Methodology and algorithm to correct the thermal neutron porosity for the effect of rare elements and rock minerals with high neutron absorption probability

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Abstract

The thermal neutron porosity is routinely acquired in almost every well. When combined with the density, gamma ray and resistivity logs, the basic petrophysical parameters of a reservoir are evaluated. The design of the thermal neutron tool is simple, but its interpretation is complex and affected by the formation constituents. The most challenging situation occurs when the formation contains elements with high absorption probability of the thermal neutrons. The existence of such elements changes the neutron transport parameters and results in a false increase in the measured porosity. The problem is reported by many users throughout the years. In 1993, higher thermal neutron porosity is reported due to the existence of an iron-rich mineral, Siderite, in the Nazzazat and Baharia formations in Egypt. Siderite and all iron-rich minerals have high thermal neutrons absorption probability. Recently, in 2018, high thermal neutron porosity in Unayzah field in Saudi Arabia is also reported due to the existence of few parts per million of gadolinium. Gadolinium is a rare element that has high probability of thermal neutron absorption. Currently, none of the existing commercial petrophysics software(s) have modules to correct the thermal neutron porosity for such effects. This represents a challenge to the petrophysicists to properly calculate the actual reservoir porosity. In this paper, the effects of the rare elements and other minerals with high thermal neutron absorption probability on the thermal neutron porosity are discussed, and a correction methodology is developed and tested. The methodology is based on integrating the tool design and the physics of the neutron transport to perform the correction. The details of the correction steps and the correction algorithm are included, tested and applied in two fields.

keywords Neutron · Thermalization · Absorption · Slowing down length · Migration Length

Introduction

The thermal neutron porosity tool is a simple tool in design but rather difficult in interpretation (Asquith and Krygowski 2004; Bassiouni 1994; Ellis and Singer 2007; Serra 1988; Wu et. al 2013; Ellis et al 1987). The reason is the complex physics of the neutron transport and interactions with the formation constituents.

The tool design

The thermal neutron tool design consists of three main components, Fig. 1:

1. High energy neutron source (~4.5 Mega Electron Volts, MeV)
2. Near thermal neutron detector and
3. Far thermal neutron detector.

The formation porosity is obtained by correlating the ratio of the near and the far thermal neutron detectors' count rates with the formation porosity, Eq. 1.

$$\phi = f\left(\frac{N}{F}\right) \quad (1)$$

All service companies derived the ratio–porosity relationship for clean formations (with no thermal neutron absorbers). If a formation contains elements and/or minerals with high thermal neutron absorption probability, the correlation provides incorrect formation porosity, usually higher than the actual porosity.

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Fig. 1 Generic thermal porosity tool

Fig. 2 Slowing down length

The neutron transport parameters

Formation porosity using the thermal neutron tool is controlled by multiple neutron transport parameters. These parameters are the slowing down length, the diffusion length and the migration length.

The slowing down length defines the ability of the formation constituents of reducing the high energy of the neutrons (~ 4.5 MeV) to the thermal energy level (0.025 electron volt, eV). The straight-line connecting the neutron source and the thermalization point represents the slowing down length, L_s , Fig. 2.

Fig. 3 Diffusion length

Fig. 4 Migration length

Table 1 L_s coefficients

	Matrix		
	Limestone	Sandstone	Dolomite
C1	3.672	5.953	2.699
C2	-0.5245	-0.3972	-0.5948
C3	0.0379	0.0223	0.0545
C4	4.141	1.94	5.475

Table 2 L_d coefficients

	Matrix		
	Limestone	Sandstone	Dolomite
C1	0.1933	0.1874	0.1962
C2	-0.995	-1.003	-1.003
C3	0.1366	0.1107	0.1627
C4	-0.0011	0.0006	0.0005

After the neutron energy reaches its thermal level, the diffusion process becomes dominant and is evaluated by the diffusion length. The thermal neutron diffuses until it is absorbed by the formation elements. The straight-line connecting the start of the thermal energy and the absorption point is the diffusion length, Fig. 3. It is important to mention that the effect of the high thermal neutron absorbers occurs only at this thermal energy level and in turn affects the diffusion length.

