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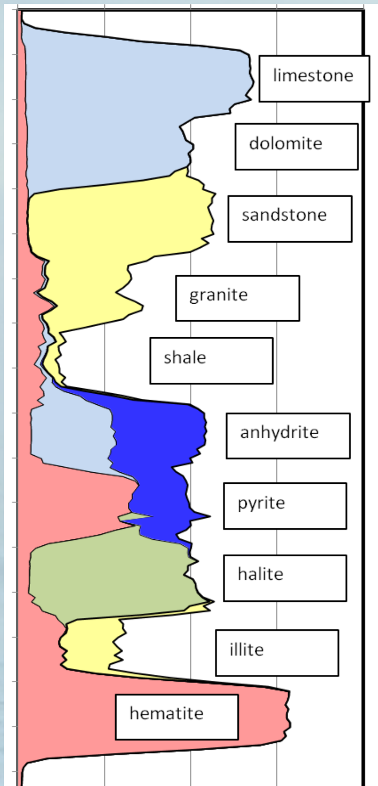
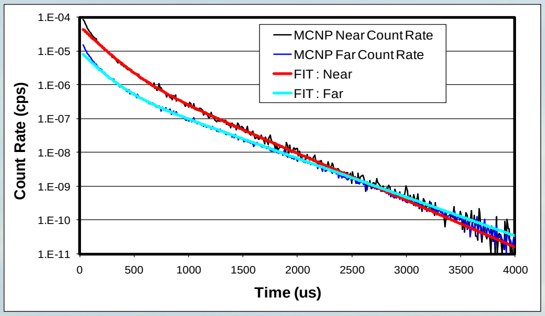
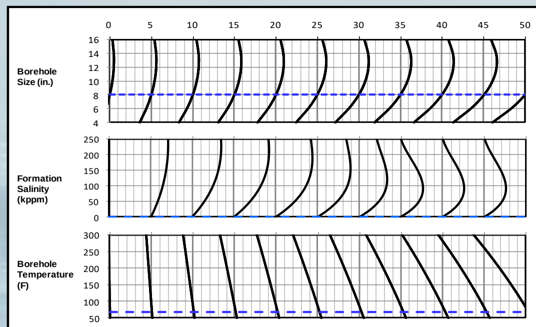
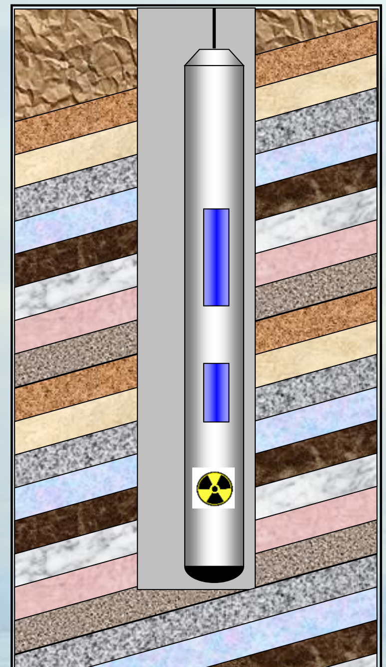
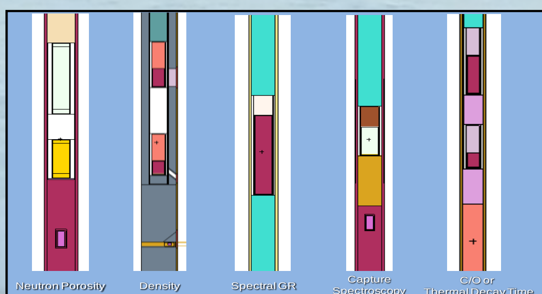
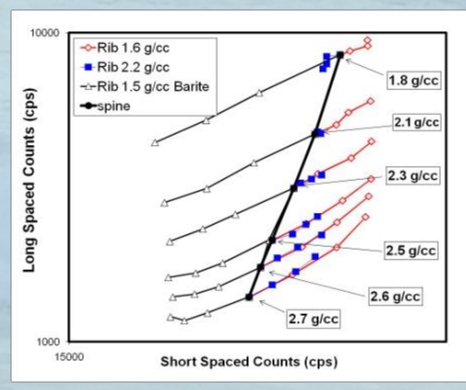


