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Scoping Study on Developing Alternatives to Radionuclide-based Logging Technologies

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1. Executive Summary

I. Introduction

Subsurface devices utilizing radioisotopes, ^{241}Am and ^{137}Cs, are critical for reservoir characterization and related completion and production decisions. Being small, mobile and used widely worldwide, these sources can pose radiological dispersal device (RDD) security risks. The security concerns have been exacerbated by recent stolen or missing source incidents, existence of a black-market on sources in general, and attempts at their malevolent use. Consequently, in addition to decades-long industry effort to develop non-nuclear and nuclear-based alternative logging technologies, governments, international agencies, and national labs are actively assessing measures and technologies to mitigate risks of such sources. Risk mitigation efforts include enhanced regulations, source-use guidelines, research and development on electronic tracking of sources, and continued exploration of alternative technologies by both the petroleum industry and US Department of Energy (DOE). In recent years, the petroleum industry has continued to explore new nuclear-based and nonnuclear alternative techniques and several DOE-sponsored reports have been prepared on the topic. However, there has been no significant synergy between the industry and DOE efforts in developing alternatives.

The present report is based on a study commissioned by the National Nuclear Security Administration (NNSA) earlier in the year to systematically assess the potential of proposed and promising alternatives as replacement to radionuclide logging sources. The study utilized literature survey, targeted analysis, and formal input received from a significant number of industry players. The study noted the source risk profile, surveyed the current state of logging technologies including tested alternatives to define key requirements of an alternative to be replacement, gauged interest in promising but untested alternatives, and identified the industry landscape, to better define both technical and non-technical roadblocks that could arises in efforts to replace radionuclide-based logging tools. Active and continuous engagement with the industry is perhaps the distinctive feature of the present study. The report details the effort, identifies areas of further research and development (R&D) and suggests elements of a roadmap to proceed.

The Executive Summary briefly discusses the major findings and delineates the elements of a roadmap to pursue both research and development and efforts to continue the dialog that developed between the industry and the DOE during the study. The Full Report discusses the details with examples.

II. Summary and Roadmap Elements

A. Summary

1. Logging source risk profile. The profile is complex. Their small size, mobility, high specific activity level, and geographical locations of use, make logging sources vulnerable to diversion with an RDD potential. Attempts at malevolent use of sources in general, and incidents of lost, missing or stolen logging sources have heightened this concern, but the RDD potential of logging sources would vary across the world. There is no common internationally accepted source handling guideline yet. A multipronged approach that includes tighter regulations and their enforcement, possibly use of enhanced security regimes, especially during

transport, use of internationally accepted source handling guidelines, electronic tracking of sources, and potentially alternative logging technologies would be needed to address the challenge.

2. Petroleum industry landscape. This multifaceted landscape is a mix of multiple players, domestic and international, who have differing business drivers, a diverse customer base with a range of technology need, source type and radioactivity requirement, and a varying degree of financial resources, and technical capabilities. Small independent service companies, reliant on third party suppliers of technology and many self-funded, provide nearly 70% of the logging units in the US, primarily to small oil companies, who generally may not require more complicated techniques such as nuclear magnetic resonance (NMR) or neutron-gamma (n,ɣ) spectroscopy in their fields. Integrated service companies design, test and deploy their own technologies and serve major operators with complex fields, such as shale reservoirs which would benefit from such techniques.

   The collective cost of source replacement could be high, based on cost parameters noted in a recent paper by Gilchrist et al (2011). There are over 9000 logging sources in the field, and assuming that half are ^{241}Am-Be sources, the cost of replacing these sources alone, with D-T generators at \$50,000/generator, would be \$225,000,000. This does not include testing, calibration, additional deployment cost or costs due to data interpretation differences. Obviously, these costs have to be balanced against security and safety costs and the potential cost of an RDD incident. Risk of RDD detonation would vary across the world, however. Clearly, a more thorough cost/benefit analysis is needed. In any case, the strategy of deploying alternatives will involve a long time-frame and would require careful planning.

3. Requirements to be replacement

   (i) *General*: Subsurface characterization is a complex multiple parameter non-linear inverse problem that requires multiple independent measurement techniques. The requirements need to be viewed in that context.

   (ii) *Accuracy:* Tools based on alternative technologies must be cost-effective to design and operate, and at least as accurate as radionuclide-based tools. This will require a density accuracy of 0.015 g/cc equivalent to 1 porosity unit (pu) [1] obtained with the ^{137}Cs source tool and the same quality of lithological information and gas signature as obtained with the ^{241}Am-Be tool. In liquids where density and neutron overlap, the difference between a new neutron technology and density should be within 1.5 pu.

   (iii) *Reliability and design*: Alternative technologies must operate reliably in complex geological conditions in wells where operating conditions may be extremely harsh, over 400 deg. F, 30,000 psi, 1000 g in vibration for logging-while-drilling (LWD) and 40 g for wireline. Radionuclide sources never fail; they are fit-for-purpose technologies in what they do.

