U.S. DEPARTMENT OF ENERGY

PNNL-20831

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Evaluation of Non-Nuclear Techniques for Well Logging: Final Report

LJ Bond
JW Griffin
RV Harris
KM Denslow
TL Moran

August 2011

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

This document was printed on recycled paper.
(9/2003)

PNNL-20831

Evaluation of Non-Nuclear Techniques for Well Logging: Final Report

LJ Bond
JW Griffin
RV Harris
KM Denslow
TL Moran

August 2011

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Abstract

Sealed, chemical isotope radiation sources have a diverse range of industrial applications. There is concern that such sources currently used in the gas/oil well logging industry (e.g., americium-beryllium [AmBe], ^{252}Cf, ^{60}Co, and ^{137}Cs) can potentially be diverted and used in dirty bombs. Recent actions by the U.S. Department of Energy (DOE) have reduced the availability of these sources in the United States. Alternatives, both radiological and non-radiological methods, are actively being sought within the oil-field services community. The use of isotopic sources can potentially be further reduced, and source use reduction made more acceptable to the user community, if suitable non-nuclear or non-isotope–based well logging techniques can be developed. Data acquired with these non-nuclear techniques must be demonstrated to correlate with that acquired using isotope sources and historic records. To enable isotopic source reduction there is a need to assess technologies to determine: (1) if it is technically feasible to replace isotopic sources with alternate sensing technologies and (2) to provide independent technical data to guide DOE (and the U.S. Nuclear Regulatory Commission [NRC]) on issues relating to replacement and/or reduction of radioactive sources used in well logging.

This document is a final report on the project that prepared an initial review of state-of-the-art nuclear and non-nuclear well logging methods and sought to understand the technical and economic issues if AmBe (and potentially other isotope sources) are reduced or even eliminated in the oil-field services industry. Prior to considering alternative logging technologies, there is a definite need to open up discussions with industry regarding the feasibility and acceptability of source replacement. Industry views appear to range from those who see AmBe as vital and irreplaceable to those who believe that, with research and investment, it may be possible to transition to electronic neutron sources and employ combinations of non-nuclear technologies to acquire the desired petro-physical parameters. In one sense, the simple answer to the question as to whether petro-physical parameters can be sensed with technologies other than AmBe is probably "Yes." The challenges come when attention turns to record interpretation. The many decades of existing records form a very valuable proprietary resource, and the interpretation of subtle features contained in these records are of significant value to the oil-gas exploration community to correctly characterize a well. The demonstration of equivalence and correspondence/correlation between established and any new sensing modality, and correlations with historic records, is critical to ensuring accurate data interpretation. Establishing the technical basis for such a demonstration represents a significant effort.

The focus of this study is the understanding of the technical obstacles that hinder the replacement of and the disadvantages from the loss of extensive interpretation experience based on data accumulated with AmBe. Enhanced acoustic and electromagnetic sensing methods in combination with non-isotope–based well logging techniques have the potential to complement and/or replace existing isotope-based techniques, providing the opportunity to reduce oil industry dependence on isotopic sources such as AmBe.

Acknowledgments

This work was supported by the United States Department of Energy, National Nuclear Security Administration, Office of Nonproliferation and Verification R&D (NA-22). The authors gratefully acknowledge the kind and generous support of Professor Richard Liu, University of Houston, Well Logging Laboratory and Dr. Arthur Cheng, Society of Exploration Geophysicists.

Acronyms and Abbreviations

AmBe	americium-beryllium
BHA	borehole assembly
CPMG	Carr, Purcell, Meiboom, Gill
DOE	U.S. Department of Energy
D-T	deuterium-tritium
EPA	U.S. Environmental Protection Agency
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley Laboratory
LWD	logging-while-drilling
MRIL	magnetic resonance imaging logging
NMR	nuclear magnetic resonance
NRC	U.S. Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
psi	pounds per square inch
RF	radio frequency
SBIR	Small Business Innovation Research
SIG	Special Interest Group
SNL	Sandia National Laboratory
SPWLA	Society of Petrophysicists and Well Log Analysts
SWD	seismic-while-drilling
T-T	tritium-tritium
VSP-WD	vertical seismic profiling while drilling

Contents

Figures

Tables

1.0 Introduction

Sealed, chemical isotope radiation sources have a diverse range of industrial applications. There is concern that such sources currently used in the gas/oil well logging industry (e.g., americium-beryllium [AmBe], ^{252}Cf, ^{60}Co, and ^{137}Cs) can potentially be diverted and used in dirty bombs. Recent actions by the U.S. Department of Energy (DOE) have reduced the availability of these sources in the United States. Alternatives, both radiological and non-radiological methods, are actively being sought within the oil-field services community. The use of isotopic sources can potentially be further reduced, and source use reduction made more acceptable to the user community, if suitable non-nuclear or non-isotope–based well logging techniques can be developed. Data acquired with these non-nuclear techniques must be demonstrated to correlate with that acquired using isotope sources and historic records. To enable isotopic source reduction there is a need to assess technologies to determine: (1) if it is technically feasible to replace isotopic sources with alternate sensing technologies and (2) to provide independent technical data to guide DOE (and the U.S. Nuclear Regulatory Commission [NRC]) on issues relating to replacement and/or reduction of radioactive sources used in well logging.

This document presents the final report on the project. Deliverables have included a report that provided an initial review of the state-of-the-art nuclear and non-nuclear well logging methods and seeks to understand the technical and economic issues if AmBe (and potentially other isotope sources) are reduced or even eliminated in the oil-field services industry (Bond et al. 2010a). Prior to considering alternative logging technologies, it was determined that there is a definite need to open up discussions with industry regarding the feasibility and acceptability of source replacement. Industry views appear to range from those who see AmBe as vital and irreplaceable to those who believe that, with research and investment, it may be possible to transition to electronic neutron sources and employ combinations of non-nuclear technologies to acquire the desired petro-physical parameters. In one sense, the simple answer to the question as to whether petro-physical parameters can be sensed with technologies other than AmBe is probably "Yes." The challenges come when attention turns to record interpretation. The many decades of existing records form a very valuable proprietary resource, and the interpretation of subtle features contained in these records are of significant value to the oil-gas exploration community to correctly characterize a well. The demonstration of equivalence and correspondence/correlation between established and any new sensing modality, and correlations with historic records is critical to ensuring accurate data interpretation. Establishing the technical basis for such a demonstration represents a significant effort.

The focus of this study was to understand the technical obstacles that hinder the replacement of and the disadvantages from the loss of extensive interpretation experience based on data accumulated with AmBe. Enhanced acoustic and electromagnetic sensing methods in combination with non-isotope–based well logging techniques have the potential to complement and/or replace existing isotope-based techniques, providing for the opportunity to reduce oil industry dependence on isotopic sources such as AmBe. This study provided initial insights to establish the information resources needed to provide independent technical data to guide DOE (and NRC) on issues relating to replacement and/or reduction of radioactive sources used in well logging (Bond et al. 2010a).

The project was initiated in FY2009 with acquisition of a porosity-calibrated sandstone library that could be used for laboratory measurements. Throughout the first year, the sandstone samples were subjected to acoustic, electromagnetic, and nuclear measurements with the goal of enabling the team to truly understand the challenges and issues relating to establishing correlations between rock physical properties (acoustic velocity, complex electromagnetic permittivity, etc.) and rock permeability. In the second project year, following an external review by industry experts, the scope of the project was considerably narrowed to investigate only acoustic/ultrasonic diffuse field methods, nuclear magnetic resonance, and electro-seismic methods. The primary task in Year 3 was organization and leadership of a government-industry workshop at the University of Houston to discuss the state-of-the-art in nuclear logging alternatives for petrochemical well logging.