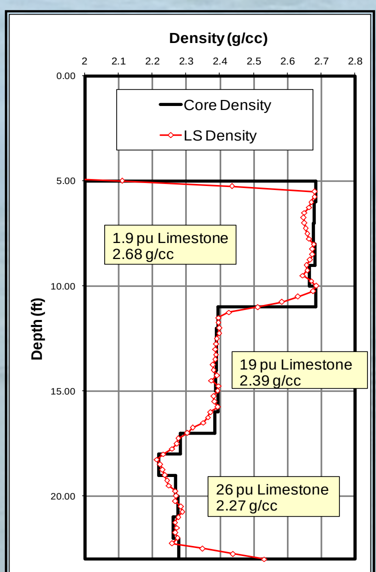


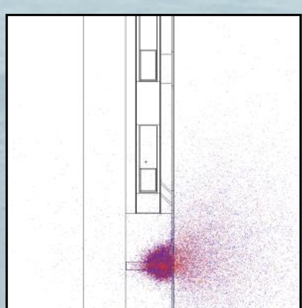


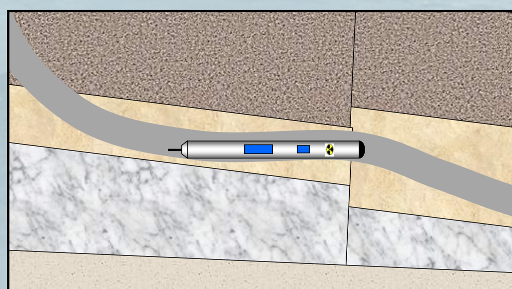












Technology

- High-end computer simulation of nuclear logging tools
- Generation of simulated nuclear logs
- Generic Monte Carlo models of most logging tools
- Customized Monte Carlo codes

Applications

- Environmental corrections for logging tools
- Optimizing tool design
- Neutron porosity response
- Density spine and ribs analysis
- Characterization of logging tools in unique environments
- Cased hole interpretation

Logging Tool Models

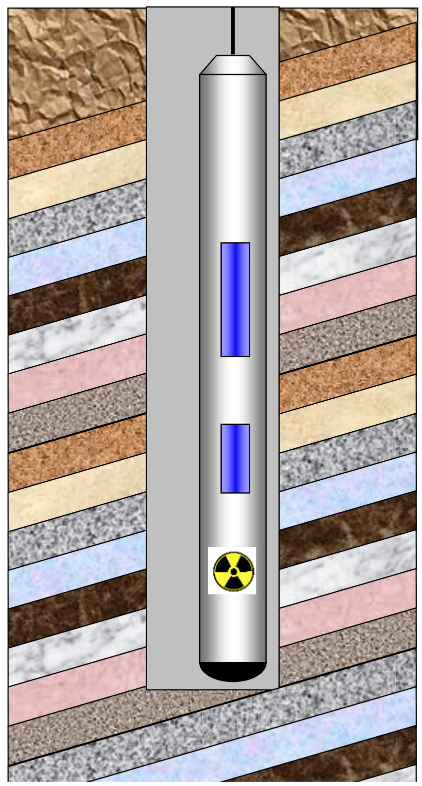
In addition to customized tool models, generic tool models exist for

- Neutron porosity
- Litho density
- Carbon/Oxygen saturation
- Thermal decay time (sigma)
- Natural gamma-ray
- Capture spectroscopy
- Neutron activation
- LWD neutron & density
- Open hole and cased hole
- Vertical and horizontal wells

Benefits

- Understanding nuclear tool response in complex boreholes
- Tool response in dipping beds
- Cased hole evaluation
- More accurate interpretation of logs
- Fine-tuning of reservoir models
- Verification of environmental corrections
- Predicting log data for quality control during logging operations

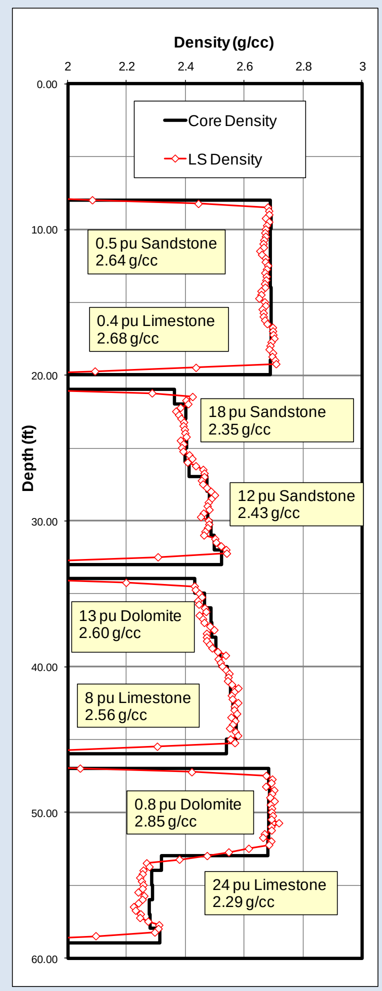
Downhole nuclear measurements are used to identify and quantify hydrocarbons in reservoirs. Even with a large amount of data from different sensors, the problem is underdetermined. Downhole borehole conditions, such as mudcake and washouts, present additional challenges to log interpreters.



Rock formations are seldom clean quartz or calcite: they contain minerals and clays. Boreholes snake around as they are drilled. Formations dip relative to the borehole. Washouts and mudcakes are encountered. Advanced drilling muds affect a tool's response. Fluids vary in content, salinity, hydrocarbon type and density.

But computer modeling of nuclear logging tools can be used to improve our understanding of log data. The computer horsepower today makes computer modeling more valuable than ever. The challenge is no longer the speed of the computer, but rather the skill of the physicist.

Nuclear computer modeling is a powerful and cost-effective method for designing and interpreting nuclear logging tools. Modeling a complex logging tool with neutrons and gamma-rays flying around is a difficult challenge. The LANL-developed MCNP Monte Carlo code is specifically designed to model nuclear physics. But using the MCNP code is far from easy: success requires experience and software tools.