The combined slowing down length and the diffusion length is the migration length, L_m . The migration length is

the straight-line connecting the source and the absorption point, Fig. 4, and is defined by Eq. 2.

$$L_m = \sqrt{L_s^2 + L_d^2} \quad (2)$$

Modeling the neutron transport parameters

The neutron transport parameters are modeled by many authors (Ellis et. al 1987) and (Wu et. al 2013). Ellis developed the relationships of the slowing down length, Eq. 3, and the diffusion length, Eq. 4, using the formation porosity and the neutrons absorption probability.

$$L_s = c_1(\phi + c_3)^{c_2} + c_4$$

$$L_d^2 = \frac{c_1(\phi + c_3)^{c_2} + c_4}{\Sigma_a}$$

Table 3 The $L_m - \Phi$ coefficients

	Matrix		
	Limestone	Sandstone	Dolomite
C1	0.4585	0.589	0.5538
C2	−4.937	−4.946	−4.912
C3	−0.05132	−0.05313	−0.0713

Table 4 The neutron parameters-clean formation

Por	Slowing down length			Diffusion length			Migration length		
	Lime	Sand	Dolo	Lime	Sand	Dolo	Lime	Sand	Dolo
0.15	12.97	13.91	12.41	8.49	10.02	9.27	15.73	17.80	15.56
0.16	12.73	13.64	12.22	8.28	9.71	9.02	15.34	17.29	15.18
0.17	12.51	13.40	12.04	8.08	9.43	8.78	14.97	16.81	14.82
0.18	12.31	13.17	11.87	7.89	9.16	8.56	14.64	16.37	14.50
0.19	12.12	12.96	11.71	7.71	8.90	8.34	14.32	15.97	14.19
0.20	11.94	12.76	11.57	7.54	8.66	8.14	14.03	15.59	13.91
0.21	11.77	12.57	11.43	7.37	8.43	7.94	13.75	15.24	13.64
0.22	11.62	12.39	11.30	7.21	8.22	7.76	13.50	14.92	13.40
0.23	11.47	12.23	11.18	7.06	8.01	7.58	13.26	14.61	13.17
0.24	11.33	12.07	11.06	6.92	7.82	7.41	13.03	14.32	12.95
0.25	11.20	11.92	10.95	6.78	7.63	7.25	12.82	14.05	12.75

Table 5 The neutron parameters- for formation with two additional capture units

Por	Slowing down length			Diffusion length			Migration length		
	Lime	Sand	Dolo	Lime	Sand	Dolo	Lime	Sand	Dolo
0.15	12.97	13.91	12.41	7.81	9.01	8.36	15.34	17.13	15.02
0.16	12.73	13.64	12.22	7.63	8.77	8.16	14.97	16.67	14.68
0.17	12.51	13.40	12.04	7.46	8.53	7.96	14.64	16.25	14.37
0.18	12.31	13.17	11.87	7.30	8.32	7.78	14.32	15.86	14.08
0.19	12.12	12.96	11.71	7.14	8.11	7.61	14.03	15.50	13.81
0.20	11.94	12.76	11.57	7.00	7.91	7.44	13.76	15.16	13.55
0.21	11.77	12.57	11.43	6.86	7.72	7.29	13.50	14.85	13.32
0.22	11.62	12.39	11.30	6.72	7.55	7.13	13.27	14.55	13.10
0.23	11.47	12.23	11.18	6.60	7.38	6.99	13.04	14.27	12.89
0.24	11.33	12.07	11.06	6.47	7.22	6.85	12.83	14.01	12.69
0.25	11.20	11.92	10.95	6.35	7.06	6.72	12.63	13.77	12.51

Tables 1 and 2 contain the coefficients of slowing down length and the diffusion equations for the different formation lithologies. The migration length can then be calculated using Eq. 2.

Ellis corrected the migration length for the effect of the formation water salinity since it reduces the hydrogen index of the formation water. The correction took the form,

$$L_m^* = \sqrt{L_s^2 + f(L_s)L_d^2} \quad (5)$$

where $f(L_s)$ is defined as

$$f(L_s) = \sqrt{L_s} - 2.5 \quad (6)$$

Finally, the formation porosity is correlated with the migration length L_m . The correlation takes the form,

Fig. 5 The correction algorithm

$$\phi_0 = C_1(\log(L_m^*))^{C_2} + c_3 \quad (7)$$

Table 3 contains the coefficients for the different clean formations (without high neutron absorbers).