Year 1 (FY2009) Tasks

1) *Assembly of Sandstone Sample Library*

A seven-sample collection of sandstone materials was procured from TerraTek, Salt Lake City spanning ambient porosity values of 9% through 25%. These samples, both dry and water-saturated, were used for all of the laboratory acoustic, nuclear, and electromagnetic measurements.

2) *Acoustic Measurements on Sandstones*

Acoustic propagation measurements were performed on dry and wet sandstone slabs in order to: (1) investigate correlations between longitudinal ultrasonic wave velocity and sandstone porosity; and (2) to assess the feasibility of using diffuse-field ultrasonic backscatter methods to derive porosity, density, or other important physical properties of sandstones.

3) *Electromagnetic and Nuclear Measurements on Sandstones*

Sandstone library samples were subjected to passive gamma spectroscopy measurements, gamma/neutron attenuation measurements, electromagnetic permittivity measurements, and radio-frequency (RF) attenuation measurements. These experiments served to educate the technical team regarding measurement geometries, sample variability, and the technical challenges associated with petrochemical well logging. The most promising predictors of rock porosity proved to be AC electrical permittivity and/or RF attenuation. However, due to the high attenuation losses anticipated in water-saturated rock formations, the method was deemed impractical.

Year 2 (FY2010) Tasks

1) *Project External Review*

An external project review was conducted at Pacific Northwest National Laboratory (PNNL) facilities on February 24, 2010. Reviewers included Dr. Richard Liu, Director, Well Logging Laboratory, University of Houston; Dr. Arthur Cheng, Vice President, Society of Exploration Geophysicists and; Dr. Fred Paillet, University of Arkansas. Technical re-direction and conclusions from this review resulted in the decision to re-focus efforts on acoustic diffuse fields, nuclear magnetic resonance, and seismo-electric methods.

2) *Collaborations with LBL and LANL*

With encouragement from the NA-22 program manager, Frances Keel, collaborative interactions were initiated with two other NA-22–funded principal investigators contributing to the radioactive source replacement program—Dr. Gregory Dale, Los Alamos National Laboratory (LANL) and Dr. Thomas Schenkel, Lawrence Berkeley Laboratory (LBL). The LANL and LBL teams are both working on electronic neutron sources.

Year 3 (FY2011) Tasks

1) *Radioactive Source Replacement Workshop*

A government-industry workshop on radiation source replacement in the petrochemical industry was held at the University Center, University of Houston on October 27–28, 2010. The Day 1 agenda focused on "The National Security Perspective and Federally Funded R&D" and consisted of presentations by representatives from government agencies (NRC, U.S. Environmental Protection Agency [USEPA]), DOE National Laboratories (LBL, LANL, Sandia National Laboratory [SNL]), and DOE-funded Small Business Innovation Research (SBIR) contractors (Berkion Technology Inc. and Radiabeam Technologies Inc.). The second day of the workshop focused on "Emerging Alternatives to Nuclear Well Logging" and featured industry speakers from Chevron, Groundflow Ltd., Baker Hughes, Schlumberger, and Halliburton.

2) *Publications/Presentations*

Dr. Leonard Bond presented an overview paper summarizing the Radioactive Source Replacement Project at the SEG Annual Meeting in Denver, Colorado, entitled "Neutron Source Replacement in Petrochemical Well Logging" (Bond et al. 2010b)

This present report presents a summary of the conclusions from the technology evaluation in Section 2.0. This is followed by some specific discussion of the results of an experimental investigation in the basis of diffuse field methods (Section 2.2) and an assessment of the potential of nuclear magnetic resonance (NMR) in Section 2.3.

A summary of the community engagement workshop on Alternatives to Chemical Radiation Sources for Petrochemical Well Logging is given in Section 3.0. Section 4.0 gives a summary of the conclusions that can be drawn on the basis of the project, Section 5.0 provides references, and Section 6.0 lists presentations and reports that resulted from the project.

2.0 Technology Evaluation

There is a diverse range of industrial applications for sealed radiation sources. However, there is concern that such sources (including americium-beryllium currently used for neutron logging by the oil and gas industry) can potentially be diverted and used in dirty bombs. Recent actions by the DOE have reduced the availability of such sources in the United States. Alternatives, both radiological and non-radiological, are actively being sought within the oil-field services community. The use of isotopic sources could be further reduced, and source use reduction made more acceptable to the user community, if suitable non-nuclear or non-isotope–based techniques could be developed and demonstrated.

This study is focused on the need to assess petrochemical well-logging technologies to determine if it is technically feasible to replace logging techniques requiring isotopic sources (such as AmBe, ^{252}Cf, ^{137}Cs, ^{60}Co) with alternative non-nuclear sensing methods. It also will provide the independent technical data needed to guide DOE (and the NRC) on issues relating to replacement and/or reduction in radioactive sources used in well logging. The initial phase of this study:

- provided a preliminary assessment of the neutron-based measurement methods (using AmBe sources);
- defined the parameters for a rock reference library needed for sensor evaluation and comparison;
- identified both acoustic/ultrasonic and electromagnetic techniques (including NMR) as having the potential to determine formation parameters of composition and porosity currently measured using nuclear methods; and
- established the experimental approach and identified some of the key issues to be addressed.

In looking at alternatives to the current AmBe sources, three approaches are being considered:

1. Reduction in the activity of the required AmBe source (through approaches that included the deployment of enhanced sensors)
2. The use of electronic deuterium-tritium (D-T) neutron generators (although these provide neutrons with different spectra and data inter-comparison requires attention)
3. The use of enhanced and novel acoustic and electromagnetic sensing tools, including NMR, used either in combination with reduced-activity AmBe sources and/or D-T generator-derived data.

These activities, under the Radiological Source Replacement Program, are positioning PNNL and partnering laboratories to be able to provide independent technical assessment and technical advice to DOE and the NRC. This support includes guidance regarding the issues encountered in reducing use of isotopic sources by the oil and gas well-logging industry and implementing alternative well-logging technologies. The National Academies report (NRC 2008) on radiation source use and replacement identifies the pertinent issues relating to well logging and other uses of isotopes. That report acknowledges that the radioactive sources, in particular AmBe, are at some risk of loss and diversion for use in dirty bombs, and indicates that the use of alternatives should be investigated. This project is investigating various technologies in order to determine the barriers to source replacement and to determine whether it is technically feasible to replace isotopic sources with alternate technologies. The study is seeking to identify the critical technological issues and determine what can be done to work with the industry to reduce the need for radioisotope sources. In reviewing this body of knowledge and the industry activities, the project is seeking to collect and organize independent technical data needed to guide DOE (and NRC) on issues relating to replacement and/or reduction of radioactive sources used in well logging.

Current well logging tools transmit data to the surface via the low-bandwidth channels of mud and/or drill string. The drilling mud, being either oil- or water-based, impacts some of the measurements, as do the casing and the grouting for production wells. From a security perspective, the use and deployment of D-T neutron generators is not totally issue-free, as it is a defense dual-use technology.

In the development of structural models (inversion of the well-logging data), there are complementary data that can be used to enhance evaluations. There would appear to be opportunities for extracting more petro-physical parameters through combinations of seismology and down-hole acoustic measurements. These methods measure and acquire similar formation parameters, but are operated in very different frequency regimes due to significant differences in the sound-medium interactions (considered in terms of scale of wavelength and measurement). There is also increased interest in some more innovative approaches, including seismic-while-drilling (SWD) that uses the drill-generated noise as a source that produces signatures recorded at the surface. The implications for potential to reduce isotope use are still being developed.