Simulated density log for the 8 formations at the CALLISTO test well. Each zone consists of six 1-ft thick sections of rock. The facility has limestone, dolomite and sandstone formations with porosities ranging from 0.5 to 25 pu. For plotting simplicity, the 8 formations were modeled as a single test well. .

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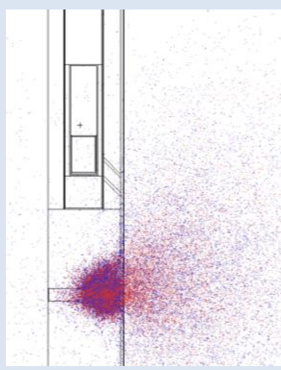
What is Monte Carlo simulation?

Monte Carlo modeling is a mathematical technique for predicting the movement of nuclear particles – neutrons or gamma rays -- in the tool, borehole and formation. Nuclear particles are "tracked" or followed as they are first emitted from a nuclear source until they are detected by a nuclear sensor.

As nuclear particles scatter in the tool, borehole and formation, random numbers are used to determine the position, direction and energy of the particle. The tracking of particles in a Monte Carlo simulation is called a "random walk" because no two particles follow the same path.

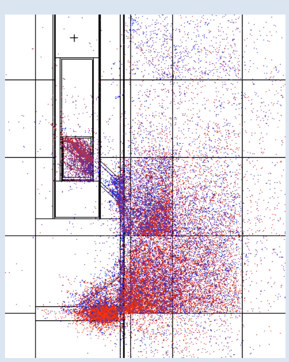
A Monte Carlo simulation consists of following a large number of source particles, typically in the tens of millions. The technique is well suited for complex geometries and nuclear reactions. Computer run times can vary from hours to days, depending on the complexity of the problem.

The figure to the right shows a litho-density tool and particle tracks from a gamma-ray source. This plot visually illustrates the difficulty of modeling a density tool. Namely, very few gamma-rays ever make it to a detector. The majority of the time the Monte Carlo code is tracking gamma rays in and around the source capsule. Very few gamma rays make it into the formation. Even fewer make it to the detector.



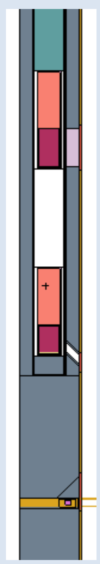
An un-optimized MCNP density model. Note the large number of collisions around the source.

But computer programs are not constrained by the laws of physics. Physicists can improve the efficiency of a MCNP simulation by a factor of 500x by utilizing Russian Roulette. In a nut shell, an optimized Monte Carlo simulation will spend most of the time tracking important gamma rays while ignoring those that are unlikely to reach a detector.



A highly optimized MCNP density model. Note the large number of gamma rays that reach the short-spaced detector.

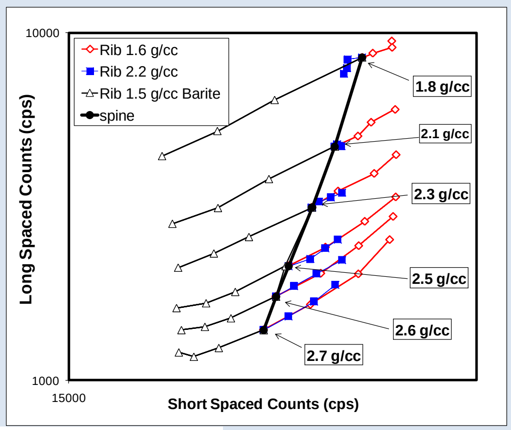
Litho-Density Tool (Gamma-gamma)



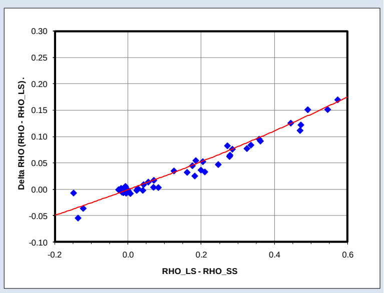
Generic Density Tool

The MCNP code was used to model a generic litho-density tool. Gamma-gamma density tools contain a ^{137}Cs source and two collimated detectors. Collimation is needed to isolate the effect of a mudcake on the shallow-reading tool.

The density tool model was used to generate a spine & ribs plot (below). The spine (black line) was built from formations with densities from 1.8 to 2.7 g/cc. The ribs were built from 3 different mudcakes. Two non-barite mudcakes had densities of 1.6 and 2.5 g/cc and a barite mudcake had a density of 1.5 g/cc. Mudcake thicknesses up to 0.75” thick were modeled.

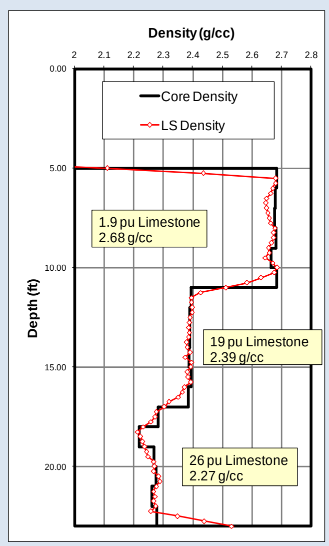


The data from the spine and ribs is plotted so that the x-axis is the difference between the short-spaced and long-spaced detectors. The y-axis is the correction needed to the long-spaced density to obtain the formation density. This is the delta-rho ($\Delta\rho$) plot.

