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Neutron Generators and Well Logging

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Introduction

Neutron logging was introduced in 1941 using a “chemical” neutron source (RaBe).

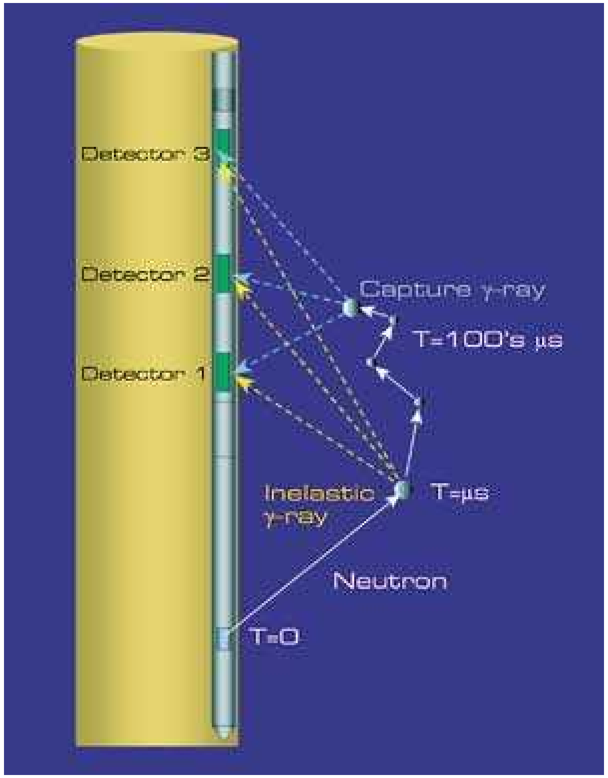
The first commercial pulsed neutron logging tool was introduced in 1963 by Dresser Atlas, a predecessor of Baker Atlas.

The Neutron Lifetime Log® service proved to be very successful for determining water saturation in saltwater-bearing reservoirs

Basic Theory

Neutrons are emitted from the source and interact in the surrounding rock in several ways depending on the local geology:

- Water and hydrocarbons will slow down (thermalize) the neutrons
- Neutrons will scatter inelastically from some elements resulting in the emission of gamma rays.
- Certain elements will capture the neutrons either right away or after they slow down, emitting gamma rays and reducing the neutron flux.



Well Logging

Two basic methods:

- Wireline measurements
  - Entire drill string is removed and the measurement tool string is inserted into the well
  - Measurements done from bottom up

- Logging While Drilling (LWD)
  - The measuring tools are included in the drill string
  - Data is telemetered to the surface

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Advantages

Neutron generators

- Output about 3 times as many neutrons/sec as the AmBe sources they're replacing
- Cause less dose to workers and are easier to store because when they're off, there is no external radiation to deal with
- Are less difficult to license
- Do not require leak testing
- Are less of a headache if lost down-hole due to recent changes to the NRC rules
- Are easier to ship
- Allow more types of measurements because of timing

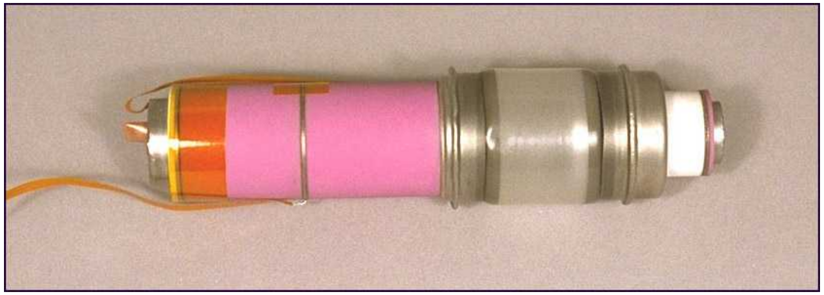
Disadvantages

Neutron generators

- Cost a lot
- Still contain tritium so require controls when not in use
- Need to be operated once a month to maintain tube life
- Have a limited tube life and require more frequent replacement (see first bullet)

Description

Neutron Generators used in well logging range in size from about 8” diameter to less than 2” in diameter.



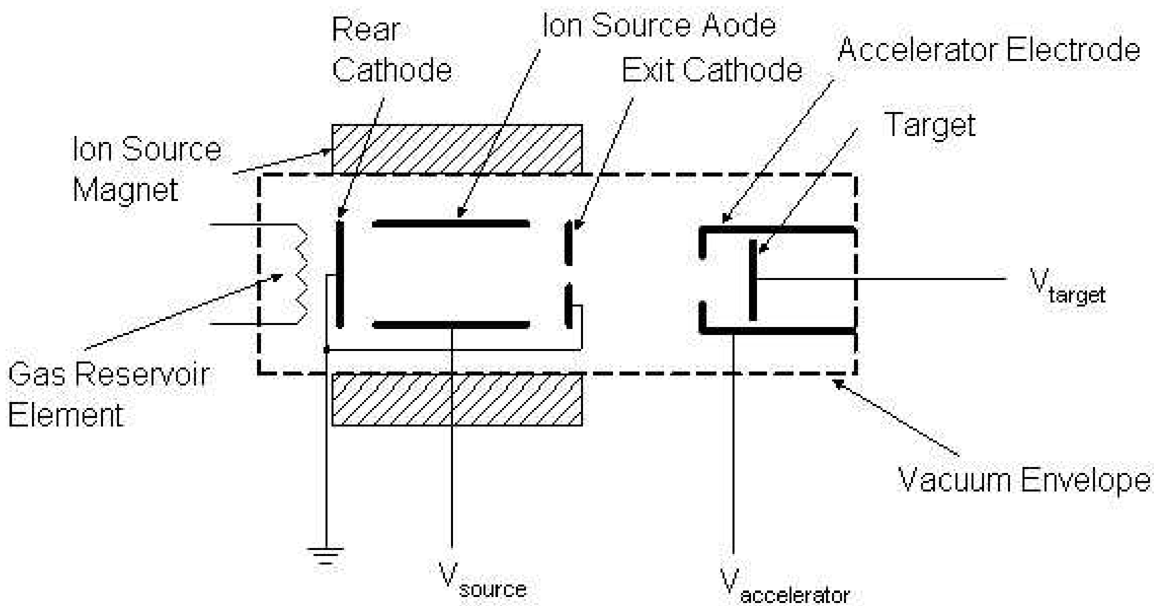
Thermo is now the only manufacturer of the Sandia-designed Zetatron tube and now supplies them to Sandia and others.

