Advancing Wellsite Radiation Safety

Elimination of radioactive material from the wellsites is closer to reality because of a safety program that is reshaping nuclear logging tools and techniques.

Oilfield radiation safety in the 1990s is a road that branches in three directions. On one road are new logging tools and techniques that avoid the need for chemical nuclear sources—either replacing nuclear techniques with nonnuclear ones, or replacing radioisotopes with particle accelerators, which lack sources of high radioactivity.

On another path, where chemical sources are still needed, is the upgrading of shields and handling techniques to further reduce risk of exposure to personnel and the environment. This road also involves more efficient fishing capabilities and better detection of concentrations of naturally occurring radionuclides, such as radium in the scale buildup in tubing.

And on the third branch is replacement of conventional wellsite calibration sources with sources of negligible radiation intensity or with nonnuclear wellsite verification of shop calibration. This article reviews these three efforts at enhancing radiation safety.

The Accelerator Frontier

Considerable effort is being devoted to development of logging methods that eliminate or reduce dependence on radioactive material. One way is to increase the number of measurements made with a downhole particle accelerator, which does not generate radiation until it is switched on.

The miniature accelerator, called a minitrion, generates neutrons by bombarding a tritium $^3$H target with deuterium $^2$H. Tritium is relatively innocuous because it emits only beta ($\beta$) particles (electrons), which cannot escape their encapsulation.

The neutrons stream out of the minitrion and "activate" the formation, generating radioactive isotopes. As these isotopes decay, they give off gamma ($\gamma$) rays. When the logging tool detector passes the activated interval, it records a gamma ray count rate that can be related to the weight percent of the activated elements.

The activated elements of interest—aluminum, chlorine, iron, oxygen, silicon and sodium—each give off gamma rays with characteristic energies and unique half-lives, the time in which half the activated population decays to a stable state (see "Radiation Units of Measure," page 161). The duration of these half-lives allows easy identification of each element: the oxygen half-life is 7.13 seconds, silicon and aluminum 2.3 minutes, chlorine 37 minutes, iron 2.6 hours and sodium 15 hours. This half-life fingerprint has opened the door to two new accelerator-based techniques, one for gravel pack logging and another for measurement of water flow behind casing.

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Gravel Pack Logging

Conventional gravel pack logging is performed by lowering a chemical source of γ rays into the borehole and counting the number of γ rays that reach the detector. This count rate is inversely proportional to the density of the material crossed by the γ rays and can be related to voids in the gravel pack.

In place of the chemical gamma ray source of the conventional Nuclear Fluid Densimeter (NFD) tool, the new gravel pack method employs the minitron of the Dual-Burst Thermal Decay Time (TDT®) tool. Although this neutron source activates many elements, the appropriate logging speed—600 to 900 feet [180 to 275 meters] per hour—favors the counting of only γ rays from silicon and aluminum (top). Because silicon and aluminum are major constituents of gravel packing material, and because most of the signal comes from near the borehole, most of the measurement is of gravel packing material rather than formation. Activation gamma ray counts can therefore be correlated with percent pack (below). The neutron activation log agrees well with the conventional NFD log in the gravel pack zone (next page, above).

In addition to the advantage of no downhole chemical source, the neutron activation log sidesteps a resolution problem inherent in the conventional method: the densities of the carrier fluid and the packing material become similar, the conventional method has more difficulty distinguishing packed from unpacked intervals. This is becoming a more common problem with increased use of low-density particles and high-density fluids. The new method is insensitive to changes in borehole fluid density and has a better dynamic range (defined as the ratio of the range of count rate variation between fully packed and void completions to the maximum count rate).

A limitation of the technique is that its sensitivity to formation beyond the gravel pack increases as hole diameter decreases. For example, in a 10-inch borehole, a 20 to 40 percent porosity sand, the formation contribution creates an error in the packing efficiency estimate of ±20 percent. Also, as with the NFD tool, the upper and lower limits of log response—zero pack and 100 percent pack—are picked by hand. Under development is a computer code that will calculate the end points based on casing inner diameter, bit size, screen outer diameter and screen thickness.

