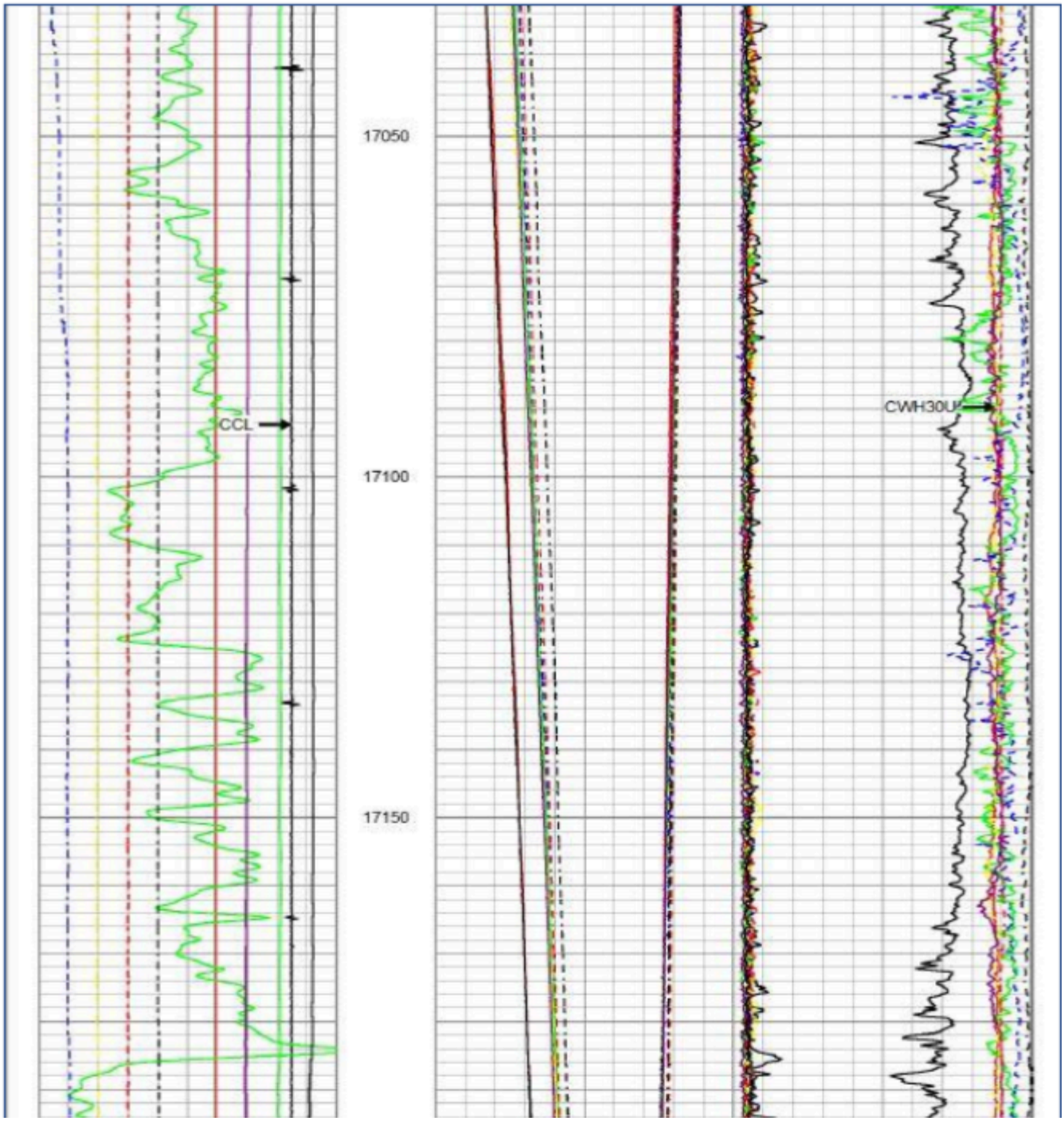
Chapter 4 - Gamma Rays



Chapter 4 - Gamma Ray

Content

Natural Gamma Ray

Natural gamma ray tools provide measures of the amount of naturally occurring gamma radiation emitted by a formation. These gamma rays are produced by the radioactive decay of the elements potassium, uranium and thorium which occur in variable amounts in all formations.

Applications

The most fundamental use of a natural gamma ray tool is to assist in determining formation lithology. Different types of rocks contain differing quantities of potassium, uranium and thorium. Accurate lithology determination is only possible by incorporating the gamma ray measurement with other lithology-dependent measurements such as those provided by the density and neutron logging tool.

