Environmental Assessment of Energy Compensation Sources for Well Logging and Other Regulatory Clarifications - Changes to 10 CFR Part 39

Final Report

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ENVIRONMENTAL ASSESSMENT OF ENERGY COMPENSATION SOURCES FOR WELL LOGGING AND OTHER REGULATORY CLARIFICATIONS -- CHANGES TO 10 CFR PART 39

EXECUTIVE SUMMARY

This environmental assessment (EA) examines the potential environmental, health and safety (EH&S) impacts arising from a set of changes to the existing well logging regulations in 10 CFR Part 39. The changes accommodate the use of well logging technology that was not incorporated when the NRC issued the existing well logging regulations (52 *Federal Register* 8225), and proposes other modifications to improve, clarify and update Part 39. These changes are described in a proposed rule dated April 19, 1999 (64 *Federal Register* 19089) and in a May 1998 Rulemaking Plan (SECY-98-105) entitled, "Energy Compensation Sources for Well Logging and Other Regulatory Clarifications - Changes to 10 CFR Part 39.

As required by 10 CFR Part 51 regulations, this EA evaluates the potential EH&S impacts associated with two regulatory options: (1) the proposed action and (2) the no-action alternative. Under the proposed action, the U.S. Nuclear Regulatory Commission (NRC) intends to establish a limit of 3.7 megabequerels (MBq) [100 microcuries (μCi)] for energy compensation sources (ECSs) and 1,110 gigabequerels (GBq) [30 Ci] for tritium neutron generator target sources. This EA evaluates radioactive sources currently used in ECSs, namely Americium-241 (Am-241), Cesium-137 (Cs-137), and Thorium-232 (Th-232), as well as Curium-250 (Cm-250), which serves as an upper bound for the health risk assessment. The assessment also evaluates tritium for tritium neutron generator sources. Under the no-action option, NRC will not change the existing regulations in Part 39 to specifically accommodate ECSs or tritium neutron generator target sources.

For the proposed action, this EA estimates the maximum dose to workers exposed to these sources. Based on the analytical method described herein, the EA concludes that:

- Under the limits proposed for ECS and tritium neutron generator target source designs, the maximum estimated dose to workers is below the annual Federal public health limit of 100 millirem per year (mrem/yr).

For the no-action, a 1987 EA of the original Part 39 rulemaking resulted in a finding of no significant impact (FONSI) for well-logging devices using licensed material, which typically contain activity levels of 110 to 740 GBq (3 to 20 Ci).

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1.0 BACKGROUND

1.1 Introduction

Almost all oil and gas produced today comes from accumulations in the pore spaces of reservoir rocks – usually sandstones, limestones, or dolomites. The amount of oil or gas contained in a unit volume of the reservoir is the product of its porosity and hydrocarbon saturation. The volume of the formation containing the hydrocarbons is used to estimate total reserves and determine whether the accumulation is commercially viable. Knowledge of formation thickness of the reservoir is needed to compute the volume. Evaluating the productivity of a reservoir requires knowing its permeability (i.e., how easily the fluid can flow through the pore system). Thus, the main parameters needed to evaluate a reservoir are porosity, hydrocarbon saturation, thickness, area, and permeability. In addition, the reservoir geometry, formation temperature and pressure, and lithology can play a major role in the evaluation, completion, and production of a reservoir. Downhole well logging provides a method of deriving or inferring accurate values for the hydrocarbon and water saturations, porosity, permeability, and lithology of the reservoir rock.

One method to obtain downhole information about oil and gas reservoirs is by using well logging tools. Downhole well logging provides a method of deriving or inferring accurate values for the hydrocarbon and water saturations, porosity, permeability, and lithology of the reservoir rock. Licensed radioactive materials (sealed radioactive sources with associated radiation detectors) are contained in well logging tools. Americium-241 and cesium-137 are the radioactive materials most frequently used for this purpose. Traditionally, these tools are lowered into a well on a wireline. The depth of the well could range from several hundred feet to greater than 30,000 feet. Information collected by the detectors is sent to the surface through a wireline and plotted on a chart as the logging tool is slowly raised from the bottom of the well. Licensed radioactive materials are also used for similar purposes in coal and mineral exploration.

When NRC first promulgated its 10 CFR Part 39 regulations, well logging technology required drilling to stop. After removing portions of the drilling pieces, field workers then lowered logging tools -- encapsulated radioactive sources with associated detector crystals -- into the well on a wireline. More recent technology, referred to as "logging while drilling" (LWD) allows well logging to be accomplished during drilling. The technology provides “real-time” data during drilling operations and improves evaluation of geologic formations. In addition to the larger sources, logging while drilling technology uses a low activity radioactive source to calibrate the larger source.

1.1.1 Energy Compensation Sources

An ECS is a low activity source (typically less than 3.7 megabequerels (MBq) [100 microcuries (μCi)]) compared to the normal 110 to 740 gigabequerels (GBq) [3 to 20 Ci] sources used in traditional wireline well logging as well as the newer LWD operations. Typical radionuclides used in these sources are Am-241, an alpha particle emitter, and Cs-137, a beta and gamma emitter. Source sizes vary depending upon the manufacturer and the intended use of the ECS. The majority of the tools used in well logging operations are custom designed for specific applications. Even so, the standard design is fairly typical: the encapsulated source is mounted inside a steel (or other similar metal) pressure housing in the interior of the LWD tool. The pressure housing (and other tool components) provides additional encapsulation to protect the source from operational impacts (e.g., pressure, stresses). An example of a licensed ECS source is provided below.

- **Steering and Gamma Ray Sub** -- Manufactured by Anadrill, Inc., this device uses two 0.081 MBq (2.2 μCi) Am-241 sources. This model is designed for downhole use during logging (or measurement) while drilling operations. It provides a spectrum of gamma radiation in the wellbore due to the naturally occurring concentrations of thorium, uranium, and potassium in the surrounding rock formations. The gamma spectrum is measured using a ruggedized gamma ray spectrometer. The spectrometer uses two detectors; each containing its own Am-241 source acting as a reference for energy and activity, allowing the detector to compensate for efficiency fluctuations due to temperature changes in the borehole. The spectrometer and associated electronics operate at one atmosphere pressure within a sealed pressure housing made of stainless steel. This housing is positioned to allow drilling mud to flow between the outer diameter of the pressure housing and the inner diameter of the drilling collar (which acts as an additional encapsulation for the source). The diameter of the tool ranges from between 16.5 and 23 centimeters (cm) [6.5 and 9 inches (in)], with an overall length of approximately 338 cm (133 in). The Am-241 sources are mounted within the pressure housing on the side of each of the scintillating crystals of the spectrometer. The entire detector is then wrapped with 0.25 cm (0.10 in) thick silicone rubber and Teflon shrink tubing to assist in shock isolation. The wrapped detector is then press fit within the pressure housing. The pressure housing and drill collar shield all of the Am-241 gamma rays emitted toward the outside of the tool. Therefore, the presence of the Am-241 cannot be detected from outside the tool. The device is designed to operate in a high pressure and temperature environment. Testing of the devices indicates an ability to withstand both normal and extreme conditions of handling and use.