4. Mark of Schlumberger
5. Mark of Dowell Schlumberger

Water Detection

Another new minitron-based measurement, the Water Flow Log (WFL®) service, provides a measure of water flowing behind casing (next page, below). The technique uses a Dual-Burst TDT tool to perform oxygen activation for water flow evaluation, some of which has traditionally been done by injecting a radioactive tracer, 131Iodine. The technique has four applications:

- To locate the source of water in production wells
- To replace radioactive tracer surveys
- To show whether water is flowing toward aquifers—important information where the safety of agricultural or drinking water is of concern
- To measure water cut inside casing (when used with the fullbore flowmeter). The fullbore flowmeter measures total flow, and the WFL measures water flow only. This is a potentially important application in horizontal wells, where the Gradiomanometer® tool does not work because it uses a pressure difference over height at different depths to give a fluid density.

The WFL measurement is based on activation of oxygen to 18nitrogen, which emits γ rays as it decays with a 7.13-second half-life. Doing away with 131I gives the WFL survey a safety advantage because even tiny amounts of the tracer are biologically active (see “Radiation Effects,” page 19).

Because of its biological activity, usage of 131I is carefully controlled. Many countries require that all fluids produced from a well recently surveyed with 131I be held in tanks for six to eight half-lives (46 to 64 days). This short half-life is both blessing and curse. Although the radioactivity dissipates relatively quickly, getting potent 131I to a
Remote location can be difficult. Indeed, regulatory control can delay transport even to accessible wellsites.

From an operations standpoint, the main advantage of the WFL measurement is that it does not have to reference to a zero flow measurement. In application of the conventional measurement, stationary oxygen in the borehole, cement and annulus is activated along with oxygen in the flowing water. The method must be calibrated to a zone of zero flow so that the zero-flow count rate can be subtracted from subsequent measurements to determine the net count rate from flowing oxygen. But because the new method uses a very short activation period followed by a longer data acquisition interval, it can detect oxygen from flowing water as it passes each detector. The stationary oxygen signal dies out.

**NFD (left) and neutron activation logs for gravel pack evaluation.** The logs react inversely to changes in borehole hardware. At 260 m, the centralizer positions between the two screens results in an increase in the apparent density measured by the NFD. The silicon-bearing gravel being replaced by steel results in a decrease in the neutron activation gamma ray over the same zone. Similarly, above 200 m, where the screen is replaced with smaller tubing OD, the increased volume of gravel causes an increased activation count rate and, on the NFD log, a small decrease in apparent density as the thickness of the dense pipe wall is reduced.

**Water Flow Log results of a 2.8-feet/min water flow in the Environmental Protection Agency (EPA) Leak Test Well in Ada, Oklahoma, USA.** The well is specifically completed to simulate a flow channel in the cement annulus. Only the far detector is used because it is most sensitive to water flowing in the annulus. The stationary oxygen and background signal are curve fitted to the measured raw data from the far detector. The flowing oxygen signal is separated from the background and stationary signals by a weighted least-squares regression. An iterative technique is used to estimate the shape of the flowing oxygen profile. (From McKeon et al, reference 2.)
enough to allow the moving oxygen signal to appear as a clear bump. Also, because the WFL method makes measurements at three detectors, it covers a wider range of velocities, from 1.4 feet per minute to 200 feet per minute [43 centimeters (cm) to 61 meters per minute].

The WFL technique has some limitations. Because it measures a product of oxygen activation, it is sensitive to water only, not hydrocarbon, so it cannot detect hydrocarbon flowing behind casing. Also, it does not tell where water is coming from as a tracer would—only that water is flowing at a given interval in the well. A tracer survey, furthermore, can measure up-flow and down-flow in the same trip, but with the WFL measurement, the tool string must be pulled out and flipped upside down to measure down-flow.

Several variables govern WFL measurement sensitivity: flow velocity, flow rate inside the casing versus outside the casing, distance to the water channel and channel size.

Consider just the last two. The signal from flow inside the casing at 5 feet [1.5 meters] per minute may be large enough to mask that from flow outside the casing at 20 feet [6 meters] per minute. As a rule, the bigger the casing, the bigger the channel must be to be visible to the WFL measurement. The practical limit to casing diameter is probably 13 3/4 inches.

Boron Injection Logging
A service similar to WFL measurement has been developed on the North Slope of Alaska, using pulsed neutron logging instead of radioactive tracers for detection of cement channels. The technique, originally tried and abandoned 30 years ago, has been resurrected and refined by ARCO Alaska and British Petroleum. It has been successfully applied in difficult settings, such as logging through two strings of pipe and logging in horizontal wells.