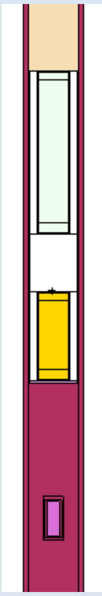


Delta-rho plot from Monte Carlo modeling.

(Right) Simulated Density Log at the University of Houston API Neutron Calibration Facility. The test pit contains three limestone zones, each 6-ft thick. Each zone consists of six 1-ft thick sections of rock. Average zone densities are 2.68, 2.39 and 2.27 g/cc, although there is some variation in the 1-ft sections.



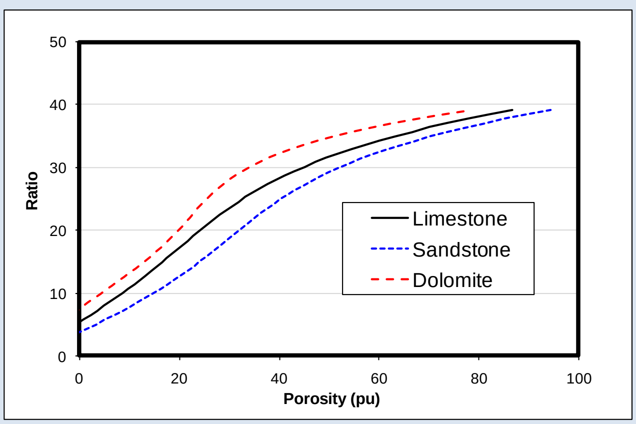
Compensated Neutron Porosity Tool



Generic Neutron Porosity Tool

A neutron porosity tool determines the formation porosity by comparing the counts from a near detector to the counts from a far detector. The count rates depend on slowing-down length, and slowing-down length is a very strong function of hydrogen content. For clean lime, sand or dolomite formations, the hydrogen comes from the pore fluids. However, when clays, coal or some minerals are present, the hydrogen can come from the rock. In that case, a neutron tool is going to read high.

To understand the counts from a neutron porosity tool, the first step is to develop the ratio-to-porosity transforms. The limestone, sandstone and dolomite transforms shown below were generated with the MCNP Monte Carlo code. The transforms were generated for a fresh water, 8-in. borehole. With the transforms, measured count rate ratios are easily converted into uncorrected porosities.

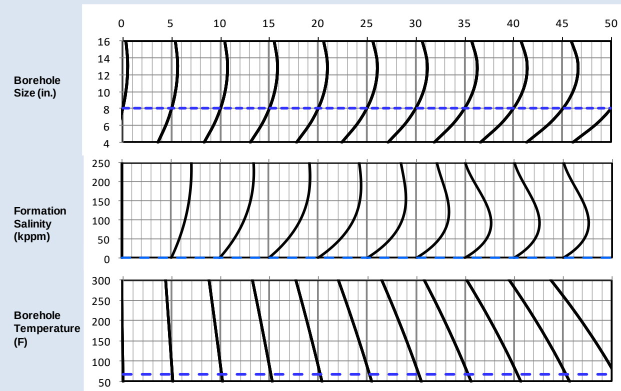


Ratio-to-porosity transforms for limestone, sandstone, and dolomite.

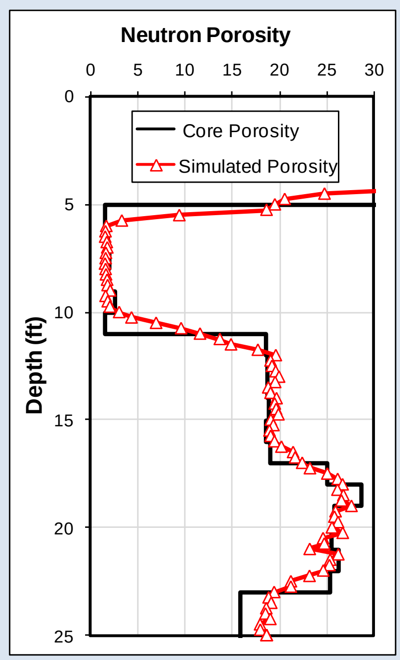
Once the limestone porosity transform has been developed, a large number of computer simulations are generated to develop environmental correction charts. A neutron tool responds to many downhole conditions: hole size, lithology, clay content and type, porosity, drilling mud composition, mudcake, formation fluids, salinity, downhole temperature and pressure.

In cased hole applications, additional parameters of interest are casing size, casing weight, cement type, tubing, gas content, hydrocarbon composition, and casing position. In addition, formation dip and invasion fronts complicate the tool response. Horizontal wells add additional effects on tool response.

Three environmental correction charts for a generic compensated neutron tool are shown below. The upper charts is the hole size effect, the middle chart is for formation salinity, and the bottom chart is downhole temperature. With this data, raw porosity readings from a tool can be converted into corrected porosities.



Once the porosity transform and the environmental charts have been built, the tool model can be used to generate simulated logs. In fact, the environmental corrections are only required when computing a corrected porosity log. To model the raw detector count rates from the tool, only the ratio-to-porosity transform is required. This is important when the correction charts are in question or when the tool is used in a new environment.