1.1.2 Tritium Neutron Generator Target Sources

Tritium neutron generator target sources are used in neutron logs. Neutron logs are used principally for delineation of porous formations and determination of their porosity. They respond primarily to the hydrogen in the formation. Thus, in clean formations whose pores are filled with water or oil, the neutron log reflects the amount of liquid-filled porosity. Neutrons are uncharged particles, each having a mass almost identical to the mass of a hydrogen atom. High energy neutrons are continuously emitted from a radioactive source (tritium) in the tool. These neutrons collide with nuclei of the formation materials, and with each collision, lose energy. The energy lost per collision depends on the relative mass of the nucleus with which the neutron collides. Thus, the slowing of the neutrons is dependent on the amount of hydrogen in the formation. These tools are used similar to wireline drilling, whereby the tool is lowered into the well on a wire and measurements are taken while drilling has ceased. A neutron stream is only generated when a voltage is applied to the tritium neutron generator target source. An example of a licensed tritium neutron generator target source is provided below.

- **Downhole Accelerator** -- This source, manufactured by Haliburton Logging Sources, Inc., uses tritium, with a maximum activity of 110 GBq (3 Ci), for both oil and gas well logging applications. The design consists of a pulsed deuterium-tritium accelerator, a scintillation detector, a digital telemetry system, and associated electronics. This entire system is approximately 7 m (23 ft) long and 4.3 cm (1-11/16th in) wide. The deuterium-tritium accelerator tube is 18 cm (7 in) long, with a 3.3 cm (1-5/16th in) diameter. The device is used for neutron activation of underground formations for quantitative and qualitative analysis and is designed to operate at pressures up to 20,000 pound per square inch (psi) and at temperatures of 204°C (400°F). A radiation hazard exists only when the accelerator is energized. It will then produce 1E+8 neutrons per second. The expected useful life of the accelerator is more than 400 hours.

1.2 Rulemaking Plan

Based on information about the changing technology in the well logging industry, NRC decided to develop a rulemaking plan to possibly update Part 39. On May 28, 1997, NRC published the draft rulemaking plan entitled, "Energy Compensation Sources for Well Logging and Clarifications -- Changes to 10 CFR Part 39" (SECY-97-111). The States of Utah, Illinois, and Washington provided comments on the draft rulemaking plan. These States generally supported the proposal and provided specific information and comments. Where appropriate, NRC staff incorporated these comments into the final rulemaking plan contained in SECY-98-105, dated May 12, 1998. (NRC, 1998) In April, 1999, NRC issued its proposed rule incorporating the changes contained in the rulemaking plan (64 *Federal Register* 19089). The NRC received five comments on the proposed rule. These comments and NRC's responses are discussed in the preamble to the final rule in the "Comments on the Proposed Rule" section.

In the final rule, NRC determined that Part 39 has no specific provisions for low activity sources, and that several requirements, when applied to either ECSs or tritium neutron generator target sources, may be overly burdensome. Further, because the existing regulations do not allow for variations based on the activity of the source, licensees that use an ECS must meet all the requirements of Part 39. Examples of overly burdensome requirements include well abandonment (Sections 39.15 and 39.77), leak testing (Section 39.35), design and performance criteria for sealed sources (Section 39.41), and monitoring of sources lodged in a well (Section 39.69).

NRC's final rule addresses these issues by modifying the regulations in Part 39 to define an ECS and tritium neutron generator target source and provide appropriate regulations for using these technologies in well logging applications. The most significant change will exempt users of these technologies from the costly well abandonment procedures currently found in Part 39. Well abandonment, in addition to specific reporting and approval requirements, requires that the source be immobilized and sealed in place with a cement plug, that the cement plug be protected from inadvertent intrusion, and that a permanent plaque be mounted at the surface of the well. NRC will implement less stringent abandonment requirement for ECS sources measuring less than 3.7 MBq (100 μCi) and tritium neutron generator target sources measuring less than 1,110 GBq (30 Ci). In addition, NRC will change other sections of Part 39 to improve, clarify, and update the regulations.

1.3 Purpose of this Environmental Assessment

The purpose of this environmental assessment (EA) is to examine the potential environmental, health and safety (EH&S) impacts arising from the proposed changes to the existing regulations in Part 39. As required by 10 CFR Part 51, this EA describes the proposed action, the need for the proposed action, alternatives to the proposed action, including no-action, and the potential EH&S impacts of each action.

2.0 NEED FOR THE PROPOSED ACTION

2.1 Proposed Action

Under the proposed action, NRC would allow licensees to obtain regulatory relief from the current licensing and radiation safety requirements for well logging using low activity sources (e.g., ECSs) and tritium neutron generator target sources. Specifically, NRC plans to reduce the regulatory burden on licensees while maintaining adequate protection of health and safety. In the final rulemaking plan, NRC proposes several specific changes to improve, clarify, and update Part 39 requirements to provide regulatory relief and account for the use of new well logging technology. The possible changes are discussed below:

- **Revise requirements for ECSs containing less than 3.7 MBq (100 μCi) for oil and gas wells.** NRC is proposing to eliminate the well abandonment requirements for ECSs containing less than 3.7 MBq (100 μCi). Well abandonment, in addition to specific reporting and approval requirements, requires that the source be immobilized and sealed in place with a cement plug, that the cement plug be protected from inadvertent intrusion, and that a permanent plaque be mounted on the surface of the well. Current requirements in Section 39.35 specify that leak testing shall be conducted for beta-gamma emitting sources with activities above 3.7 MBq (100 μCi), and for alpha-emitters (above 0.37 MBq [10 μCi]) no less frequently than every six months. Current industry practices use several radionuclides in ECSs, the most typical being Cs-137 and Am-241. Typical activity levels of these radionuclides used in well logging applications do not exceed 1.8 MBq (50 μCi). Beta-gamma emitters with activity levels below 3.7 MBq (100 μCi) are already exempt from leak testing requirements. NRC proposes modifying Section 39.35 by changing the time interval for leak testing ECSs to not less than three (3) years for non-exempt low activity sources. The changes proposed by NRC would, therefore, only affect those licensees using non-exempt sources.

- **Revise requirements for tritium neutron generator target sources containing less than 1,110 GBq (30 Ci) of tritium.** Tritium neutron sources typically contain less than 740 GBq (20 Ci) of tritium. The neutron generator target sources only produce a neutron stream when a voltage is applied. For well logging applications, NRC is proposing that the tritium neutron generator target sources below 1,110 GBq (30 Ci) be subject to all requirements contained in Part 39 except: (1) sealed source design and performance criteria (Section 39.41) and (2) well abandonment procedures (Sections 39.15 and 39.77) when a surface casing is used. Tritium neutron generator target sources are already exempt from leak testing requirements contained in Section 39.35. NRC believes that the potential hazards associated with these sources do not warrant the existing well abandonment requirements in the event of an irretrievable source.

