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THE QUESTION OF THE FAST NEUTRON ABSORPTION IN MOISTURE MEASUREMENTS BY THE NEUTRON METHOD

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THE QUESTION OF THE FAST NEUTRON ABSORPTION IN MOISTURE MEASUREMENTS BY THE NEUTRON METHOD

ZAGADNIENIE ABSORPCJI NEUTRONÓW PRĘDKICH W POMIARACH WILGOTNOŚCI METODĄ NEUTRONOWĄ

ВОПРОС ЗАХВАТА БЫСТРЫХ НЕЙТРОНОВ В ИЗМЕРЕНИЯХ ВЛАЖНОСТИ НЕЙТРОННЫМ МЕТОДОМ

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Summary

The question of the fast neutron absorption has been discussed from the point of view of the calibration of neutron moisture gauges. An approximated m thod has been proposed for calculating the probability that the neutron of a given energy would escape the absorption during slowing down in the medium. The method has been employed for the water-saturated sandstone, limestone, dolomite and some types of soils. It was shown that the probabi..ity of non-capture in slowing down depends on the moisture content of the soil and changes in the range over a dozen percent. (auth)

Streszczenie

W pracy przedyskutowano problem absorpcji neutronów prędkich z punktu widzenia cechowania sond neutronowych do pomiaru wilgotności. Zaproponowano przybliżoną metodę obliczania prawdopodobieństwa, że neutron o zadanej energii uniknie absorpcji podczas spowalniania w ośrodku. Wykonano tą metodą obliczenia dla nasyconego wodą piaskowca, wapienia i dolomitu, a także dla pewnych typów gruntów. Stwierdzono, że prawdopodobieństwo uniknięcia absorpcji w trakcie spowalniania zależy od zawartości wody w gruncie i zmienia się w granicach kilkunastu procent.

Резюме

В работе обсуждается вопрос захвата быс ых нейтронов из точки зрения эталонирования ных влагомеров. Представлено приближённый метод расч а вероятности того, что нейтрон с данной энергией избежит захвата во время замедления в среде. Этим методом выполнено вычисления для насыщенного водой песчаника, известняка, доломита и некоторых типов грунтов. Получено, что вероятность избежать захвата во время замедления зависит от влажности грунта и изменяется в диапазоне более десяти процентов.

INTRODUCTION

In the vast literature concerning the neutron method for measuring the water content in soils little attention is drawn to the problem of the absorption of fast neutrons. It is usually assumed that the neutron absorption during the slowing down process influences in a negligible way the moisture measurements. However some theoretical predictions combined with existing experimental data of the fast neutron absorption cross sections suggest that the above conviction should be revised.

The thermal neutron flux, $\Phi_{th}(r)$ which is the most interesting quantity from the point of view of the moisture content determination, and the output Q of the point fast neutron source, are related by the equation /cf BECKURTS and WIRTZ [1] / :

$$K_Q \cdot \int_0^\infty \Sigma_{a,th} \cdot \Phi_{th}(r) \cdot 4\pi r^2 \, dr = p \cdot Q \qquad (1)$$

where p is the probability of non-capture in slowing down process, K_Q is the correction factor for the neutron absorption in the source and $\Sigma_{a,th}$ is the thermal neutron absorption cross section of the medium.

Thus, thermal neutron flux in the medium depends explicitly on the non-capture probability during slowing down. The question arises to what extent parameter p can change with chemical composition of the soil and its moisture content. Because of lack of direct experimental data this question has to be treated theoretically.

