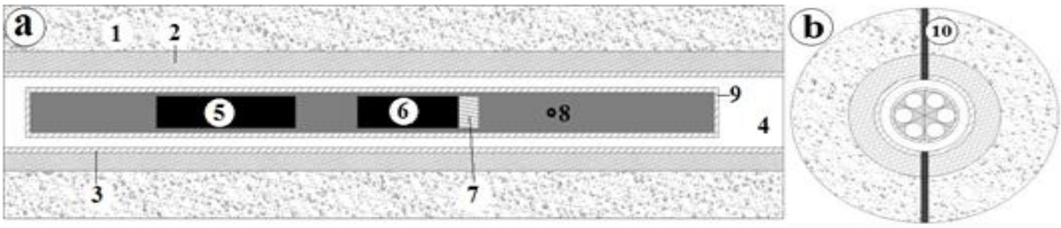

Figure. 1 – Mathematical model of the neutron logging tool placed inside the hydraulically fractured well.

The tool's outer diameter is 90 mm, casing thickness is 6 mm (made of 12×18H10 steel[10]). Near and far detectors are sets of six separate gas-filled thermal neutron detectors (20×120 mm) pressed against the inner wall of the tool. The number of detectors in the tool is limited by its size. Fast neutron source is 30 cm from the near detector. To prevent direct neutron flux from the source to the detectors, a filter made of nylon and cadmium is placed between them. The modeled media is a homogeneous rock (limestone) cut by a vertical borehole (d=216 mm) with metal casing 9 mm thick. The cement sheath is 35 mm thick. The borehole is filled with fresh water. The rock massis cut by vertical crack 10 mm wide, filled with a mixture of doped (gadolinium oxide Gd_2O_3)proppant (75%) and water (25%) (Figure. 1b).

2. Detectors Collimation Quality Control

Fast neutrons motion is random and depends on lots of factors, e.g. neutron's energy, density and elemental composition of the medium, etc. Trajectories of neutrons flowing in the medium surrounding the detectors are schematically shown in Figure 2.

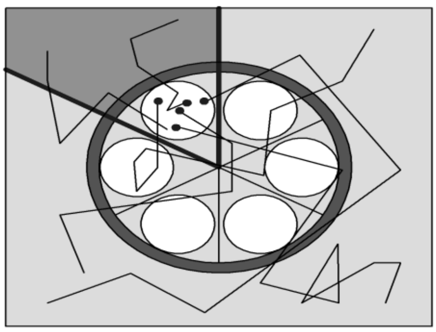

Figure. 2 – Neutrons moving around the detector.

To evaluate neutron properties of the specific formation, the detector must register only neutrons that come from this very formation. Neutrons coming from the neighbouring sectors have to be excluded. For this purpose, it is necessary to ensure detector collimation. Optimal tool design providing for detector collimation is one of the main objectives of this project. For quantitative estimation, a mathematical model simulating the radiation generated by one sector of the rock mass was created. Figure 3 shows a model developed specifically for collimation quality control. It consists of a limestone cylinder (K_p = 5%) with a detector unit pressed towards its outer side.So, in this case only one detectoris exposed to direct neutron radiation.

Fast neutron source is located at the center of the rock cylinder. Neutrons now can be registered only by this single detector. The whole area outside the cylinder or the log tool is considered "black hole" area, where neutrons are completely lost and will not be registered.

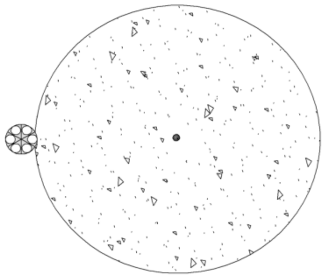

Figure. 3 – Collimation quality control model schematic.

The estimation was made as follows: the number of neutrons registered by the detector adjacent to the rock cylinder (main detector)was considered 100%. The number of neutrons registered by other detectors wascalculated as the percentage from main detector records. In the course of the work, a number of detection unit models have been created. All of them contain six detectors and differ only in materials used and mediafilling the space between the detectors.

There are 4 different designs of the detection unit shown in Figure 4: 4a – detectors are covered with cadmium from the inside of the tool; 4b – detectors are covered with cadmium plus nylon core is placed at the center, detectors are shielded from one another by nylon plates; 4c differs from 4b in that cadmium plates are used instead of nylon ones; 4d – nylon core plus cadmium plates, no covering. Calculations have shown that the most efficient design is presented in Figure. 4c (the number of neutrons, registered on "neighboring" detectors is only 1,3%). This construction is best suited for fracture location determination.