   (iv) *Key attributes*: Possessing of key attributes for acceptable quality data acquisition and interpretation is another key requirement. Among these are logging speed (standard wireline logging suite operate at 1800 ft/hr in conventional reservoirs), tool combinability, ability to correct for or mitigate well-bore or other

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[1] A 1-pu error in a 15-pu reservoir with a nominal reserve of one billion barrels would result in an uncertainty of 67 million barrels [Badruzzaman et al 2009].

effects that the alternative technique may have, and the ability to mitigate or correct for liquid invasion effects on the signal.

4. Current logging techniques

Density, neutron, and resistivity tools, together with the natural gamma ray (GR) detector constitute the standard logging suite, known in industry jargon as "Triple Combo." Inclusion of acoustic makes it a Quad Combo. Acoustic tools may not always be run in a logging job. NMR constitutes more of a specialty log. Currently, NMR and acoustic are often complementary to conventional tools. (n,ɣ) capture spectroscopy tools to construct mineralogy are also run in special cases.

5. Tested nuclear-based alternatives.

Several nuclear-based techniques have been tested by the industry as alternatives to radionuclide-based logging tools for over 30 years. Each has its advantages and challenge as noted next.

(i) *D-T generator neutron porosity*. Of the nuclear-based alternatives for neutron porosity tested by the industry, the D-T generator could possibly replace the ^{241}Am-Be source in many cases, both in logging-while-drilling (LWD) and wireline logging, thereby reducing the use of the radionuclide source. However, a number of physics, design and interpretation issues, discussed elsewhere in the report and in references, have to be addressed. In addition to neutron porosity, an appropriately designed single D-T generator tool will also be able to supply a multitude of other petrophysical parameters, from mineralogy, saturation, and even a density, albeit a less accurate one, that now require multiple tools. The technology will be expensive, generator failure will be costly but the impact could be minimized with proper protocols. In expensive operations, such as offshore, a spare generator would be recommended. Industry has decades of experience with D-T generators used for monitoring reservoirs through cased wells.

(ii) *LINAC-based density tool*. Such a tool was tested successfully for wireline logging in the 1980's as an alternative to ^{137}Cs density, but was not commercialized due to a number of remaining technical challenges and inadequate business drivers. However, it demonstrated the technical promise of such direct source of photons.

(iii) *(n,ɣ) density*. This density, computed using gamma rays produced from inelastic collisions of high-energy neutrons from a D-T generator, a concept borrowed from cased-hole logging and implemented in an LWD tool, offered some advantages such as a greater depth of investigation. But, in general, it was not sufficiently accurate relative to the conventional ^{137}Cs based density reliant entirely on photon physics. The resultant porosity is unlikely to be sufficiently accurate in cases where stringent porosity accuracy is essential. Its complex, coupled neutron-photon physics would make it difficult to mitigate the associated accuracy challenges. Thus, the concept will likely be a special-case technology where the ^{137}Cs tool is unavailable due to government restrictions or where porosity accuracy requirements are less stringent. A careful assessment of available field data is needed to delineate the latter conditions.

(iv) *Response simulation techniques*. Monte Carlo radiation transport methods and corresponding deterministic methods to a lesser extent have played a key role in developing and then judiciously utilizing nuclear logging tools in complex conditions, thereby reducing development cost and the design-to-deployment duration. The techniques are playing a central role in studying advanced concepts. However, their application has been confined to integrated service companies and major oil companies. Adoption of these techniques by smaller players may help them transition more smoothly to advanced generator-based tools but they will need help with such adoption.

Also, work is needed to further advance these techniques to better simulate more complex concepts such as those using (n,ɣ) spectroscopy.

6. Non-nuclear technologies:

(i) *NMR*: Current NMR tools give several petrophysical parameters, including a lithology-independent porosity.[2] They have certain limitations such as low signal/noise ratio (SNR), slow wireline logging speed (~ 200 ft/hr.) and a shallow depth of investigation (1.5” to 4.5” beyond the borehole wall), that have limited their use. Some parameters such as SNR may be improved upon by design improvements, while others such as the slow logging speed due to incomplete polarization and challenges of the method in heavy oil or nano-pores may be harder to overcome. Slow logging speed is not an issue in logging-while-drilling (LWD.)

(ii) *Acoustic*: Acoustic tools can supply the porosity and identify the lithology, but neither is as accurate as those from radionuclide-based tools. The porosity determination from acoustic signal is empirical and there are multiple correlations that the industry utilizes, based on geology, to obtain the porosity using acoustic techniques.

In summary, both NMR and acoustic can compute porosity, and acoustic can be a lithology indicator. Both often play a confirmatory role, and add great value by supplying additional information. Industry practice indicates both techniques have their own limitations and require targeted research and development to alleviate these limitations. Acoustic and NMR tools supply additional information that radionuclide tools cannot, such as rock mechanical properties and fluid types, respectively. Such information is important in complex reservoirs. As in the case of nuclear tools, greater use of response simulation techniques with Acoustic and NMR tools in full wellbore conditions could more quickly advance the state-of-the art of such tools, by allowing assessment of concepts and performing trade-off studies, a priori, before tools are built.

The response to the study team’s query in the Questionnaires, suggests that the major requirements for a technology to be a replacement is the ability to obtain the porosity and lithology information of at least current quality, without adversely impacting the operational and interpretation attributes, and within reasonable costs, design to deployment. All potential alternatives will require further R&D, including use of tool response simulation techniques, to perform at the levels of technical specifications that would be required for them to be replacement quality.