Clay minerals—the main components of shale—often contain large quantities of potassium. Therefore, the gamma ray response can also be used to estimate the volume of shale (or VSH) of a formation.

The natural gamma ray measurement also provides a means of correlating log responses from one well to another so that the geologic structure and stratigraphic setting of a region can be interpreted. Formation boundaries between two contrasting lithologies and formation thickness can also be determined from the gamma ray. Finally, the gamma ray measurement is often used for depth control correlation between multiple logging passes in the same well.

Logging Conditions

Natural gamma ray tools are among the most universal of all logging tools and are capable of acquiring data in most well conditions, including cased holes. The natural gamma ray tool is designed to measure the total gamma radiation resulting from the radioactive decay of potassium, uranium and thorium. If knowledge of specific concentrations of these elements is necessary for more advanced applications, then a spectral gamma ray tool is needed.

Physics of the Measurement

A gamma ray is a form of high-energy electromagnetic radiation that is spontaneously emitted from the nucleus of an atom. Gamma rays are photons; they have no mass and no charge. They can be thought of as either particles or waves that travel at the speed of light (Fig. 1).

Figure 1. Gamma rays are one form of electromagnetic radiation.

Radiation Type	Energy Level
Gamma Rays	1 GeV - 1 MeV
X-Rays	1 keV
Infrared	1 eV
Short Radio Waves	1 μeV to 1 meV
Long Radio Waves	< 1 μeV

Gamma rays are emitted through the process of radioactive decay of potassium (K40), uranium (U238) and thorium (Th232). These elements exist in variable quantities in all formations. Many rock-forming minerals contain K40. One example is the feldspar mineral orthoclase. On average, sandstones contain about 12% orthoclase, although some sandstones can contain a significantly larger or smaller quantity.

Orthoclase $KAlSi_3O_8$

Clay minerals such as montmorillonite also contain significant quantities of K40. These clay minerals are the main components of shale.

Montmorillonite $KAl_4(Si_4O10)(OH)_8$

Igneous rocks such as granite may have high concentrations of uranium and thorium. If these igneous rocks are eroded to produce sediments that are ultimately deposited to form sandstones and other sedimentary rocks, then the resulting sedimentary rocks will inherit the radioactive characteristics of their parent rock.

The igneous rock granite can also contain large quantities of orthoclase. Therefore, sediments derived from granite can have high levels of gamma radiation produced by the radioactive decay of K40, U238 and Th232.

Most formations spontaneously emit at least some small level of gamma radiation. The average concentration of potassium in Earth's crust is about 2%, whereas uranium and thorium exist in much smaller concentrations; 2.7 ppm and 9.6 ppm, respectively. The relative amounts of these elements can vary between different rock types as well as within a single formation.

Deep water marine shale often contains the largest quantity of these elements, and continental shale deposited in delta and lake environments contain somewhat smaller quantities. Continental shales contain roughly twice the amounts of these elements as the average sandstone. Carbonates often contain only small quantities of these elements, although some dolomites may exhibit large concentrations of uranium.

Radioactive Decay

The elements K40, U238 and Th232 exist in at least trace amounts in all formations. These elements are transformed into other elements over millions and millions of years. This transformation, or radioactive decay, involves the emission of energy in the form of gamma rays as an element attempts to achieve its lowest energy state. The radioactive decay of elements began when the universe was formed, and continues today as the primary source of heat within Earth.

Potassium-40 Decay

Potassium-40 (K40) with a half-life[1] of 1.3 billion years, ultimately decays to the stable element argon (Ar40). During this decay process (Fig. 2), the nucleus of Ar40 will emit a single gamma ray with energy of 1.46 MeV[2]. The larger the quantity of K40 in a formation, the more gamma rays emitted.

Figure2. The radioactive decay sequence of potassium-40.

Uranium-238 Decay

Uranium-238 (U238) experiences a much longer and more complex decay sequence (Fig. 3) than K40, and it ultimately transforms into a stable lead element (Pb). The half-life of U238 is 4.4 billion years.

Figure 3. The radioactive decay sequence of uranium-238.

The decay of U238 involves a series of individual decays, some of which produce gamma rays at different energy levels. Therefore, gamma rays resulting from the radioactive decay of uranium will have a range of energies. However, a measurement of the amount of gamma rays emitted provides an indication of the relative amount of uranium in the formation.