SWD specifically encompasses the seismic techniques operated while the drill string is lowered into the borehole, during effective drilling, during maneuvers, or while connecting drill pipes. A related concept introduced by Schlumberger is vertical seismic profiling while drilling (VSP-WD). VSP-WD records the seismic signal generated by a surface seismic source on seismic sensors integrated inside the down-hole borehole assembly (BHA). There are also more novel measurement schemes that are receiving attention in well-logging applications. These include both NMR and use of electro-kinetic effects to induce sound wave material interactions (piezo-seismic interactions).

In addition to technical issues, there are various economic and political issues, including the proprietary nature of well-log information. These issues are particularly acute for smaller logging service companies. Smaller independent well-logging companies find a substantial market in re-logging old wells. These companies are more likely to require comparisons of old AmBe data to new AmBe data. Major oil-field service companies win most contracts for logging-while-drilling (LWD), and thus are better poised to deploy new technologies, at least for new well applications. These issues need attention, but detailed analysis of them is beyond the scope of this report.

To speed adoption of new sensors, there is a need for rock reference samples that can function as standards (calibrated rock-fluid samples) to be used in studies to demonstrate sensor equivalence.

Discussions have been initiated with industry regarding the feasibility of source replacement. Views range from those who see AmBe as vital and irreplaceable to those who view, that with research and investment, chemical source replacement may be possible. In a strict technical sense, the simple answer to the question as to whether petro-physical parameters can be sensed with technologies other than AmBe is probably "Yes."

The challenges come when attention turns to record interpretation and product development in the forms and methods of data interpretation. The many decades of existing records form a very valuable proprietary resource. Methods of interpretation derived from these records are of significant value to the oil-gas exploration community.

The demonstration of equivalences and/or correlations between established and new sensing modalities and the ability to make correlations with historic records are critical to ensuring accurate data interpretation. Such an equivalence demonstration represents a significant technical effort. Electronic (accelerator) neutron sources and ^{252}CF show promise for replacement of AmBe sources.

The goal of this study is to gain an understanding of the technical obstacles to AmBe source replacement and to assess the disadvantages (e.g., the loss of extensive interpretation experience) associated with the use of newer non-nuclear technologies (e.g., NMR).

The aim of this study is to understand the technical obstacles that hinder the replacement of AmBe sources and to identify disadvantages due to loss of extensive interpretation experience based on data accumulated with AmBe. Enhanced acoustic and electromagnetic sensing methods, in combination with non-isotope–based well-logging techniques, have the potential to complement and/or replace existing isotope-based techniques, providing the opportunity to reduce AmBe use. To enable inter-technology comparisons there is a need for a library of well-calibrated rock samples with fluid-filled porosities. Demonstrations of sensor equivalence (e.g., AmBe vs. electronic neutron sources and those using non-nuclear modalities) must ultimately accommodate realistic downhole pressure and temperature variations. However, room temperature measurements offer the potential to acquire proof-of-concept data that demonstrates feasibility.

2.1 Path Forward

The goal for this study is to move beyond insights provided in the current report to establish the information resources needed to provide independent technical data to guide DOE (and NRC) on issues relating to the potential for replacement and/or reduction in radioactive sources used in well logging.

To address the issues that hinder elimination of the use of AmBe in well logging the industry must:

1. Develop a better understanding of the equivalence in formation measurements using chemical radiation sources (gamma density, neutron activation, neutron inelastic scattering, etc.) and other non-nuclear sensing technologies (electromagnetic propagation, NMR, etc.). Questions include:
    a. How are indirect physical parameter data used to infer formation parameters (e.g., how is formation porosity derived from neutron scattering measurements)? How is formation porosity derived from non-nuclear NMR measurements?
    b. How to develop a better understanding of the relative sensitivity (and accuracy) and measurement regions of logging methods (there are differences in the physics) including the depth of investigation and achieved spatial resolutions. The technology comparison matrix must be completed. How does the performance (sensitivity, range, robustness) of non-isotopic nuclear methods compare with isotopic nuclear methods? For example, is there an advantage in using the higher-energy neutrons provided by the D-T source (14.1 MeV) over the low-energy neutrons provided by a chemical source (2–6 MeV)? Does the D-T source afford greater range and/or accuracy? Does the relative similarity of the neutron spectra from the T-T (tritium-tritium) reaction and from AmBe sources offer opportunities for cross-calibration?

2. Establish a well-characterized library of rock reference samples, which are needed to support an investigation of the equivalence of nuclear well-logging sensor responses and those from other methods (in terms of ability to sense petro-physical parameters).

3. Investigate the potential for new sensing ideas which can better quantify petro-physical parameters; for example, acoustic/ultrasonic diffuse field, which is not currently implemented for well logging.

4. Engage and encourage discussion within the industry. Seek to focus attention on articulation of issues relating to barriers to eliminating AmBe sources in well logging. Determine which issues are based on technical challenges and which are based on capability perceptions.

Other technical hurdles are those issues where the replacement techniques require more sophisticated packaging and can be more operationally complex. AmBe sources are simple passive sources, robust, and able to operate over a large range of well-bore conditions (i.e., temperature, well completions, etc.).

2.2 Acoustics (Becker et al. 2003; Jia 2004)

There is a risk that radiological sources including those using AmBe, which is currently used in well logging by the oil and gas industry, can be diverted and used in dirty bombs. The use of isotopic sources can potentially be reduced, and source use reduction made more acceptable to the user community, if suitable non-nuclear or non-isotope–based techniques can be developed and demonstrated. This project has identified both acoustic/ultrasonic and electromagnetic techniques as having potential to determine parameters of rock composition and porosity, currently commonly measured using nuclear methods.

This document reports initial acoustic diffuse field measurements on sandstone surrogate samples, which form part of an evaluation of alternative non-nuclear techniques for well logging. Diffuse field measurements are a new proposed approach to rock characterization and are complementary to traditional acoustic velocity and acoustic attenuation logging data. Measurements were performed on saturated glass bead mixtures that represent water-saturated sandstone. Two different glass bead sizes were used to prepare two surrogate samples. The experimental system used is discussed and initial acoustic measurements performed at frequencies of 250 kHz to 1 MHz are reported. This laboratory evaluation has established the initial experimental approach to be adopted and identified key issues that need to be addressed.

The activities discussed in this report help to position PNNL to be able to provide independent technical assessment and technical advice to DOE and NRC regarding the issues encountered in reduction of the use of isotopic sources by the oil and gas industry well-logging community (Denslow et al. 2010).

An acoustic diffuse field develops when the acoustic energy wavelength in the material under test is on the order of or comparable to the size of the micro-structural length scale (e.g., particle or pore size). Acoustic diffuse field data reported in the open scientific literature for glass bead and water mixtures are often acquired at frequencies that have wavelengths that are comparable to the particle size (ka values equal to or greater than one, where ka is the product of the acoustic wave number k and particle radius a) (Weaver and Sachse 1995). However, acoustic diffuse field development in such mixtures is also achievable at ka values of less than one, where the energy wavelength is larger than the particle size. Diffuse field measurements at ka values less than one are preferable for acoustic well-logging applications, as sand grain sizes and pore sizes of consolidated sandstone rock formations are small (e.g., tens to hundreds of micrometers) and, in order to achieve *ka* values of one or larger, high acoustic frequencies that would be highly attenuated and have very limited measurement ranges would be required. Lower acoustic measurement frequencies that will result in *ka* values of less than one will allow for larger measurement ranges while also facilitating the development of an acoustic diffuse field.