THE MULTIGROUP APPROACH FOR CALCULATING THE PROBABILITY OF NON-CAPTURE IN SLOWING DOWN

The exact method for calculating the probability that a neutron of a given energy would escape the absorption during its slowing down in the investigated medium would be the Monte Carlo method. In this work the multigroup method has been adopted which though being a certain approximation is much less time consuming than Monte Carlo method. The multigroup approach requires the knowledge of the appropriate sets of averaged neutron constants, which, in this case, have been taken from the work by ABAGYAN et al [2]. The Abagyan's tables contain the neutron constants for the energy range from 10,5 MeV to 0,215 eV. This range has been split into 25 intervals, i.e. energy groups /see Table I/. The tables contain the averaged values of microscopic neutron cross sections for different elements. Among the others, there are listed the following cross sections :

$\sigma_{el(e),i}$ - the elastic slowing down cross section out of i-th group,

$\sigma_{in,i}$ - the inelastic scattering cross section,

$\sigma_{c,i}$ - the capture cross section,

$\sigma_{in(i,k)}$ - the cross section of inelastic transfers out of i-th group into k-th group,

$\sigma_{e(i,k)}$ - the cross section of elastic transfers out of i-th group into k-th group.

These cross sections have been used for computing the cross sections for removing the neutron from the i-th group $\sigma_{r,i}$, and for slowing down the neutron out of the i-th group to the k-th group $\sigma_{sl(i,k)}$, according to the formulas :

$$\sigma_{r,i} = \sigma_{sl(e),i} + \sigma_{in,i} - \sigma_{in(i,i)} + \sigma_{c,i} \;, \qquad (2)$$

$$\sigma_{sl(i,k)} = \sigma_{s(i,k)} + \sigma_{in(i,k)} \;.$$

The probability p_i of non-capture of the neutron of the i-th group can be expressed in terms of the appropriate cross sections according to the recurrence formulas/cf KREFT [3] / :

$$p_i = \frac{1}{\Sigma_{r,i}} \cdot \sum_{k=i+1}^{k=26} \Sigma_{sl(i,k)} \cdot p_k \;, \qquad (3)$$

where
$p_{26} \overset{df}{=} 1$, $\Sigma_{r,i}$ is the macroscopic cross section for removing the neutron from the i-th group,
$\Sigma_{sl(i,k)}$ · is the macroscopic cross section for slowing down the neutron out of i-th group to the k-th group.

Making use of the equation (3) one can calculate the probabilities of non-capture in slowing down for the neutron energies corresponding to the upper limits of the energetic intervals showed in Table I.

For the polyenergetic neutron source the following averaging operation has to be applied :

$$p = \frac{\sum_{i=1}^{m} Q_i \cdot p_i}{\sum_{i=1}^{m} Q_i} \;, \qquad (4)$$

where Q_i are the partial neutron outputs corresponding to the i-th energy values, the total number of energy lines being equal to m .

The argumentation presented above establish the procedure for calculating the probabilities p for a neutron source of any energy spectrum. First the actual energy distribution has to be approximated by a sum of monoenergetic neutron sources, each of them having the output Q_i and the initial energy being one of the boundary energies given in Table I. Then the probabilities p_i are to be calculated and averaged according to the formula (4). In this work it has been decided to use the following set of the initial energy values : 10.5; 6.5; 4.0; 2.5; 1.4; 0.8; 0.4; 0.2 MeV.

EXAMPLES OF THE CALCULATIONS

The procedure has been used for calculating the probabilities of non-capture during slowing down in water-saturated sandstone, limestone and dolomite. The choice of the media have been stimulated by the fact that they constitute most widely met compounds of soils and rocks. The calculations have been performed for monoenergetic neutrons as well as for radioisotope sources Ra-Be, Pu-Be, Po-Be and spontaneous fission source ^{252}Cf /the actual energy spectra of these sources have been approximated with discrete spectra given in Table II/. The results of the calculations are shown in Fig.2 and in Tables III - VIII.

The calculations were carried out with the help of FORTRAN programs FK01 and FK03, the description of which can be found in the earlier paper of the author [3].