7. Untested nuclear-based techniques.

(i) *Neutron porosity*: A number of untested neutron generator concepts, such as α-Be Dense Plasma Focus (DPF) accelerator, D-D, T-T, D-^{7}Li, etc., can provide a greater porosity sensitivity than a D-T generator tool inherently can. Of these, the DPF accelerator generated some interest by its ^{241}Am-Be-like spectrum and promise of the neutron yield being comparable to that from ^{241}Am-Be. However, each concept has several

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[2] This is correct in the traditional sense of lithology dependence but there are definite lithology affects as noted elsewhere.

limitations discussed in the report. All would require long-term research and development efforts. Issues such as sufficiency of neutron yield to allow logging at least at current speeds, detection rates, power requirements, miniaturization, ability to operate in harsh logging environments, and acceptable failure rates in all conditions, are issues that must be addressed a priori, before prototype tools are developed. Of course, trade-offs may be necessary within the acceptable ranges of these parameters.

(ii) *Photon generator:* While the LINAC density tool tested in the mid-1980's demonstrated the feasibility of the concept, detection issues, power requirements, reliability and cost remain major hurdles. One service company has been investigating the betatron concept. A mono-energetic photon generator based on the ^{9}Be(d,γ) reaction was recently demonstrated in the lab, but the photon yields from the source would be several orders of magnitude lower. Current techniques to enhance the yield are likely to be inadequate in practical applications.

8. Non-technical roadblocks. The major challenges will be the cost of transition and the complex industry landscape noted previously, coupled with the multifaceted source risk profile resulting in a variable set of drivers for change. Even in a normal business climate, the small independent service providers would need external support on both funds and technology while integrated service companies would likely be able supply both, if needed. The current industry downturn has compounded these challenges for both large and small companies. Specifically, mandating a switch to alternatives, without providing support, will likely bankrupt the independents and give rise to a monopoly by integrated service companies and drive up logging costs in the US.

   In view of the complex multiple-parameter, inverse nature of subsurface characterization, the various techniques, radionuclide- and nonnuclear-based, are used both in confirmatory and complementary roles. The industry survey clearly identified this and leads to the conclusion that no single method or small subset will suffice. However, judicious choice of methods, including non-radionuclide nuclear and nonnuclear methods may, in combination, be able to significantly reduce, and in some cases eliminate the use of radionuclides in logging.

One must also be cognizant of the complexities of the technologies, the geological conditions they are to be applied, and of the landscape of the industry these are aimed for. The study makes it apparent that source replacement undertaking will be complex involving a longer term effort and significant R&D costs, even when new technologies prove to be of replacement quality in laboratory calibration. Thus, a clear roadmap needs to be identified if replacement is desired. The roadmap must take into account the variable risk profile, industry landscape, cost, technology appropriateness, and technical and financial requirements. Here we identify a number of elements of such a roadmap. Development of the roadmap should be collaborative with participation of government and industrial players, large and small.

B. Elements of a Roadmap

These are discussed in detail in **Section XII**. We highlight the key points next.

- Develop a framework for a phased, diverse, and collaborative approach to advance technology.

- Take a broad view of source risk mitigation with multiple components including alternatives, source tracking, regulations, and enhanced security regimes. A greater international collaboration may be very helpful. Continue to fine-tune the source risk profile to guide the mitigation steps.

- Use a multi-pronged strategy to promote consideration of alternatives. These should include non-technical and technical components, with possible DOE-industry collaboration.

- Non-technical components would need to include attention to the industry landscape, use of business drivers, being cognizant of technology needs of a broad cross-section of users, delineating the additional information and benefits new technologies could supply to ultimately reduce cost of information, instead of just relying on the issue of security. R&D and transition support, especially to small independent industry players, would likely be required.

- Industry-DOE collaboration for technology advance will be beneficial. However, national labs focusing on hardware concepts and simulation codes, and industry focusing on tool development, with possible collaboration on technology transfer and processing algorithms would be the best option.[3]
- Technical components are summarized as follows. The details can be found in **Sections XI** and **XII.**

  - Research and development will be needed in all proposed alternatives, nuclear-, acoustic-, and NMR-based, to establish their proximity to being replacement to radionuclide tools.
  - For nuclear, both enhancement of tested alternatives and exploration of untested but promising techniques deserve continued attention, in terms of hardware, including advanced detectors, advanced processing and data mining analysis. One must avoid increasing tool size and or making measurements more complex without adding information.
  - For acoustic, a further theoretical development to understand the complex physics and advanced hardware and software for implementing new ideas are needed.
  - For NMR, higher frequency techniques, increasing signal/nose ratio (SNR) and approaches to increasing the logging speed without increasing tool size need to be considered.
  - In all techniques, advances in computational methods and associated computer codes to simulate corresponding tool response in three dimensions, with full physics representation, would be very helpful in advancing the state-of-the art. This offers an opportunity for direct collaboration between national labs and industry.
  - Combination of techniques such as NMR with acoustic, (n, ɣ) density with NMR, or acoustic with generator-based neutron porosity should be explored. Together they may significantly reduce the need for radionuclide sources, even if they cannot do so singly.
  - Longer-term DOE support on technology development/assessment in nuclear, non-nuclear, and combination of approaches would be important.