- **Modify Section 39.15 to provide for performance-based criteria for inadvertent intrusion on an abandoned source.** The current requirement at Section 39.15(a)(5)(ii) requires a mechanical device to prevent inadvertent intrusion on the source that must be set at a point above the cement plug, unless the cement plug and source are not accessible to any subsequent drilling operations. NRC believes this requirement is too restrictive in some cases. Therefore, NRC proposes that licensees "prevent inadvertent intrusion on the source," which would require that the source be protected but allow the licensee the flexibility to determine the best method. This change would not affect the requirement in (a)(5)(i) for a well logging source to be immobilized with a cement plug or the requirement in (a)(5)(iii) for a permanent plaque. This modification would allow licensees greater procedural latitude while continuing to ensure source integrity. For example, if a significant amount of drilling equipment is abandoned in the well, this equipment may be effective in preventing inadvertent intrusion on the source, but may not meet the requirements of Section 39.15. Those requirements would only apply to larger sources (i.e., above 3.7 MBq [100 μCi] or tritium neutron generator target sources above 1,110 GBq [30 Ci]).

- **Modify Section 39.77 requirements for notification.** This section specifies that NRC approval must be obtained prior to implementing abandonment procedures for an irretrievable source. NRC proposes to modify Section 39.77 to allow immediate abandonment without prior approval if a delay could cause an immediate threat to public health and safety. Notification would still be required after completing the abandonment. The existing notification requirements of Section 39.77 would still apply to larger sources (i.e., above 3.7 MBq [100 μCi]) or tritium neutron generator target sources above 1,110 GBq (30 Ci).

- **Include the generic exemption for sealed sources in 1989 within the regulations.** NRC issued a generic exemption from the current design and performance criteria for sealed sources (Section 39.41), allowing the use of older sealed sources which meet an older standard for well logging operations. Sealed sources manufactured prior to July 14, 1989, may use design and performance criteria specified under United States of America Standards Institute (USASI) N5.10-1968 or the criteria contained in Section 39.41. The use of the USASI standard is based on the NRC Notice of Generic Exemption (54 *Federal Register* [FR] 30883). This exemption is currently in use, but has not been incorporated in Part 39. NRC proposes to revise Part 39 to include this exemption within the regulations.

- **Update Part 39 to remove date that was time sensitive at the original date of promulgation.** Section 39.49 contains a requirement that was dependent on a date that has already passed and are is longer appropriate. NRC proposes to remove references to this date in Part 39 that has already passed, to avoid confusion on the part of licensees.

- **Update Sections 39.15, 39.35, and 39.41 of Part 39 to conform with NRC's metric policy by stating parameter values in dual units with metric units first and with English units in brackets.**

2.2 No-Action

For the purposes of this EA, the no-action alternative is to keep the existing regulations for well-logging sources codified in 10 CFR Part 39.

3.0 POTENTIAL ENVIRONMENT, HEALTH, AND SAFETY IMPACTS OF THE PROPOSED ACTION AND ALTERNATIVES

3.1 Proposed Action

3.1.1 Introduction

As described in Section 2.1, the proposed action comprises seven recommended changes to 10 CFR Part 39. The first five recommendations, which address radioactive source limits for both ECSs and tritium neutron generator target sources, design performance, inadvertent intrusion of abandoned sources, notification, and generic exemptions for sealed sources manufactured prior to July 14, 1989, are applicable to EH&S. Thus, each of these recommendations is evaluated in this EA. The remaining two recommendations, which are administrative, are not applicable to EH&S and are not evaluated.

3.1.2 Discussion of Recommendations with Potential EH&S Impacts

Energy compensation sources incorporate an encapsulated source of licensed material, most commonly Am-241 and Cs-137, which is prepared to be as insoluble and nondispersible as practicable to comply with 10 CFR 39.41(a)(2).[1] Although the encapsulated source can be physically placed in different types of drilling assemblies, the fundamentals of the technology are the same. That is, the encapsulated source is mounted inside a steel (or other similar metal) pressure housing in the interior of the LWD tool. The pressure housing (and other tool components) provide additional encapsulation to protect the source from operational impacts (e.g., pressure, stresses).

Radioactive Source Limits

The proposed source limits of 3.7 MBq (100 μCi) for ECSs and 1,110 GBq (30 Ci) for tritium neutron generator target sources are based on NRC's understanding of the latest designs. As discussed previously, current ECS and tritium neutron generator target source designs use up to 1.8 MBq (50 μCi) of Am-241 (or another radionuclide) and 740 GBq (20 Ci) of tritium, respectively.[2] To provide licensees flexibility in their designs while maintaining reasonable assurance of human health and environmental protection, NRC proposes establishing an upper limit of 3.7 MBq (100 μCi) and 1,110 GBq (30 Ci) for ECS and tritium neutron generator target source designs, respectively.

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[1] In an industry survey conducted in support of this rulemaking found one licensee that uses Thorium-232 (Th-232) in its ECSs.

[2] See Attachment A for more information.

Design Performance

Based on both an industry survey conducted in support of this rulemaking (see Attachment A) and a review of reportable events information in NRC's Nuclear Material Events Database (NMED), these LWD tools are highly robust.[3] The survey found that no licensee had ever experienced any failures (i.e., leakage) of these encapsulated sources. Further, several licensees reported that their sources are doubly encapsulated, which would exceed NRC's proposed design regulations for ECS designs. Several licensees stated that their ECSs are routinely used at depths of about 4,600 m (15,000 ft), and another licensee mentioned that its design can withstand forces of up to 30 g. From the NMED review, since 1993, out of the fourteen reportable events to NRC involving well logging sources, none identified any design failures or leakages of either ECS or tritium neutron generator target sources.

Given that the source is effectively isolated inside the pressure housing, the likelihood of failure by corrosion, particularly within the economic lifetime of any oil or gas well, is highly improbable. Source capsules manufactured to regulatory standards can withstand normal downhole pressures and temperatures, and they are highly corrosion resistant. According to the Society of Petroleum Engineers (SPE), provided no erosion due to fluid movement, an encapsulated source should maintain its integrity in excess of 750 years. (SPE, 1994)

Notification

NRC proposes to modify Section 39.77 to allow immediate abandonment without prior approval if a delay could cause an immediate threat to public health and safety. Notification would still be required after completing the abandonment. Although notification is an important requirement, NRC believes that the licensee should first take prompt action toward protecting human health and the environment in the event of an abandonment, then make the necessary notifications to contact NRC of this event. Therefore, this proposed action should generally result in improved human health and safety benefits.