The method involves making a pulsed neutron run after injection of a boron solution, a strong thermal neutron absorber. Cement channels are inferred based on large changes in the formation neutron capture cross section as the boron is pumped through perforations and channels and into the rock matrix. Cement channels are readily apparent from the large magnitude of change in the log—on the order of 20 capture units.

Unlike radioactive tracer studies, the boron injection method allows easy discrimination of borehole and formation signals. This reduces error in detection of cement channels, since it is sometimes difficult to tell whether a tracer signal is coming from the wellbore or a channel behind perforated casing. The boron method also gives reservoir information—depths of the gas/oil and oil/water contacts. A limitation of the technique is that residual borax can change the formation neutron capture cross section and impact baseline monitoring, at least until a new baseline is established. Although boron injection procedures have not hindered production rates at Prudhoe Bay, ARCO is studying boron-formation compatibility.

Improving Radiation Handling
Because sourceless alternatives have been developed for only a handful of nuclear measurements, engineers continue to improve the safety of handling radioactive material. This effort has focused on three main areas: upgrading of shields and handling techniques to further reduce exposure risk to personnel and the environment; efficient and secure fishing capabilities of sources for Logging While Drilling (LWD, measurements performed by tools that are integrated into drill collars); and downhole detection of radioactive material from naturally occurring radionuclides.

There are two notable improvements in source handling and shielding. One concerns the “wipe test,” which checks the integrity of source containment. The other concerns the shielding of LWD neutron and gamma ray sources.

Wipe Testing
A wipe test is exactly as it sounds—a plug in the steel capsule (pressure vessel) that contains the source is wiped with a solvent-impregnated filter paper and the paper is assayed for radioactive activity, which would reveal a source leak. The test is performed every three to five months on logging and calibration sources.

New shields and wipe test procedures have been developed for both the gamma ray sources (1.5-curie [Ci] [113]cesium [Cs]) for the density measurement and neutron sources (16-ci [24]americium-beryllium [Am-Be] for porosity measurement). These modi-
Radioactive: This unit of exposure measures the ability of X- or gamma rays to ionize air at 0°C and 1 atmosphere, equal to the amount of radiation producing one electrostatic unit of positive or negative charge per cubic centimeter of air.

Sv (Sievert): The SI unit that replaces the rem as the unit of dose equivalence (1 Sv = 100 rem).

Transport Index: This represents the exposure in mrem/hr at 1 meter from the surface of the source shield.


Radiation Sources and Dosages

<table>
<thead>
<tr>
<th>Radiation Source</th>
<th>Annual Dose Equivalent (mrem/person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Sources</td>
<td></td>
</tr>
<tr>
<td>Foods grown on fertilized land (thorium, uranium and potassium associated with phosphorus)</td>
<td>0.5-5</td>
</tr>
<tr>
<td>Cosmic radiation during a one-way flight, New York to Los Angeles</td>
<td>1-2</td>
</tr>
<tr>
<td>Domestic water supplies (from radon)</td>
<td>1-6</td>
</tr>
<tr>
<td>Exposure to aggregates such as granite in highways</td>
<td>4</td>
</tr>
<tr>
<td>Using a natural gas cooking stove (from radon)</td>
<td>5-15</td>
</tr>
<tr>
<td>Living in a brick or concrete home</td>
<td>7</td>
</tr>
<tr>
<td>Cosmic radiation during a one-way flight, London to Los Angeles (polar route)</td>
<td>10</td>
</tr>
<tr>
<td>Average natural terrestrial radiation in US Gulf Coast</td>
<td>23</td>
</tr>
<tr>
<td>Cosmic radiation at sea</td>
<td>30-35</td>
</tr>
<tr>
<td>Average natural terrestrial radiation in Midwest</td>
<td>46</td>
</tr>
<tr>
<td>Cosmic radiation, Denver, Colorado, USA (elevation 5,280 feet [1,600 meters])</td>
<td>60-70</td>
</tr>
<tr>
<td>Cosmic radiation, Leadville, Colorado, USA (elevation 10,000 feet [3,000 meters])</td>
<td>125</td>
</tr>
<tr>
<td>Average natural terrestrial radiation in Granitic regions of New England</td>
<td>up to 150</td>
</tr>
<tr>
<td>Man-Made Sources</td>
<td></td>
</tr>
<tr>
<td>Living 1-5 miles [2-8 km] from a nuclear energy plant</td>
<td>0.05-0.5</td>
</tr>
<tr>
<td>Tritium exposure from weapons testing</td>
<td>1.5-4</td>
</tr>
<tr>
<td>Typical medical X-ray examination (entrance skin dose)</td>
<td>100-200/ examination</td>
</tr>
<tr>
<td>Typical dental X-ray examination (entrance skin dose)</td>
<td>10-15/examination</td>
</tr>
<tr>
<td>Occupational radiation exposure: Dental personnel</td>
<td>50-125</td>
</tr>
<tr>
<td>Schlumberger field engineer</td>
<td>100-200</td>
</tr>
<tr>
<td>Medical X-ray &amp; nuclear medicine personnel</td>
<td>300-500</td>
</tr>
<tr>
<td>Permissible occupational dose (NRC/ACEB): Whole body (head and trunk, active blood-forming organs, lens of eyes, gonads)</td>
<td>1,250 (per quarter)3</td>
</tr>
<tr>
<td>Annual US average from all radiation sources, natural and man-made</td>
<td>180</td>
</tr>
</tbody>
</table>