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[3] The work by Jasper Jackson of Los Alamos in the mid-1980's in developing the modern NMR concept for logging and its adoption by Numar to build the new generation tools is an excellent example of the benefits of such an approach. Similarly the developments that have taken place over the last 30 years in the Los Alamos Monte Carlo code, MCNP, with ongoing industry input is another such example. The code is now industry mainstay in nuclear tool response modeling. In contrast to these, foray about five years back by a national lab to develop a D-T-based advanced nuclear tool was not well-received by the industry (Griffin 2010) and no further progress was made on it.

Scoping Study on Developing Alternatives to Radionuclide-based Logging Technologies

2. Full Report

I. Background

For decades, radionuclide-based subsurface devices have been an integral part of the suite of instruments sent downhole to determine the porosity and lithology, two of the four petrophysical parameters used in estimating hydrocarbon reserves, designing well-completion for safe operation, and ultimately making hydrocarbon production decisions [Ellis 1987]. The other two, (fluid) saturation of the pore space and permeability of the rock, are determined, respectively, using downhole electrical measurements and analyzing core samples collected from selected points downhole.[4] Lithology impacts all three other parameters and the porosity is an input to determining saturation [Archie 1942; Ellis 1987]. ^{137}Cs-based tools measure formation density which provides the most accurate estimate of total porosity. ^{241}Am-Be source tools are used to measure the apparent neutron porosity which helps identify gas in conjunction with density and delineate the lithology.[5] ^{241}Am-Be source-based (n,ɣ) capture spectroscopy tools allow mineralogy determination [Herron and Herron 1996]. Mineralogy information is becoming increasingly important in assessing unconventional (primarily shale) reservoirs.

Despite having built-in safety features discussed later and their utilization in compliance with all governmental transport and handling regulations, it has always been recognized that radionuclide logging sources can pose safety risks from inadvertent exposure. Consequently, the petroleum industry has explored nuclear-based alternatives for over 30 years but with mixed results [King *et al* 1987; Mills *et al* 1988; Scott *et al* 1994; Badruzzaman 1998; Odom *et al* 1999; Evans *et al* 2000].

In addition, major logging companies deployed modern non-nuclear tools based on acoustic and nuclear magnetic resonance (NMR) techniques that can determine the total porosity and liquid-filled porosity, respectively; acoustic tools have been explored for determining the lithology [Jackson 1984; Straley *et al* 1993; Coates *et al* 1999; Ellis and Singer 2007; Dunn *et al* 2002][6]. In general, the porosity from these tools is not as accurate as the density-based porosity and acoustic-based lithology is not as accurate as nuclear-based lithology. NMR-based porosity is generally noted as lithology-independent in the traditional senses, in terms of it not being affected by dry clay materials, but it depends on the delineation of clay and capillary-bound waters from free fluids, have different values of cut-off parameters for clastic (sand/shale) vs, carbonate reservoirs, and will be affected by clays with paramagnetic materials present. Both acoustic and NMR techniques play an important role, however. They are used to validate a parameter computed by a standard logging technique, provide an answer in conditions radionuclide techniques have failed, and supply additional information such as, rock mechanical properties and

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[4] Porosity is the fraction of the rock that is void with the ability to hold fluid. The fraction of the void fraction that is filled with a given fluid is denoted as the saturation of that fluid. Porosity and saturation are used to estimate reserves volumes. Permeability determines the ability of a fluid to flow. Lithology collectively indicates rock types. Reservoir rocks are sandstones, limestone, and dolomite. Non-reservoir rocks are various types of clay-bearing rocks, including those with paramagnetic substances, volcanic rocks, etc. Lithology affects porosity, saturation, permeability and well completion and placement decisions. The latter in turn may affect well safety.

[5] In the present report ^{137}Cs and ^{241}Am-^{9}Be would be used interchangeably with Cs-137 and Am-Be, respectively.

[6] In fact, acoustic techniques preceded nuclear techniques in computing the porosity and indicating the lithology [Wylie 1956, [Pickett 1963]. Nuclear methods proved more accurate in determining both attributes and thus, in general, replaced acoustic methods to obtain these parameters [Ellis 1987]. NMR techniques for porosity, permeability, and residual water saturation in sandstone reservoirs have been investigated since the late 1960's [Timur 1968]. The work by Jackson 1984, Straley et al 1993, and Coates et al 1999 established the basis of modern NMR logs that allow porosity calculation and permeability estimation.

fluid types, using acoustic and NMR, respectively, that radionuclide-based tools are usually unable to supply. In addition, when used with other techniques, they help to identify formation properties that a single technique by itself may not be able to identify or quantify [Ellis and Singer 2007; Akkurt *et al* 1995; Akkurt *et al* 1998; Herron *et al* 2011; Skelt 2011].