Manufacturers

- Thermo Electron Corp. – Colorado Springs
- Baker Hughes, Inc. – Houston
- Halliburton Co. – Houston
- Schlumberger Ltd – Princeton, NJ

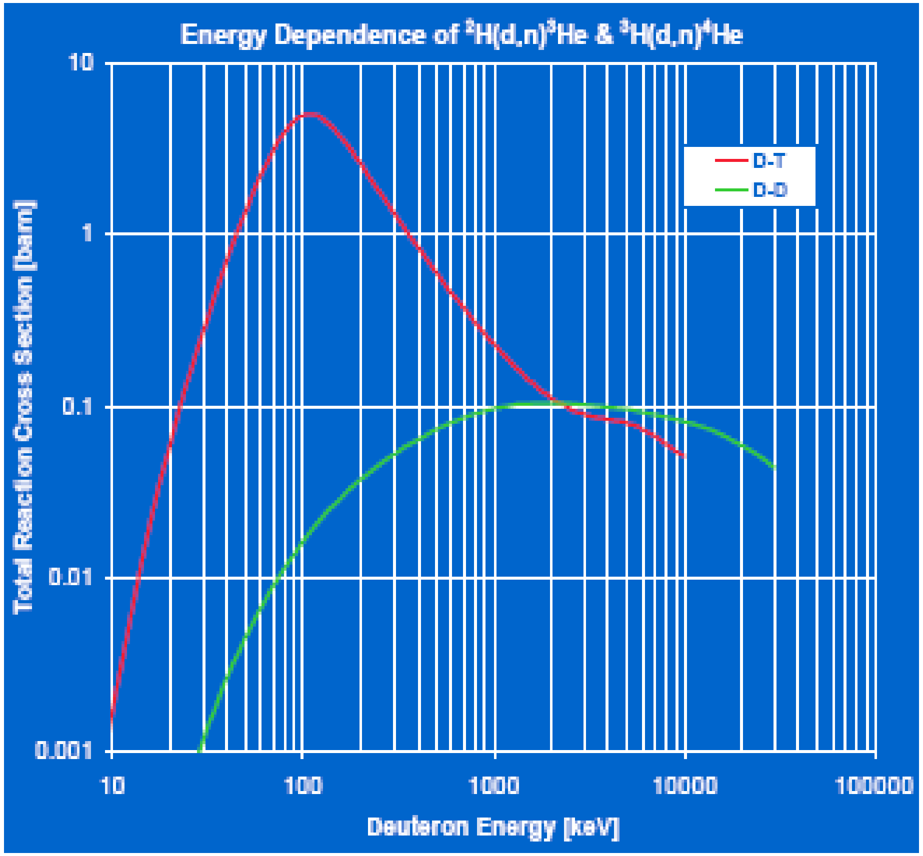
- All-Russia Research Institute of Automatics – Moscow
- Eads Sodem – Paris
- China Petroleum Technology and Development Corporation - Beijing

Schematic



NEUTRON TUBE SCHEMATIC

Tube Operation



The source creates ionized deuterium (and/or tritium) ions which are accelerated to about 110 keV before striking the tritium (and/or deuterium) loaded target.

Neutron Generator Output

Neutron Generators used for well logging typically use 1-20 curies of tritium in the D-T reaction

D + T $\longrightarrow$ He-4 + n + 17.6 MeV

Output: ~10^6 neutrons/pulse
Pulse width: ~10 microsecond

Pulse rate: 1 - 20,000/sec

Thermo Model B 211

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Tube Output

A typical pulse rate of 100/sec results in an output of 10^8 neutrons/sec.

Tube lifetimes are typically quoted as about 1000 hours at the normal output rate.

Thermo Model B-320

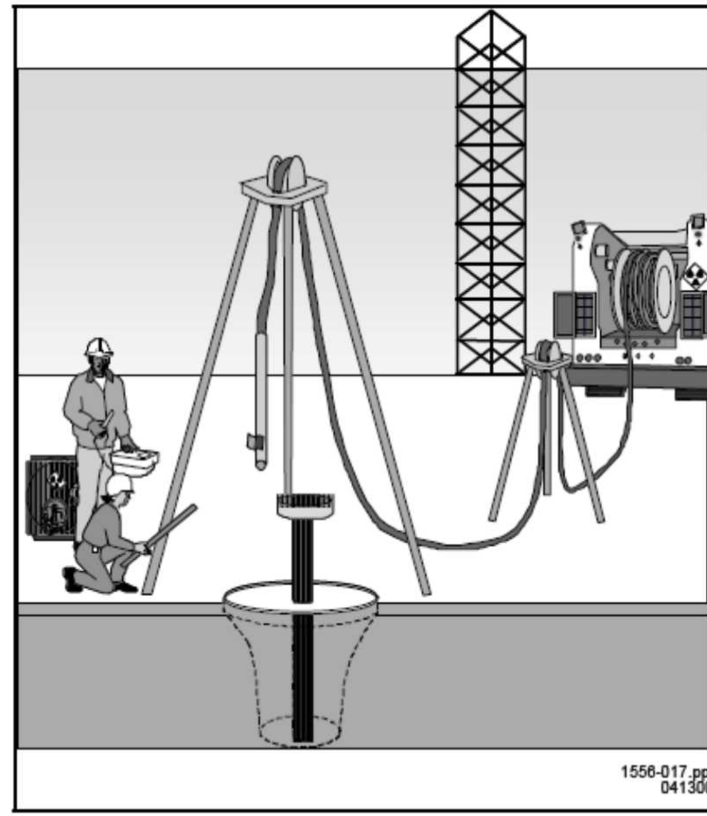
Radiation Safety

Dose rates from 10^8 n/sec:

@ 1 foot: 5.6 rem/hr

@ 1 meter: 520 mrem/hr

Radiation Area posting would be required at over 10 meters from a continuously operated (unshielded) tube at this output level.



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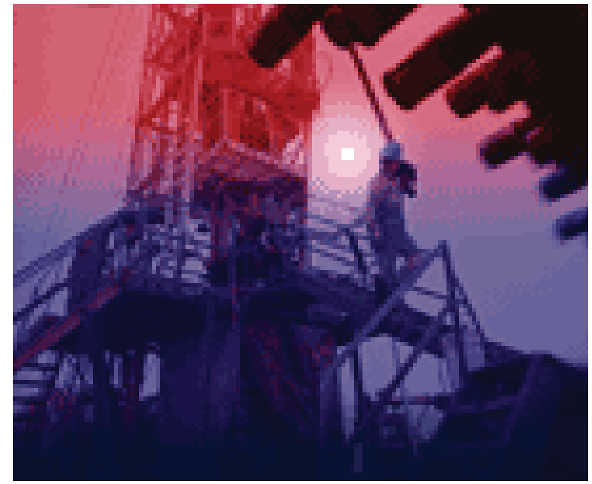
Radiation Safety (Cont'd)

Tritium is a regulated material so a license is required from either a State or the NRC as applicable.

Standard requirements for licensees include:

- **A license application describing the radiation safety program**
- **Designation of a qualified RSO**
- **Operating and Emergency Plans**
- **Regular audits and inspections**
- **Compliance with regulations**
- **Payment of fees**

Neutron production is not regulated by the NRC so State rules apply.



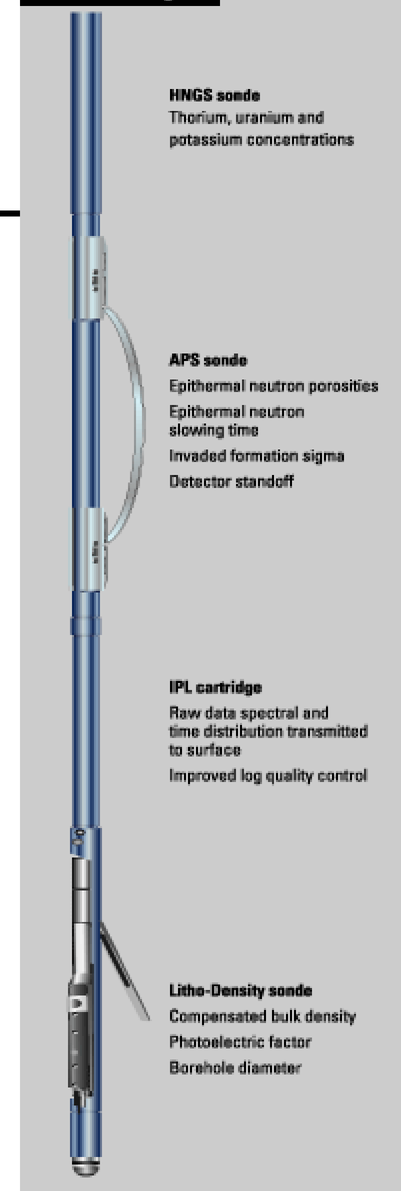
As long as the generator contains less than 30 curies of tritium it is exempt from leak testing, some down-hole abandonment requirements, and performance testing.

Application

Neutron generators are included in a pipe "string" with other measuring and detection equipment. The neutron source is used to measure:

- porosity
- salinity
- elemental composition
- oxygen content
- water/hydrocarbon boundary

There will typically be a gamma source (usually ~ 1- 2 Ci Cs-137) and several gamma and neutron detectors in addition to other sensors measuring temperature, pressure, and several other parameters.



IPL tool string.

Porosity Measurements

Significant energy loss occurs when the neutron strikes a hydrogen nucleus of equal mass, which is mainly present in pore water.