Simulated neutron porosity log for the University of Houston API Neutron Calibration Facility. The test pit contains three limestone zones, each 6-ft thick. Each limestone zone consists of six 1-ft thick sections. Average zone porosities are 1.9, 19, and 26 pu. The Monte Carlo values were calculated every 3" and are shown in red. The core porosities are shown in black.

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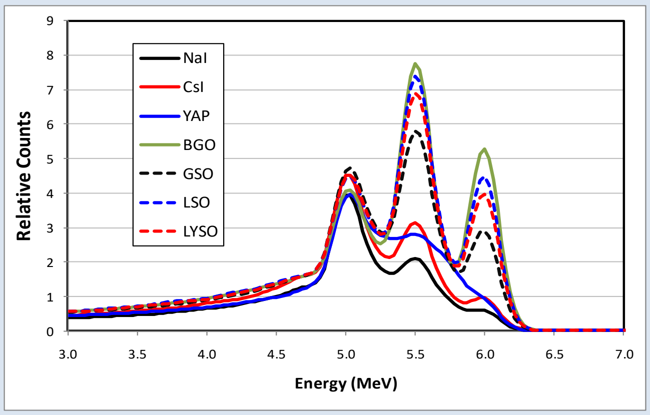
Detector Modeling

The MCNP code can be used to model the response of different scintillators for gamma-ray detection. The figure below shows the detector response for 7 different crystals: NaI, CsI, YAP, BGO, GSO, LSO and LYSO. The incident gamma-ray energy in this study was 6 MeV. While NaI is the most widely-used detector material, it is not very efficient at detecting high-energy gamma rays. It has the lowest sensitivity of all 7 detectors. On the other hand, BGO has the best response, due to its density and the high atomic-number of bismuth.

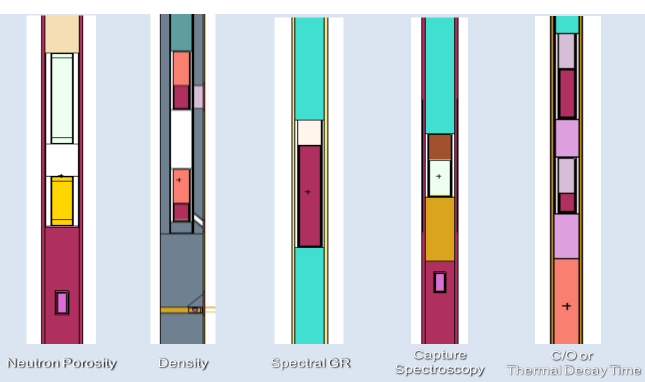


Monte Carlo generated pulse-height spectra for 7 different gamma-ray detectors. In terms of detection efficiency, NaI is the lowest and BGO is the highest.

Generic Tool Models

Generic tool models have been developed that may be used when detailed tool information is not available. Additional models can be created as needed.

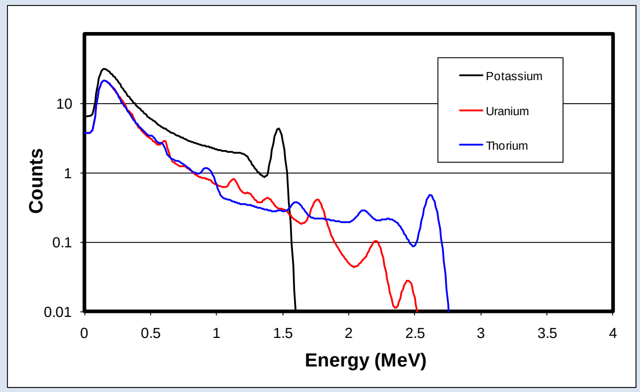
- Neutron porosity
- Litho density
- Carbon/Oxygen saturation
- Thermal decay time (sigma)
- Natural gamma-ray
- Capture spectroscopy
- Neutron activation
- LWD neutron and density.



Generic Wireline Tool Models

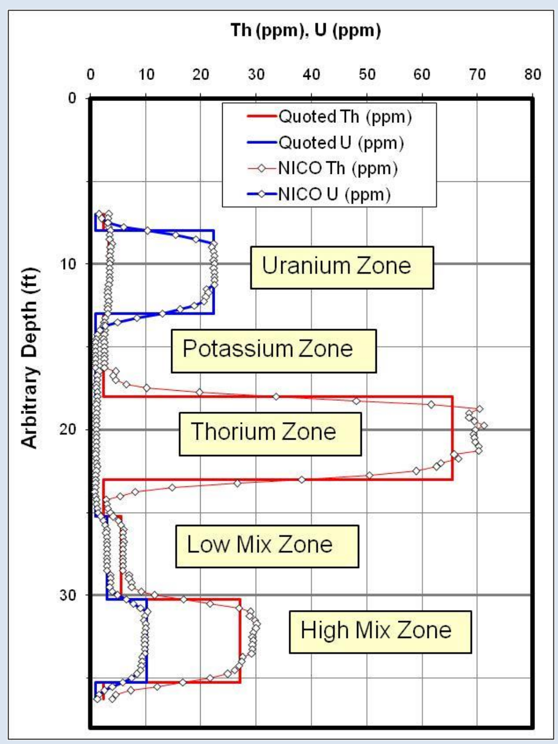
Natural Gamma-Ray Spectroscopy

A natural gamma-ray log is important for detecting shales and minerals. Th, U and K atoms slowly decay releasing characteristic gamma rays. Matching the characteristic gamma rays with the measured gamma rays from the tool allows the determination of the Th, U and K concentrations in the formation. A MCNP model can be used to generate the detector response to Th, U and K characteristic gamma rays, as shown in the figure below.