Security issues, post-9/11, refocused the attention of agencies and governments on radionuclide source safety, and more importantly, on the potential *security* risk posed by these sources used in various industries, including for well logging in the petroleum industry. This risk relates to the potential of sources being used in a radiological dispersal device (RDD) [IAEA 2002]. For logging sources, their small size, ease of mobility, and use in potentially dangerous parts of the world have been highlighted as factors that make them particularly vulnerable, despite their much lower radioactivity content than in sources used in most other industries. According to the IAEA-developed risk classification of nuclear radiation sources (IAEA 2003), a 2 Ci ^{237}Cs source used in logging tools is approximately a Category 3 source with the potential for permanent health injury.[7] ^{241}Am-Be logging sources are currently no more than 16 Ci but there are older sources 20 Ci or more. Thus, these are high Category 3 to Category 2 sources.

Post-9/11 source incidents involving industrial sources, including well logging sources, further heightened the security/safety concerns and a number of reports and papers were published noting these risks and suggesting mitigation steps. The 2008 National Academy of Sciences report commissioned in 2005 by US Congress to examine risks and benefits of all industrial sources made a number of recommendations on replacing sources including the ^{241}Am-Be logging sources [National Research Council 2008]. Design improvements were reported for certain logging-while-drilling (LWD) tools to avoid sources falling downhole being drilled into [Aitken *et al* 2002]. Following a missing source incident and a downhole breached source incident (NRC 2006), the state of safety protocols of well logging sources was reviewed and a number of improved protocols and consideration of alternatives were recommended [Badruzzaman *et al* 2009]. The NAS report was followed by Interagency Task Force reports recommending further research on alternatives to sources. The petroleum industry nuclear experts' group, the Nuclear SIG of the Soc. of Petrophysicists and Well Log Analysts (SPWLA), reviewed the state of nuclear-based alternatives and urged its members to keep the issue in focus.

The above resulted in an ongoing effort on improving nuclear-based alternative technologies by the industry (Fricke *et al* 2008; Reichel *et al* 2012) and in studying new replacement ideas by USDOE labs (Bond *et al* 2010; Chen *et al* 2013; Dale 2013).[8] Industry R&D efforts cited have advanced the state-of-the art of proposed nuclear-based alternatives but issues remain in making them replacement quality [Xu *et al* 2010; Gilchrist *et al* 2011; Badruzzaman 2014]. USDOE-sponsored studies noted, often had limited industry input or recognition of past industry effort on alternatives and focused on technical solutions only. While some showed scientific promise, interest in them remained confined mostly to the labs with limited interest by the industry [Griffin *et al* 2010].

In 2015, the National Nuclear Security Administration (NNSA) initiated the current scoping study to do a systematic assessment of both technical and non-technical issues that would arise in attempting to replace radionuclide sources used in logging and suggest a path forward. One major difference of the present study with previous such studies on the topic is the significant input received from the industry through Questionnaires, e-mails, etc., on the state of various logging techniques, and the industry interest in new techniques. Briefly, the study seeks to make

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[7] Category 1 and 2 sources would cause death.

[8] Alternative logging technologies are part of a broader set of steps underway to mitigate logging source risks. Others are tighter regulations, improved protocols, and electronic tracking of sources. These are not part of the proposed scoping study. It will focus only on alternatives.

its assessment and recommendations based on a clearer understanding of the industry landscape, current well logging practices, and requirements an alternative must meet to be a replacement and possibly an enhancement. **Section II** recaps the charge to the Scoping Study Team by the NNSA. **Section III** briefly describes the methodology used in the Study. **Sections IV** and **V** discuss the logging source risk profile and industry landscape, respectively. Current logging techniques are reviewed in **Section VI**, while key requirements an alternative technology must meet to be replacement are discussed in **Section VII**. Tested alternative are discussed in **Section VIII** and promising untested techniques are covered in **Section IX**. **Section X** discusses the non-technical roadblocks. **Section XI** notes the advanced R&D required by various techniques. **Section XII** outlines a suggested roadmap.

II. Elements of Current Study

The NNSA defined the elements of the study as follows:

"The proposed scoping study will (1) *briefly* note the source risks, (2) review current down-hole logging technologies, (3) delineate key requirements alternative technologies need to meet to be of replacement quality, (4) evaluate the performance of tested alternatives and identify research to close gaps, (5) do a preliminary assessment of untested but promising alternatives to guide a fuller research plan, and (6) identify non-technical roadblocks to implement alternative technologies. The study will identify areas where additional information can be obtained using alternative technologies. A roadmap for future research on alternatives will be suggested."

III. Methodology

The study utilized a large number of references, assessed the response to formal input solicited from industry players, performed a number of technical analyses, and held regular group webinars to share information and discuss progress. Both tool designers/logging service providers and oil company users were solicited for feedback using specifically designed Questionnaire for each group, following an initial solicitation of interest from members of three major oil industry-related professional societies[9] in providing input. Feedback was solicited on current state and use of various logging techniques, technical and non-technical requirements the respondents expected alternative technologies to meet to be replacement, and the interest in collaboration with national laboratories in developing advanced technologies.

Seven out of nine logging service providers and experts from six of the seven oil companies thus solicited for feedback responded. In addition to the responses to the Questionnaires, input was received from key industry players via e-mails and formal letters. Most but not all of the respondents gave the input in their individual capacity as either expert users or designers. Collectively, respondents covered a large fraction of the oil industry.