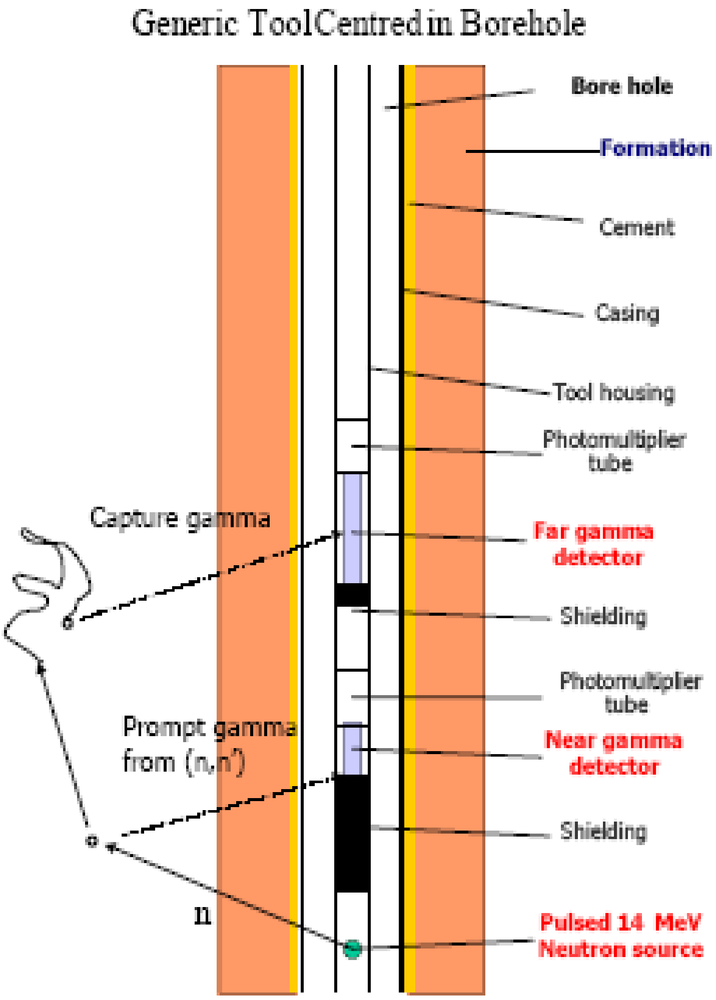
The neutron detectors record both the numbers of neutrons arriving at various distances from the source and the neutron arrival times.

Porosity is measured using a neutron generator and up to five neutron detectors (four epithermal and one thermal) positioned at different spacings along the tool.

Porosity is quoted in API units. In general, the higher the count the less porous the rock.

Elemental Analysis

- There are three major types of nuclear reactions that are used in elemental analysis:
  - Prompt inelastic scattering reactions (n, n’g)
  - radiative capture reactions (n, g)
  - long half life activation
- These three types of reactions have different temporal characteristics.
- This fact may be exploited by using pulsed neutron generators and appropriate timing of detector circuitry.



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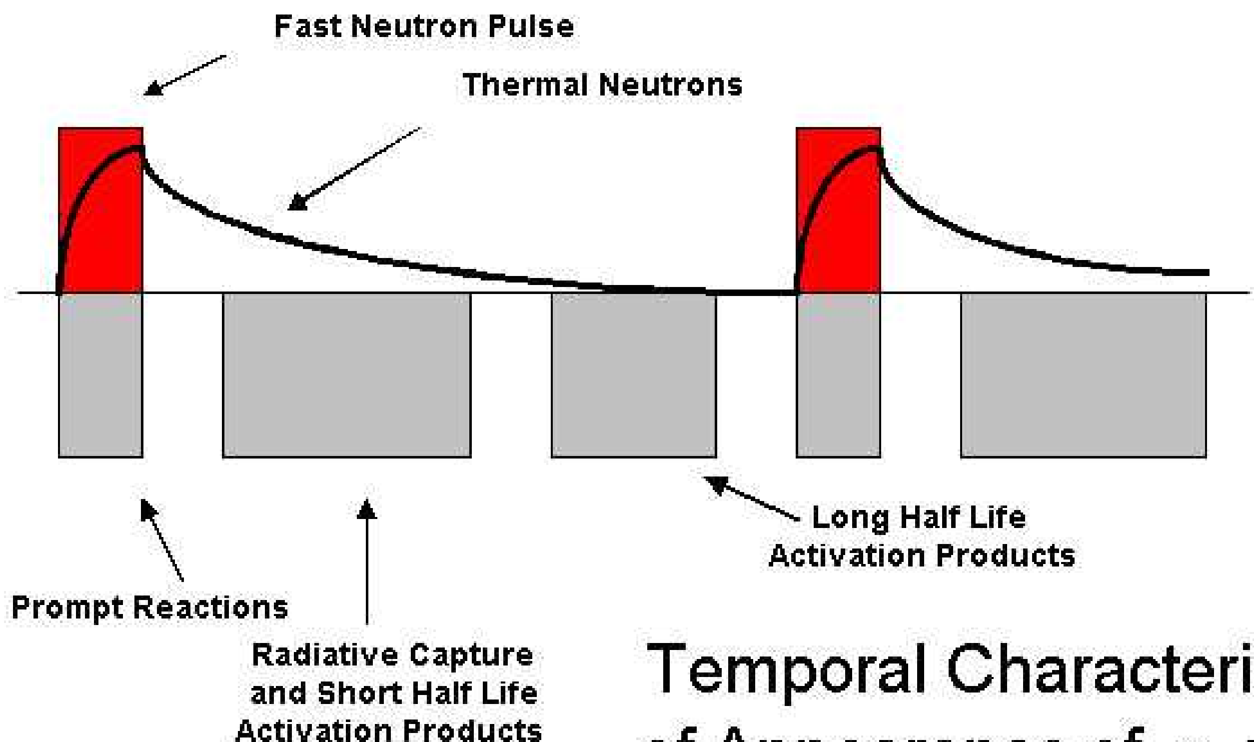
Timing



