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High Gamma Ray in the Steam Chamber:
A New Method for Continuous Observation of the EOR Process

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Summary

Well logs from heavy oil development wells in the San Joaquin Valley, California, frequently record high gamma ray (GR) values through intervals of the hot, vapor-filled rock that remains after injected steam at temperatures greater than 250 degF displaces heavy oil. GR values that exceed 20,000 GAPI and are 400 times greater than those in similar, but liquid-filled, rock have been observed. These high GR values occur on open-hole logs through new wells that intersect a steam chamber, after circulation of mud while drilling temporarily cools a well, causing hot vapor to condense around the well. After a completed well re-heats, GR decreases to normal levels. Subsequent circulation of cool water regenerates the high GR. The GR energy spectra matches the uranium series and identifies highly mobile radon and its progeny as the GR source. An experiment demonstrates that radon adsorbs to pentane molecules in the vapor phase, and condensation concentrates these molecules, causing GR to increase. The increase in GR is proportional to the rock volume that supplies the radon, implying that the volume of investigation can be hundreds of times greater than the normal volume sampled by the GR logging tool. The experiments and observations described here are at the foundation of a new technology for observing and optimizing EOR processes.

Introduction

Heavy oil reservoirs in the San Joaquin Valley, California have been developed with cyclic and continuous steam injection since the 1960s. The targeted reservoirs for these giant oil fields consist of massive sands, spanning an interval up to 600 feet thick, with few shale barriers. Quartz and plagioclase feldspar comprise 75% or more of the reservoirs, and clay content is typically less than 5%. Average porosity for these clean sands is 25 to 35%, and permeability is greater than 1,000 mD, but the viscosity of the oil can be 10,000 times greater than water. Steam injection is used to lower the viscosity, and gravity drainage is used to recover the oil. Thousands of vertical wells have been drilled to implement the steam flood process, typically with total depth less than 2000 feet. Prior to steam injection, logs show that oil-saturated reservoir rock has natural gamma ray values less than 100 GAPI. After steam displaces the heavy oil, these clean sands contain hot vapor, residual oil and water.

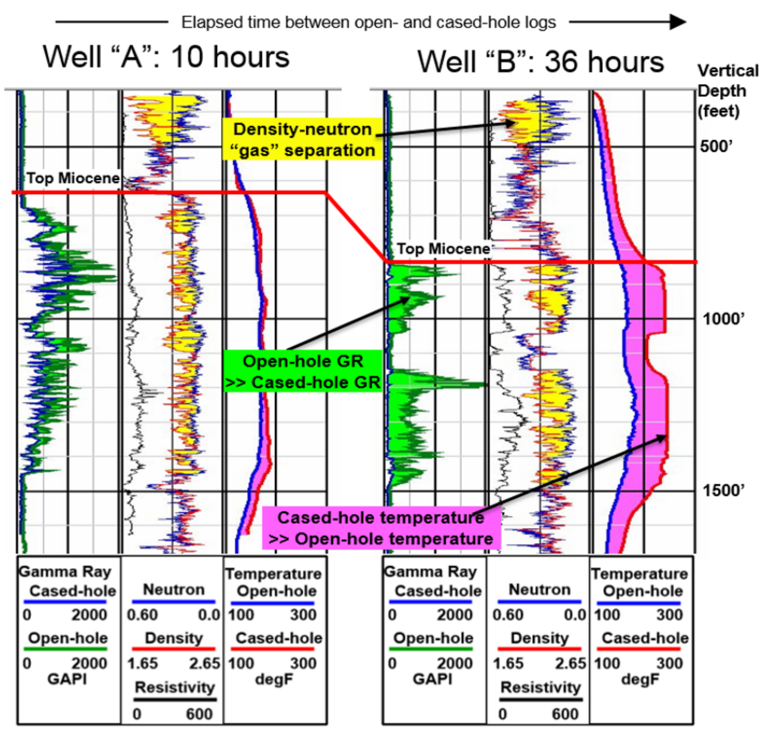

Figure 1. Open- and cased-hole logs from two wells. For well "A", elapsed time between logs is only 10 hours, the cased-hole well is still cool, and the GR log repeats. For well "B", the well has reheated after 36 hours, and GR returns to normal.

When the steam chamber is logged in new wells targeting deeper reserves, GR often exceeds 1000 GAPI, but only while the well is cool.

Figure 1 shows examples of logs from two wells, drilled through developed steam chamber hotter than 250 degF. In well "A" the elapsed time between the open- and cased-hole logs was only 10 hours. While the well was still cool, the cased-hole GR log repeated the open-hole log, with values through the steam chamber that approach 2000 GAPI. For well "B", which has equilibrated with the hot reservoir, the cased-hole GR is much lower than the open-hole GR. To convincingly demonstrate that cooling causes the GR signal to be generated, a cased well that had exhibited the transient high GR signal was cooled by circulating water. After 6 hours, the open-hole GR was regenerated (O'Sullivan, 2008).