The feasibility and potential for novel acoustic methods, based on diffuse field measurements, was investigated. The need for a reference sample for technique evaluation was identified and glass bead slurries were identified as the most appropriate medium. A paper by Weaver and Sachse (1995) was selected to provide the data for comparison and validation in an initial calibration. Experiments were designed to take data on a semi-infinite volume of water-saturated glass beads. Initial calibration measurements using 3-mm precision-grade borosilicate glass beads in distilled water were performed in accordance with the experimental parameters reported by Weaver and Sachse (1995). Measurements on the 3-mm glass beads and other glass bead sandstone surrogates were also performed in a cylindrical diffuse field test cell that was designed and assembled at PNNL. The cylindrical test cell was fabricated with a relatively large measurement volume capacity of 21 liters to minimize the risk of edge effects. Measurements in the test cell were performed with saturated glass bead and water mixtures using glass bead sizes of 205 µm and 3 mm, selected to give data that can scale to that seen in previous studies and correspond to scale (particle/wavelength) combinations expected in rocks. To hold beads in contact, and so limit fluid motion between beads, the test cell can be pressurized up to 100 pounds per square inch (psi) using a manually driven top piston.

A bead size of 205 µm was selected for initial measurements because it is representative of typical sandstone sand grain sizes of the Castlegate, Colton, Berea, Torrey Buff, and TerraTek sandstone samples procured in FY09. For example, sand grain sizes reported in a sandstone characterization report by TerraTek reveals that the average sand grain size of Castlegate sandstone is 127 µm, that for the Colton sandstone is 147 µm, and that for the Berea sandstone is 182 µm. Other types of sandstone such as Red sandstone, Gold sandstone, and Nugget Formation sandstone are reported to have average grain sizes of 68 µm, 88 µm, and 170 µm, respectively.

During diffuse field measurements in the test cell, the small acoustic transducers ("pinducers" – of similar type to those used by Weaver and Sachse) were located 180 degrees across the diameter of the test cell at a fixed path length of 29 cm (11.4 inches). These pinducers are 1.35 mm (0.053 inch) in diameter and have acoustic bandwidths of 10 kHz to 10 MHz. The pinducer pair was operated in transmission mode, with one pinducer serving as the transmitter and the other as the receiver. The transmitting pinducer was excited with a ten-cycle sinusoidal tone-burst generated by a Ritec RPR-4000 pulser-receiver unit and the diffuse field signals received by the receiver pinducer were amplified and filtered by the Ritec unit. Measurements of the diffuse field signals were acquired at acoustic frequencies of 250 kHz, 500 kHz, 750 kHz, and 1 MHz. Averaged signals generated by 1000 individual pulses were collected three to five times for each set of measurement parameters. The bead mixtures were stirred between each measurement to achieve statistically independent ensembles of the packing configuration. The measurements were performed on the sandstone surrogates at ambient temperature at pressures of 0 psi and up to 80 psi. Measurements at ambient and pressurized conditions were performed with and without foam insulation inside the test cell. The purpose of using foam insulation is to reduce unwanted acoustic reflections from the walls and corners of the test cell.

For the 205 µm particle size of the sandstone surrogates, the *ka* values were less than one at the acoustic measurement frequencies used during diffuse field measurements for this study and resulted in the observation of good diffuse field development. These data appear to have characterization potential, for both flaw size, and also, fluid present.

Measurement procedures and data analyses were validated through comparison with those reported by Weaver and Sachse (1995) using the 3-mm glass beads and a measurement frequency range of 250 kHz to 1 MHz. The resulting diffuse field dissipation and diffusivity data are generally in good agreement with the data values and trends reported by Weaver and Sachse (1995) when presented in a normalized *ka* (wavenumber – scatterer size) space.

A detailed report of diffuse field measurements and analyses is given in Denslow et al. (2010).

2.3 Assessment of NMR Potential

In the context of petrochemical well logging, NMR provides a ***direct measurement*** of the mechanical behavior of fluids and gases in the formation pore spaces (Coates et al. 1999). This is achieved in three steps: (1) polarizing the randomly oriented hydrogen nuclei with an external DC magnetic field (B_0), (2) tipping the polarization to a new orientation with a high-power RF pulse, and (3) monitoring the relaxation of the nuclei back to the original B_0 direction. The times required to achieve polarization and relaxation are direct indicators of the fluid type (oil, brine, gas), viscosity, diffusion rate, and formation pore size distribution. These times are designated the longitudinal relaxation time constant (T_1) and the free induction decay constant (T_2).

2.3.1 Theory (Fukushima and Roeder 1981; Cowan 1997; Macomber 1998; Ellis and Singer 2007)

As applied to well logging, the nuclear magnetic resonance method relies on the fact that protons (the nuclei of hydrogen atoms) exhibit a permanent magnetic moment. This moment arises from the positive proton charge and angular momentum. In water and oil, the number density of hydrogen atoms is very high and the orientation of their magnetic moments can be manipulated with external steady state (DC) or oscillating magnetic fields to produce a net magnetization, M_0.

Figure 2.1 depicts the precession of a hydrogen nucleus in the presence of a superimposed DC magnetic field, B_0. The precession frequency is termed the Larmor frequency and varies linearly with applied magnetic field. Note that, while the tip of the magnetic dipole vector traces out a circle, there is a net DC magnetization in the direction of the applied field. The Larmor frequency for a proton (hydrogen nucleus) precessing in Earth's magnetic field of 0.5 Gauss is roughly 2 kHz. For the higher DC magnetic fields used in the Halliburton magnetic resonance imaging logging (MRIL) NMR tool, the Larmor frequency varies with the gradient magnetic field from 600–750 kHz.

In formation fluids, the hydrogen atoms are bound to water and hydrocarbon (oil or gas) molecules. As the hydrogen nuclei attempt to orient in the direction of the static B_0 field, they exert a torque on the entire molecule. Molecules residing in a viscous matrix (oil) require longer polarization times.

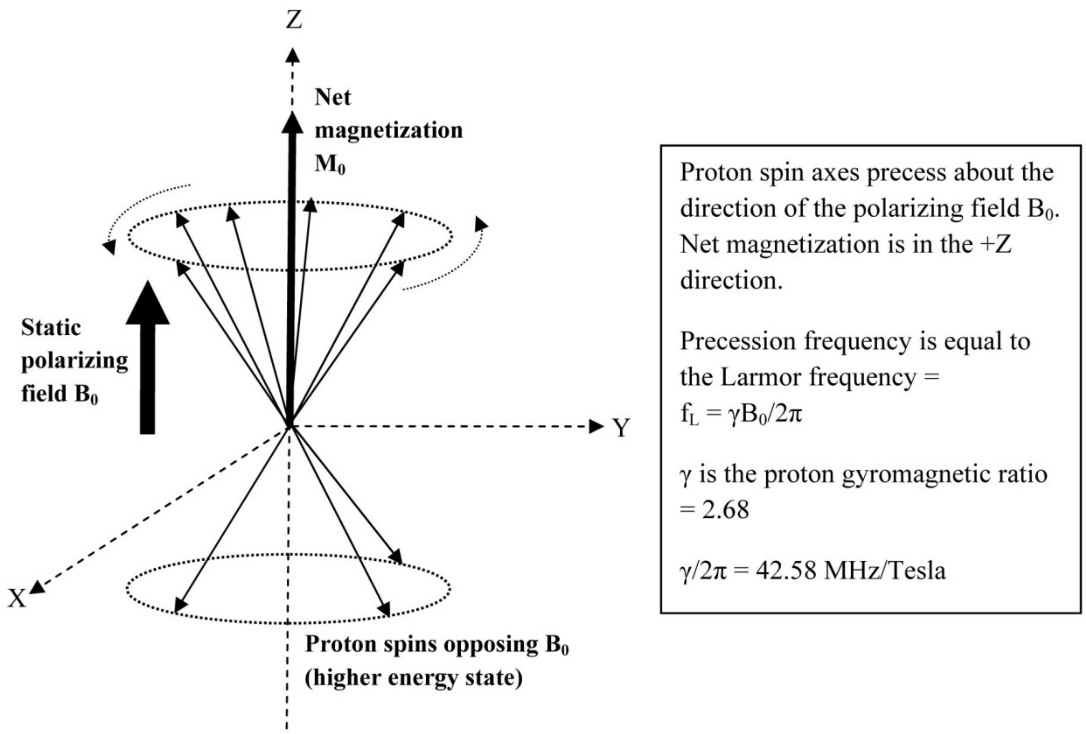

Figure 2.1. Precession of Hydrogen Nuclei in a Superimposed Static Magnetic Field B_0