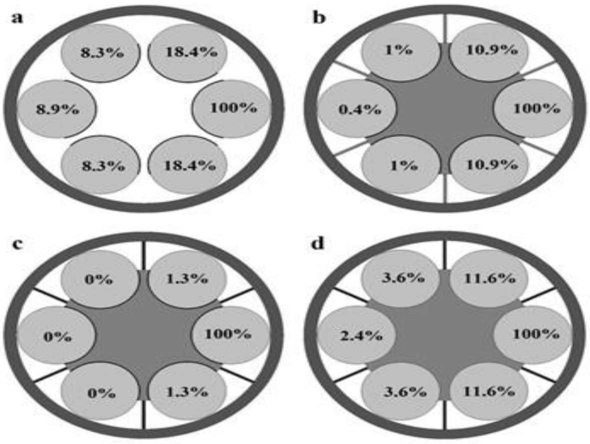

Figure. 4 – Various configurations of the detection unit.

3. Fast Neutron Source Collimation Model

Obviously, when developing neutron log tool with multiple detectors, the problem of neutron flux reduction occurs.If the number of neutrons recorded by detector occupying the whole available space inside the tool (i.e. by "integral" detector) is taken as 100%, this number will be reduced in several times in case of multisector device– in correspondence with number of detectors. In our case, the flux will be reduced in (at least) 6 times, compared to the integral detector Figure.5).

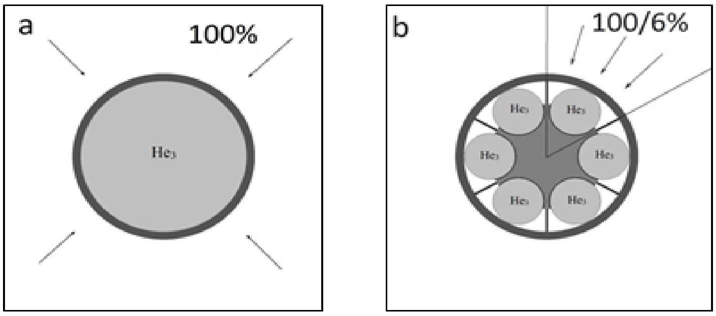

Fig.5 – Comparison of neutron flux registered by integral and multisector detector units.

Let's take a closer look at neutron flux emitted by the fast neutron source. Schematic of neutron log tool presented in Figure 6 includes two detection units and a neutron source. Neutron source produces a spherical isotropic neutron flux, whichcan be divided into three parts. First part is represented by neutrons passing directly from the source to the detectors (Figure. 6, (1)). Log tools developers always do their best to minimize this part of neutron flux by adding filters which slow down these neutrons or capture them [6]. The second part consists of neutrons flowingfrom the source to the detectors through the upper half-space of the rock mass (Figure. 6, (2)). These neutrons pass through the drill mud and cement column, and eventually reach the detector units (near and far). It also should be noted that this particular part of the neutron flux has an informative value. The third part of the neutron flux goes into the lower half-space (Figure. 6, (3)). These neutrons are considered lost, because the probability of their detection tends toward zero.

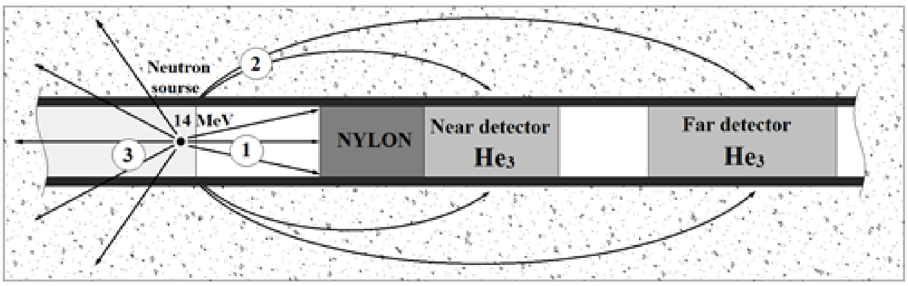

Figure. 6 – Neutron flux separation schematic.

To increase the number of "informative" neutrons, the first and the third parts of the flux should be directed to the upper half-space, i.e. to the area of interest. To do this, PNL tool was upgraded by adding some specific constructional parts. Two constructional parts were modeled: “reflection cone” and “deflector”. The “cone” is a part of the thermal neutron filter. The term “deflector”meansthe specific constructional part designed to direct the third part of the neutron flux toward the detectors.