Theory and Method

Figure 2 compares GR spectra for a 10-minute station, at a depth where the open-hole GR log was 2000 GAPI, to a uranium standard for which counts were accumulated for days. The GR station is noisier because it was only recorded for 10 minutes, but peaks at 1378 and 1764 keV closely match the uranium standard. These peaks are due to the decay of bismuth-214, which is produced less than 1 hour after radon decays. Small differences exist for potassium and thorium because these elements are present downhole, but not in the uranium standard.

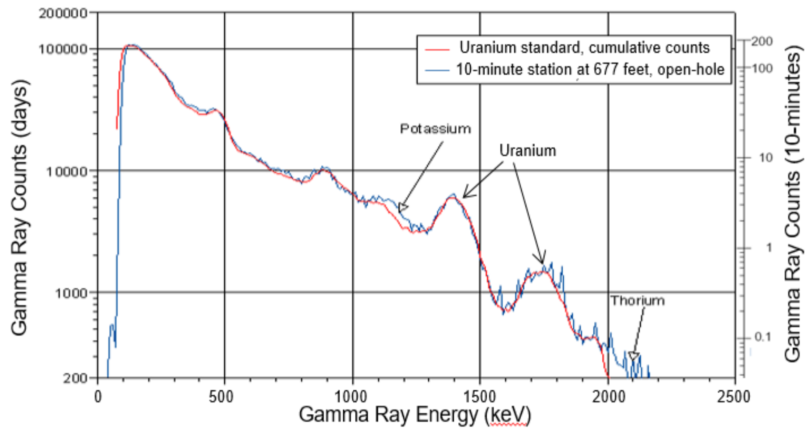

Figure 2. Open-hole gamma ray spectra matches uranium, but also has small amounts of potassium and thorium.

In Figure 3, cased-hole GR decreased to 100 GAPI and temperature increased to 218 degF. Comparison of the spectra shows that the uranium peaks on the cased-hole log are greatly diminished. As a result, GR decreased from 2000 to 100 GAPI specifically because, at the time of the cased-hole log, the concentration of radon (and therefore bismuth emissions) has greatly decreased.

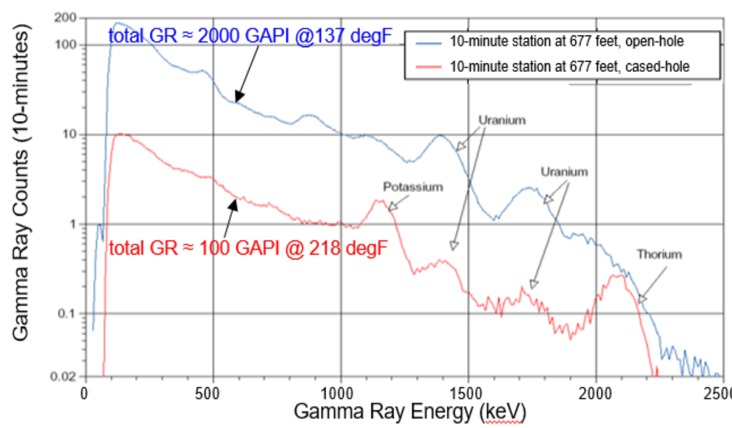

Figure 3. Open- and cased-hole gamma ray spectra do not match because uranium is missing from the cased-hole spectra. Note the large decrease in counts, compared to the open-hole GR.

Two factors appear to cause radon to become concentrated near a cool well: 1) physisorption enables non-polar radon to adsorb to carbon compounds (Noel, 2015), causing radon to be 300 times more soluble in hydrocarbon than in water (UNSCEAR, 1982), and 2) in a hot vapor cloud, condensation near a cool well causes vapor with adsorbed radon to become concentrated by 100 times or more as condensate accumulates at the well. There is a problem with this theory, however, because the attractive force of physisorption is not known to be strong enough to enable radon to adsorb to vapor.

A simple experiment was used to determine if it is possible for radon to adsorb to hydrocarbon molecules in the vapor cloud and then migrate with condensing vapor as it moves to the well. In the experiment, pentane (BP 97 degF) saturated with radon was contained in a closed vessel, while the temperature of the vessel slowly varied from 60 to 110 degF, driven by diurnal cooling and heating. As temperature and pressure increased, pentane vaporized and GR counts measured at the bottom of the tank decreased (Figure 4). The decrease in GR occurred because radon vaporized with the pentane, effectively moving radon-tagged pentane molecules away from the detector. GR increased as the tank cooled and radon-tagged vapor condensed. The pattern of GR increase and decrease repeated consistently for 4 days.