CORRECTION ALLOWING FOR THE FAST NEUTRON ABSORPTION

As it follows from the obtained results, the dependence of the parameter p on the moisture content is well conspicious in the cases of all the examined media and neutron sources. Thus, neglecting the fast neutron absorption will lead to errors in establishing the theoretical calibration curve. The increase of the probability of non-capture during slowing down influences the thermal neutron flux in the same way as an increase of the source output. Therefore, this probability, dependent on the moisture content should be introduced into the calculated calibration curves as the multiplicative factor. Namely

$$CR^{*}(m) = \frac{p(m)}{p_{st}} \cdot CR(m) \quad , \qquad (5)$$

where CR(m) is the theoretical curve obtained on the assumption that the fast neutron absorption can be neglected,

$CR^{*}(m)$ is the corrected calibration curve,

p(m) is the probability of non-capture in slowing down calculated for the given source and for the investigated type of soil,

p_{st} is the probability calculated for calibration standard.

In order to verify suggestion given above, results of a calibration procedure published by ØLGAARD [4] have been used. Due to the fact, that Ølgaard gives the chemical compositions of the media, as well as the type of the neutron source it was possible to calculate the function p(m). The calculations have been carried out for three types of Danish soils: Ødum, Borris, St.Jyndevad [4]. The results are shown in Fig. 2. Corrections were introduced to the Ølgaard's curves. An example for the soil of Ødum type is presented in Fig. 3, where one can see the original and corrected calibration curves together with experimental points.

CONCLUSIONS

The calculations performed for different media have shown out that the probability of non-capture of a neutron during its slowing down depends on the neutron energy as well as on the chemical composition of the medium, especially on its water content. This probability decreases with increasing initial energy of neutrons. Its dependence on the moisture content is sharper for higher initial energies of neutrons ; for example the effect of the fast neutron absorption is smaller for ^{252}Cf source than for (α,n) sources.

The effect of the fast neutron absorption on the moisture content measurements can reach few percent of the measured value.

ACKNOWLEDGMENT

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TABLE I. Division into the energy groups used in the ABAGYAN's tables [2]

i	E_i
1	6.5 - 10.5 MeV
2	4.0 - 6.5 MeV
3	2.5 - 4.0 MeV
4	1.4 - 2.5 MeV
5	0.8 - 1.4 MeV
6	0.4 - 0.8 MeV
7	0.2 - 0.4 MeV
8	0.1 - 0.2 MeV
9	46.5 - 100 keV
10	21.5 - 46.5 keV
11	10 - 21.5 keV
12	4.65 - 10 keV
13	2.15 - 4.65 keV
14	1 - 2.15 keV
15	465 - 1000 eV
16	215 - 465 eV
17	100 - 215 eV
18	46.5 - 100 eV
19	21.5 - 46.5 eV
20	10 - 21.5 eV
21	4.65 - 10 eV
22	2.15 - 4.65 eV
23	1 - 2.15 eV
24	0.465 - 1 eV
25	0.215 - 0.465 eV

TABLE II. Discrete approximation of the energy spectra for different neutron sources /partial outputs are given in relative units/

Source / E, in MeV	Ra-Be	Pu-Be	Po-Be	^{252}Cf
10.5	0.09	0.12	0.13	0.014
6.5	0.25	0.28	0.26	0.062
4.0	0.31	0.27	0.29	0.140
2.5	0.21	0.16	0.19	0.218
1.4	0.11	0.09	0.09	0.228
0.8	0.02	0.05	0.03	0.171
0.4	0.01	0.02	0.01	0.103
0.2	-	0.01	-	0.064

Discrete spectra have been obtained basing on the actual neutron source spectra : Ra-Be [5], Pu-Be [6], Po-Be [7], ^{252}Cf [8] .