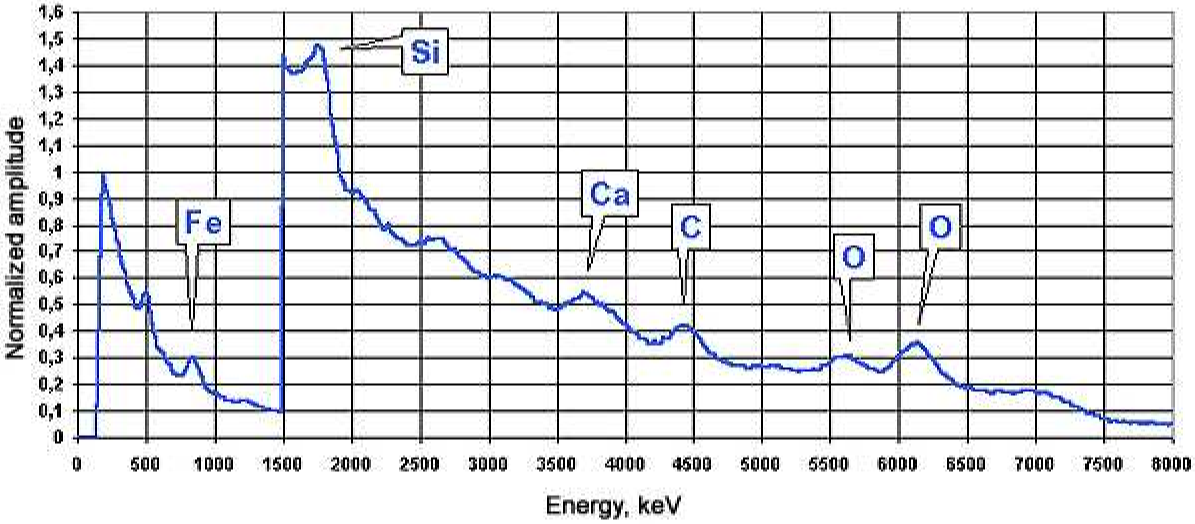
Temporal Characteristic of Appearance of γ–rays

Inelastic Scattering

Prompt Inelastic scattering reactions produce gamma rays when a neutron is <u>scattered</u> by a target nucleus.

There is no delay in the emission of the gamma ray.

These reactions are useful for detection of C, N, O, Mg, Al, Si, S, and Ca.



Inelastic spectrum for a silicate model.

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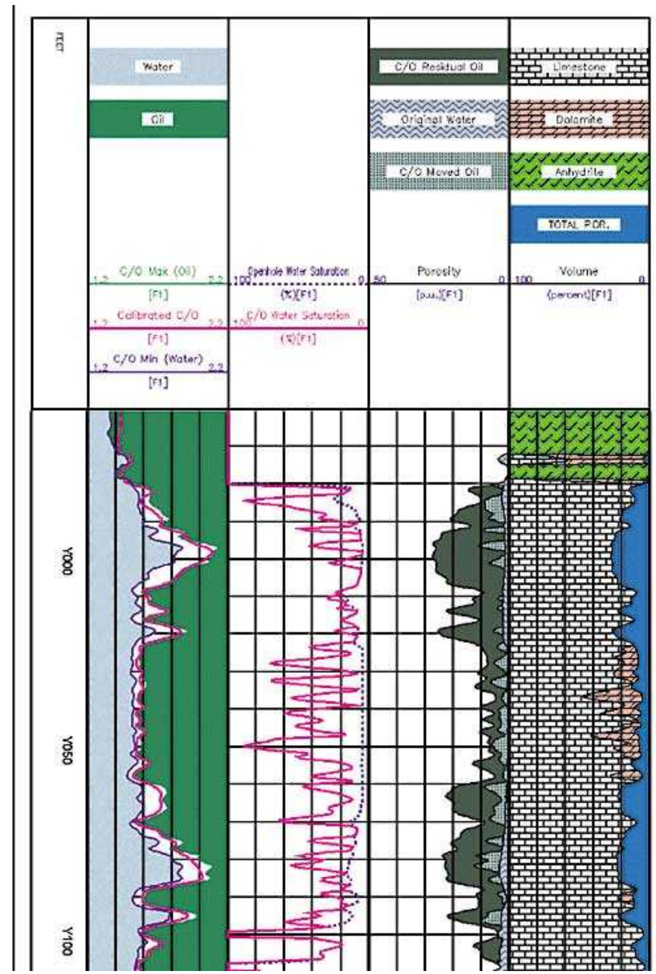
Inelastic Scattering (cont'd)

The most important application of this in well logging is the analysis of <u>oxygen content.</u>

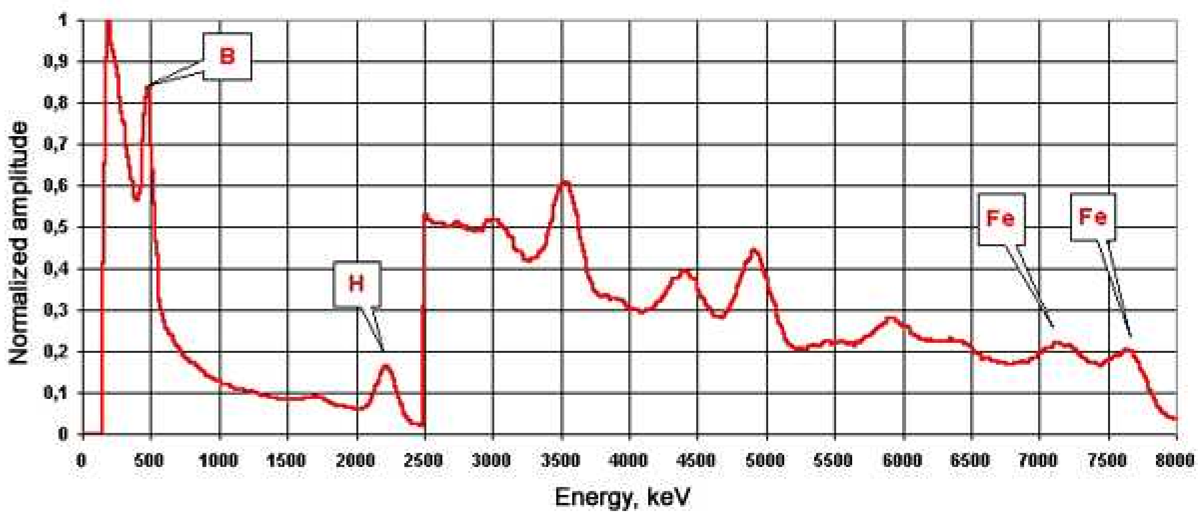
The carbon/oxygen (C/O) ratio is used to determine the formation <u>oil saturation</u> independent of the formation water salinity.