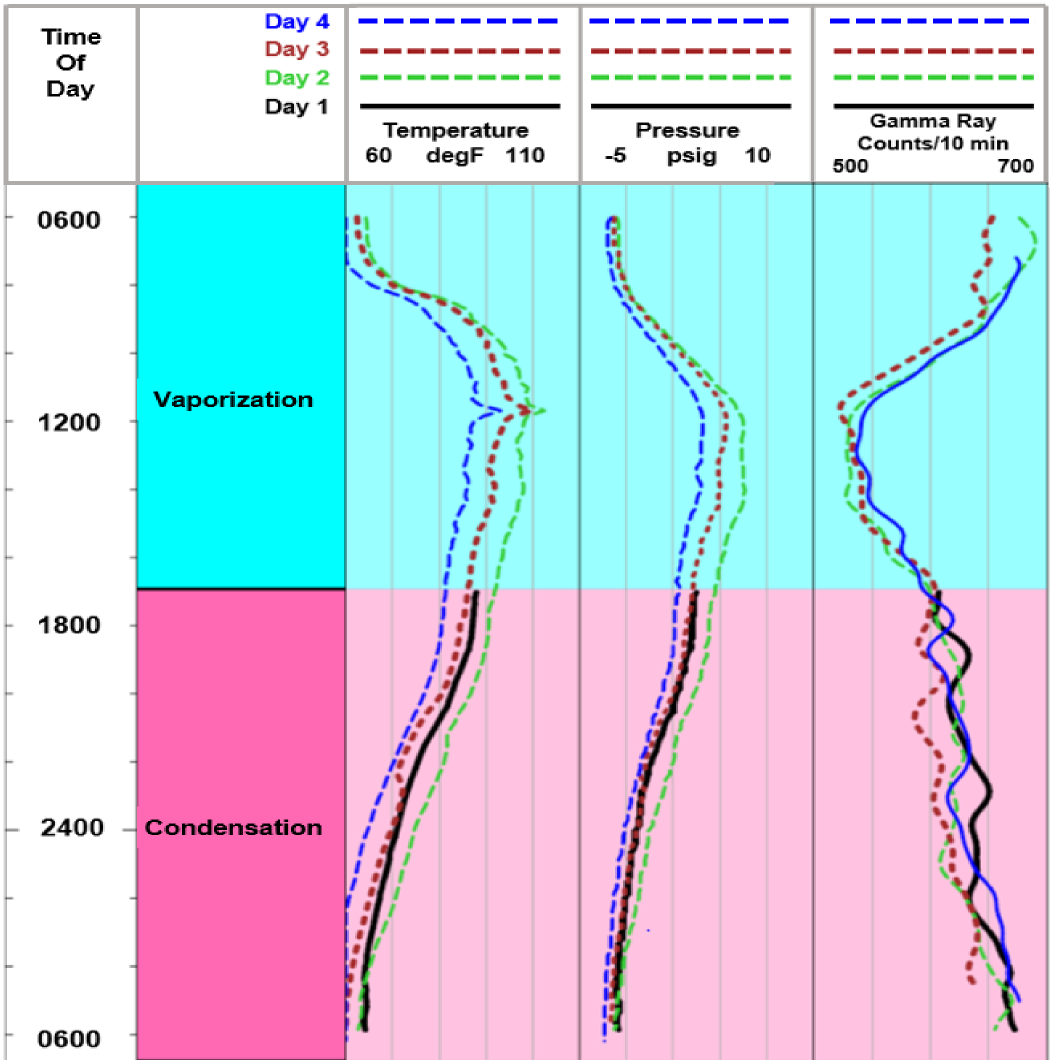

Figure 4. *For a pressure vessel containing pentane and a radon source, GR measured on liquid at the base of the tank varied as pentane saturated with radon vaporized and condensed.*

Examples

Transient and high GR values observed in individual wells are interesting, but do they reflect reservoir properties or simply a localized phenomenon? To evaluate this, a regional study involving thousands of wells was completed (O'Sullivan, 2015). Figure 5 includes logs from 7 wells that have GR values as high as 25,000 GAPI. The wells were drilled through this developed interval to a deeper target. Distance between the wells, which were drilled over a 7-year period, is less than 200 feet. The strong correlation and persistence of the high GR response indicates that there is a connection to a reservoir-scale process, but the extremely high amplitude of the GR in these wells is surprising. Residual oil saturation in these high permeability steam-flooded sands is very low, so if GR amplitude increases with hydrocarbon vapor concentration, these sands would be expected to have low GR. The explanation for the high GR is that there is a deeper reservoir, containing lighter oil that is in communication with this shallow, heavy oil reservoir. Lighter, more volatile hydrocarbons have higher vapor pressure and should adsorb more radon. Time-lapse analysis showed that the high GR values only developed after a steam injection process began in the deeper reservoir, driving the volatile hydrocarbons upward.