Monte Carlo pulse-height spectra for Th, U and K.

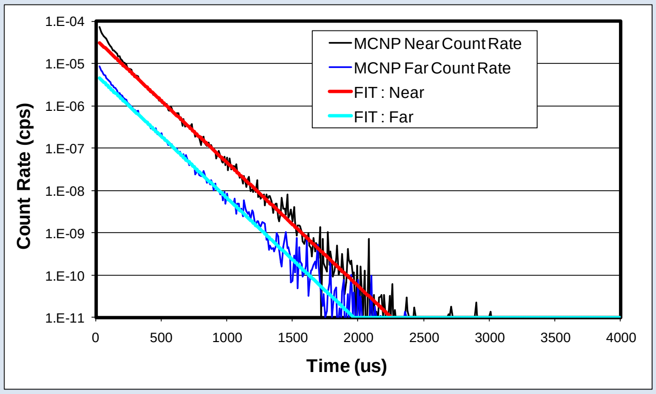
A simulated TUK log for the University of Houston TUK Calibration Facility is shown below. The facility contains several 5-ft zones of varying amounts of Th, U and K. Due to leaching of K, the K zones are not used for calibration.



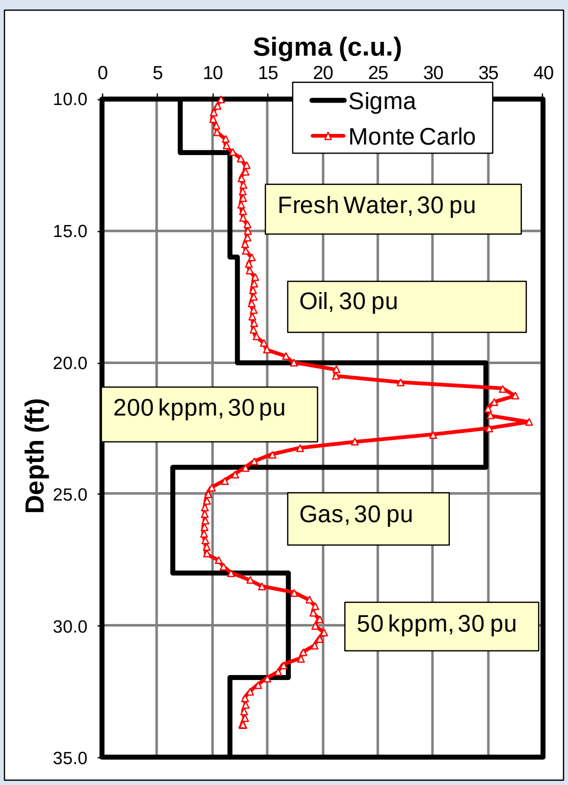
A simulated TUK log for the University of Houston TUK Calibration Facility.

Thermal Decay-Time Measurements

A thermal decay-time tool was modeled in a simulated test well. The borehole was fresh and the formation sigma was 26 cu. Near and far counts are shown below. The red and cyan lines shown are two-exponent least-squares fits to the near and far detector count rates.

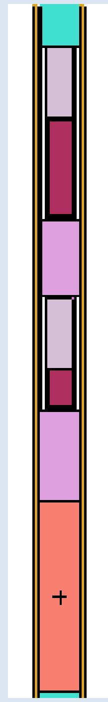


The tool was modeled in a simulated test well containing five 30-pu limestone beds with different pore fluids. The formation capture cross sections and the simulated far sigma are shown below. The simulated sigmas were based on a single-exponent fit to the MCNP data. The Monte Carlo sigmas are higher than the intrinsic sigmas due to neutron diffusion.



A simulated thermal decay-time log with different pore fluids. The upper 30 pu zone is fresh water, and the lower zones are oil, 200 kppm water, gas, and 50 kppm water.

Simulated C/O Tool



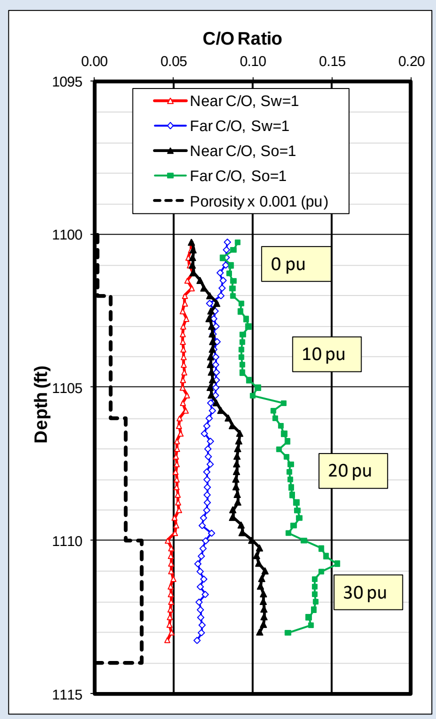
Generic C/O or Sigma Tool

The MCNP code was used to simulate a pulsed neutron carbon-oxygen (C/O) saturation tool. The MCNP code was modified to directly calculate the inelastic elemental yields, thus spectral fitting was not needed to determine the carbon and oxygen yields.