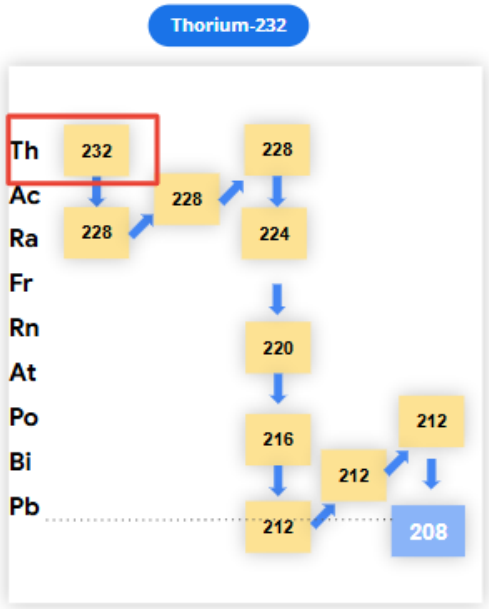
[1] Half-life is the period of time required for a radioactive material to lose one-half of its radioactivity by decay. In other words, over this time half of the radioactive element has spontaneously disintegrated.

[2] An electron volt (eV) is a unit of energy equal to the kinetic energy acquired by an electron passing through a potential difference of 1 volt. A gamma ray with an energy of 1 MeV (mega-electron volt) would have the same striking power as an electron accelerated through a 1,000,000 volt potential.

Thorium-232 Decay

Thorium-232 (Th232), like U238, experiences a long and complex decay sequence (Fig. 4), resulting in a stable lead element (Pb). The half-life of Th232 is 14 billion years.

Figure 4. The radioactive decay sequence of thorium-232.



Thorium-232 decay involves a series of individual decays, some of which produce gamma rays at different energy levels. Gamma rays resulting from the radioactive decay of Th232 therefore have a range of energies. However, a measurement of the amount of gamma rays emitted provides an indication of the relative amount of thorium in the formation.

Scintillation Detectors

Modern gamma ray tools such as the natural gamma ray tool employs scintillation detectors to measure the amount of naturally occurring gamma radiation in a formation. A gamma ray emitted from the formation interacts with a man-made crystal that creates a tiny pulse, or scintillation, of visible light. These flashes of light are detected by a photo-sensitive device that then passes an electrical signal to the measurement circuitry of the tool.

Figure 5. Scintillation detectors (4-inch at left, and 8-inch at right).

The detector assemblies of the natural gamma ray tool contain a transparent man-made crystal of sodium iodide (NaI) with small impurities of thallium (Tl). The microscopic thallium impurities are known as activators and are directly responsible for emitting a pulse of visible light when excited by a gamma ray entering the crystal.

Molecules of sodium (Na) and iodine (I) within the crystal are rather weakly bound. A gamma ray entering the crystal causes the excitation of these molecules, and this excitation is transferred to the thallium activator impurities. The thallium

activators then emit a photon in the visible portion of the electromagnetic spectrum. In other words, each gamma ray entering the NaI scintillation crystal generates a tiny pulse of light in a process that takes about 230 nanoseconds.

Photo-Multiplier Tube (PMT)

The NaI scintillation crystal is coupled to a photo-sensitive device, or photo-multiplier tube (PMT), using optical grease that allows the passage of light. This PMT (Fig. 6) consists of a photosensitive cathode, a series of dynodes at successively higher potentials, and a collection anode.

Figure 6. Schematic of a natural gamma ray detector assembly.