TABLE III. Probabilities of non-capture during slowing down to 0.215 eV in water-saturated sandstone (ρ_{SiO_2} = 2.65 g/cm^3) calculated for different initial energies of neutrons

Vol % H_2O \ Energy in MeV	10.5	6.5	4.0	2.5	1.4	0.8	0.4	0.2
0.00	0.568	0.802	0.886	0.890	0.890	0.890	0.890	0.890
0.01	0.591	0.831	0.918	0.921	0.921	0.921	0.921	0.921
0.02	0.606	0.848	0.934	0.938	0.938	0.938	0.938	0.937
0.03	0.616	0.859	0.945	0.948	0.948	0.948	0.948	0.948
0.05	0.632	0.873	0.957	0.960	0.960	0.960	0.960	0.960
0.10	0.659	0.892	0.971	0.974	0.974	0.974	0.974	0.974
0.15	0.680	0.903	0.977	0.979	0.979	0.979	0.979	0.979
0.20	0.699	0.911	0.980	0.982	0.982	0.982	0.982	0.982
0.30	0.733	0.924	0.984	0.986	0.986	0.986	0.986	0.986
0.40	0.763	0.934	0.986	0.987	0.987	0.987	0.987	0.987
0.50	0.790	0.942	0.987	0.988	0.988	0.988	0.988	0.988
0.70	0.838	0.954	0.989	0.990	0.990	0.990	0.990	0.990
1.00	0.898	0.967	0.990	0.991	0.991	0.991	0.991	0.991

TABLE IV. Probabilities of non-capture during slowing down to 0.215 eV in water-saturated limestone (ρ_{CaCO_3} = 2.72 g/cm^3) calculated for different initial energies of neutrons

Vol % H_2O \ Energy in MeV	10.5	6.5	4.0	2.5	1.4	0.8	0.4	0.2
0.00	0.699	0.810	0.878	0.881	0.881	0.881	0.881	0.881
0.01	0.723	0.837	0.907	0.910	0.910	0.910	0.910	0.910
0.02	0.738	0.854	0.924	0.927	0.927	0.927	0.927	0.927
0.03	0.749	0.866	0.935	0.938	0.938	0.938	0.938	0.936
0.05	0.763	0.881	0.949	0.952	0.952	0.952	0.952	0.952
0.10	0.783	0.901	0.965	0.968	0.968	0.968	0.968	0.968
0.15	0.796	0.912	0.973	0.975	0.975	0.975	0.975	0.975
0.20	0.807	0.920	0.977	0.979	0.979	0.979	0.979	0.979
0.30	0.823	0.931	0.982	0.984	0.984	0.984	0.984	0.984
0.40	0.837	0.940	0.984	0.986	0.986	0.986	0.986	0.986
0.50	0.850	0.946	0.986	0.988	0.988	0.988	0.988	0.988
0.70	0.871	0.957	0.988	0.989	0.989	0.989	0.989	0.989
1.00	0.898	0.967	0.990	0.991	0.991	0.991	0.991	0.991

TABLE V. Probabilities of non-capture during slowing down to 0.215 eV in water-saturated dolomite ($\rho_{CaMg(CO_3)_2} = 2.85\ g/cm^3$) calculated for different initial energies of neutrons

Vol % H_2O \ Energy in MeV	10.5	6.5	4.0	2.5	1.4	0.8	0.4	0.2
0.00	0.723	0.855	0.927	0.930	0.930	0.930	0.930	0.930
0.01	0.736	0.869	0.941	0.945	0.945	0.945	0.945	0.945
0.02	0.745	0.878	0.950	0.954	0.954	0.954	0.954	0.954
0.03	0.751	0.885	0.957	0.960	0.960	0.960	0.960	0.960
0.05	0.761	0.894	0.965	0.968	0.968	0.968	0.968	0.968
0.10	0.776	0.908	0.974	0.977	0.977	0.977	0.977	0.977
0.15	0.788	0.916	0.979	0.981	0.981	0.981	0.981	0.981
0.20	0.797	0.923	0.981	0.984	0.984	0.984	0.984	0.984
0.30	0.814	0.932	0.984	0.986	0.986	0.986	0.986	0.986
0.40	0.829	0.940	0.986	0.988	0.988	0.988	0.988	0.988
0.50	0.842	0.946	0.987	0.989	0.989	0.989	0.989	0.989
0.70	0.856	0.956	.989	0.990	0.990	0.990	0.990	0.990
1.00	0.898	0.967	[illegible]	0.991	0.991	0.991	0.991	0.991