Radiative Capture

Radiative capture reactions occur when a thermal neutron is <u>absorbed</u> by a target nucleus. Gamma rays are emitted during the reaction which are characteristic of the elements involved.

This reaction is useful for detection of H, Cl, Al, P, S, Ca, Fe, Pb, B, and many other elements.

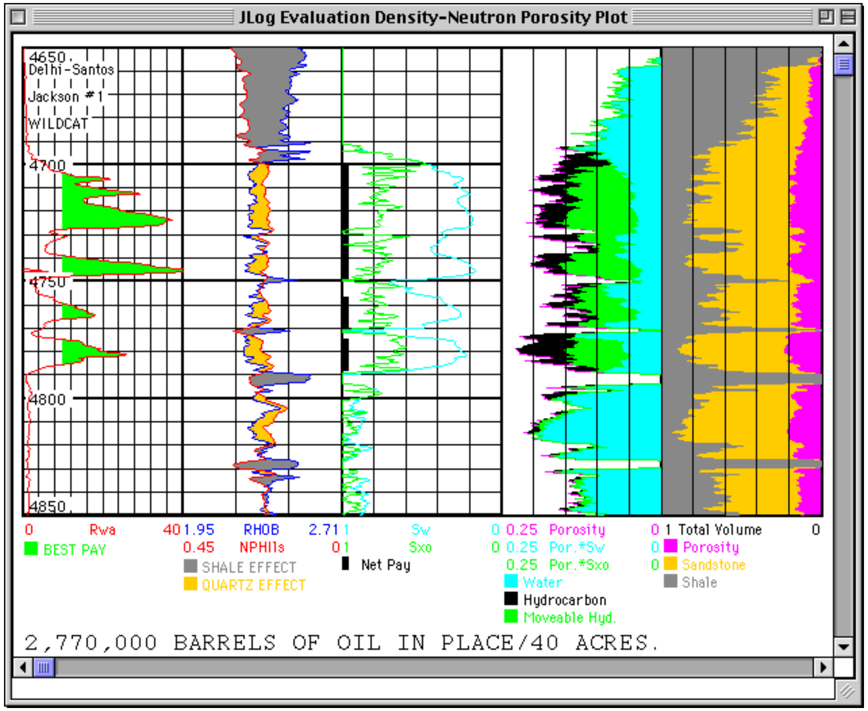


Capture spectrum for a silicate model

Radiative Capture (cont'd)

This reaction is also used to measure the position of <u>petroleum/water interfaces</u> in producing wells.

Locating the interface depends upon the fact that a neutron burst decays much more rapidly (large sigma) in saline waters than in petroleum due to chlorine's high capture cross section.



Elemental Composition Measurements

The pulsing of the neutron source allows the measurement thermal decay time which is related to the (macroscopic) thermal neutron cross section, in capture units (cu).

S (cu) = 4550 / t (microseconds)

This is a useful indicator for the presence of elements of high thermal neutron capture cross section such as boron, chloride, and rare earth elements.

$$\Sigma\left(10^{-3}\mathrm{cm}^{-1}\right) = \frac{\rho\left(\mathrm{g}\cdot\mathrm{cm}^{-3}\right)\cdot\sigma\left(\mathrm{cm}^{2}\cdot10^{-24}\right)\cdot10^{-3}}{A_r\cdot m_u(\mathrm{g})}$$

Element/Mineral	Sigma (cu)
Sandstone	8-13
Limestone	8-10
Dolomite	8-12
Anhydrite	18-21
Shale	25-50
Salt (NaCl)	748
Gas	3-12
Oil	18-22
Fresh Water	22.3
Salt Water (100 ppt NaCl)	58
Salt Water (250 ppt NaCl)	120
Boron	99000
Tungsten	1166
Sulfur	20.2
Carbon	0.41