Generic Exemption for Sealed Sources Manufactured Before 1989

Based on a Notice of Generic Exemption that was published July 25, 1989 (54 *FR* 30883), NRC issued a generic exemption for sealed sources manufactured before 1989. Although the exemption is currently in use, it has not yet been incorporated in Part 39. NRC proposes to revise Part 39 to include this exemption within the regulations. This modification to Part 39 would result in the same human health and safety benefits defined in the *Federal Register* notice.

Inadvertent Intrusion of Abandoned Sources

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[3] The Nuclear Material Events Database (NMED) is maintained by NRC under contract with the Idaho National Engineering and Environmental Laboratory (INEEL), and includes radiation exposure events reported by both NRC and Agreement State licensees.

NRC proposes that licensees “prevent inadvertent intrusion of ...” sources with activities above 3.7 MBq (100 μCi). Specifically, NRC would require that the source be protected but would allow the licensee the flexibility to determine the best method. NRC’s proposed action would not affect the existing requirement in (a)(5)(I) for a well logging source to be immobilized with a cement plug or the requirement in (a)(5)(iii) for a permanent plaque. Therefore, this modification would allow licensees greater procedural latitude while continuing to ensure source integrity.

Abandonment of Low Activity ECS or Tritium Neutron Generator Target Source

For purposes of this EA, the following failure mode is considered:

-- Damage and rupture of the encapsulated source with subsequent release of radioactive material by a drill-through event, contaminating the well bore fluids which would circulate to the surface during tripping events.[4]

Although the likelihood of damage and rupture by a drill-through event seems very low given the limited use of these sources and the low number of annual abandonments of ECSs and tritium neutron generator target sources, a radiological exposure analysis was performed to estimate the human health risks for this scenario. The analysis presumes an ECS or tritium neutron generator target source is ruptured by a drill-through event, releasing its radioactive material and causing contamination of the well bore and eventually surface equipment by the drilling muds during a tripping event. The analysis assumes, regardless of the form of the radionuclide (i.e., solid piece, compressed powder), that the radioactive material is fragmented or disturbed by the drilling bit and transported to the surface in the mud system.

The analysis identifies three potential human exposure pathways resulting from a drill through event-- inhalation, skin contamination, and ingestion -- all of which are discussed in the following sections.

3.1.3 Inhalation

Inhalation was excluded from analysis because of radionuclide entrainment in the drilling muds and a very low resuspension and evaporation rates. First, after the encapsulated source is ruptured, the radionuclide will tend to bind to both the formation and the drilling muds due to its high surface charge. Therefore, any radioactivity carried to the surface by the drilling muds will remain in the drilling muds because of this binding. Second, resuspension of deposited material on the ground surface will not become airborne, because none of the three mechanisms that result in movement of particles deposited onto surfaces, (e.g., surface creep, saltation, and true suspension) will overcome the effects of binding. Finally, given the high surface charge, evaporation of the drilling muds at the surface would not release much, if any, respirable fraction of the entrained radionuclide.

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[4] The analysis assumes that the radionuclide exposure will occur during routine “tripping” events, when the drill pipe is pulled from the hole. Based on industry experience, these events typically occur once for each 760 m (2,500 ft) of depth drilled.

3.1.4 Skin Contamination

Assumptions

This analysis makes several assumptions regarding skin contamination by exposure to the drilling muds. First, direct skin exposure to contaminated drilling muds would be unlikely because of the protective clothing (coveralls, gloves, hard hats, and goggles) worn by the workers. Second, the radioactive material concentration would be greatly diluted given the large volume of drilling muds at the typical depths for which ECSs and tritium neutron generator target sources are used (120 m [400 ft] to 4,600 m [15,000 ft]). Third, the quantity of any contaminated muds that might splatter on unprotected skin and/or penetrate (soak) the protective clothing would be minuscule. Finally, given the availability and use of portable showers and other water sources at the drill site, any contaminated muds that might splatter on the workers would be washed away relatively quickly. Nevertheless, for the purpose of this EA, the analysis assumes a skin exposure area of 6.5 cm^2 (1 in^2).

Dilution of the radioactive source accounts for the large volume of drilling muds generated by the drilling operation. The amount of dilution by the drilling muds depends on the volume of the drill hole. The analysis assumes a standard drill hole, which uses an 11.5 cm (4-1/2 in) outer diameter drill pipe, generates 0.01554 barrels (bbl)/linear foot of drilling mud volume. (Dow, 1984) Therefore, a minimum drilling depth of 120 m (400 ft) generates about 9.88E+5 cm^3 (6.2 bbl) of drilling mud.[5] The analysis also assumes that the total amount of drilling muds is a factor of ten greater than the actual volume of the well. This assumption matches a standard industry practice of accounting for the drilling fluids (water) pumped into and circulated within the entire well. Using this factor, the standard drill hole (11.5 cm [4-1/2 in] outer diameter) drilled to a minimum depth of 120 m (400 ft) generates 9.88E+6 cm^3 (62 bbl) of drilling mud volume.

Dose Calculations

The dose calculation for skin contamination is based on the dose-rate factors for ground-surface contamination presented in Table 8.2 of NUREG/CR-3332 (NRC, 1983). Starting with the proposed limit of 3.7 MBq (100 μCi) for ECSs and 1,110 GBq (30 Ci) for tritium neutron generator target sources, doses were calculated for five radionuclides, namely: (1) Cs-137, (2) Am-241, (3) Th-232, (4) Rubidium-88 [Rb-88], and (5) tritium. The first four radionuclides apply to ECS designs, while tritium applies only to tritium neutron generator target sources. Rubidium-88 has the highest dose-rate factor for ground-

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[5] See Section 3.1.5, “Assumptions” for a detailed discussion of minimum drilling depth.

surface exposure. Therefore, it serves as the upper bound for the dose calculations for skin contamination. The dose-rate factor for each radionuclide is as follows:

--	Cs-137	7.4E-5 Sv/yr per Bq/cm^2
--	Am-241	0.0 Sv/yr per Bq/cm^2
--	Th-232	No dose-rate factor
--	Rb-88	5.1E-3 Sv/yr per Bq/cm^2
--	Tritium	0.0 Sv/yr per Bq/cm^2

Based on a source limit of 3.7 MBq (100 μCi) for Cs-137 and a dose-rate factor for ground-surface exposure of 7.4E-5 Sv/yr per Bq/cm^2, and assuming:

- -- an area of exposed skin of 6.5 cm^2 (1 in^2) and
- -- a dilution volume of 9.88E+6 cm^3 (62 bbl) from the drilling muds at a minimum depth of 120 m (400 ft),

the estimated annual dose from skin contamination would be 4.3E-6 Sv/yr (0.43 mrem/yr).

