Neutrons as a multifunctional tool for geophysicists

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Our experience and achievement in nuclear geophysics
Professor Jan A. Czubek – nuclear geophysicist
Close cooperation: IFJ & AGH

NUCLEAR GEOPHYSICS

Theoretical research
- Semi-empirical calibration method for neutron tools

Field and laboratory measurements
- Sigma-a laboratory measurement method

Monte Carlo simulations
- FLUKA, MCNP
Speach outline

Borehole tools, Measurements, Comprehensive interpretation

Spectrometric Neutron-Gamma Logging Tool

Neutron-Neutron Logging Tool

Neutron Lifetime Logging Tool \( \Sigma_a \)

Complex Nuclear Tool CxNT
Borehole geophysics

Well logs

- Electric
- Acoustic
- Nuclear

(...)

+ Laboratory analysis of the core

Measured values

- Resistivity, LLD, LLS
- Transit interval time, DT
- Bulk density, RHOB
- Neutron porosity, NPHI
- Natural radioactivity, GR

(...)

Laboratory analysis of the core
### Comprehensive interpretation of well logs

#### Input data:
- Measurements (logs) in the borehole along the depth

#### Output results:
- Lithology
- Porosity
- Saturation of fluids of the rock
Comprehensive interpretation of well logs

For example: natural gamma measurement

\[ \gamma = \phi S_w \gamma_w + V_{cl} \gamma_{cl} + V_{sand} \gamma_{sand} + V_{lim} \gamma_{lim} + \sum_{k} V_{min k} \gamma_{min k} \]
Spectrometric Neutron-Gamma Logging Tool

- Measurement method
- Tool calibration
  - Calibration Facility
  - Monte Carlo simulations
    *(library problems)*
\[ \frac{A}{Z} X + n \rightarrow \frac{A+1}{Z} X^* \rightarrow \frac{A+1}{Z} X + \gamma \]

\( \gamma \) from radiative capture

Counts rate [pulse/600 s]

Number of channel

Sandstone Radków
Limestone Józefów
Sandstone Mucharz
Calibration of the Neutron-Gamma Tool

- Measurement in calibration blocks of known concentration of H, Si, Ca, Fe
- Multiple linear regression

<table>
<thead>
<tr>
<th>Element</th>
<th>$E_\gamma$ [MeV]</th>
<th>Window $\Delta E_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2.22</td>
<td>2.001 – 2.521</td>
</tr>
<tr>
<td>Si</td>
<td>3.54, 4.93</td>
<td>2.625 – 5.228</td>
</tr>
<tr>
<td>Ca</td>
<td>6.42</td>
<td>5.332 – 6.789</td>
</tr>
<tr>
<td>Fe</td>
<td>7.631, 7.645</td>
<td>6.893 – 8.975</td>
</tr>
</tbody>
</table>

$$C_{\text{chem}}^\text{el} = b_0^\text{el} + \sum_{i=1}^{4} b_i^\text{el}_i I_{\text{pom}}^{\text{el}_i} \quad \text{el: H, Si, Ca, Fe}$$

**concentration**

**gamma counts**
General view of Calibration Facility site during calibration measurements. The wood board covers two big pools where all calibration blocks are stored. The pool contains 18 natural rocks standards for basic neutron tool calibration (4 limestones, 4 sandstones and 1 dolomite - each of them for two hole diameters).

Proprietor:
Geofizyka Kraków Company & AGH University
Experimental Tool Calibration:
Basic neutron porosity/lithology calibration,
- Natural gamma calibration (API, K, U, Th),
- Vertical response tool analysis.

Artificial rock models for a determination of the Vertical Response Function for nuclear tools. The models are constructed of the specially prepared ceramic bricks and consist of the set of thick and thin layers. The dimension of the single brick is 30 x 30 x 7.5 cm.

