Importance and Role of Isotopes in the Petroleum Industry

Eric L. Rosemann, CSP
Chairman of the Subcommittee for Radiation Safety and Security for the Association of Energy Service Companies (AESC)
Terms

- **Logging** – the process of taking geophysical and other wellbore measurements using electrical, magnetic, acoustic, nuclear and mechanical means and can be performed during or after drilling operations or both.
- **Open Hole** – freshly drilled well held open by the weight of the drilling fluid
- **Cased Hole** – casing pipe that is cemented into place after drilling to hold the well open
- **Tubing** – removable smaller pipe that is used for the actual production of the oil and/or gas
- **Production formation** – usually Sandstone, Limestone, Dolomite and certain Shales
- **Porosity** (includes fractures and other voids) – the space between the solid formation materials that can hold oil, gas, water and/or clay
World Energy – Anticipated Demand though 2030

National Petroleum Council Report
Facing Hard Truths - 2007
World Energy Supply – Historical and Predicted through 2030

1988
288 Quadrillion BTU/Yr.

2004
455 Quadrillion BTU/Yr.

2030
678 Quadrillion BTU/Yr.


National Petroleum Council Report
Facing Hard Truths - 2007
The Logging Business is a vital part of every well!

- Every Well requires formation evaluation, logging is a key part of this evaluation.
- The quality and accuracy of data is key to decide and ascertain if the well is a producer or dry hole.
- This evaluation supports and drives:
  - Production estimations,
  - Well economics,
  - Reserve calculations,
  - Corporate and Gov. energy assets,
  - Overall market fundamentals.

### Forecast - Drilling

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>2009</th>
<th>% WW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot WTI ($/bbl)</td>
<td>$114.81</td>
<td>$120.00</td>
<td></td>
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<tr>
<td>Spot Gas Price</td>
<td>$9.26</td>
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</table>

### Rig Count

<table>
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<tr>
<th></th>
<th>US</th>
<th>Canada</th>
<th>International</th>
<th>Russia</th>
<th>China</th>
<th>Total</th>
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<tr>
<td>2008</td>
<td>1,870</td>
<td>361</td>
<td>1,077</td>
<td>352</td>
<td>n/a</td>
<td>3,660</td>
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<tr>
<td>2009</td>
<td>1,980</td>
<td>406</td>
<td>1,141</td>
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<td>3,897</td>
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### Wells Drilled

<table>
<thead>
<tr>
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<tr>
<td>2008</td>
<td>59,789</td>
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<td>115,250</td>
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<td>2009</td>
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<td>20,223</td>
<td>14,332</td>
<td>19,324</td>
<td>122,003</td>
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</table>

Source: Spears and Ass. – DPO June 08
The Logging Business is a vital part of every well!

- Supports ability to commit to long term projects with less than certain payback.

- Provides support for filing Company’s statement of reserves.

- Helps value royalty payments back to state and federal government and drives legislation.

- The US is most affected:
  - ½ of worlds activity
  - ¼ of world consumption
  - < 5% of world reserves
  - greatest need for immediate continuity of supply

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Source: Spears and Ass. – DPO June 08
How Big is the Logging Business?

Wireline Logging

15% compound annual growth

Wireline logging includes both open hole and cased hole services. Open hole logging occurs during the drilling process and usually measures characteristics of the rock and the fluids and gases contained therein. Cased hole logging occurs in both new and old wells. Whether in new or old wells, wireline logging includes acquiring data from downhole and interpreting that data to help the operator decide what action to take next. Wireline logging includes formation and production logs run off slick line units.

This is a market segment that was threatened in the “Nineties by its sister technology, Logging-While-Drilling (LWD). LWD ate into the openhole logging market offshore, shrinking the available dollars in this space, but LWD reached saturation earlier this decade and wireline logging is again growing with global rig count.

Wireline Evaluation Logging Market ($B)

<table>
<thead>
<tr>
<th></th>
<th>North American</th>
<th>International</th>
<th>Total</th>
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<tr>
<td>Open Hole</td>
<td>$1.2</td>
<td>$2.4</td>
<td>$3.6</td>
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<tr>
<td>Cased Hole</td>
<td>$2.6</td>
<td>$2.6</td>
<td>$5.2</td>
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<tr>
<td>Total</td>
<td>$3.8</td>
<td>$6.0</td>
<td>$8.8</td>
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</tbody>
</table>

Source: Spears and Ass. – OMR 2007
How Big is the Logging Business?