The first step in the NMR measurement process is polarization of the formation fluids. The time evolution of this process appears in Figure 2.2. As can be seen, the polarization grows exponentially with time constant T_1 (termed the "longitudinal relaxation time").

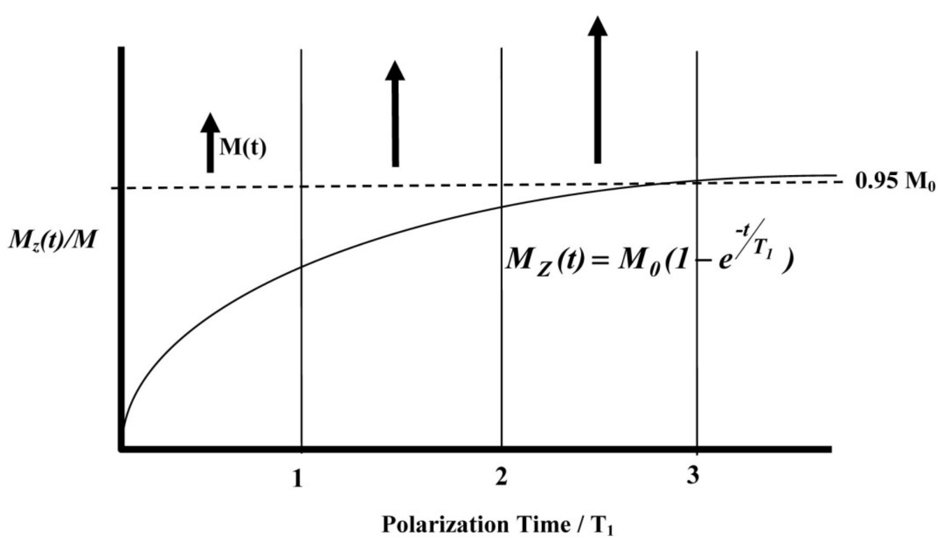

Figure 2.2. Polarization of Hydrogen Nuclei in a Superimposed Static Magnetic Field B_0. Peak magnetization is M_0.

After $3T_1$ the magnetization has reached 95% of its peak value M_0. In well logging, polarization is achieved using an array of permanent magnets in the tool. The logging process cannot progress any faster than the longitudinal relaxation process. A summary of T_1 times for a variety of pore constituents appears in Table 2.1 (Coates et al. 1999). Note that for oil, relaxation times ($3T_1$) can be several seconds.

Table 2.1. Longitudinal Relaxation Times for Formation Fluids

Fluid	T_1 (msec)	Viscosity η (centipoise)
Brine	1–500	0.2–0.8
Oil	300–1000	0.2–1000
Gas (methane)	30–60	0.011–0.014

If, after a period of $3T_1$, the static magnetic field B_0 is switched off, the hydrogen nuclei (and the molecules to which they are attached) would relax to their former random orientation.

The next step in the NMR measurement process is achieved using a series of polarized RF pulses launched into the formation adjacent to the borehole. These pulses are generated by a high-power RF transceiver matched to an antenna on the tool and have a B-field polarization component perpendicular to B_0. The pulse series, termed the CPMG (Carr, Purcell, Meiboom, Gill) sequence, performs two functions. The first pulse (dubbed the “90° tipping pulse”) temporarily rotates (precesses) the fluid magnetization (M_0) perpendicular to the B_0 direction and synchronizes (phase locks) the individual proton precessions. Immediately following this pulse, the proton spins begin to relax back to the B_0 direction. This process is called “free induction decay” and occurs with time constant T_2. The following multiple (<100) pulses (termed “180° tipping pulses”) re-phase the precessions of the hydrogen nuclei not yet relaxed to the original B_0 direction. Hence, the 180° pulses serve to “interrogate” the spin orientation of the pore fluid. The process is depicted in Figure 2.3.

When the proton precessions are re-synchronized (using the 180° tipping pulses), electromagnetic energy is emitted at the Larmor frequency. The emission is termed a “pulse echo.” The amplitudes of a series of pulse echoes enables reconstruction of the free induction decay curve. This process is depicted in Figure 2.4.

All of the information obtainable from the NMR measurement is contained in the free induction decay curve. Typical T_2 decay constants for a variety of formation fluids and gases are given in Table 2.2. The entire NMR measurement process is summarized in Figures 2.5 and 2.6.

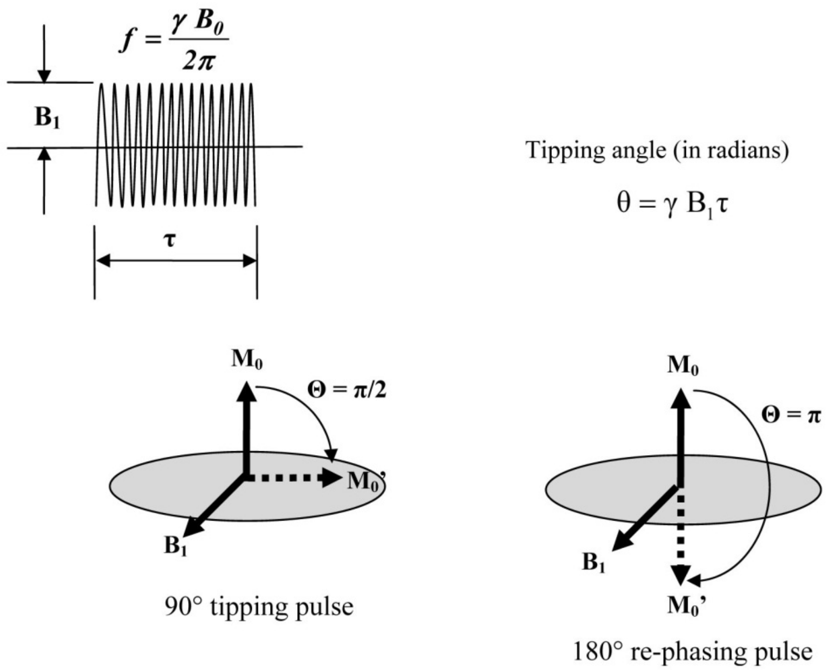

Figure 2.3. Rotation (precession) of the Net Magnetization Vector (M_0) with an Orthogonal Magnetic Field B_1