TABLE VI. Probabilities of non-capture during slowing down to 0.215 eV in water-saturated sandstone calculated for different neutron sources

Source / Vol % H_2O	Ra-Be	Pu-Be	Po-Be	^{252}Cf
0.00	0.838	0.826	0.824	0.879
0.01	0.868	0.855	0.854	0.910
0.02	0.884	0.872	0.870	0.927
0.03	0.895	0.882	0.881	0.937
0.05	0.908	0.896	0.894	0.950
0.10	0.924	0.912	0.911	0.964
0.[illegible]	0.932	0.921	0.920	0.970
0.20	0.938	0.928	0.926	0.974
0.30	0.947	0.937	0.936	0.978
0.40	0.953	0.945	0.944	0.981
0.50	0.958	0.951	0.950	0.983
0.70	0.967	0.961	0.960	0.985
1.00	0.976	0.973	0.972	0.988

TABLE VII. Probabilities of non-capture during slowing down to 0.215 eV in water-saturated limestone calculated for different neutron sources

Vol % H_2O \ Source	Ra-Be	Pu-Be	Po-Be	^{252}Cf
0.00	0.846	0.838	0.838	0.874
0.01	0.874	0.866	0.866	0.903
0.02	0.891	0.883	0.883	0.920
0.03	0.902	0.894	0.894	0.931
0.05	0.916	0.909	0.908	0.945
0.10	0.934	0.926	0.926	0.961
0.15	0.943	0.936	0.935	0.969
0.20	0.948	0.941	0.941	0.973
0.30	0.956	0.949	0.949	0.978
0.40	0.961	0.955	0.954	0.981
0.50	0.964	0.959	0.959	0.983
0.70	0.970	0.966	0.965	0.985
1.00	0.976	0.973	0.972	0.988

TABLE VI. I. Probabilities of non-capture during slowing down to 0.215 eV in water-saturated dolomite calculated for different neutron sources

Source / Vol % H_2O	Ra-Be	Pu-Be	Po-Be	^{252}Cf
0.00	0.892	0.883	0.883	0.922
0.01	0.906	0.898	0.897	0.937
0.02	0.915	0.907	0.906	0.946
0.03	0.921	0.913	0.912	0.952
0.05	0.930	0.921	0.921	0.960
0.10	0.941	0.933	0.932	0.969
0.15	0.947	0.939	0.938	0.974
0.20	0.951	0.944	0.943	0.977
0.30	0.957	0.950	0.949	0.980
0.40	0.951	0.955	0.954	0.982
0.50	0.964	0.959	0.958	0.984
0.70	0.970	0.965	0.965	0.986
1.00	0.976	0.973	0.972	0.988