Three porosities: 16, 25 and 60% are available for these models. The models are located inside the 3 m deep concrete pool filled always by water. These models were constructed by the AGH University.
Modeling of the spectrometric neutron-gamma well logging probe, SO-5-90-SN
Calibration of the Neutron-Gamma Tool

Experimental calibration points

Numerical calibration points
Problems with the ENDF libraries

Cl(n,γ)Cl - gamma ray lines

\( I_\gamma \) (per 100 captures)

\( E_\gamma \) (MeV)
Problems with the ENDF libraries

Al(n,γ)Al gamma-ray lines

- ACTIA

1.779 MeV (delayed)
Neutron-Neutron Logging Tool

- Neutron field in rock medium

- Calibration of the n – n tool
  - Semi-empirical method
  - Monte-Carlo simulation

- Thermal neutron absorption cross section
  - Laboratory measurement
  - Borehole neutron generator
  - NNTE - tool
Neutron-Neutron Tool

- Neutron source e.g. AmBe
- Neutron detectors
- Isolines of the neutron field
Homogenous infinite medium:

\[ \phi_{th}(r) = \frac{Q}{4\pi \Sigma_a} \frac{P}{L_s^2 - L_d^2} \frac{e^{-r/L_s} - e^{-r/L_d}}{r} \]

\[ I_{th} = f(L_m, \Sigma_a, P) \]

Similarly:

Borehole geometry:

\[ I_{th} = f(L_{map}, \Sigma_{ap}, P_{ap}) = f(GNP) \]
Calibration of the Neutron-Neutron Tool

GNP:
- slowing down length
- diffusion length
- absorption cross section
(i.e.: integral neutron parameters)

Neutron measurement

Geological parameter

A, B, C - Borehole diameter
Calibration of the Neutron-Neutron Tool

Procedures

- Real measurements
  Calibration Facility

- Simulation measurements
  Monte Carlo

Analytical solutions of the neutron transport phenomena
in a borehole geometry

necessarily

not necessarily
The important parameter of the rock medium indispensable for the geological interpretation of the neutron – neutron tool:

Thermal neutron absorption cross section of the rock matrix

\[ \Sigma_a \]

- **Laboratory measurement** on core samples
- **in situ:** Neutron Lifetime Log
- **in situ:** Improved neutron-neutron tool NNTE
Calibration of the Neutron-Neutron Tool

$\Sigma_a$ Laboratory measurement …

Rock sample
Moderator
Cadmium surrounding
Calibration of the Neutron-Neutron Tool

... using a pulsed neutron generator

(Czubek’s method)
Neutron lifetine logging: borehole pulsed neutron generator

source: http://www.spwla.org/library_info/glossary/
Neutron-neutron thermal-epithermal well logging tool NNTE

Prototype: AGH University and Geofizyka Kraków Company
Idea of the Complex Nuclear Tool CxNT

- During last three years we made field measurements using the NNTE, SNG and SNA methods, working as the separate experimental tools.

- These works confirmed that expected valuable geological information can be retrieved from this kind of measurement.

- It became clear that the new complex tool must be made because of the optimisation of the time service.

- Thin – bedded, shaly – sand gas formation in Carpathian Foredeep, Poland was place of experiments.
Cable (7 wires, 5000 m)

Digital data transmission block (at least 25 channels)

Spectral Gamma-Ray Log SGR (BGO, 0.2 – 2.8 MeV)

3He Far detectors (thermal/epithermal)

3He Near detectors (thermal/epithermal)

AmBe neutron source (6 – 18 Ci)

Spectral Neutron-Gamma SNG (BGO, 0.4 – 8 MeV)

Neutron Activation SNA (BGO, 0.2 – 2.8 MeV)

K, U, Th

Σ$_a$, porosity

Σ$_a$, porosity

Si, Ca, Fe

Cl, S

Al

NNTE
Comprehensive interpretation of well logs

- POROSITY (WATER, HYDROCARBONS)
- QUARTZ
- LIMESTONE
- CLAY
Each log is described by the equation which joint porosity, saturation and various mineralogical components with the tool response:

\[ ML_i = \sum_{j=1}^{n} (a_{ij} V_j) \quad i = 1, \ldots, m \]

Measured signal of the \( i \)-th tool

Volume fraction of the \( j \)-th component

Solution of the set of equations \( ML_i \):

\[ V_j : \begin{align*}
\Phi & \quad \text{porosity} \\
S & \quad \text{saturation (water, hydrocarbons ...)}
\end{align*} \]

\[ V_m \quad \text{mineral components (rock marix, clay ...)} \]