The tool was modeled in a simulated test well with an 8.5" borehole and a 7"-23-lb casing. The simulated test well contains a 2-pu limestone zone from 1100-1102 ft, a 10-pu limestone zone from 1102-1106 ft, a 20-pu limestone zone from 1106-1110 ft, and a 30-pu limestone zone from 1110-1114 ft.

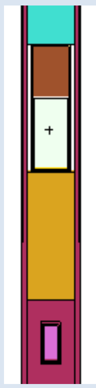
Two logs were generated: one assuming water in the pore volume and the other assuming oil. When the pore fluid is water, the C/O ratio decreases as porosity increases due to the reduction of carbon relative to oxygen. However, when oil fills the pore space, the C/O ratio increases with porosity due to the carbon content in the oil.

The two logs (water-filled and oil-filled) can be used to determine the formation oil saturation by comparing the measured yields from the tool with the two Monte Carlo logs.



Simulated C/O logs for water-filled and oil filled formations.

Capture Spectroscopy Modeling

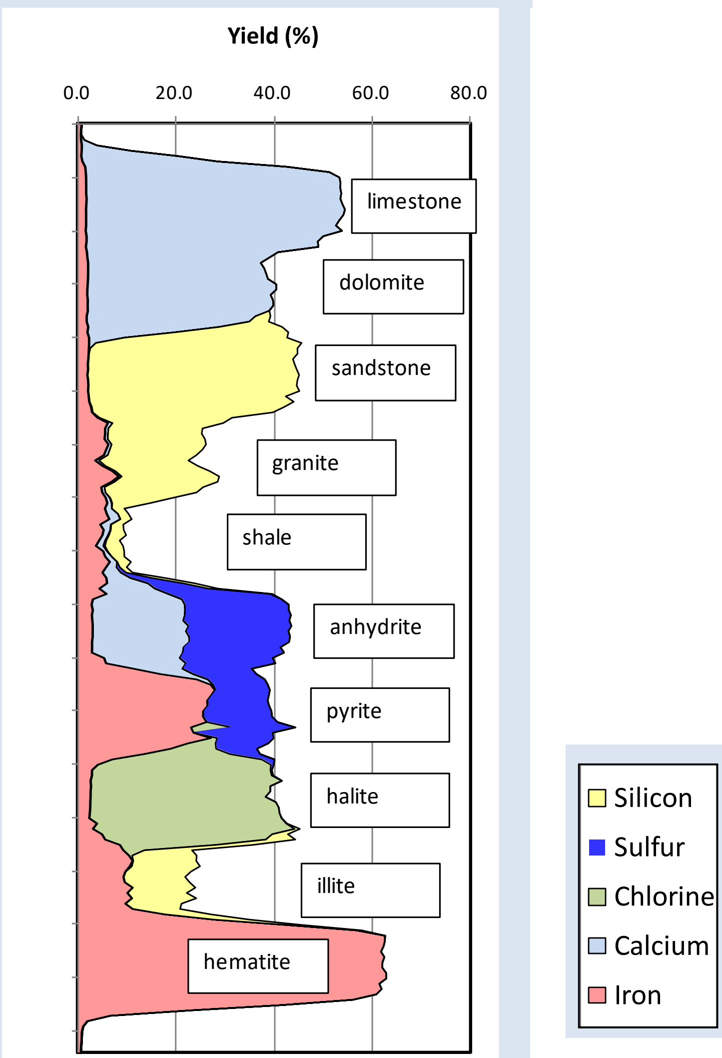


Generic Capture Spectroscopy Tool

A Monte Carlo model of an AmBe neutron capture spectroscopy tool was used to generate a simulated log. The tool was modeled in a simulated test well containing ten 4-foot zones of different minerals:

- 20 pu limestone;
- 20 pu dolomite
- 20 pu sandstone
- 20 pu granite
- 0 pu black shale (230 cu)
- 0 pu anhydrite
- 0 pu pyrite
- 0 pu halite
- 0 pu illite
- 20 pu hematite.

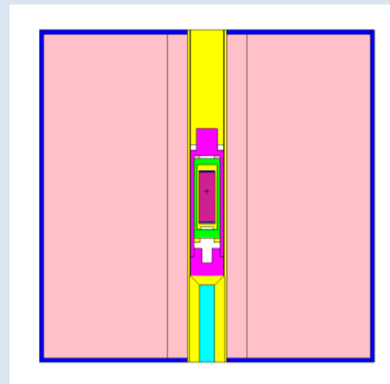
The simulated data clearly shows the presence of silicon, sulfur, chlorine, calcium and iron.