To calculate the estimated annual dose through skin contamination, multiply the dose-rate factor for ground-surface exposure for skin by the source limit and by the skin contamination rate, then divide that product by the dilution volume and the area of exposed skin:

(7.4E-5 Sv/yr per Bq/cm^2 x 3.7E+6 Bq/
(9.88E+6 x 6.5 cm^2) = 4.3E-6 Sv/yr

Table 1 summarizes the estimated annual doses from skin contamination for these radionuclides. As shown below, the expected annual dose to drilling workers from skin contamination is below Federal public health limit of 100 mrem/yr.

Table 1. Estimated Annual Skin Contamination Dose for Each Radionuclide

Cs-137 (100 μCi)	**Am-241 (100 μCi)**	**Th-232 (100 μCi)**	**Rb-88 (100 μCi)**	**Tritium (30 Ci)**
4.3E-6 Sv/yr (0.43 mrem/yr)	0.00 Sv/yr (0.00 mrem/yr)	NA[6]	2.9E-5 Sv/yr (29 mrem/yr)	0.00 Sv/yr (0.00 mrem/yr)

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[6] Table 8.2 of NUREG/CR-3332 (NRC, 1983) does not indicate a dose-rate factor for Th-232, therefore no skin contamination dose can be calculated.

3.1.5 Ingestion

Assumptions

The ingestion risk analysis relies on several assumptions to reflect conditions likely to occur as part of the drill-through event of an abandoned source. For convenience, Table 2 contains a summary of these assumptions. Detailed explanations are provided later in this section.

Table 2. Summary of Assumptions Used in Ingestion Exposure Analysis

Assumption	Description
Radionuclide exposure during routine tripping events	Ingestion exposure to contaminated muds only occurs during tripping events, when the workers raise the pipe to the surface -- an activity that typically occurs once every 760 m (2,500 ft) of depth drilled.
Maximum ingestion rate of 30 cm^3 (1 oz)	A trip occurs once for every 2,500 ft of well depth drilled. The analysis assumes that the maximum ingestion rate increases by 30 cm^3 for each 2,500 ft drilled because of the increased time available for possible exposure. This value represents a factor of fifty (50) greater than the predicated ingestion rate of not more than 0.6 cm^3 (0.02 oz), but has been chosen for conservatism.
Drill hole size	Based on standard of 11.5 cm (4-1/2 in) outer diameter drill pipe.
Minimum depth	Abandonment can only occur outside the well casing, which runs to a minimum depth of 120 m (400 ft).
Well volume	Based upon drill hole size, depth drilled, and the standard industry practice of applying of factor of ten (10) to the well volume to account for drilling fluids.
Dilution of the radionuclide concentration by the drilling muds	The radioactive source term is diluted by the total volume of drilling muds generated at depths from 120 m (400 ft) to 4,600 m (15,000 ft).
Additive exposure effects of deeper drilling	The dose estimate at a minimum depth of 120 m (400 ft) is added to the dose estimates calculated for subsequent depths (up to 4,600 m [15,000 ft]).
Drill workers would only be exposed to abandoned ECS or TNG sources once per year	The abandonment rate for ECS and TNG sources averages eight (8) per year. Therefore, the likelihood of a single worker being involved in a drilling event that ruptures more than one source annually is extremely small based upon the total number of wells undergoing logging while drilling.

Dose Calculations

The dose calculation for ingestion is based on the dose conversion factors (DCFs) presented in Table 2.2 of the Federal Guidance Report No. 11.[7] Starting with the proposed limit of 3.7 MBq (100 μCi) for ECSs and 1,110 GBq (30 Ci) for tritium neutron generator target sources, doses were calculated for five radionuclides, namely: (1) Cs-137, (2) Am-241, (3) Th-232, (4) Cm-250, and (5) tritium. The first four radionuclides apply to ECS design, while tritium applies only to tritium neutron generator target sources. Curium-250 has the highest ingestion DCF of all radionuclides. Therefore, it serves as the upper bound for the annual ingestion dose. The DCF for each radionuclide is as follows:

--	Cs-137	1.35E-8 Sv/Bq
--	Am-241	9.84E-7 Sv/Bq
--	Th-232	7.38E-7 Sv/Bq
--	Cm-2502.10E-5 Sv/Bq	
--	Tritium	1.73E-11 Sv/Bq

As described earlier, the ingestion scenario considers a drill-through event of an ECS or tritium neutron generator target source. The drill-through event ruptures the encapsulated source, releasing its radioactive material and causing contamination of the well bore and eventually surface equipment by the drilling muds. Based upon industry experience, ECSs and tritium neutron generator target sources can always be retrieved if somehow lodged inside the casing of the well, which typically run at least 120 m (400 ft) deep. The analysis assumes a minimum depth of 120 m (400 ft), or just beyond the bottom of the casing, for a drill through event. In addition, the analysis assumes the occurrence of a tripping event, though an actual one might not occur at a depth of 120 m (400 ft) to ensure a conservative exposure estimate.[8]

The analysis assumes a standard drill hole, which uses 11.5 cm (4-1/2 in) outer diameter drill pipe, generates 0.01554 bbl/linear foot of drilling mud volume. A minimum drilling depth of 120 m (400 ft) generates about 9.88E+5 cm^3 (6.2 bbl) of drilling mud. The analysis also assumes that the total amount of drilling muds is a factor of ten greater than the volume of the well (see Section 3.1.4 above).

For ingestion, the analysis assumes that the radionuclide exposure will occur during routine tripping

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[7] "Exposure-to-Dose Conversion Factors for Ingestion," Federal Guidance Report No. 11. (EPA, 1988).

[8] A tripping event might occur at the minimum depth of 120 m (400 ft) if it was necessary to inspect the drill bit after drilling through parts of the logging tool.

events (assumed to occur once for every 2,500 ft of well depth drilled), when the drill pipe is pulled from the hole. Based on industry experience, these events typically occur once for each 760 m (2,500 ft) of depth drilled.[9] For each event, the analysis postulates a maximum ingestion rate of 30 cm^3 (1 oz) of drilling mud for every 2,500 ft of well depth drilled. This value is a factor of fifty (50) greater than expected, because, according to an industry representative, the actual ingestion rate would probably be no more than 1/50th of one ounce per tripping event.[10] However, a value of one ounce was used to ensure conservatism in the analysis.

Based on a source limit of 3.7 MBq (100 μCi) for Cs-137, an ingestion rate of 30 cm^3 (1 oz), and a DCF of 1.35E-8 Sv/Bq, and assuming:

-- a minimum well depth of 120 m (400 ft),

-- a single trip per well, and

-- a dilution volume of 9.88E+6 cm^3 (62 bbl),

the estimated ingestion dose would be 0.0152 mrem/well.