4.1. “Reflection cone” model

The “cone” was chosen for deflecting “direct” neutron flux (Figure. 7). Conical shape provides the right reflection angle directing neutrons straight into the rock mass due to elastic and inelastic collisions with the “cone” material. Standard neutron shield is located behind the “cone”.

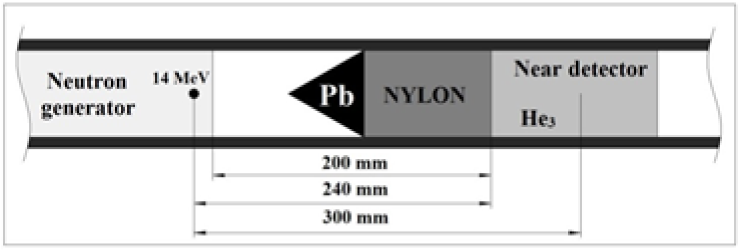

Figure. 7 – Neutron source collimation schematic.

Two possible models of the “cone” are shown in Figure 8. The first model (Figure. 8a)consists of a cylinder and a cone. Both parts are made of nylon [12]. The second model (Figure. 8b) implies alead (^{208}Pb) cone. Lead was chosen due to its high-energy neutron cross section [13].

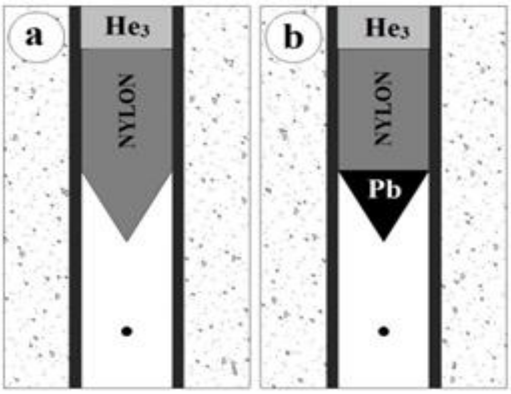

Figure. 8 – The neutron reflection“cone” models.

The model shown in Figure 8a was taken as a base model – following the strategy of the previous part of the project. Total number of detected neutrons was considered 100% to be then compared with all the other models results.

In the course of this work, a number of models with different apex angles of the cone and various distances from the source to the cone were developed. The difference between number of neutrons registered with the base model and all the other models is shown in Figure 9. It was also experimentally proved that the optimal designimplies a cone of 70 mm height placed at the distance of 70 mm from the neutron source.It is unpractical to use a greater distance, because thiswill not increase the number of registered neutrons,while at the same time willcertainly cause shielding properties degradation [6]. The model presented in Figure 9e shows the best results increasing the number of registered neutrons by 17.4% compared to the base model.

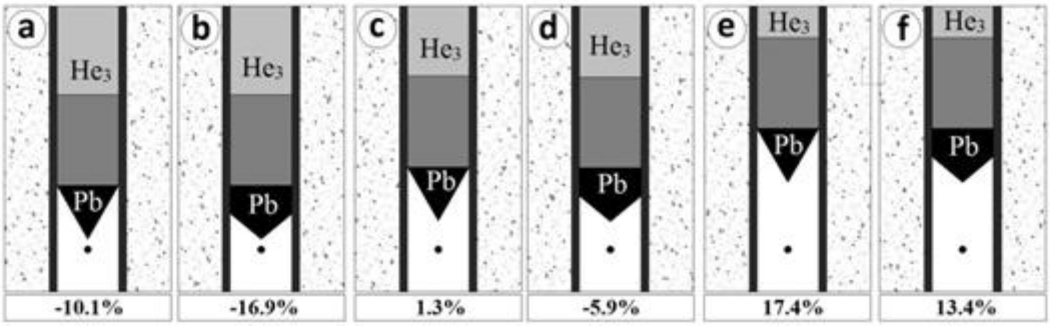

Figure. 9 – Optimal location and form of the neutron reflection "cone".

4.2. "Deflector" model.

In order to make use of the third part of the neutron flux, the "deflector" was modeled. It is represented by a lead cylindrical covering [11] filling the inner space between the neutron source and the tool body."Deflector" models are presented in Figure 10. Models 10a and 10b are copies of the above-mentioned base models. The rest of the models differ from one another in lead covering height and form. Modeling results were also compared with the base (nylon) model (Figure 10a).

Final results show the possibility to further increase the number of neutrons by 3% with 10e model (compared to 10b). This means that the total number will increase by 20,4% compared to the basic nylon model.