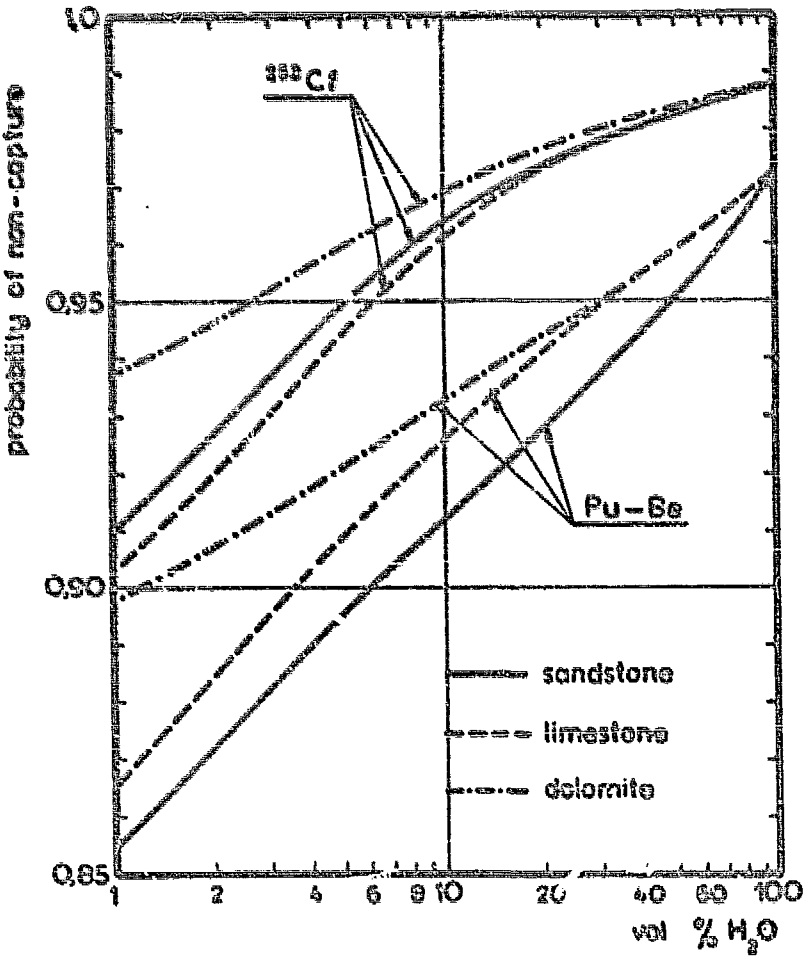
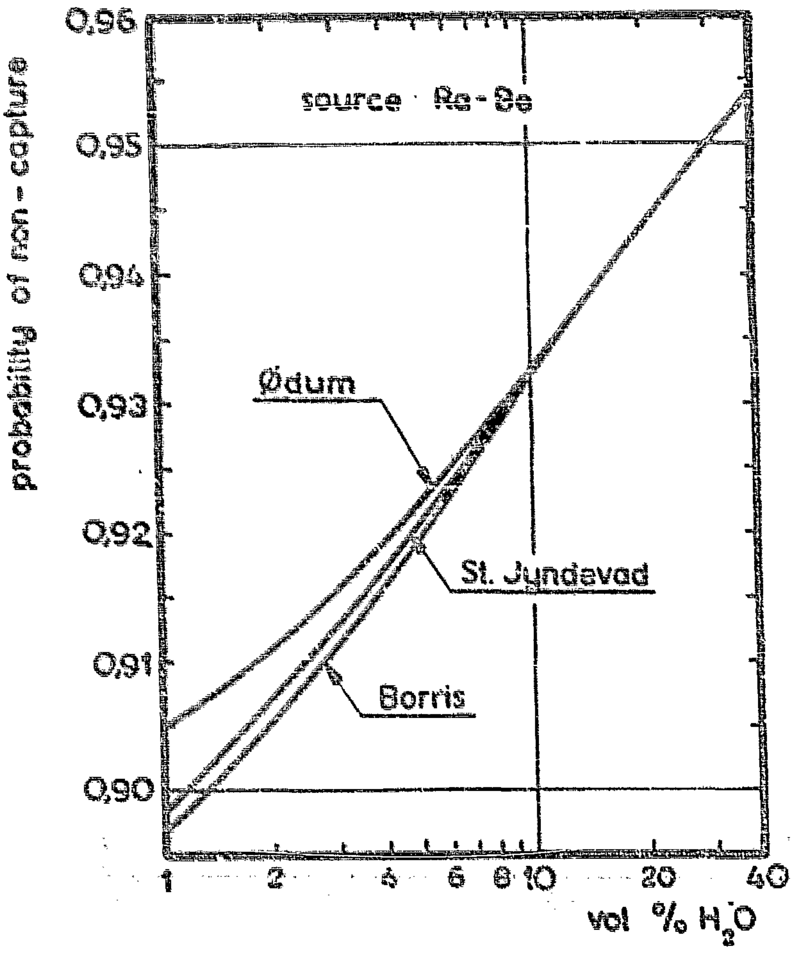