At this same depth, the estimated ingestion doses for the other radionuclides are:[11]

--	Am-241	1.11 mrem/well
--	Th-232	0.829 mrem/well
--	Cm-25023.6 mrem/well	
--	Tritium	5.83 mrem/well

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[9] Personal communication with Mr. Ray Dickes, Radiation Safety Officer, Schlumberger, January 5 and 6, 1999.

[10] Ibid.

[11] See Attachment B for calculation.

At greater depths (760 m to 4,600 m [2,500 ft to 15,000 ft]), the effects of tripping will incrementally increase the estimated dose as more and more exposures occur. Therefore, for an upper bound to the dose calculation based on greater depths, the estimated ingestion dose for greater depths includes the estimated ingestion dose at shallower depths. The dose calculations for Cm-250, for a drill through event at different well depths, is shown below.

Given: D_Y = [(Source limit) x (Ingestion quantity) x (DCF)]/(Dilution volume)

where, D_Y = Dose contribution at y feet from ingestion of 1 oz of contaminated mud. for each 2,500 ft of well depth drilled.

Note: Contamination occurs during removal of the drill assembly, which occurs once for every 2,500 ft of well depth drilled. For example, at a depth of 5,000 ft, the total dose includes the dose contribution at 400 ft, 2,500 ft, and 5,000 ft.

D^{total}_{x} = Total dose t to a worker from a drill through event at 400 ft at a certain well depth X is:

$$D^{total}_{x} = D_{400} + D_{2500} + D_{5000} + \ldots + D_X$$

Using Cm-250 for a drill through event at 5,000 ft

$$D^{total}_{5000} = D_{400} + D_{2500} + D_{5000}$$

$$D_{400} = [(100\ \mu Ci) \times (30\ cm^3) \times (2.1E\text{-}05 \times 3.7E\text{+}09\ mrem/\mu Ci)]/(9.88E\text{+}06\ cm^3) = 23.6\ mrem/well$$

$$D_{2500} = [(100\ \mu Ci) \times (60\ cm^3) \times (2.1E\text{-}05 \times 3.7E\text{+}09\ mrem/\mu Ci)]/(6.17E\text{+}08\ cm^3) = 7.56\ mrem/well$$

$$D_{5000} = [(100\ \mu Ci) \times (90\ cm^3) \times (2.1E\text{-}05 \times 3.7E\text{+}09\ mrem/\mu Ci)]/(1.23E\text{+}08\ cm^3) = 5.66\ mrem/well$$

Therefore,

$$D^{total}_{5000} = (23.6 + 7.56 + 5.66)\ mrem/well = 36.82\ mrem/well$$

Attachment B shows the total dose estimates for all five radionuclides down to a maximum depth of 4,600 m (15,000 ft). For convenience, Table 3 summarizes the results of the dose calculation for each radionuclide for all drilling depths.

Table 3. Total Estimated Ingestion Dose for Each Radionuclide (mrem/well)

Depth m (ft)	**Cs-137 (100 μCi)**	**Am-241 (100 μCi)**	**Th-232 (100 μCi)**	**Cm-250 (100 μCi)**	**Tritium (30 Ci)**
120 (400)	0.0152	1.11	0.829	23.6	5.83
760 (2,500)	0.0200	1.46	1.09	31.2	7.70
1,520 (5,000)	0.0237	1.73	1.29	36.8	9.10
2,280 (7,500)	0.0269	1.96	1.47	41.9	10.3
3,040 (10,000)	0.0299	2.18	1.64	46.6	11.5
3,800 (12,500)	0.0329	2.39	1.80	51.1	12.6
4,500 (15,000)	0.0357	2.60	1.95	55.5	13.7

3.1.6 Comparison of Results to NRC's Annual Public Health Limit

The results shown in Table 3 represent estimated doses for an individual worker involved in drilling a single well. Given an abandonment rate of 8 sources per year (see Attachment A, Section A.2), the analysis assumes that drill workers would receive exposures to abandoned sources only once per year. Therefore, the estimated doses shown in Table 3 for each radionuclide, at all depths, can be considered annual, and are less than NRC's public health limit of 100 mrem/yr. In the unlikely event that a worker receives multiple exposures in a given year, the total dose for each radionuclide, except Cm-250, which is not actually used or anticipated to be used as an ECS source, would still be below NRC's annual public health limit.

3.2 No-Action

For the no-action, a 1987 EA of the original Part 39 rulemaking resulted in a finding of no significant impact (FONSI) for well-logging devices using licensed material, which typically contain activity levels of 110 to 740 GBq (3 to 20 Ci). Thus, the current regulations as they apply to LWD sources would result in no change to potential EH&S impacts.

4.0 AGENCIES AND PERSONS CONSULTED

One Federal agency and several Part 39 licensees provided technical, economic, and safety-related information on LWD tools to enhance NRC's understanding of this technology. These organizations participated in a telephone survey to answer questions about source abandonments, LWD tool design and performance, regulatory exemptions, and leak testing. Attachment A summarizes the survey questions and results.

4.1 Agencies Consulted

U.S. Department of the Interior -- U.S. Geological Service

4.2 Licensees Consulted

Baker Atlas[12]
Halliburton Energy Services
Schlumberger
Sperry-Sun[13]
Computalog Wireline Services, Inc.
BPB Instruments, Inc.
Tucker Technologies[14]
AEA Technology, QSA Inc. (formerly Amersham Corp.)

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[12] Formerly known as Western Atlas International, Inc.

[13] A subsidiary of Dresser Industries, Inc.

[14] This firm does not use either ECSs or TNGs.

5.0 REFERENCES

(Dow, 1984) Dowell Division of Dow Chemicals U.S.A. "Field Data Handbook," p. 85.

(EPA, 1988) U.S. Environmental Protection Agency, "Limiting Values Of Radionuclide Intake And Air Concentration and Dose Conversion Factors For Inhalation, Submersion, and Ingestion -- Federal Guidance Report No. 11," EPA 520/1-88-020.

(NRC, 1998) U.S. Nuclear Regulatory Commission, "Rulemaking Plan: Energy Compensation Sources for Well Logging and Clarifications - Changes to 10 Part 39," SECY-98-105, May 12.

(NRC, 1983) U.S. Nuclear Regulatory Commission, "Radiological Assessment: A Textbook on Environmental Dose Analysis," NUREG/CR-3332, September.

(SPE, 1994) Society of Petroleum Engineers, "Operational and Environmental Safety with Nuclear LWD Tools," Second International Conference on Health, Safety & Environment in Oil & Gas Exploration & Production, January 25-27.

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Cade, R.W., Joshi Technologies International, *Horizontal Wells: Development and Applications,* October 1998.

Schlumberger Educational Services, *Log Interpretation Principles/Applications*, 1989.