Logging-While-Drilling

18% compound annual growth

Logging-While-Drilling (LWD) includes all formation evaluation measurements conducted while drilling. This $2.2 billion market has been growing at >25% per year even though rotary steerable technology – RST – drills faster and takes away drilling days, generating less revenue per job.

With the success of rotary steerable, a portion of the LWD market is threatened. RST is sold on a performance basis, charging effectively a high day rate, but LWD is still rented by the day. Offshore, where a well drilled with RST is drilled in half the time, LWD charges are half the size they used to be. Service companies have not been able to raise the LWD day rate, in fact, increasing competition has put downward pressure on day rates.

Source: Spears and Ass. – OMR 2007
Radioisotopes Usage in Formation Evaluation Measurements

Well Logging 101
Well Logging 101

- Reserve Estimates and Archie – the math
- Well Logging – Vertical and Horizontal
- Density Logs – the Gold Standard for porosity
- Neutron Logs – more than just porosity
- Spectral Gamma Ray – clay is deadly to a well
- Frac-Tagging Operations – optimizing the completion
- Tracer and Production Logging – checking the health of the well
- Other Non-Logging Radioisotope Applications
Reserves Estimates and Archie – the math

Producible Oil In Place

\[ N_R = 7,758 \frac{AF}{B_o} \sum_{i=1}^{n} h_i \phi_i (S_o)_i, \]

Producible Gas In Place

\[ G_R = 43,560 \frac{AF}{B_g} \sum_{i=1}^{n} h_i \phi_i (S_g)_i, \]

Porosity

Saturation
Reserves Estimates and Archie – the math

Producible Oil In Place

\[
N_R = 7,758 \frac{A F_R}{B_o} \sum_{i=1}^{n} h_i \phi_i (S_o)_i,
\]

Producible Gas In Place

\[
G_R = 43,560 \frac{A F_R}{B_g} \sum_{i=1}^{n} h_i \phi_i (S_g)_i,
\]
Reserves Estimates and Archie – the math

Archie’s Equation determines the water saturation for each zone being measured

\[ S_w = \left( \frac{R_0}{R_t} \right)^{1/n} = \left( \frac{F R_w}{R_t} \right)^{1/n} = \left( \frac{a R_w}{\phi^m R_t} \right)^{1/n} \]

- Where \( R_t \) is the formation resistivity from electrical and magnetic logs
- \( R_w \) comes from electrical and magnetic and near-by production
- \( \phi \) is the formation porosity from nuclear and acoustic logs
- \( a, m \) and \( n \) are empirically determined parameters
Well Logging - Vertical

1. Data Recording Truck or Unit
2. Conveyance System
   - Armored Electrical Cable
   - Drill Pipe
3. Survey Instruments
Well Logging - Horizontal

30 Foot Average Pay Zone

3000 Foot (or More) Pay Zone
Standard Log Presentation
Density Logs – the Gold Standard for porosity

- Gamma-gamma density measurements depend on interactions between gamma rays and electrons or atomic nuclei within the formation.

- Three types of interactions are important:
  - Pair Production can occur at high gamma ray energies.
  - Compton scattering dominates at moderate energies.
  - Photoelectric effect has an influence at low energies.

- Compton scattering is the most important of these three in gamma-gamma density measurements.
Gamma Ray Absorption Mechanisms

In the energy range between 0.5 and 5 MeV for most abundant elements the COMPTON-effect dominates.
Bulk Density and Electron Density

Gamma-gamma density tools actually respond to electron density rather than bulk density. Electron density is related to the number of electrons per molecule, $\Sigma Z$, and bulk density is related to the total atomic mass per molecule, $\Sigma M$. For most common Earth minerals, the ratio