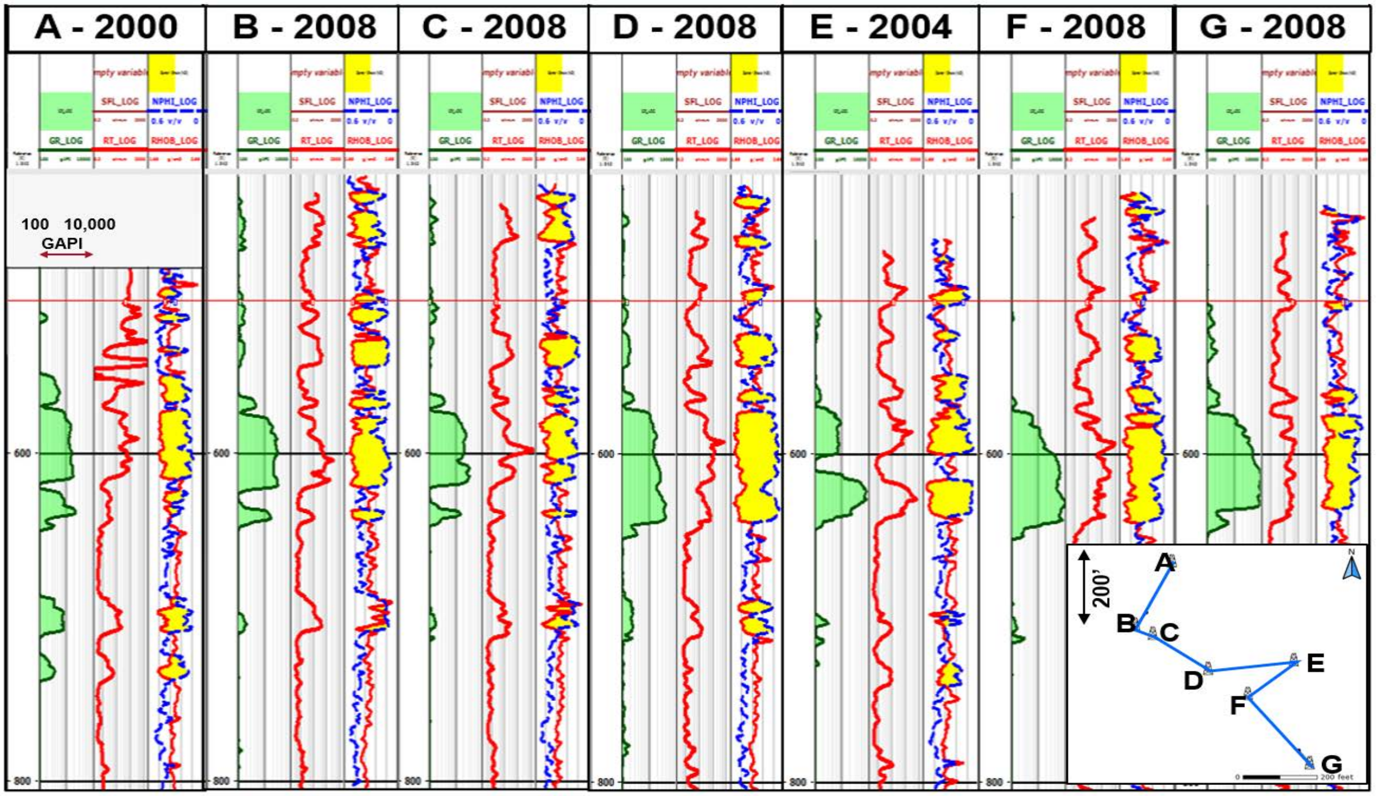

Figure 5. *High GR is strongly correlated for a group of closely-spaced wells at South Belridge Field.*

Conclusions

The transient and high GR response in cooled wells through rock containing vapor is an unexpected reservoir-scale transport phenomena that develops after naturally-occuring radon adsorbs to vapor, especially hydrocarbon vapor. Condensation of hot vapor surrounding a cool well causes radon-tagged vapor to be transported to the well. This concentration process enables a small amount of condensate to generate a very large increase in GR. An increase in GR by a factor of 100 requires radon to be transported from a volume of rock that is at least 100 times larger than the GR measurement volume. The actual volume is larger because the transport process is not perfectly efficient.

Observation of vapor properties and transport, together with simulation of the process, is expected to provide a new technology that will enable operators to continuously monitor and optimize the efficiency of enhanced oil recovery processes, especially those that involve the injection of steam and solvent.

References

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