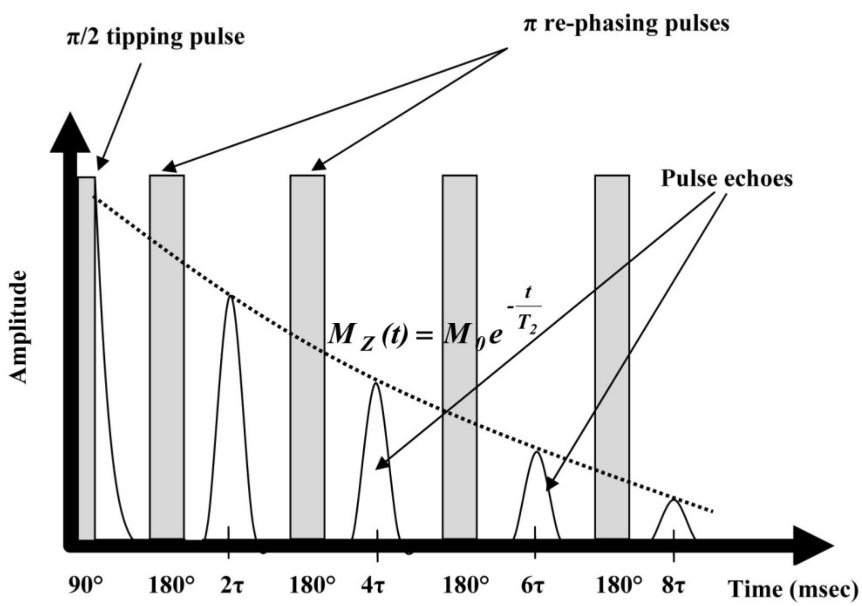

Figure 2.4. Free Induction Decay Curve Constructed from Amplitudes of "Pulse Echoes" Following the 180° Re-Phasing Pulses. Single-component decay constant is T_2.

Table 2.2. Free Induction Decay Time Constant for Formation Fluids

Fluid	T_2 (msec)	Viscosity η (centipoise)
Brine	1–500	0.2–0.8
Oil	300–1000	0.2–1000
Gas (methane)	30–60	0.011–0.014

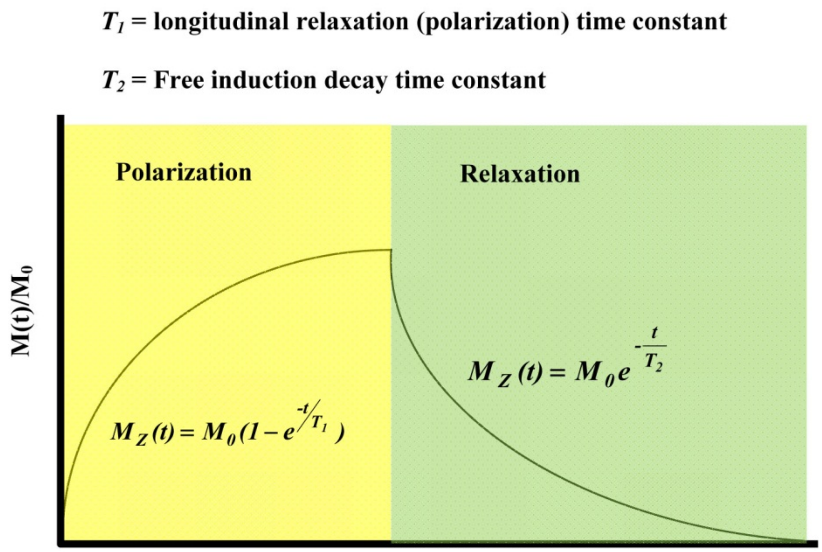

Figure 2.5. Summary of the Entire NMR Measurement Process

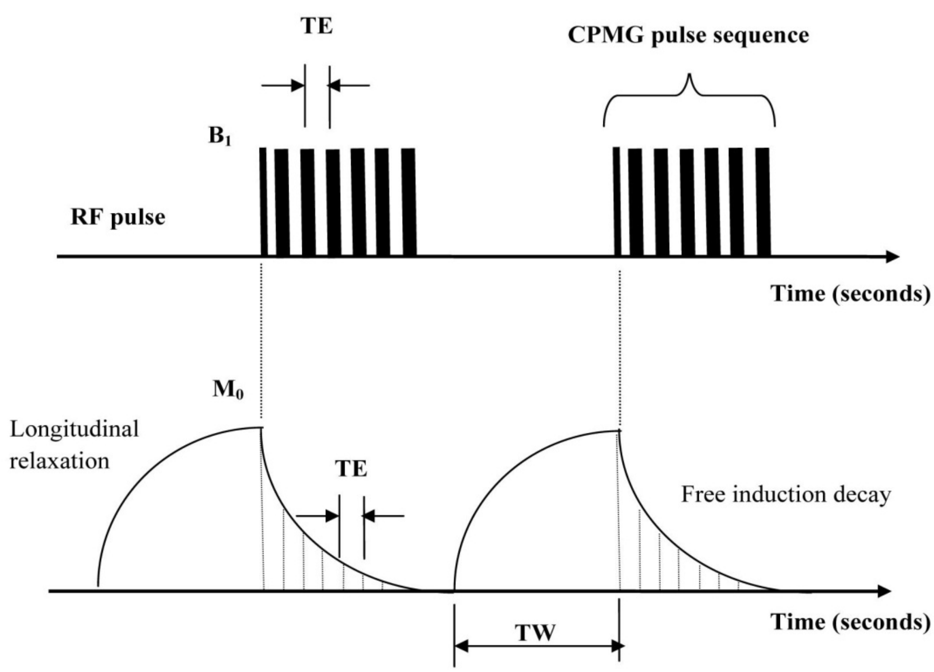

Figure 2.6. The Carr-Purcell-Meiboom-Gill (CPMG) Pulse Sequence. TE is the time between π (180°) pulses and also the time between echoes. TW is the polarization wait time.

2.3.2 Interpretation of T_1 and T_2

In practice, T_1 is not actually measured during the logging process. However, the NMR tool must be moved slowly enough to ensure complete polarization of the hydrogen-bearing formation species (oil, methane, brine). This requirement places a limitation on NMR logging speed. The logging speed is chosen on the basis of the longest ***anticipated*** T_1 time constant—up to 4 seconds for oil and 5 seconds for methane gas. Polarization to 95% of M_0 requires roughly $3T_1$ seconds (12 seconds for oil and 15 seconds for gas).

General relationships between T_1 and T_2 are summarized in Table 2.3.

Table 2.3. Effect of Formation Parameters on T_1 and T_2

General Relationships Between T_1 and T_2			
Protons in solids		$T_2 << T_1$	
Protons in formation fluids	Homogenous B_0	$T_2 = T_1$	For brine $\frac{1}{T_2} \cong \frac{1}{T_{2Surface}}$
			For heavy soil $\frac{1}{T_2} \cong \frac{1}{T_{2Bulk}}$
	Gradient B_0 with CPMG sequence	$T_2 < T_1$	For light oil $\frac{1}{T_2} \cong \frac{1}{T_{2Bulk}} + \frac{1}{T_{2Diffusion}}$
			For gas $\frac{1}{T_2} = \frac{1}{T_{2Diffusion}}$
Fluids in porous media		T_1 and T_2 decrease	$\frac{1}{T_1} = \frac{1}{T_{1Bulk}} + \frac{1}{T_{1Surface}}$
			$\frac{1}{T_2} = \frac{1}{T_{2Bulk}} + \frac{1}{T_{2Surface}} + \frac{1}{T_{2Diffusion}}$

T_{2Bulk} = relaxation time of pore fluid with no pore surface effects.
$T_{2Surface}$ = includes pore surface relaxation effects.
$T_{2Diffusion}$ = relaxation time induced by diffusion in the magnetic field gradient.

The various relaxation times can be used to derive physical properties of the pore fluids including fluid viscosity and pore surface-to-volume ratio. The quantitative relationships are summarized in Table 2.4.