5. Nuclear Regulatory Commission (USA); Atomic Energy Control Board (Canada). These standards are widely used by other countries. The regulatory limit is higher than the exposure rate normally received by Schlumberger field employees. Company regulations require a full investigation if any radiation badge is in excess of 600 mrem/quarter, including the reason for the higher than normal readings and actions taken to prevent recurrence of the exposure.
6. The NRC recommends that prenatal exposure not exceed 500 mrem for the gestation period.

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Loading the CDN sources: (1) Eddie Joe Mach, lab technician at Schlumberger Logging While Drilling in Sugar Land, Texas, USA, guides the shield as it is hoisted up the catwalk onto the rig floor. The gamma ray source is to his left and the neutron source to his right. (2) With feet attached, the shield stands on the rig floor. Eddie has removed the door to later permit guiding the sources into the tool. The tool, behind him, is now sitting in the rotary table, ready to receive the sources. (3) Using a handling rod, he guides the sources into the tool. The neutron source is still within the primary shield and the density source is within the secondary shield, the widened lower part of the post. (4) Eddie guides the source loading tool, which will latch onto the fishing head of the source. (5) Phil Kurkoski, LWD senior project engineer (left), disengages the source locking mechanism. The sources now hang off the loading tool, via the source fishing head. (6) The handling tool has lowered the sources into position, with the (uppermost) neutron source 15 feet [4.5 meters] below the rig floor. Eddie rotates the loading tool to lock the sources in place. The loading tool and empty shield are then removed from the rig floor. Throughout loading, neither source was unshielded.
Radiation Effects

Types of Radiation
Radiation involves the transfer of energy from a source to another location. The common ionizing radiations are X-rays, γ rays and charged particles, particularly β radiation (electrons), protons and α particles (helium nuclei). Neutrons produce radiation effects by colliding with atoms to produce ionizing radiation.

Alpha radiation is positively charged particles emitted from natural elements such as uranium and radium as well as from man-made materials. Alpha radiation barely penetrates the skin surface and can be stopped by a sheet of paper.

Beta radiation is more penetrating than α radiation. Depending on its energy, it can pass through ½ to 1 inch [1 to 2 centimeters] of water or skin. Aluminum several millimeters thick can block β radiation. Tritium, used as a target in pulsed neutron logging, emits β radiation, which does not escape its containing vessel.

Like X-rays, γ rays are electromagnetic waves that travel at the speed of light. When a nucleus decays, α or β particles are emitted, depending on the properties of the nuclide. Many transitions leave the daughter nucleus in an excited state; the excitation energy is emitted as gamma radiation. Since they lack charge, γ rays penetrate farther than most particles. Among the many gamma ray sources is natural radioactivity, occurring in thorium, uranium and potassium.