IV. Logging Source Risk Profile

Source Features: **Figure 1** displays typical density and neutron source capsules. Their small size is noteworthy. Each capsule is placed in appropriately designed respective shielded container, such as those shown in **Figure 2**, for transportation to the field. There are over 9000 such encapsulated logging sources around the world.

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[9] Society of Petrophysicists and Well Log Analysts (SPWLA), Association of Energy Service Companies (AESC), and Society of Petroleum Engineers (SPE).

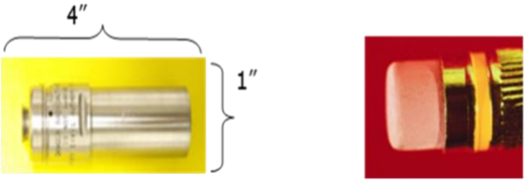

Figure 1a. A ^{137}Cs density source capsule left and illustration of size of actual source with an image of an eraser (Badruzzaman et al., 2009)

Figure 1b. An ^{241}Am-Be neutron porosity source capsule (Hearn, 2014)

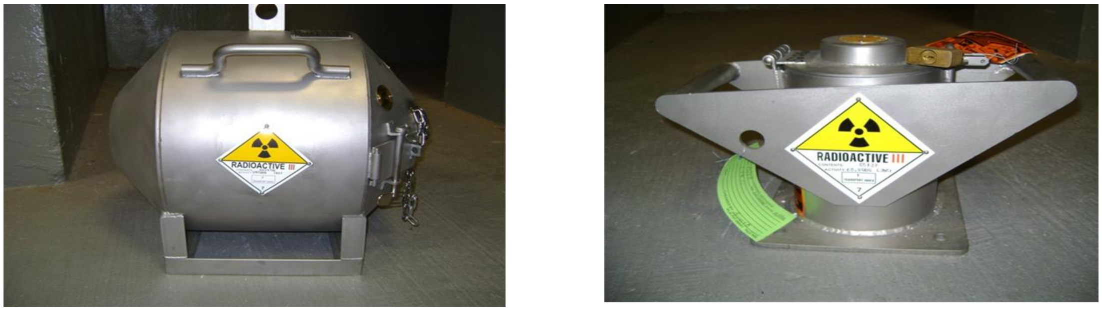

Figure 2. Representative shielded containers, neutron on left and density on right (Figures courtesy of Halliburton and adopted from Badruzzaman et al., 2009).

Despite the industry following all current regulations (NRC 1987; NRC 1991) in transporting and safeguarding these sources, their small size, ease of mobility, high specific activity, and use in remote and often politically unstable regions of the world make them vulnerable to being diverted with relative ease and potentially utilized in a radiological dispersal device (RDD) device. This concern, heightened by the tragedy of 9/11, has been exacerbated by recent stolen/missing logging source incidents.

Recent source Incidents: There have been several other logging source incidents in addition to the lost- and breached-source incidents noted in the Introduction.[10] For example, in 2012, a 15-Ci ^{241}Am-Be source used in neutron porosity tools was lost between wells [Hearn 2014]. Efforts by multiple agencies, federal, state, and local, could not locate the source. Fortunately, the source was later found by a member of the public. In 2009, an ex-employee of a service company stole a 2-Ci ^{137}Cs source from the company's source vault and demanded a ransom [Johnson 2014]. He was apprehended before any harm could come. Theft of sources by disgruntled employees is not new. In 1993, four employees, including the radiation safety officer of a foreign service company operating in India stole three logging sources, two ^{241}Am-Be and one ^{137}Cs [Mishra and Pradhan 1997]. The sources were recovered after an extensive search and retrieval effort, and the culprits were sentenced to prison terms [Parthasarathy 2013].

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[10] Sources stuck downhole and abandoned using established protocols are buried over 1000 ft deep and are not of concern in the context of the present report.

While these and other such incidents have not led to a public scare and no significant exposure was reported, they point to the potential of malevolent activities that could result in an RDD. Alternative technologies will clearly be one step towards mitigating the risks. An examination of the source incidents cited indicates that a multipronged approach is needed. For example, the ability to electronically track sources, coupled with stricter regulations now in place such as background checks, and enhanced user guidelines with better training would have gone a long way in preventing the incidents in Texas and Nigeria, possibly allowing a quicker recovery or both. One major weak link in source security is their transportation in remote locations and without escort. Enhancing the transportation security regime would likely be a major complement to the other mitigation efforts. In this report, we focus on alternative technologies.

V. Petroleum Industry Landscape

In order to successfully address the challenge of an industry to adopt new technology, we need to understand the industry landscape, even if a technology appears appropriate technically. Our survey indicates that the petroleum industry landscape is diverse and complex, with multiple demands and drivers. It includes major US- or Europe-based international oil companies (IOC's), government-funded national oil companies, small domestic oil companies, primarily in the US and Canada, integrated logging service companies who design, build, test, and deploy logging tools and provide geological interpretation, and small independent service providers, mainly in the US who rely on third-party vendors for the technology and have almost no internal R&D capability. In the US, nearly 70% by of the logging units are from small independents [Jordan and Fisher 2014].