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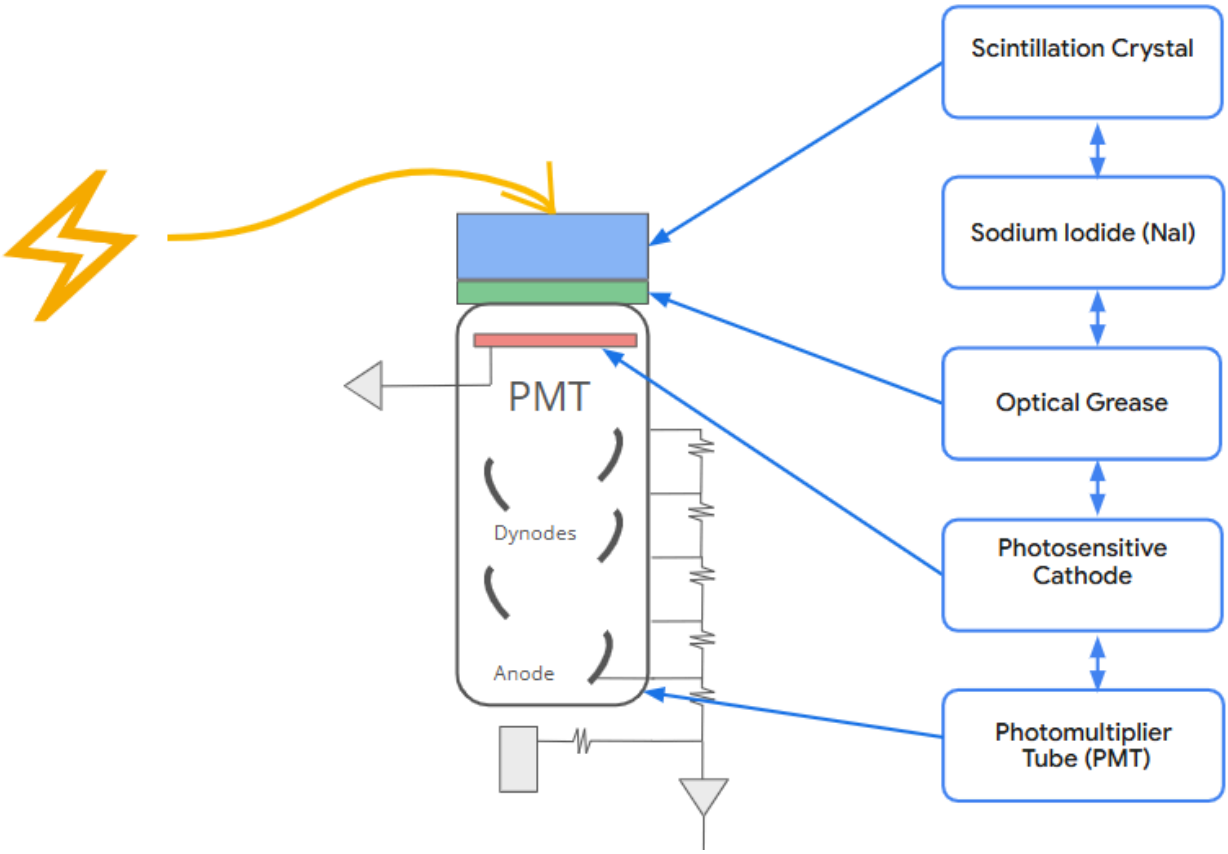


The photo-sensitive cathode of the PMT emits electrons each time it is struck by a light pulse passed from the scintillation crystal. These electrons pass through a

high voltage field to the first dynode where they have high enough energy to produce several more secondary electrons. These secondary electrons are accelerated to the next dynode in the series where additional multiplication takes place. A typical MPT with 9 to 11 dynodes results in a multiplication of 105 to 107 electrons for every gamma ray detected.

The avalanche of an ever-increasing number of secondary electrons is ultimately collected at the anode of the PMT which then generates a small electrical pulse for each gamma ray detected. This electrical pulse is amplified and passed through a discriminator to eliminate any electronics noise, and is then counted as a single gamma ray. The number of gamma rays detected over a specified interval of time (or count rate) is proportional to the total amount of potassium, uranium and thorium in the formation.

With a spectral gamma ray tool such as the Spectral Gamma Ray, the height of the electrical pulse is used to identify the energy level of the detected gamma ray. Therefore, the relative contributions of potassium, uranium and thorium to the overall count rate can be determined with the Spectral Gamma Ray for use in more detailed lithology identification.

Standardization of Units

The measurement acquired by a natural gamma ray tool is simply a count rate of gamma rays received at its detector. This measurement (in units of counts per second) is not particularly useful and must be converted to engineering units. Conversion of the raw measurement to engineering units is accomplished through calibration. The calibration process also ensures all gamma rays tools, regardless of service company or tool model, measure the same response in the same formation.

Factors Influencing Count Rates

The count rate of gamma radiation measured at a scintillation detector is not solely a function of the amount of natural gamma radiation emitted by a formation. Certain factors such as the type and size of the scintillation crystal and the composition of the tool housing can also influence the count rate. For example, two gamma ray tools would present a different response when logged in the same well.