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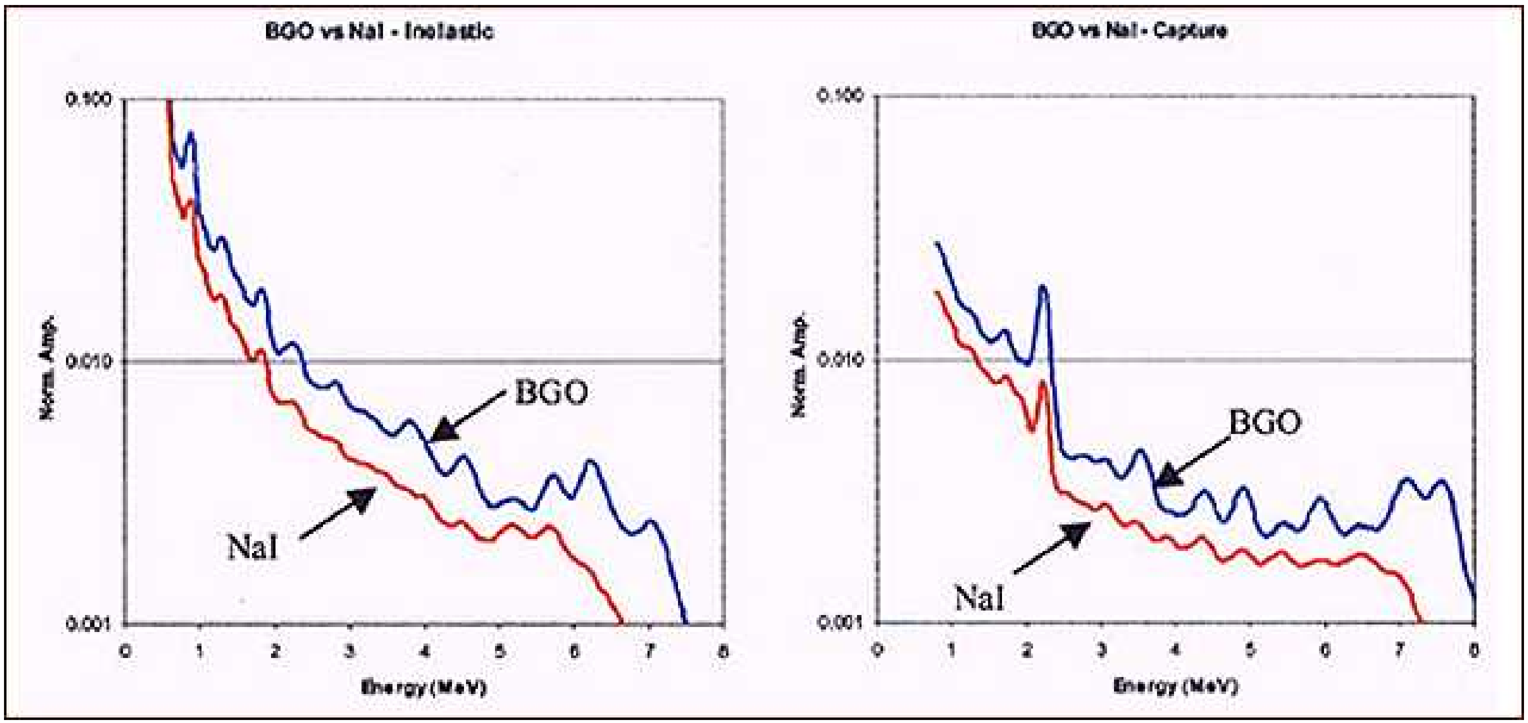
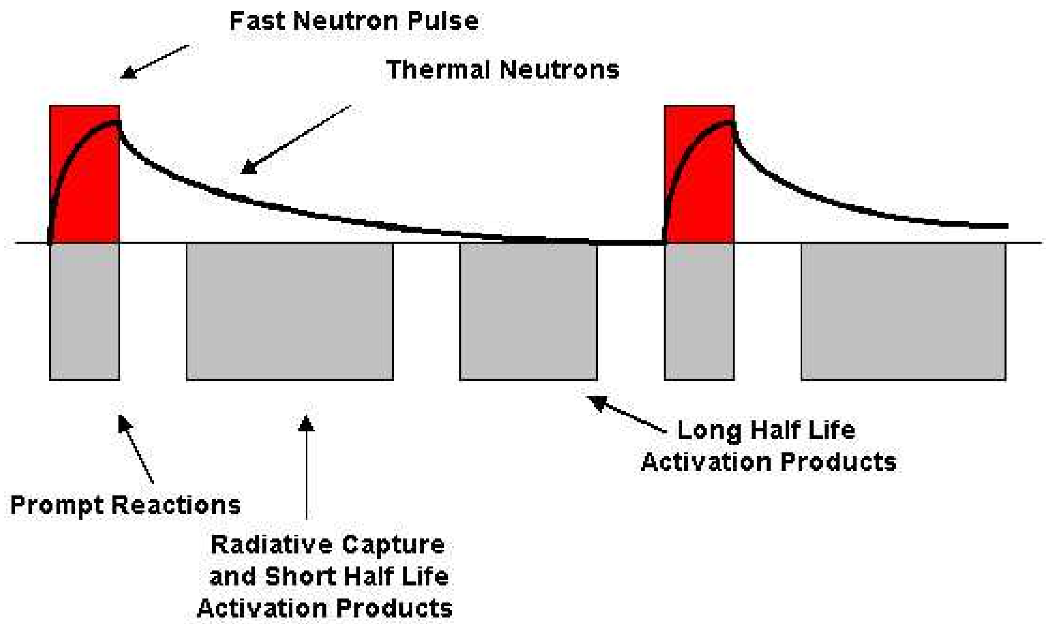
BGO vs NaI



BGO vs NaI - Inelastic
Norm. Amp.
0.100
0.010
0.001
BGO
NaI
0 1 2 3 4 5 6 7 8
Energy (MeV)
BGO vs NaI - Capture
Norm. Amp.
0.100
0.010
0.001
BGO
NaI
0 1 2 3 4 5 6 7 8
Energy (MeV)

Long-Half-Life Activation

- **Primarily used to determine levels of aluminum, vanadium, and other elements with suitable neutron absorption and decay characteristics.**



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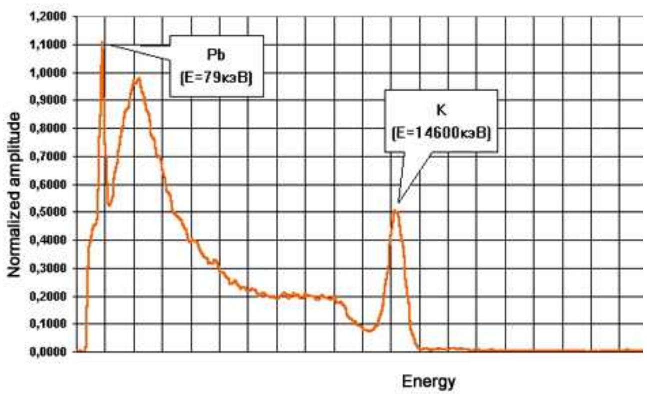
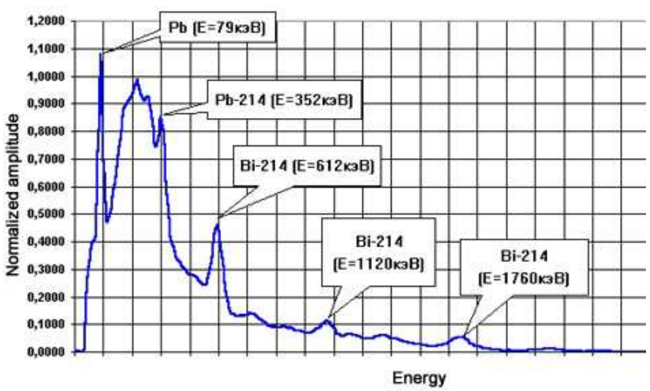
Measuring Natural Activity