Since service companies perform all logging measurements, they retain control of sources and thus their source handling guidelines are utilized in all cases. This led to the challenges for a major IOC, noted by Badruzzaman *et al.* (2009) when a source went missing and another was breached downhole. Consequently, some oil companies have developed internal source handling guidelines for use in conjunction with service company guidelines. The IAEA has drafted a logging source handling guideline for international deployment. It is under review [IAEA 2012].

The business drivers for each group of service providers are different often leading to differing technology needs and capabilities. Many small independent service companies are self-financed while integrated service companies are publicly traded with shareholder support. Most small service providers deal with conventional onshore assets, mainly owned by small oil companies, where complex logging technologies, based on NMR, acoustic, or neutron generators, are not usually deemed necessary by their users. They mostly utilize radionuclide-based logging tools.

Integrated service companies, currently only four and soon to be three due to merger,[11] provide both offshore service and often onshore service in unconventional resources. In both situations, radionuclide-based density, porosity, and mineralogy tools are used, often along with NMR and acoustic techniques. In addition, generator-based mineralogy tools are also being tested. These companies have extensive R&D capabilities. The majority of the business of integrated service companies is with major oil companies which operate in very complex geological conditions, and around the world.

While small independent service companies have been responsible for keeping logging costs in the US reasonable and prevented a monopoly by the integrated service companies, their limited financial resources, together with almost no internal R&D need or capability would make it difficult for them to switch to alternatives on their own.

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[11] These are Schlumberger, Halliburton, Baker Hughes, and Weatherford. At the time of preparing the current report Halliburton was in the process of acquiring Baker Hughes.

In fact, they had viewed source replacement as a long time-horizon prospect, even when the industry was thriving and indicated that they could consider only ready-to-deploy technologies from third party suppliers or national labs [Jordan and Fisher 2014].

In the current industry downturn, adaptation or developing alternatives will be a challenge for all. Even integrated service companies are struggling; they have recently laid-off thousands of workers. For almost all small independents, adapting technologies such as NMR and new acoustic approaches, which may not be needed in their business, or switching to existing neutron generator tool concepts which could possibly replace the ^{241}Am-Be source would be impossible without external support. Thus, mandating such adaptation will likely drive them out of business. They made this point emphatically in their feedback to the current Scoping Study [AESC 2015]. Consequently, small independents would need R&D and funding support for the long run. During the feedback process they indicated that they may consider these under the right circumstances. Integrated service companies are willing to explore collaborative research with national labs. But they collectively gave no definitive indication of their willingness to accept government funding support.

VI. Current Logging Techniques and Their Applications

Table 1 summarizes the techniques and their applications. Typically, the standard logging tool suite consists of radionuclide-based tools (natural GR and those with active sources) to determine lithology, porosity and locate gas, and electrical (resistivity and induction) devices to obtain the fluid saturation. Almost all logging jobs to characterize a formation utilize these techniques. In addition, acoustic, NMR, nuclear spectroscopy, and recently-introduced dielectric techniques, play confirmatory roles and in special conditions provide complimentary information that nuclear-based methods alone cannot supply. The reader can find an excellent expose of logging techniques and their applications in Ellis and Singer (2007).

Table 1. Logging Technologies for Reservoir Characterization, post-drilling or while-drilling [Ellis and Singer 2007]

Technique	Measured Parameters	Key Interpretation	Comment	Depth of investigation
Electrical -Induced - Natural	Resistivity, induction Spontaneous potential	Saturation Permeability indication?	Rocks and oil have low conductivity Saline water has high conductivity	Tens of feet
Natural gamma ray (GR)	Total GR counts Spectra (K, Th, U)	Shale (Clay) vs. sand; clay volume Delineate shale radioactivity from ‘hot’ sands	K and Th ɣ-rays are shale indicators U ɣ-rays indicate fluid movement U ɣ-rays often are a useful indicator of shale resource	Varies: 8 -18 inches
^{137}Cs: 662 keV ɣ-rays	Intensity vs. energy	Density to porosity Gas with neutron PE for lithology Rock image	Typically two scintillation detectors; one company has three-detector device. Density accuracy is .015 g/cc in both clean formations and shale	2-4 inches
^{241}Am-Be neutrons	Total neutron counts and ratio of counts in two detectors	Apparent porosity: Gas; shale (clay) vs. sand, especially when natural GR is unusable; lithology	Typically, a dual-detector device Also helps make casing-cement placement decisions	~ 18 inches

		Lithology is input to porosity and saturation.		
^{241}Am-Be spectra	(n,ɣ) capture spectra	Capture yields Mineralogy	Typically a single detector. Determine mineralogy Cannot identify Carbon (C), Potassium (K) at all or Magnesium (Mg) well Logging speed ~ 1800 ft/hr	~ 18 inches
Acoustic	Transit time, intensity, attenuation, and dispersion	Porosity, lithology indicator, seismic tie, Rock anisotropy Rock mechanical properties, Permeability estimate Fluid/hydrocarbon identification, viscosity	Centered in hole Correlation-based	Can be a few feet
NMR	Polarization and relaxation times, etc.	Liquid porosity: lithology-independent; Permeability estimate Viscosity Fluid typing	Signal/noise ratio (SNR) issues Current wireline tool logging speed: 200 ft/hr Typical accuracy ~2 pu Challenged in: heavy oil nano pores in unconventional reservoirs	Not straightforward. See comments in the text of the report

Depth of investigation: Electrical and nuclear tools perform volumetric measurements. Thus, their depth-of-investigation is defined in the traditional way as the distance radially from which one gets a defined fraction of the signal (usually 90%). Due to design variation and operations principles differences, the depth of investigation of NMR tools is difficult to define. One tool, centralized in the borehole, measures a cylindrical region approximately 2 inches around the entire wellbore. A second tool, operated like a padded tool, investigates the formation about 1 inch from the borehole wall in front of the permanent magnet on the face of the tool. A third tool sees a 120-degree segment of a cylinder approximately 2 inches into the formation. There are other tools that have DOI as high a 4” into the formation.