Effects of thermal neutrons absorbers on the transport parameters

To show the effect of the high thermal neutron absorbers on the measured neutron porosity, the slowing down length, the diffusion length and the migration length are calculated for the three clean lithologies: limestone, sandstone and dolomite using Eqs. 2–6 as shown in Table 4 for porosity ranging between 15 and 25 PU. The absorption cross section, Σ_a , in Eq. (4) is calculated as,

$$\Sigma_a = \phi\Sigma_w + (1 - \phi)\Sigma_m \quad (8)$$

where Σ_w is 22.2 capture units for fresh water, and Σ_m is 7.03, 4.55 and 4.3 capture units for clean limestone, sandstone and dolomite, respectively.

The same calculations are performed for a formation having additional thermal neutron absorbers to show their effect. Equation 8 is modified to account for such effect.

$$\Sigma_a = \phi\Sigma_w + (1 - \phi)\Sigma_m + \Sigma_x \quad (9)$$

where Σ_x is the additional absorption cross section caused by the neutron absorbers. Table 5 shows the neutron parameters for a formation having two additional capture units (Σ_x) caused by the neutron absorbers. Comparison between the migration lengths of the clean formation and the formation with the additional neutron absorbers clearly shows the absorption effects.

For example, the 15 PU limestone in Table 5 is showing a migration length of 15.34 cm. This value shows 16 PU using the clean limestone in Table 4. This comparison illustrates that only 2 additional capture units in a 15 PU limestone formation increase the neutron porosity by one porosity unit causing a 6% error in the neutron porosity.

The correction methodology

A methodology to correct for the effect of the neutron absorbers on the thermal neutron porosity is developed. The methodology requires measuring the formation absorption cross section and the neutron porosity tool. This can be obtained either by running the geochemical logging tool (Schweitzer et. al 1987) or by the sigma tool (Allan et al 1986).

The correction steps are:

1. Calculate the *Apparent* migration length, L_{m1} using the thermal neutron porosity, Φ_{tool} , in Eq. 10. The calculated L_{m1} using this equation assumes that the formation is clean (has no additional neutron absorbers)

$$L_{m1} = 10 \left(\frac{\phi_{tool} - c_3}{c_1} \right)^{\frac{1}{c_2}} \quad (10)$$

2. Use Eqs. 3–6 to calculate the migration length, L_{m2} , by iterating over porosity, using the measured formation sigma absorption, Σ_a . The porosity is increased by $\Delta\Phi$ until the migration length L_{m2} equals to the calculated apparent migration length L_{m1} . Figure 5 is the flow chart of the algorithm.

Fields applications

The correction methodology is applied in two fields; the first is the Unayzah field in Saudi Arabia using the published mineralogy and elemental core data (Khalifa et al. 2018), while the second is a well in North Africa where the sigma absorption log is acquired.

Application I: Unayzah field

Khalifa et al. (2018) reported the existence of gadolinium and other rare elements in the Unayzah sandstone

Table 6 Gadolinium concentration in Unayzah field

Well	Number of samples	Mean Gadolinium, ppm
1	37	1.57
2	101	1.74
3	70	1.55
4	38	1.33
5	10	3.11
6	28	3.03
7	54	1.29
8	51	2.08

Table 7 Gadolinium Σ_a for different concentrations

Mean gadolinium, ppm	Σ_a , CU
0.5	0.2516
1	0.5032
1.5	0.7548
2	1.0065
2.5	1.2581
3	1.5097

formation in Saudi Arabia. The mineralogy and elemental core analysis for eight wells showed variable concentrations of gadolinium, Table 6. The average concentration varied between a minimum of 1.29 ppm and a maximum of 3.03 ppm. The absorption cross section, Σ_a , is calculated as,

$$\Sigma = W_i \frac{\rho_i A_v}{A_i} \sigma_i \quad (11)$$

where W_i = weight of the element; ρ_i = density of the element; σ_i = microscopic absorption cross section; A_i = atomic mass number of the element; A_v = Avogadro's number.

The absorption cross sections for all elements are included shown "Appendix." The sigma absorption of gadolinium for variable concentrations in the Unayzah field is calculated and shown, Table 7.