Natural gamma radiation from isotopes of potassium, thorium, and uranium is measured using two bismuth germanate (BGO) scintillation detectors and five-window spectroscopy to determine concentrations of:

- **K-40 (in weight percent),**
- **Th-232 (in parts per million), and**
- **U-238 (in parts per million).**

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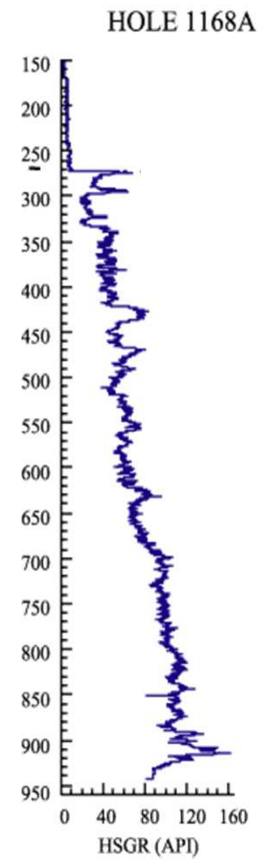
Measuring Natural Activity (cont'd)

- **Sodium iodide (NaI) scintillation detectors are also used to measure the total natural gamma ray emission, combining the spectral contributions of potassium, uranium, and thorium concentrations in the formation.**

- **This detector provides high-resolution total gamma ray data, rather than spectral analysis, for depth correlation.**



Russian Neutron Generators

The All-Russia Research Institute of Automatics (VNIIA) develops and produces neutron generator driven equipment for such applications as:

- gas and oil well-logging;
- neutron radiation analysis of elements;
- research of the physics of nuclear reactors and critical assemblies;
- detection and monitoring of nuclear material content;
- detection of explosives.

Specifications:

- weight from 0.5 to 10 kg
- neutron yield up to 10^{11} n/s
- pulse duration from 0.01 microseconds up to constant flux

VNIIA supplies its neutron generators to the USA, the UK, Germany, China, the CIS countries as well as to domestic customers.

French Neutron Generators

Eads Sodern developed the SODILOG tube for Well Logging applications

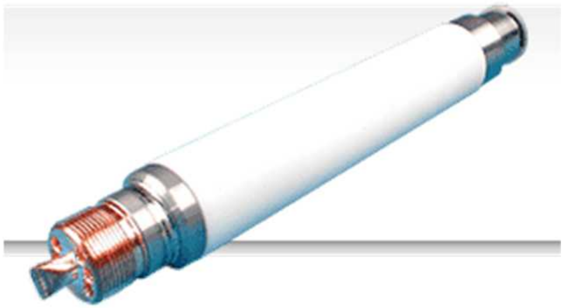
Tube Life: 8000 hours

Diameter: <2 inches

Loading: Mixed D/T (5 Ci T)

Pulse width: 1-10 milli-seconds

Yield: 10^8 n/sec



SODILOG

Chinese Well Logging Tools

Pulse width:

10 micro-seconds

Pulse rate:

20,000/sec

Output:

10^8 n/sec

OD:

3 inches

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Summary

- **Neutron use in well-logging has been around a long time and is part of a very mature science involving the integration of data from a large number of measurements under the worst of conditions.**
- **Neutron generator use has allowed the development of new measurements not previously available and increased the overall safety of the operation.**

Links

http://www.ga.gov.au/odp/publications/206_IR/chap_02/c2_11.htm
http://www.thermo.com/com/cda/products/product_application_details/1,,11286,00.html
http://www.thermo.com/com/cda/category/category_lp/1,2152,15205,00.html
http://www.bakerhughes.com/bakeratlas/reservoir_production/RPM_index.htm
http://www.slb.com/media/services/evaluation/petrophysics/porosity/ipl_ds.pdf
http://www.sprensky.com/publishd/survey.html
http://www.sodern.com/
http://www.atcng.com/products.htm
http://www.slb.com/content/services/evaluation/petrophysics/index.asp
http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1556/v14/index.html
http://vniia.ru/eng/ng/index.html
http://www.megasignal.com/index.php?topgroupid=12&groupid=69
http://www.cptdc.com/product/index/scripts/html/c_product/1_3.HTM
http://www.rockware.com/catalog/pages/jlog.html
http://www.sprensky.com/bibliogs/tla.html

More Links

- http://www.antares-geo.de/techinfo/pulsed%20neutron.htm
- http://www.appscintech.com/products/gs20-6Li-glass.html
- http://www.nucsafe.com/Technology/detecting_neutrons.htm
- http://www.wellog.com/webinar/interp_p2_p3.htm
- http://www.wellogginglab.org/page1.html
- http://www.acad.ro/sectii2002/proceedings/doc_2005_3/03-Borsaru.pdf
- http://www.serralog.com/console.php?page=2
- http://www.ldeo.columbia.edu/BRG/ODP/LOGGING/MANUAL/Pat/text.html
- http://www.accutechtechnologies.com/public/Accu%20Tech%20Flier.pdf

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Comments/Questions