$$\frac{\Sigma Z}{\Sigma M} \approx 1/2,$$

and thus

$$\rho_e = 2 \frac{\Sigma Z}{\Sigma M} \rho_b.$$
Values for Common Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical Formulas</th>
<th>$\Sigma Z/\Sigma M$ (charge/amu)</th>
<th>$\rho$ (g cm$^{-3}$)</th>
<th>$\rho_b$ (g cm$^{-3}$)</th>
<th>Pe (b/e)</th>
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</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>SiO$_2$</td>
<td>0.499</td>
<td>2.65</td>
<td>2.64</td>
<td>1.806</td>
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<tr>
<td>Calcite</td>
<td>CaCO$_3$</td>
<td>0.500</td>
<td>2.71</td>
<td>2.71</td>
<td>5.084</td>
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<td>Dolomite</td>
<td>CaMg(CO$_3$)$_2$</td>
<td>0.499</td>
<td>2.87</td>
<td>2.87</td>
<td>3.142</td>
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<tr>
<td>Montmorillonite</td>
<td>(Na, Ca)$_{0.33}$ (Al, Mg)$_2$</td>
<td>0.502</td>
<td>2.06</td>
<td>2.02</td>
<td>2.04</td>
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<tr>
<td>Illite</td>
<td>KAl$_4$(Si, Al)$<em>8$O$</em>{20}$</td>
<td>0.499</td>
<td>2.64</td>
<td>2.63</td>
<td>3.45</td>
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<tr>
<td>Illite</td>
<td>(OH)$<em>4$(O, OH)$</em>{10}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Kaolinite</td>
<td>Al$_2$O$_3$:2SiO$_2$:2H$_2$O</td>
<td>0.504</td>
<td>2.59</td>
<td>2.61</td>
<td>1.83</td>
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<tr>
<td>Chlorite</td>
<td>Mg$_5$(Al, Fe)(OH)$_8$</td>
<td>0.497</td>
<td>2.88</td>
<td>2.88</td>
<td>6.30</td>
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<tr>
<td>(Al, Si)$<em>4$O$</em>{10}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-Feldspar</td>
<td>KAlSi$_3$O$_8$</td>
<td>0.496</td>
<td>2.56</td>
<td>2.53</td>
<td>2.86</td>
</tr>
<tr>
<td>Plagioclase (Na)</td>
<td>NaAlSi$_3$O$_8$</td>
<td>0.496</td>
<td>2.62</td>
<td>2.59</td>
<td>1.68</td>
</tr>
<tr>
<td>Plagioclase (Ca)</td>
<td>CaAl$_2$Si$_2$O$_8$</td>
<td>0.496</td>
<td>2.76</td>
<td>2.74</td>
<td>3.13</td>
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<tr>
<td>Barite</td>
<td>BaSO$_4$</td>
<td>0.446</td>
<td>4.48</td>
<td>4.09</td>
<td>266.8</td>
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<tr>
<td>Siderite</td>
<td>FeCO$_3$</td>
<td>0.483</td>
<td>3.94</td>
<td>3.89</td>
<td>14.69</td>
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<tr>
<td>Pyrite</td>
<td>FeS$_2$</td>
<td>0.483</td>
<td>5.01</td>
<td>4.99</td>
<td>16.97</td>
</tr>
</tbody>
</table>
A Simple Lab Experiment

Gamma Ray Source

Gamma Rays

Gamma Ray Detector
Single Detector Gamma-Gamma Density

Gamma Ray
Absorption, or
Gamma-Gamma Density Logs
Dual Detector Wireline Density Tool

Typical instrument configuration:

NaI detectors

Source \( \text{Cs}^{137} \)
Strength \( \sim 2.5 \text{ curie} \)
GR Energy 662 keV
A Dual-Detector MWD Density Tool

- γ Source
- Near detector
- Far detector
- “Fluid displacer” to bring detectors closer to the formation.
- Collimated source and detector windows
- Tungsten shielding
Neutron Logging – more than just porosity

- Neutrons from the source enter the formation and lose energy, mostly by elastic (billiard ball) scattering
- Hydrogen, located in the pore space, normally plays the most important role in this process
- Porosity is determined from neutron counting rates
- Neutron and other measurements are used together for more detailed analysis
Elastic Neutron Scattering – “Slowing Down”

- Neutrons are slowed through collisions with atomic nuclei until they reach thermal equilibrium.
- Hydrogen usually plays the most important role in this process.
Thermal neutrons diffuse from volumes of higher concentration towards volumes of lower concentration.
Thermal Neutron Capture

- Thermal neutrons are captured by atomic nuclei which then emit gamma rays.
- Chlorine usually plays the most important role in this process.
A Simple Experiment

Formation of porosity $\phi$ and thickness $D$

Neutron Source

Neutron Flux

Thermal Neutron Detector
Compensated Neutron Log

Typical instrument configuration:

He$^3$ detectors

Source: AmBe or Cf$^{252}$
Strength: 15 - 18 Ci or $\sim$18 mCi
Output: 4.5 or 2.35 MeV Neutrons
Half-life: 432 years or 2.6 years
Rate: $\sim$4 X $10^7$ Neutrons/sec
Typical CN Log Responses
Spectral Gamma Ray – clay is deadly to a well

- The energies of the gamma rays are used to measure amounts of potassium, uranium and thorium in the formation.
- Concentrations of these, plotted along with total gamma ray counts are used in the identification of clay type and for other reasons:
  - Adjustment for total pore space available due to clogging by the clays (subtracts available porosity).
  - Affect of clay types on the design of stimulation and treatment practices for the well (Clay swelling).
Radioactive Tracer & Production Logging – checking the health of the well.

- Short half-life radioactive tracers are injected into the well fluids under dynamic or static conditions to monitor flow of the fluids.
- Dual detectors can calculate the direction and flow rates inside and outside of the casing or tubing.
- Density-type production logs can detect changes of produced fluid density within the well-bore to determine contribution of fluids and gasses vs depth to optimize the production.
- Pulsed-neutron logs are used for monitoring changing fluid levels behind pipe in the formation and giving indications of by-passed production.
Other - Non-Logging Radioisotope Applications

- Essential in the life of oil and gas wells
  - New Well Completions
    - Frac Tagging, Pips, ROP
  - Old Well Re-completions
    - Frac Tagging, ROP

- Improvement in efficiencies and safety
  - Stimulation
  - Production
  - Deliverability (Pipeline)
    - Industrial Radiography
  - Refining (Process Piping)
    - Industrial Radiography
Frac-Tagging Operations

- Radioisotopes introduced into the fluids that are used to force the rock formations to fracture by pump pressure and to remain open by proppant.

- Isotopes commonly used
  - Iridium-192 and 194 (40-100 mCi)
  - Scandium-46 (40-100 mCi)
  - Antimony -124 and 122 (40-100 mCi)

- Identifies fracture height, depth and efficiency
  - Spectral GR detector measures
    - Emergence of pumped-in isotopes back to the wellbore vs time for frac flow efficiencies
    - Shape of fracture envelope
    - Total vertical height of fracture
Frac-Tagging Log
Other - Non-Logging Radioisotope Applications

- Industrial Radiography
- Radiological Positioning - pips
- Radiological Orientation – perforating (ROP)
- Storage Cavern Fluid Levels
- Density Gauges
Tracer Isotopes and Half-lives

- Iridium-192 (Ir-192) 73.8 days
- Iridium-194 (Ir-194) 19.3 hours
- Scandium-46 (Sc-46) 83.81 days
- Antimony -124 (Sb-124) 60.2 days
- Antimony -122 (Sb-122) 2.7 days
- Sodium -24 (Na-24) 14.96 hours
- Iodine-131 (I-131) 8.1 days
- Silver-110m (Ag-110m) 249.8 days
- Bromine – 82 (Br-82) 1.5 days
- Cobalt-60 (Co-60) 5.3 years
- Gold-198 (Au-198) 2.7 days
# Typical Source Summary

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<tr>
<th>Service</th>
<th>Source Field</th>
<th>Calibrator/Verifier</th>
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<tbody>
<tr>
<td>Gamma Ray</td>
<td>none</td>
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</tr>
<tr>
<td>Spectral GR</td>
<td>none</td>
<td>2.5 μCi Ra-226</td>
</tr>
<tr>
<td>Tracer logging</td>
<td>tracer</td>
<td>2.5 μCi Ra-226</td>
</tr>
<tr>
<td>Spectral Density</td>
<td>2.5 Ci Cs-137</td>
<td>540 μCi Cs-137</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.8 μCi Cs-137 ECS</td>
</tr>
<tr>
<td>CN</td>
<td>15 - 18 Ci AmBe</td>
<td>400 mCi AmBe</td>
</tr>
<tr>
<td></td>
<td>10 – 20 mCi Cf$^{252}$</td>
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</tr>
<tr>
<td>PNL (all modes)</td>
<td>pulsed D-T $\sim 10^8$ n/s</td>
<td>2.5 μCi Ra-226</td>
</tr>
</tbody>
</table>

Sources used by other companies will be slightly different
QUESTIONS?