Fig.1. Probabilities of non-capture during slowing down to 0,215 eV in fully water-saturated sandstone, limestone and dolomite, calculated for the radioisotope neutron source Pu-Be and the fission neutron source ^{252}Cf.



ig.2. Probabilities of non-capture during slowing down to 0,215 eV calculated for three types of Danish soils and the Ra-Be source /all the curves have been calculated for dry soil density of 1,4 g/cm^3, i.e. for the same conditions as those assumed in the Ølgaard's paper [4] /.

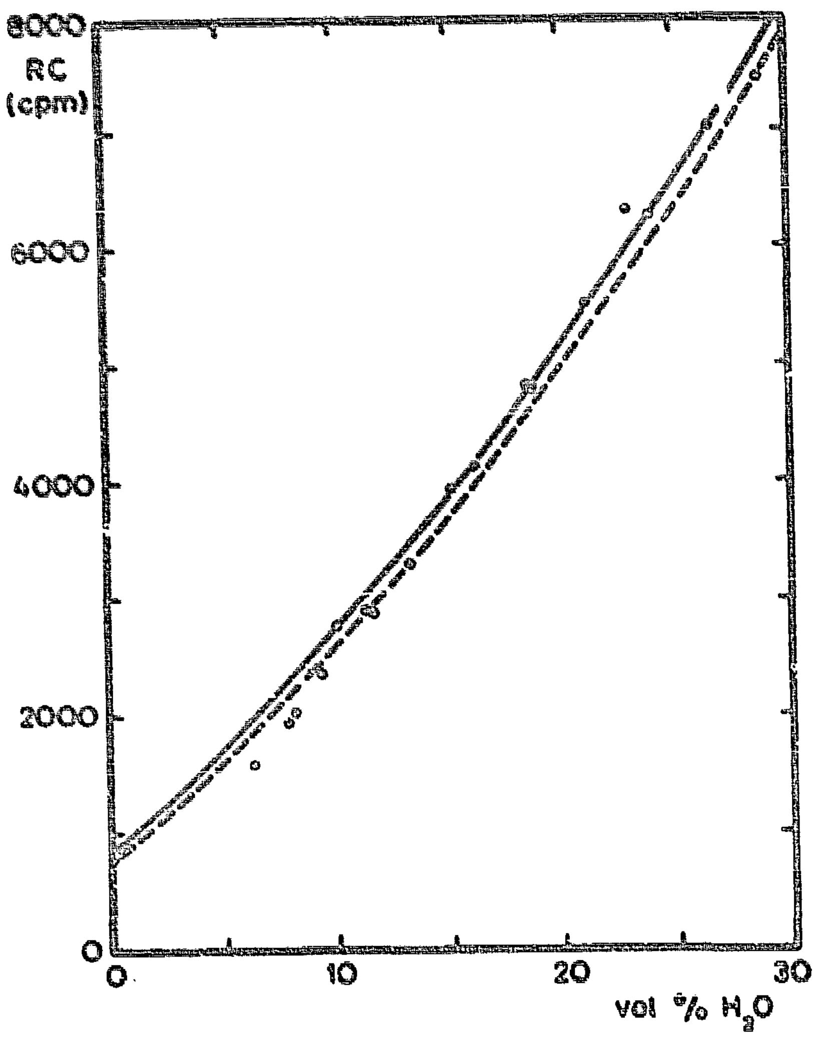


Fig.3. The effect of the fast neutron absorption on the calibration curve of the neutron gauge. Solid line is the original Ølgaard's curve for the soil of Ødum type and dashed line is the corrected calibration curve.