Table 2.4. Relationships Between T_1 and T_2 and Fluid/Formation Parameters

	Bulk Relaxation	Surface Relaxation	Diffusion Induced Relaxation $\frac{1}{T_{2\text{Diffusion}}} = \frac{D(\gamma\ GTE)^2}{12}$
Water	$T_{1\text{Bulk}} \approx 3(T_K)/298\eta$ $T_{2\text{Bulk}} \approx T_{1\text{Bulk}}$	$\frac{1}{T_{2\text{Surface}}} = \beta_2\left(\frac{S}{V}\right)_{\text{Pore}}$ $\frac{1}{T_{1\text{Surface}}} = \beta_1\left(\frac{S}{V}\right)_{\text{Pore}}$	$D_{\text{Gas}} \cong 8.5\times10^{-2}\left(\frac{T_K^{\ 0.9}}{\rho_{\text{Gas}}}\right)\times10^{-5}\,\text{cm}^2/\text{sec}$
Gas	$T_{1\text{Bulk}} \approx 2.5E4\left(\rho_{\text{Gas}}/T_K^{\ 1.17}\right)$ $T_{2\text{Bulk}} \approx T_{1\text{Bulk}}$		$D_{\text{Oil}} \cong 1.3\left(\frac{T_K}{298\eta}\right)\times10^{-5}\,\text{cm}^2/\text{sec}$
Oil	$T_{1\text{Bulk}} \approx 0.00713\ T_K\eta$ $T_{2\text{Bulk}} \approx T_{1\text{Bulk}}$		$D_{\text{Water}} \cong 1.2\left(\frac{T_K}{298\eta}\right)\times10^{-5}\,\text{cm}^2/\text{sec}$

T_K = temperature (°K)
(S/V) = pore surface area to volume ratio
η = fluid viscosity (centipoises)
γ= proton gyromagnetic ratio
ρ_{Gas} = gas density (g/cm^3)
G = field strength gradient (gauss/cm)
D = molecular diffusion coefficient
TE = inter-echo spacing used in the CPMP sequence
β_1 and β_2 = surface relaxivities determined by laboratory measurements

3.0 Workshop: Alternative to Chemical Radiation Sources for Petrochemical Well Logging

This Radiation Source Replacement Workshop was held in Houston, Texas, on October 27–28, 2010, and provided a forum for industry and researchers to exchange information and to discuss the issues relating to replacement of AmBe, and potentially other isotope sources used in well logging.

The workshop had about 60 attendees, with the majority from the petrochemical well-logging sector. Federal government speakers introduced terrorism scenarios, including recent threats and how stolen radioactive sources might be used. A presentation by the EPA stimulated considerable discussion around possible nuclear source alternatives being pursued. NRC regulations specific to the well logging industry in Texas were discussed.

A series of presentations reported development/improvement of electronic neutron sources and described products in the pipeline industry (both gamma and neutron sources) with potential application to the well-logging industry.

The Nuclear Special Interest Group (SIG) of the Society of Petrophysicists and Well Log Analysts (SPWLA) was introduced as an excellent vehicle for staying abreast of nuclear needs and developments in the petrochemical well logging industry.

Presentations then followed on the seismo-electric well-logging method, the use of local gravity measurements for measuring rock density, and an overview of electronic radiation sources (x-ray, gamma ray, and neutron). This was followed by a discussion of a combined NMR/acoustics tool for source-less porosity measurements. Due to the slow logging speed, it was reported that NMR tools will not make nuclear logging obsolete.

Legacy porosity logs acquired with AmBe sources were discussed and it was shown that they can be compared with logs acquired using high energy D-T neutron sources. However, some in the industry dispute this point and prefer neutron log data that resembles historic records. Finally, the presentation by Ron Cherry from Halliburton pointed out that nuclear (gamma-gamma) density measurements are necessary to correctly interpret NMR log data.

Group discussions both during and after the presentations made clear the following points:

- New AmBe neutron sources are expensive and hard to obtain.
- ^{252}Cf looks to be a near-term neutron source replacement because the neutron energy is comparable to AmBe and because the cost is only 20% of that for an AmBe source (^{252}Cf sources now cost what AmBe sources *used to* cost). Some uncertainty exists regarding the future *availability* of ^{252}Cf.
- NMR tools do not eliminate the need for nuclear logging. ^{137}Cs gamma backscatter measurements are still required for rock density. NMR logging is expensive due to the requirement for slow logging speeds.

- The smaller well-logging companies do not have access to NMR tools or electronic neutron sources. They rely heavily on AmBe sources but can potentially accommodate ^{252}Cf sources assuming they are available at reasonable cost.

  For more information, refer to Griffin et al. (2011).

4.0 Conclusion

The study provided the DOE NA-22 with a better understanding of the requirements for and extent of use of chemical radiation sources in petrochemical well logging.

Three approaches are being investigated to reduce the requirements for AmBe sources in well logging:

1. Reduction in the activity of the AmBe source required (through approaches that included the deployment of enhanced sensors);

2. The use of alternate electronic neutron generators (based on D-T, D-D, and T-T reactions, although these provide neutrons with different spectra and data inter-comparison requires attention); and

3. The use of enhanced and novel acoustic and electromagnetic sensing tools, including nuclear magnetic resonance, used either in combination with reduced activity AmBe sources and/or D-T generator-derived data.

In looking at issues that inhibit the replacement of chemical isotope sources in well logging:

- Formation density measurements implement the Compton scattering method, requiring the use of ^{60}Co or ^{137}Cs isotopic gamma sources. There is no non-chemical replacement for these radiation sources.
- Formation fluid identification (brine or oil) uses elastic/inelastic neutron backscattering and/or neutron activation methods with chemical neutron sources (AmBe or ^{252}Cf). Electronic neutron sources are potentially a replacement for these chemical neutron sources. An emerging neutron-free method, nuclear magnetic resonance, may eventually permit elimination of neutron sources all together.
- Formation porosity measurements can require the use of both gamma and neutron sources (as well as non-nuclear sensing methods).

This study has identified reasons for the reluctance of the well-logging industry to embrace the use of non-chemical radiation sources. These include:

1. <u>The difficulty of inter-comparing neutron logs acquired with low-energy AmBe or ^{252}Cf sources to those acquired using a high-energy, directional electronic neutron source</u>. This "data interpretation gap" could be addressed by a focused NA-22 program (discussed below).

2. <u>The unavailability of low-cost, robust electronic neutron sources to the re-logging industry</u>. Electronic neutron sources are generally limited to expensive LWD tools used by the larger well-logging services companies (Schlumberger, Halliburton, Baker-Hughes, etc.). Lower hardware costs and improvements in electronic source reliability could speed use in the re-logging industry.

3. <u>Electronic sources must be re-furbished after several hundred hours of use</u>. Chemical sources require no maintenance.

4. Electronic neutron sources have not yet achieved high reliability. Consequently, two neutron logging tools are often required at the well site in the event one fails.

Electronic neutron sources offer important potential advantages over chemical sources:

1. Well-logging personnel are not required to handle radioactive materials, thus eliminating potential exposure or contamination.

2. Electronic neutron sources can be interlocked to only operate below a chosen well depth, eliminating the possibility of personnel exposure.

3. Down-well loss of an electronic neutron source does not result in well contamination. Tool neutron activation is minimal and the radioactive tritium gas (a beta-emitter) in the D-T source is rapidly dissipated.

4. Electronic sources are pulsed, permitting acquisition of time-dependent gamma and neutron scattering/activation data. These time-dependent signals are indicative of "neutron slowing down time," a measure of hydrogen and carbon content in the formation. This information cannot be obtained using a continuous, chemical neutron source.