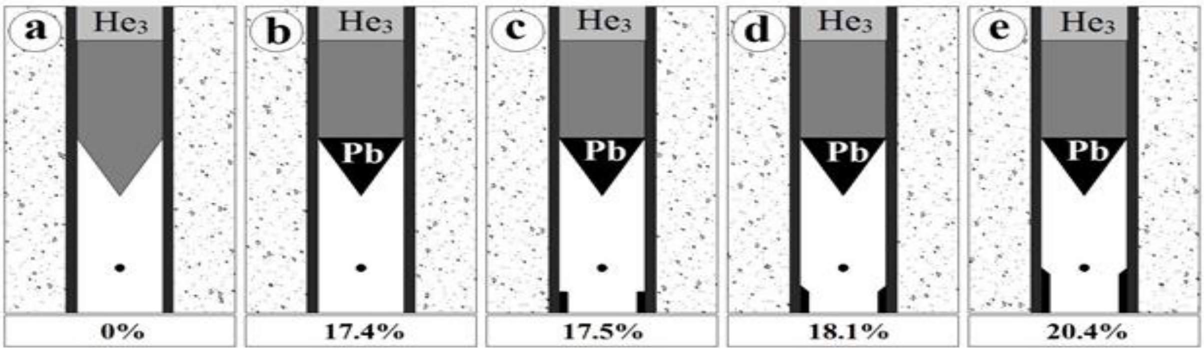

Figure. 10 – Optimal "deflector" configuration development.

5. Multisector PNL Tool Models As Applied To Hydraulic Fractures Azimuth Evaluation

The above-described optimal PNL tool was tested for a possibility of determining the hydraulic fracture azimuth. To do this, a model of carbonate rock massif (K_p=5%) cut by a fracture (10mm wide) was created. The fracture was filled with a tracer proppant (0.45%Gd_2O_3). Model test results are shown in Figure 11. The dashed line represents integrated number of neutrons registered by all 6 detectors (labeled 1-6) before hydraulic fracturing. Near detectors are represented by gray circles. Hydraulic fracture is located along the line connecting detectors 2 and 5. The solid line shows integrated number of neutrons after fracturing (may be approximated by an ellipse). As is seen from the figure, the number of neutrons after fracturing is lower than before fracturing. It also should be pointed out that the diagram tends to assume the elongated form, and the minor axis of an ellipse follows the fracture orientation. This fact can be easily explained by the increased absorptive capacity of the fracture due to presence of Gd_2O_3.

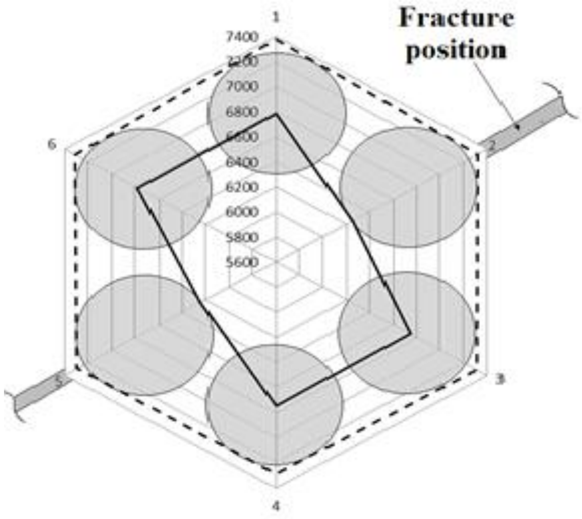

Figure. 11 – Integrated number of neutrons measured by 6 detectors before (dashed line) and after (solid line) hydraulic fracturing.

Executive Summary

The project resulted in specific PNL tool design implying multiple detectors (of neutrons or gamma rays) placed circumferentially inside the tool. The proposed design allows to estimateneutron properties of different rock sectors around the cased well. In order to eliminate the influence of neutrons coming from neighboring sectors, a specific construction of the detection units was developed providing reliable detectors collimation. A set of additional constructional parts increasing the number of registered neutrons was also proposed. Obviously, these ideas can be applied for classical neutron logging tools as well.

As a result, modified detection units allowboth evaluating standard parameters (thermal-neutron capture cross-section, porosity, etc.) and solving the problem ofhydraulic fracture azimuth determination.

Conclusion

Modeling results have shown the possibility of using PNL tool to determine fracturing location. Further researchesare going to be devoted to the use of such tools for fracture angle determination (in horizontal and deviated wells) andPNL tools resolution estimation.

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