If these two tools are logged in the same well, then their measured count rates of gamma radiation might be quite different. The differences can be attributed to any number of potential causes, including:

• The type of crystal used. Natural gamma ray detectors often employ NaI crystals, bismuth germinate (BGO) or cesium iodide (CsI). The more dense the crystal, the better its counting efficiency.

• Differences in the lengths of crystals. Some tools use a 4-inch crystal while other employs an 8-inch crystal. Larger crystals measure higher count rates.

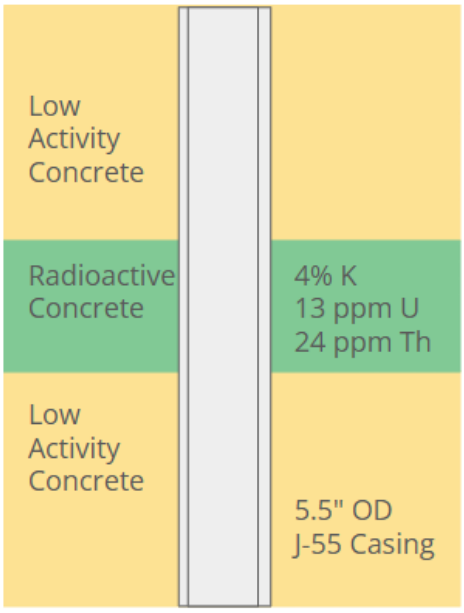
• Differences in crystal diameters. Crystals with larger diameters measure higher count rates.

• Differences in tool housings. The composition and thickness of the tool housing influences the amount of gamma radiation that reaches the detector.

Calibration Standards

Until the 1960s, service companies presented gamma ray results as raw count rates. This caused inconsistent gamma ray responses between service companies, and often between different gamma ray tools from one service company that were logged in the same well. Even identically designed gamma ray tools might have small impurities in their detector crystals or other irregularities that result in different count rates in the same formation. A standard calibration method was first prescribed for all gamma ray tools by the American Petroleum Institute (API) which constructed a gamma ray test pit (Fig. 7) at the University of Houston in 1958.

Figure 7. The API gamma ray test pit.



The gamma ray test pit consists of an "artificial shale" with known concentrations of potassium, uranium and thorium. This high-radioactivity interval is layered between two very low-radioactivity intervals of cement. Each service company designates a standard tool that is to be used for measuring the count rates of gamma radiation produced by these high- and low-radioactivity intervals in the API test pit.

The engineering unit for a gamma ray measurement is the Gamma API (GAPI). One GAPI is defined as 1/200th the difference in log deflection (or measured count rates) between the zones of high-radioactivity and very low-radioactivity in the API test pit.

For the standard tool that is logged in this test pit, a sensitivity factor (or gain) is calculated by the following equation:

$$\text{Sensitivity} = \frac{200\ \text{GAPI}}{\text{High Count Rate} - \text{Low Count Rate}}$$

Sensitivity is the conversion factor (or "gain") used for transforming the raw measurement (counts per second) into engineering units (GAPI). Once sensitivity for

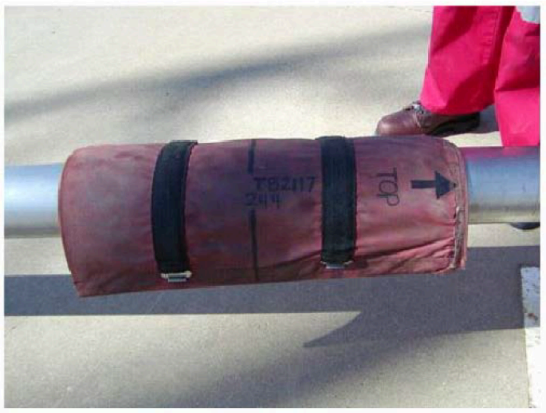
the standard tool is known, its response in any well is governed by the following equation:

$$GAPI = Sensitivity \times Raw\ Count\ Rates$$

It would not be practical for service companies to calibrate each of their gamma ray tools in the API test pit. However, it is necessary that each tool be calibrated in such a way that a response identical to that of the standard tool is ensured. Service companies, therefore, use their standard tool and its known sensitivity to measure the GAPI values of a calibrator.

Almost all oil services providers use thorium blanket calibrators (Fig. 8) for calibrating the response of its gamma ray tools. These calibrators, containing a small concentration of Th232, are assigned a GAPI value determined by the standard tool. The calibrator is then used for shop calibrations and wellsite verifications. This method ensures that all gamma ray tools from different service providers provide identical responses.