Neutrons are neutral particles with a rest mass similar to that of a proton. Neutron radiation occurs inside nuclear reactors and, in nature, in the upper atmosphere. In logging

LWD
Safe handling of sources on the rig floor is also a chief design criterion for the Compensated Density Neutron (CDN*) tool, an LWD device that measures bulk density, photoelectric factor and epithermal neutron porosity near the bit. The CDN source and tool are designed so that the neutron and gamma ray sources (7.5-CI$^{238}$uranium, 140$^{5}$-cesium) are never unshielded on the rig floor and the tool is never above the rig floor when the sources are loaded. This is accomplished by a tool design that permits source loading within the shield, and locking of the sources into position 15 feet [4.6 meters] below the rig floor. This shields the rig crew from radiation (previous page) and allows them to work safely. For the crew to keep below the 2 mrem/hr exposure (required by the U.S. Nuclear Regulatory Commission [NRC] for nonradiation workers), they need to stay only 6 feet [1.8 meters] from the CDN source during source handling.


would have to stay 13 feet [4 meters] from the tool. The driller might exceed the 2
mrem/hr exposure limit to remain in control of the rig (next page). As a further precau-
tion, if the situation were to arise that sources could not be unloaded, the tool can
be inserted into a drill collar radiation shield that assures safe unloading and transport of
the tool back to the shop. As an operational precaution, radiation is monitored on the rig
floor and, to confirm source integrity during drilling, in the mud pit.

The neutron and gamma ray sources are
designed to be fished by wireline, which
reduces the operator's abandonment cost
and environmental risk if the tool gets stuck.
The sources are connected to each other
allowing simultaneous retrieval, with the
neutron source at the top and a fishing head
atop the neutron source. This permits fishing
both sources in one trip. Successful fishing
operations have been performed at depths
greater than 18,000 feet [5500 meters]. The
tool's calibration and detector stabilization
sources—137Cesium, 211Am-Be and 214Am—are
of low enough intensity not to require
elaborate abandonment procedures nor to pose a hazard to fishing drillstring hardware.

NORM Logging
A third improvement in radiation safety is
better detection of concentrations of natu-
rally occurring radioactive material, NORM
for short. Natural radionuclides are fre-
quently concentrated in the so-called scale
that forms in tubulars and surface equip-
ment, especially in waterdrive production.
The most common radioactive component
is the sulfate of 226radium and its daughter
products, which emit alpha (α), β and γ
radiation. This radioactivity presents a
potential health hazard during removal and
cleaning of scaled equipment, which may
have to be handled as low-level radioactive
waste. In the US Gulf Coast, for example,
Louisiana requires that personnel cleaning
equipment with a radiation level of 50
prem/hr (measured at its outer surface) must
wear breathing apparatus, special clothing
and badges and shear the site in plastic.

A new logging procedure permits evalua-
tion of scale radioactivity downhole prior to
workover, allowing better management of
radioactive material. The cornerstone of the
technique is a gamma ray tool recalibrated
to produce a "reconnaissance" log of radia-
tion from 222radium. Because scale usually
forms inside tubing, a tubing wall thickness
correction is added to account for attenua-
tion and to give a dose rate at the outer sur-
face of the tubing (page 22).

Background radiation can be accounted
for with gamma ray logs run several ways:

• In tubing prior to production and sub-
  tracted from the reconnaissance gamma
  ray log

• In casing prior to production, corrected for
  attenuation of γ rays by the tubing not pre-
  sent when the casing gamma ray log was
  run, and subtracted from the reconna-
 issance gamma ray

• In open hole then corrected for the effect of
tubing, casing, and cement.

In the absence of a baseline gamma ray log,
an assumed background radiation level can
be subtracted from the reconnaissance
 gamma ray log. A typical background read-
ing in a cased interval through a 50-API
sand is about 5 prem/hr.

Safer Nuclear Calibration
Calibration of nuclear tools consists of
adjusting tool response at the district facility
to match that of the engineering reference
tool, established under laboratory condi-
tions. This accounts for variation in detector
sensitivity from tool to tool and with time. It
also accounts for variation in source
strength, which changes with time.

What is known as the "wellsite calibration"
is actually not a primary calibration, but
rather a "verification"—confirmation that
the tool is functioning and that its response
has not changed since the last shop calibra-
tion. This verification is typically done by
monitoring tool response to a point source of
γ rays or neutrons strapped onto the tool
before it is rigged for logging.