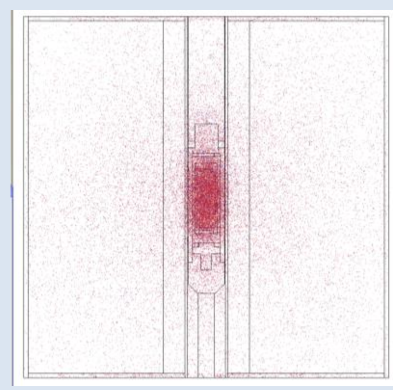
Simulated capture spectroscopy log showing the elemental yields Si, S, Cl, Ca and Fe.

Nuclear Source Shielding

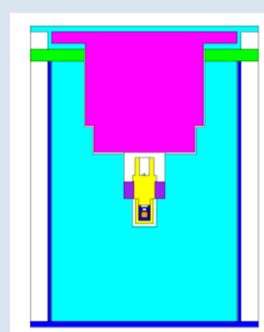
The MCNP code can be used to design neutron or gamma-ray shields. This capability is important for reducing the weight and size of shields, while still meeting regulatory dose rate limits.



Neutron Shield.



Neutron Shield Particle Tracks.



Gamma-Ray Shield.

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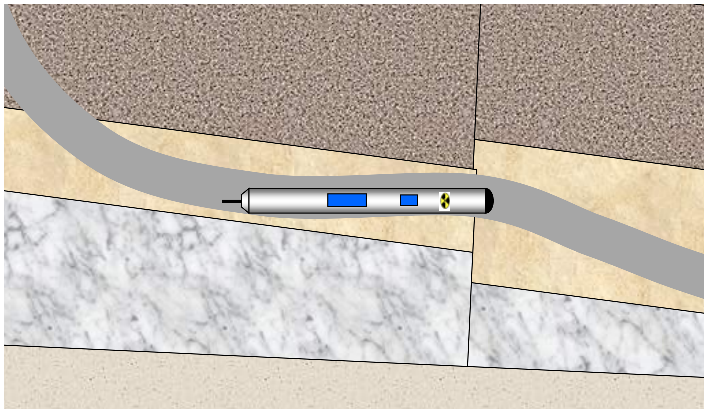
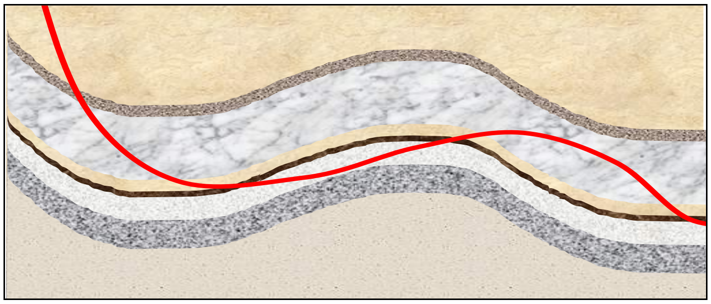
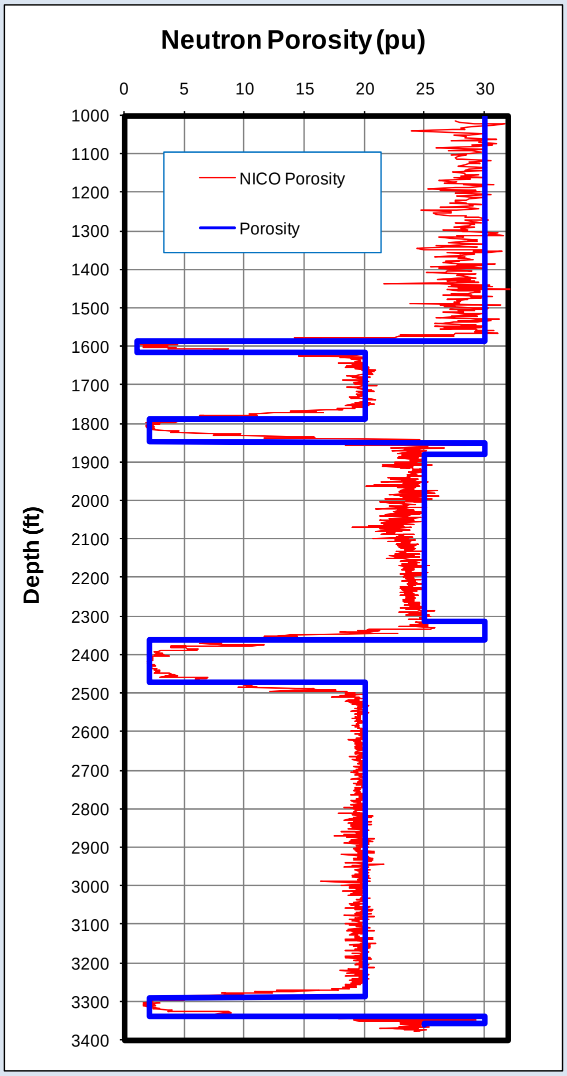
Horizontal Wells

Special software has been developed to model logging tools in horizontal wells. Horizontal well models are more complex than vertical well models, and optimization of the horizontal models is more difficult.



A simulated Monte Carlo log was generated for the simulated test well shown below. The borehole—shown in red--crosses multiple beds with porosities ranging from 1 to 30 pu. The simulated neutron log is shown to the right.





Simulated log in a horizontal well. Beds range from 1 to 30 pu.

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