ACRONYMS

AEOD	Analysis and Evaluation of Operational Data
CFR	Code of Federal Regulations
DCF	Dose Conversion Factor
EA	Environmental Assessment
ECS	Energy Compensation Source
EH&S	Environment, Health, and Safety
EPA	Environmental Protection Agency
FR	Federal Register
FONSI	Finding of No Significant Impact
INEEL	Idaho Nuclear Engineering and Environmental Laboratory
LWD	Logging While Drilling
NMED	Nuclear Material Events Database
NRC	Nuclear Regulatory Commission
SPE	Society of Petroleum Engineers
USASI	United States of America Standards Institute

Attachment A -- SUMMARY OF LICENSEE SURVEY

A.1 Summary of Licensee Survey Questions

To help quantify the effects of the proposed rule, a data collection effort was conducted to obtain information from well logging licensees using ECSs and tritium neutron generator target sources and manufacturers of ECSs and tritium neutron generator target sources. Due to time, resource and OMB clearance constraints, NRC elected to survey only a sample of licensees (less than 10). However, NRC is confident that the information obtained from these licensees represents conditions in the industry. NRC first prepared a list of licensees and manufacturers, and selected a total of nine contacts. A list of questions needed for this EA was developed to obtain information on the following topics:

- Number of abandonments due to irretrievable sources (ECSs or tritium neutron generator target sources) in an average year, including depth of source.
- Need for erection of a permanent plaque for an abandoned well to identify the horizontal and vertical location of the source.
- Description of leak tests conducted on ECSs and the time interval under which they are tested.
- Robustness of the ECS design.
- Exposure pathways for workers in the event an ECS or tritium neutron generator target source is drilled through.
- Amount of contamination that workers could be exposed to in the event an ECS or tritium neutron generator target source was drilled through.

A.2 Summary of Licensee Survey Responses

This section provides a summary of the licensee survey responses to NRC's information request for the key parameters for this analysis.

- Respondents reported an average of 8 abandoned ECSs per year. The depth at which these sources were abandoned ranged from 1,000 to 12,500 ft. Three respondents reported never abandoning an ECS in a well logging operation.
- One respondent reported abandoning a tritium neutron generator target source. This respondent stated that the depth of the source when abandoned was greater than 10,000 ft. Most respondents noted that because retrieval of a lodged source mainly depends on the depth of the

source at the time it becomes lodged and whether the source is in the well casing, the likelihood of retrieval of tritium neutron generator target sources at shallow depths, within the surface casing, is extremely high.

- Respondents mentioned that any potential radiological exposure pathways would occur at the surface via the circulating fluids (i.e., drilling muds) inside the well. One respondent suggested the containment and disposal of drilling fluids as another potential radiological exposure pathway. Most respondents stated that radiological exposure and site contamination would be negligible.

- Only one respondent reported the use of a tool containing an ECS or tritium neutron generator target source where surface casing was not set. This respondent indicated that this situation typically occurred in mineral or water well logging operations.

- Respondents indicated the need to account for dilution of the radioactive source term by drilling muds in evaluating risks associated with source abandonment. Respondents also indicated that identifying the horizontal and vertical location of the source with a permanent plaque would be useful for source abandonment. However, one respondent questioned the usefulness, while two licensees stressed that the plaque should only be mounted if practical. Another respondent suggested marking the horizontal location with a fence around the approximate area of the source.

- Respondents reported that the typical types and activity levels of radioactive materials used in ECSs were 0.8 μCi of Cs-137 and 2.6 to 50 μCi of Am-241. Licensees reported the current types and activity levels of radioactive materials used in tritium neutron generator target sources to range from 0.3 to 20 Ci of tritium.

- Two respondents do not perform leak testing because they only use (1) gamma-beta emitting sources containing less than 100 microcuries and (2) tritium neutron generator target sources; both of which are already exempted from leak testing requirements. Without exception, licensees believe that the robust nature of the sources significantly decreases the need for frequent leak testing. Not one respondent indicated that a wipe tested ECS was found to have leaked. Respondents noted that a more appropriate interval for leak testing would be during routine maintenance on the tool or when removed from service for repair.

- Several licensees emphasized the robustness of the ECS design (i.e., achieving depths of 4,600 m [15,000 ft] and withstanding forces of up to 30 g). Several licensees mentioned that their ECS sources were doubly or triply encapsulated.

- Licensees indicated that the maintenance interval for well logging tools containing an ECS is highly variable. While some licensees reported a routine interval (inspection every month, or once per year), other licensees indicated that the interval can be much longer, depending on how long the tool is in the field. Respondents indicated that maintenance and repair to these tools is not typically conducted in the field.

- Respondents providing information indicated that exposure from a drill through event of an ECS or tritium neutron generator target source would result in contamination of the fluids (drilling muds) circulating in the well casing or hole and that exposure would only occur when the fluids circulated to the surface (i.e., during a tripping event when the drill stem is removed and cleaned). In all cases, respondents providing information on this question indicated that the exposure would be very minimal if any occurred at all.

- One respondent indicated that a very conservative estimate for the amount of contaminated drilling mud a worker could ingest from a drilled through ECS or tritium neutron generator target source was one ounce per tripping event, which typically occurs once for every 2,500 ft of well depth drilled. This estimate was based on the assumption that a tripping event takes 2 minutes per 60 ft of drill stem to complete. The respondent qualified this statement, however, indicating that the actual amount of contaminated drilling mud that a worker could ingest during a tripping event was more realistically approximately 1/50th of one ounce per tripping event.

Attachment B -- DOSE CALCULATIONS FOR ECS AND TNG DESIGNS

B.1 Overview of Dose Calculations and Results

Calculations of the estimated ingestion dose (mrem/well) at various depths can be found in Tables B.1 through B.7.

Table B.1. Calculation of the Estimated Ingestion Dose at a Depth of 120 m (400 ft)

Radionuclide Source Limit (uCi)	Ingestion Rate (cm^3) [a]	Dilution Volume (cm^3) [b]	Ingestion Exposure (uCi/well)	Ingestion DCF (Sv/Bq) [c]	Estimated Ingestion Dose at Depth (mrem/well)	Estimated Incremental Ingestion Dose at Shallower Depths (mrem/well)	Estimated Total Ingestion Dose[d] (mrem/well)
100 uCi Cs-137	30	9.88E+06	3.04E-04	1.35E-08	0.015	0.000	0.015
100 uCi Am-241	30	9.88E+06	3.04E-04	9.84E-07	1.106	0.000	1.106
100 uCi Th-232	30	9.88E+06	3.04E-04	7.38E-07	0.829	0.000	0.829
100 uCi Cm-250	30	9.88E+06	3.04E-04	2.10E-05	23.600	0.000	23.600
30 Ci Tritium	30	9.88E+06	9.11E+01	1.73E-11	5.833	0.000	5.833

Table B.2. Calculation of the Estimated Ingestion Dose at a Depth of 760 m (2,500 ft)