To keep advances in wellsite verification on
course with improvements in logging tools,
alternative verifications have been de-
veloped that improve wellsie verification,
thereby improving overall log quality and
reducing dependence on calibration
sources. One calibration source—100-μCi
226radium for gamma ray devices—is tar-
geted for replacement with a source of
Radiation exposure profile during CDN source loading, received by personnel performing the operation. Purple shows the actual exposure profile; blue shows the theoretical profile if the same sources were loaded, unshielded, into the side of the tool rather than down its center. This illustrates the enhanced safety of the shielded, end-load design. In the end-load scheme total radiation dose rate is 2.2 mrem/hr. In the theoretical side-load exposure profile, the radiation dose rate is 15.1 mrem/hr. A: the source shield is brought to the rig floor; B: source shield prepared for transfer; C: source transferred to pony collar atop tool; D: source positioned on pony collar; E: source lowered into tool; F: tool lowered into well.

Biological effects also depend on a cell’s radiosensitivity—the degree to which it shows effects of radiation exposure. Cell multiplication via chromosomal division is a major determinant of radiosensitivity. In general, cells that divide frequently (such as skin cells) are more radiosensitive than those that divide rarely (such as brain or nerve cells). The most radiosensitive tissues are the blood-forming organs, gonads, skin and intestines. Fetuses, infants and children, because they are growing, undergo more cell divisions than adults and are therefore more likely to demonstrate the effects of radiation exposure.

Some cells may preferentially concentrate certain radionuclides if ingested or inhaled. Radioactive iodine used in tracer studies, if ingested, will be concentrated in the thyroid gland, which regulates metabolic rate. A sufficient dose of $^{131}$I will damage thyroid tissue. Doses of 4 to 10 mCi are used clinically to treat hyperthyroidism, a condition marked by an overactive thyroid.

Radiation alters the genetic apparatus—mediated by deoxyribonucleic acid (DNA) and ribonucleic acid (RNA)—interferes with cell division and, at high exposure levels, causes cell death. At low exposure levels, radiation mainly damages the cell nucleus and its chromosomes. This results in chromosomal breaks or "stickiness" that affects the cell's ability to divide. The degree of inhibition of cell division increases with dose.

Another form of damage is alteration of one or more of the genes within the chromosome (genes carry information, encoded in DNA, on chromosomes, controlling how proteins are assembled into cells). Although the damaged cell itself may continue to function relatively normally, the change may ultimately affect the large number of cells produced by division of this damaged cell. If reproductive cells are involved, the abnormalities may be transmitted to subsequent generations. In addition to destructive effects on important biological macromolecules such as DNA and RNA, ionizing radiation may also depress the immune system.

—RR

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6. The Council of Radiation Control Program Directors, a consortium of radiation regulators from each state, is drafting model regulations pertaining to NORM to establish uniformity across state borders. The model is expected to be in final form by early 1991.

A Cyber Norm log from the US Gulf Coast, showing a tubing radiation level well above the 50 mrem/hr dose rate, considered by convention the hazard threshold. In the right track, the plane curve up to the packers shows radiation below 50 mrem/hr. The narrow area shaded red is 5 mrem/hr wide and depicts radiation between 50 and 55 mrem/hr, which may be safe if corrected for background radiation. The purple shaded area is where the outside of tubing exceeds 55 mrem/hr and may be unsafe. In this well, the operator is planning to handle the tubing as low-level radioactive material in a forthcoming workover. In a case like this, it would be prudent to log shallower depths to check the tubing for diminished radiation levels. Tubing closer to the surface may have a lower level of contamination and could be handled as nonhazardous material.

<table>
<thead>
<tr>
<th>Gamma Ray</th>
<th>NORM Log</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 API</td>
<td>1,800 mrem/hr</td>
</tr>
</tbody>
</table>

Eliminating 226Radium is important, particularly in the US, where the last disposal site for this radioisotope is scheduled to close in 1992. The radium source for gamma ray tools has been replaced by monazite sand (from a mine in Australia), which is naturally enriched with thorium (Th). The "thorium blanket" improves the quality of calibration because it wraps around the whole detector, providing a more uniform flux than the conventional point source. At 1.68 μCi, the blanket is nearly 60 times less intense than the radium source. This means the calibration is less likely to be affected by γ rays that scatter from the ground and reflect back to the detector. Recently completed software modifications permit thorium blanket calibration of slim-hole tools.