4.1 Other Issues: "The Culture Gap"

There is another major impediment to industry adoption of alternatives to chemical radiation sources. This impediment can be termed the "Culture Gap." The nuclear well-logging industry has been accustomed to operating under modest regulatory constraints from government nuclear regulatory and security agencies. Certainly they have, in the USA, complied with Nuclear Regulatory Commission policies regarding radiation source acquisition, handling, and personnel safety. However, the industry's support for amelioration of national security issues associated with control of chemical radiation sources is tentative. They have only recently (<10 years) become more closely scrutinized over the loss of sealed neutron and gamma sources downhole (or otherwise). There is distrust on both sides. Government regulators appear to doubt industry's commitment to source control. Likewise, industry views the threatened increased in government control, and risk of loss of access to AmBe and other sources, and regulation is invasive and costly. There is a need for better communication between the two communities. To this end, it seems advisable for NA-22 to initiate a series of workshops fostering reconciliation between the two viewpoints. Such workshops could be organized and hosted by an academic organization (e.g., the Well Logging Laboratory at the University of Houston). The venue would permit government regulators to educate the well-logging industry regarding the security threat (viewed by industry as inflated). Conversely, industry would have a forum to educate the regulators regarding the technical and economic issues and impacts associated with source replacement. Surely such a dialogue would be fruitful to both parties and may result in a compromise solution short of complete chemical source replacement.

5.0 References

Becker J, LJ Jacobs and J Qu. 2003. "Characterization of Cement-Based Materials Using Diffuse Ultrasound." *Journal of Engineering Mechanics* 129(12):1478-1484.

Bond LJ, KM Denslow, JW Griffin, GE Dale, RV Harris Jr., TL Moran, DM Sheen and T Schenkel. 2010a. *Evaluation of Non-Nuclear Techniques for Well Logging: Technology Evaluation*. PNNL-19867, Pacific Northwest National Laboratory, Richland, Washington.

Bond LJ, JW Griffin, KM Denslow, RV Harris Jr., T Schenkel, A Persaud, GE Dale, A Sood, JT Rutledge, S Kovaleski and F Keel. 2010b. "Nuclear Source Replacement in Petrochemical Well-Logging." In *Society of Exploration Geophysicists*. October 18, 2010, Denver, Colorado. PNNL-SA-75821.

Coates GR, L Xiao and MG Prammer. 1999. *NMR Logging Principles and Applications*. Gulf Publishing Company, Houston, Texas. ISBN 0-9679026-0-6.

Cowan B. 1997. *Nuclear Magnetic Resonance and Relaxation*. Cambridge University Press, New York. ISBN 13 978-0-521-01811-1.

Denslow KM, P Ramuhalli, MD Flake and LJ Bond. 2010. *Evaluation of Non-Nuclear Techniques for Well Logging: Acoustic Diffuse Field Measurements*. PNNL-19850, Pacific Northwest National Laboratory, Richland, Washington.

Ellis DV and JM Singer. 2007. *Well Logging for Earth Scientists, 2nd Edition*. Springer, Dordecht, The Netherlands. ISBN 978-1-4020-3738-2.

Fukushima E and SBW Roeder. 1981. *Experimental Pulse NMR – A Nuts and Bolts Approach*. Addison Wesley Publishing Company, Boston, Massachusetts. ISBN 978-0201104035.

Griffin JW, TL Moran and LJ Bond. 2011. *Radiation Source Replacement Workshop*. PNNL-20102, Pacific Northwest National Laboratory, Richland, Washington.

Jia X. 2004. "Codalike Multiple Scattering of Elastic Waves in Dense Granular Media." *Physical Review Letters* 93(15):154303.

Macomber RS. 1998. *A Complete Introduction to Modern NMR Spectroscopy*. John Wiley and Sons, New York. ISBN 0-471-15736-8.

NRC. 2008. *Radiation Source Use and Replacement: Abbreviated Version*. National Research Council (NRC). The National Academies Press, Washington, D.C. ISBN 0-309-11015-7.

Weaver RL and W Sachse. 1995. "Diffusion of Ultrasound in a Glass Bead Slurry." *The Journal of the Acoustical Society of America* 97(4):2094-2102.

6.0 Project Bibliography

6.1 Presentations

Bond LJ. 2008. "Evaluation of Non-Nuclear Techniques for Well Logging," presentation at PNNL to NA-22, November 4, 2008.

Bond LJ. 2009. "Evaluation of Non-Nuclear Techniques for Well Logging," presented at Office of Nonproliferation R&D – RSR Program Review Meeting, September 21, 2009, DOE Headquarters, Washington, D.C. PNNL-SA-68723.

Bond LJ. 2009. "Evaluation of Non-Nuclear Techniques for Well Logging," presented at Well Logging Consortium Meeting, October 26, 2009, Houston, Texas. PNNL-SA-69333.

Bond LJ. 2010. "Evaluation of Non-Nuclear Techniques for Well Logging: NNSA –NA-22: Radiological Source Replacement Program," presentation at Independent Review Meeting, PNNL, March 15, 2010.

Denslow K. 2010. "Acoustic Measurements for Well Logging: NNSA – NA-22: Radiological Source Replacement Program," presentation at Independent Review Meeting, PNNL, March 15, 2010.

Griffin JW, P Keller, DL McMakin, J Fricke, and M Larche. 2010. "Electromagnetic Measurements on Sandstone Samples: NNSA – NA-22: Radiological Source Replacement Program," presentation at Independent Review Meeting, PNNL, March 15, 2010.

Griffin JW, A Lintereur, M Woodring, and P Keller. 2010. "Nuclear Measurements on Sandstone: NNSA – NA-22: Radiological Source Replacement Program," presentation at Independent Review Meeting, PNNL, March 15, 2010.

Bond LJ. 2010. "Evaluation of Non-Nuclear Techniques for Well Logging, Radiological Source Replacement Program Review Meeting," RSR2010, LBNL, May 13, 2010.

Bond LJ, JW Griffin, KM Denslow, RV Harris Jr., T Schenkel, A Persaud, GE Dale, A Sood, JT Rutledge, S Kovaleski and F Keel. 2010. "Nuclear Source Replacement in Petrochemical Well-Logging." Presented by Leonard Bond at *Society of Exploration Geophysicists*. October 18, 2010, Denver, Colorado. PNNL-SA-75821.

Bond LJ, JW Griffin, RV Harris Jr. and KM Denslow. 2011. "Radioactive Source Replacement in the Petrochemical Well Logging Industry." Presented by JW Griffin (Invited Speaker) at *Global Safeguards and Radiological Source Replacement Programs Annual Review Meeting*. May 11, 2011, Albuquerque, New Mexico. PNNL-SA-79538.

6.2 Reports

Denslow KM, P Ramuhalli, MD Flake and LJ Bond. 2010. *Evaluation of Non-Nuclear Techniques for Well Logging: Acoustic Diffuse Field Measurements*. PNNL-19850, Pacific Northwest National Laboratory, Richland, Washington.

Bond LJ, KM Denslow, JW Griffin, GE Dale, RV Harris Jr., TL Moran, DM Sheen and T Schenkel. 2010. *Evaluation of Non-Nuclear Techniques for Well Logging: Technology Evaluation*. PNNL-19867, Pacific Northwest National Laboratory, Richland, Washington.

Griffin JW, TL Moran and LJ Bond. 2011. *Radiation Source Replacement Workshop*. PNNL-20102, Pacific Northwest National Laboratory, Richland, Washington.

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

U.S. DEPARTMENT OF
ENERGY

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)
www.pnl.gov