Figure 8. Thorium blanket calibrator used for gamma ray tools.



Shop, field and post Calibration

A gamma ray tool should be calibrated at the shop. (at the service provider's shop), then before running in hole (at the wellsite) a field calibration should be performed to verify that the tool arrived in good conditions, after completing the logging run the gamma ray must be also calibrated to verify that the tool worked properly. So if you are in location watching wireline loggings tools being run keep an eye on the wireline engineer who should perform this procedure.

GR in logs

Figure 9. Cement evaluation log

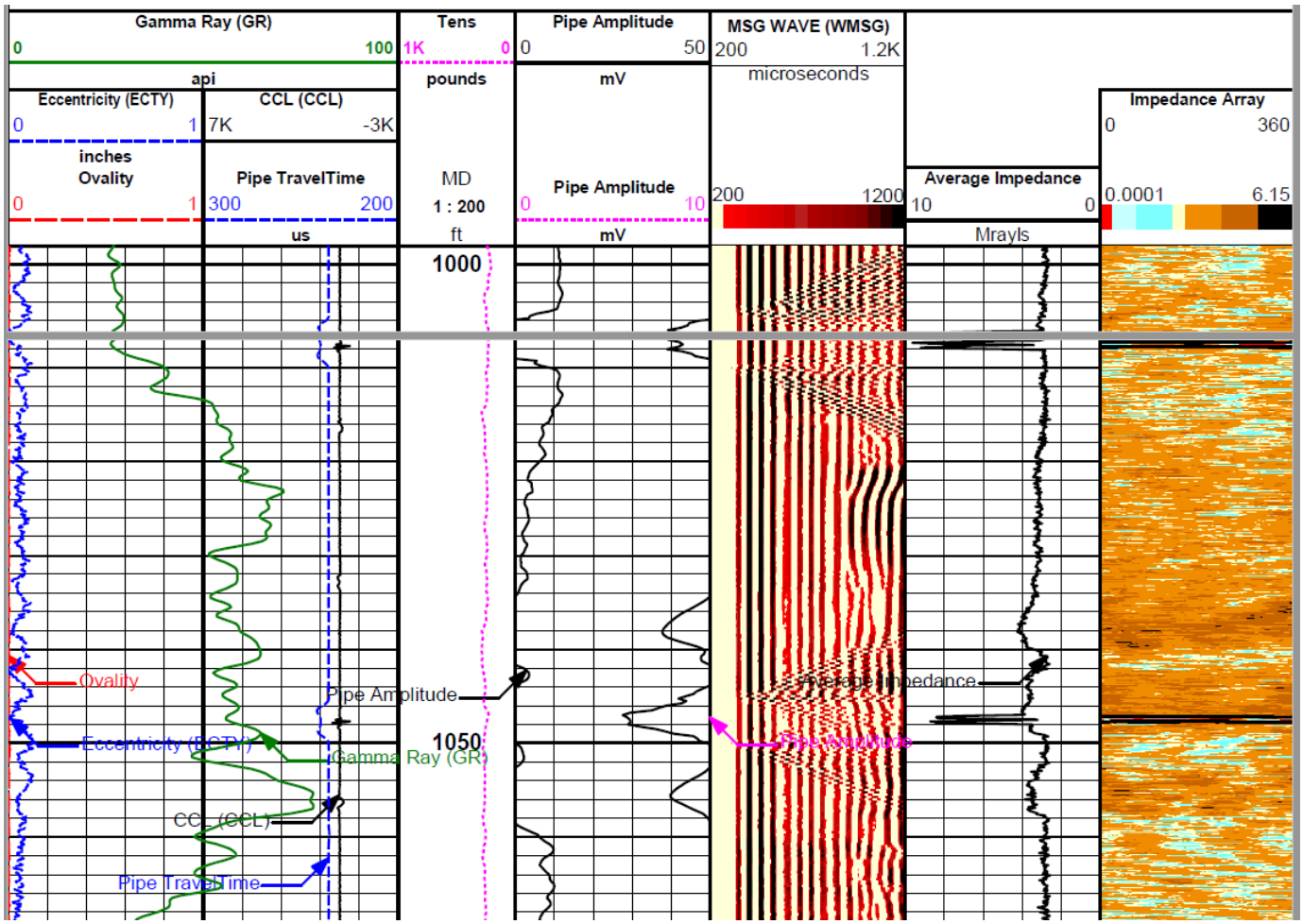


Figure 10. Pulsed Neutron log