The corrected porosities versus the measured porosities for different concentrations of gadolinium: 1, 2 and 3 ppm are shown in Table 8. The results clearly show that very low concentration of this rare element, 3 ppm, for example, will increase the thermal neutron porosity by 8%.

Table 8 Thermal neutron porosity correction for Unayzah sandstone

Tool porosity	Sigma gadolinium		Sigma gadolinium		Sigma gadolinium	
	1.5		1		0.5	
	Corrected porosity	Diff	Corrected porosity	Diff	Corrected porosity	Diff
10	9.2	−0.8	9.5	−0.5	9.7	−0.3
20	18.8	−1.2	19	−1	13.5	−0.5
30	28.3	−1.7	29	−1	29.3	−0.7

Fig. 6 North Africa well

Application II: North Africa well

The second application is in North Africa, Fig. 6.

The reservoir is clean sandstone as indicated by the GR and the photoelectric value of 2, in Track-1. The sigma tool was run, Track-2, while Track-3 shows the overlay of the neutron and the density where no sand separation is observed due to the existence of the neutron absorbers. The measured sigma absorption in this reservoir varies between 16 and 20 capture units. Based on the core analysis, the formation contains the siderite mineral which has an absorption cross section of 52 capture units. The volume of siderite in this formation ranges between 10 and 15% by volume. The siderite resulted in an increase in the absorption cross section and a false increase in the thermal neutron porosity which masked the sand separation in the neutron—density overlay. The correction algorithm is used to correct the thermal neutron porosity. The corrected porosity is then overlayed with the density tool, track-4. The corrected porosity and the density overlay restored the sandstone separation.

Conclusions

The thermal neutron porosity tool is an old technology that is routinely acquired and used in formation evaluation. The tool is simple in design but rather difficult in interpretation due to its complex physics. The neutron transport in formation rocks is controlled by many factors including the probability that the formation constituents absorb the thermal neutrons. Some rare elements and formation minerals have very high probability of absorbing thermal neutrons resulting in a false increase in the thermal neutron porosity measurements. Example of these rare elements is the gadolinium. The effect of these rare elements is recently reported in the Middle East. Also, some minerals, especially the iron-rich ones, such as siderite, glauconite and chlorite have the same effect. It is essential to correct the thermal neutron porosity before using in the evaluation of the reservoir parameters. None of the existing commercial software(s) have modules to correct the neutron tools for such effects.

In this paper, a correction methodology and an algorithm are developed based on combining the neutron transport physics and the thermal neutron tool design. The model is applied in two fields for two cases: rare elements and iron-rich minerals. The first application quantified the effect of few parts per million on the thermal porosity, while the second restored the sand separation between the neutron and the density logs which disappeared because of the increase in the thermal neutron porosity due to the existence of the siderite mineral.

Appendix

Element	Z	A	Σ microscopic
Sc	21	45	27.2
Ti	22	48	7.84
V	23	51	4.9
Cr	24	52	15.8
Co	27	59	37.2
Ni	28	58	4.8
Cu	29	63	4.5
Zn	30	64	1.11
Ga	31	69	2.18
As	33	75	4.5
Se	34	80	0.61
Br	35	79	11.07
Rb	37	85	0.48
Sr	38	88	0.058
Y	39	89	1.28
Zr	40	90	0.02
Nb	41	93	1.15
Mo	42	98	0.127
Ag	47	109	91
Cd	48	113	20,600
Sn	50	120	0.14
Sb	51	121	5.75
Cs	55	133	29
Ba	56	138	0.27
La	57	139	8.89
Ce	58	140	0.57
Pr	59	141	11.5
Nd	60	142	18.7
Sm	62	147	5822
Eu	63	153	9100
Gd	64	157	49,500
Tb	65	159	23.3
Dy	66	164	2840
Ho	67	165	64.7
Er	68	167	659
Tm	69	169	100
Yb	70	174	69.4
Lu	71	175	74.9
Hf	72	180	13.04
Ta	73	182	20.6
W	74	184	37.9
Au	79	197	98.65
Hg	80	200	372.3
Pb	82	206	0.138
Bi	83	209	0.0338
Th	90	232	7.33
U	92	238	7.64

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Declarations

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