Downhole verification checks of the CNL and TDT tools will be made through "plateau checks." The plateau refers to a flat part of the curve of total count rate vs. detector high voltage (next page, top). The threshold voltage is set high enough to eliminate noise, which occurs at lower amplitudes. The detector voltage is adjusted to keep the operating point on plateau, thereby ensuring constant detector sensitivity regardless of variation in temperature. The plateau test shows whether the tool is working in its middle range, the optimal operating point, rather than near the end. If the tool is working in the middle range of the plateau, this verifies that analog parts of the tool system have not drifted.

Before logging, this verification is done typically a few hundred feet below surface where the tool is at quasi-surface temperature and pressure. After logging, the verification is repeated typically just above the casing shoe, where the tool remains at logging temperature and pressure. The main advantage of this technique compared with conventional surface verification is that it is performed at in-situ temperature and pressure, and so verifies tool performance under operating conditions.
<table>
<thead>
<tr>
<th>Tool</th>
<th>Logging Source</th>
<th>Calibration/ Stabilization Source</th>
<th>Half-life</th>
<th>Radiation Used in Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litho-Density†</td>
<td>1.68-Ci $^{137}$Cs</td>
<td>two 0.9-$\mu$Ci $^{137}$Cs</td>
<td>30.2 yr</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>Compensated Density Neutron (CDN*) LWD</td>
<td>1.68-Ci $^{137}$Cs</td>
<td>0.9-$\mu$Ci $^{137}$Cs</td>
<td>30.2 yr</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td>50-$\mu$Ci $^{241}$Am</td>
<td>432 yr</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>Neutron</td>
<td>7.5-Ci $^{241}$Am-Be</td>
<td>0.1-$\mu$Ci $^{241}$Am-Be</td>
<td>432 yr</td>
<td>neutron</td>
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<td>Compensated Dual Resistivity (CDR*) LWD</td>
<td></td>
<td>4.5-$\mu$Ci $^{241}$Am$^1$</td>
<td>432 yr</td>
<td>$\gamma$</td>
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<tr>
<td>Compensated Neutron Log (CNL*)</td>
<td>16-Ci $^{241}$Am-Be</td>
<td>0.5-$\mu$Ci $^{241}$Am-Be</td>
<td>432 yr</td>
<td>neutron</td>
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<tr>
<td>Thermal Decay Time (TDT*)</td>
<td>Minirion tube (TH)</td>
<td>800-$\mu$Ci $^{60}$cobalt$^2$</td>
<td>5.3 yr</td>
<td>neutron (only when on) $\gamma$</td>
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<tr>
<td>Induced Gamma Ray Spectrometry (GST*)</td>
<td>Minirion tube (TH)</td>
<td>9-$\mu$Ci $^{65}$Zinc</td>
<td>244 days</td>
<td>neutron (only when on) $\gamma$</td>
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<tr>
<td>Geochemical Logging (GLT)</td>
<td>0.03-Ci $^{252}$Cf</td>
<td>See NGS, GST</td>
<td>2.65 yr</td>
<td>neutron</td>
</tr>
<tr>
<td>Natural Gamma Ray Spectrometry (NGS*)</td>
<td>none</td>
<td>50-$\mu$Ci $^{241}$Am</td>
<td>432 yr</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>Version A, B &amp; C</td>
<td>none</td>
<td>1.68-$\mu$Ci $^{232}$Th</td>
<td>$1.4 \times 10^{10}$ yr</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>Version D</td>
<td>none</td>
<td>2.7-$\mu$Ci $^{241}$Am</td>
<td>432 yr</td>
<td>$\gamma$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.68-$\mu$Ci $^{232}$Th</td>
<td>$1.4 \times 10^{10}$ yr</td>
<td>$\gamma$</td>
</tr>
</tbody>
</table>

1 $^{241}$Am is used for calibration of the gamma ray log.
2 $^{60}$Co is being replaced with an in-situ verification, a “plateau” test, that does away with calibration sources.

Radiation safety today is at a turning point. Work continues on enhancing safety by eliminating unnecessary nuclear sources, by replacing some highly radioactive sources with weaker ones, by improving tool and shield design, and by developing methods that help assess the amount of NORM—before pulling pipe. Many technical challenges lie ahead. And as concern grows for environmental and personnel safety, new tools must not only survive and make good measurements, they must also be as clean and safe as possible. —JMK