Radionuclide Source Limit (uCi)	Ingestion Rate (cm^3) [a]	Dilution Volume (cm^3) [c]	Ingestion Exposure (uCi/well)	Ingestion DCF (Sv/Bq) [d]	Estimated Ingestion Dose at Depth (mrem/well)	Estimated Incremental Ingestion Dose at Shallower Depths (mrem/well)	Estimated Total Ingestion Dose[e] (mrem/well)
100 uCi Cs-137	60	6.17E+07	9.72E-05	1.35E-08	0.005	0.015	0.020
100 uCi Am-241	60	6.17E+07	9.72E-05	9.84E-07	0.354	1.110	1.464
100 uCi Th-232	60	6.17E+07	9.72E-05	7.38E-07	0.265	0.829	1.094
100 uCi Cm-250	60	6.17E+07	9.72E-05	2.10E-05	7.552	23.600	31.152
30 Ci Tritium	60	6.17E+07	2.92E+01	1.73E-11	1.866	5.830	7.696

Table B.3. Calculation of the Estimated Ingestion Dose at a Depth of 1,520 m (5,000 ft)

Radionuclide Source Limit (uCi)	Ingestion Rate (cm^3) [a]	Dilution Volume (cm^3) [c]	Ingestion Exposure (uCi/well)	Ingestion DCF (Sv/Bq) [d]	Estimated Ingestion Dose at Depth (mrem/well)	Estimated Incremental Ingestion Dose at Shallower Depths (mrem/well)	Estimated Total Ingestion Dose[e] (mrem/well)
100 uCi Cs-137	90	1.23E+08	7.29E-05	1.35E-08	0.004	0.020	0.024
100 uCi Am-241	90	1.23E+08	7.29E-05	9.84E-07	0.265	1.464	1.729
100 uCi Th-232	90	1.23E+08	7.29E-05	7.38E-07	0.199	1.094	1.293
100 uCi Cm-250	90	1.23E+08	7.29E-05	2.10E-05	5.664	31.152	36.816
30 Ci Tritium	90	1.23E+08	2.19E+01	1.73E-11	1.400	7.696	9.096

Table B.4. Calculation of the Estimated Ingestion Dose at a Depth of 2,280 m (7,500 ft)

Radionuclide Source Limit (uCi)	Ingestion Rate (cm^3) [a]	Dilution Volume (cm^3) [c]	Ingestion Exposure (uCi/well)	Ingestion DCF (Sv/Bq) [d]	Estimated Ingestion Dose at Depth (mrem/well)	Estimated Incremental Ingestion Dose at Shallower Depths (mrem/well)	Estimated Total Ingestion Dose[e] (mrem/well)
100 uCi Cs-137	120	1.85E+08	6.48E-05	1.35E-08	0.003	0.024	0.027
100 uCi Am-241	120	1.85E+08	6.48E-05	9.84E-07	0.236	1.729	1.965
100 uCi Th-232	120	1.85E+08	6.48E-05	7.38E-07	0.177	1.293	1.470
100 uCi Cm-250	120	1.85E+08	6.48E-05	2.10E-05	5.035	36.816	41.850
30 Ci Tritium	120	1.85E+08	1.94E+01	1.73E-11	1.244	9.096	10.340

Table B.5. Calculation of the Estimated Ingestion Dose at a Depth of 3,040 m (10,000 ft)

Radionuclide Source Limit (uCi)	Ingestion Rate (cm^3) [a]	Dilution Volume (cm^3) [c]	Ingestion Exposure (uCi/well)	Ingestion DCF (Sv/Bq) [d]	Estimated Ingestion Dose at Depth (mrem/well)	Estimated Incremental Ingestion Dose at Shallower Depths (mrem/well)	Estimated Total Ingestion Dose[e] (mrem/well)
100 uCi Cs-137	150	2.47E+08	6.07E-05	1.35E-08	0.003	0.027	0.030
100 uCi Am-241	150	2.47E+08	6.07E-05	9.84E-07	0.221	1.965	2.186
100 uCi Th-232	150	2.47E+08	6.07E-05	7.38E-07	0.166	1.470	1.636
100 uCi Cm-250	150	2.47E+08	6.07E-05	2.10E-05	4.720	41.850	46.570
30 Ci Tritium	150	2.47E+08	1.82E+01	1.73E-11	1.167	10.341	11.507

Table B.6. Calculation of the Estimated Ingestion Dose at a Depth of 3,810 m (12,500 ft)

Radionuclide Source Limit (uCi)	Ingestion Rate (cm^3) [a]	Dilution Volume (cm^3) [c]	Ingestion Exposure (uCi/well)	Ingestion DCF (Sv/Bq) [d]	Estimated Ingestion Dose at Depth (mrem/well)	Estimated Incremental Ingestion Dose at Shallower Depths (mrem/well)	Estimated Total Ingestion Dose[e] (mrem/well)
100 uCi Cs-137	180	3.09E+08	5.83E-05	1.35E-08	0.003	0.030	0.033
100 uCi Am-241	180	3.09E+08	5.83E-05	9.84E-07	0.212	2.186	2.399
100 uCi Th-232	180	3.09E+08	5.83E-05	7.38E-07	0.159	1.636	1.795
100 uCi Cm-250	180	3.09E+08	5.83E-05	2.10E-05	4.531	46.570	51.101
30 Ci Tritium	180	3.09E+08	1.75E+01	1.73E-11	1.120	11.507	12.627

Table B.7. Calculation of the Estimated Ingestion Dose at a Depth of 4,600 m (15,000 ft)

Radionuclide Source Limit (uCi)	Ingestion Rate (cm^3) [a]	Dilution Volume (cm^3) [c]	Ingestion Exposure (uCi/well)	Ingestion DCF (Sv/Bq) [d]	Estimated Ingestion Dose at Depth (mrem/well)	Estimated Incremental Ingestion Dose at Shallower Depths (mrem/well)	Estimated Total Ingestion Dose[e] (mrem/well)
100 uCi Cs-137	210	3.70E+08	5.67E-05	1.35E-08	0.003	0.033	0.036
100 uCi Am-241	210	3.70E+08	5.67E-05	9.84E-07	0.206	2.399	2.605
100 uCi Th-232	210	3.70E+08	5.67E-05	7.38E-07	0.155	1.795	1.950
100 uCi Cm-250	210	3.70E+08	5.67E-05	2.10E-05	4.405	51.102	55.507
30 Ci Tritium	210	3.70E+08	1.70E+01	1.73E-11	1.089	12.627	13.716

[a] The ingestion rate assumes the ingestion of one ounce (30 cm^3) per trip (or 2,500 ft of drilling depth).

[b] One barrel equals 1.589 x 10^5 cm^3.

[c] Multiply the ingestion DCF by 3.7E+9 to convert into mrem/uCi.

[d] Total estimated ingestion dose is determined by adding the estimated ingestion dose at depth to the estimated ingestion dose at shallower depths. This accounts for the additive risk associated with multiple tripping events at depth.