Appendix A briefly discusses the techniques and associated tools. In this section, we briefly describe the measurements and the parameters they supply, with a couple of examples to depict their relative advantages. Additional examples can be found within other sections of the report.

Electrical measurements: Conceptually, the electrical conductivity (or resistivity) of the formation is measured by sending an electrical current. Rock matrix is non-conductive and the fluid in the pore space introduces a variation in the conductivity. Salt-water or brine is conductive and hydrocarbons are nonconductive. Thus, this difference is used to estimate the water saturation (and thus the hydrocarbon saturation in a two-fluid system). However, since the conductivity depends on porosity, one must know the porosity to estimate the saturation. In addition, rock properties, such as the cementation affect the result. The so-called Archie’s equation, an empirically derived relation embodies the formulation [Archie 1942]. Of course, the technology has evolved far beyond the early days and actual tools and their interpretations are much more complex [Ellis and Singer 2007].

In addition to the conductivity measured using an applied current, one can measure an inherent voltage drop vs. depth in a formation, denoted as the spontaneous potential (SP) [Ellis and Singer 2007]. SP helps identify permeable zones. It is also related to the shale content as is the natural gamma-ray signal.

Radionuclide-based techniques: These include 1) recording gamma rays from naturally-occurring radionuclides, Potassium (K), Thorium (Th) and Uranium (U) in the formation, 2) measuring the intensity of back-scattered gamma rays vs. energy using a device with a ^{137}Cs source and typically two scintillation detectors, and 3) recording the total neutron counts in a dual-detector neutron device consisting of an ^{241}Am-Be source and ^{3}He detectors.

Natural gamma rays (GR) usually denote the presence of shale or more specifically clay. The total GR counts are used to quantify clay volume by noting the minimum value in sand and the maximum value in shale to establish the primary lithology that underpins the other petrophysical parameters and well placement/completion decisions. The spectral GR signal from K, Th and U are used to compute their individual concentration. This delineation becomes important in the presence of radioactivity not associated with clay such as from Uranium or K-feldspars.

*^{137}Cs density too*ls: These tools record the backscattered gamma intensity which is related to the density which is then used to compute the porosity. This is discussed in **Appendix A.** The density accuracy from these tools is ± 0.015 gm/cc, which is equivalent to a porosity of ±1 pu or better. The density-derived porosity is the most accurate estimate of porosity.

^{241}Am-Be source neutron porosity tools: Each of the two detectors in these tools record total neutron counts (epithermal + thermal). The Near/Far detector count ratio is related to the neutron slowing down length or migration length. Both are related to the porosity the magnitude of which depends on the lithology. The neutron porosity is affected by many factors such as gas, clay or shale, or any thermal absorbers present, and thus is an apparent porosity. In liquid-filled reservoirs, the neutron and density porosity overlap; typical uncertainty is about 1.5 pu or better. In gas, the density porosity shows an excess over the neutron porosity while in clay (shale) the trend is reversed. Thus, the neutron-density separation is used to locate and quantify gas or clay (shale) to compute the clay volume, depending on the direction of separation. This method of obtaining the clay volume is particularly useful where GR data would not suffice such as in the presence of U or in K-Feldspars.[12]

Figure 3 displays an example of the use of the standard logging tool suite in a conventional reservoir [Badruzzaman 2002]. No acoustic, NMR or spectroscopic data were acquired here in view of the objective and the simplicity of the geology.

A visual inspection of the figure indicates the following.

1. The caliper log in Track 1 (from left) measuring the borehole diameter is uniform vs. depth thus indicating very smooth hole, or little or no hole rugosity in the industry jargon.

2. The natural GR log in Track 1 delineates the sand vs. shale zone. The high GR in the zone, in the interval, 6060-6142 ft. indicates that it is shale. This is confirmed by the neutron-density separation (Track 4) where the neutron porosity is high.

3. The zone, 6030-6045 ft. has low GR and, thus, is sand. The density-neutron separation in this zone is the opposite direction relative to that in the shale zone and could be either due to presence of gas or void. The high resistivity (Track 2) in this zone indeed confirms it to be a hydrocarbon-gas zone.

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[12] In fact, neutron porosity is not used as a typical porosity needed to estimate reserves. It is a utilized as a lithology indicator and to locate gas.

4. The variable GR in the zone below the 6060-6142 ft. shale zone indicates that it is likely a mixed sand/shale sequence. The variable density/neutron confirms this but their overlap, on the average, indicates the sands in this zone are liquid-filled. The low resistivity indicates that it is likely wet (water-filled).

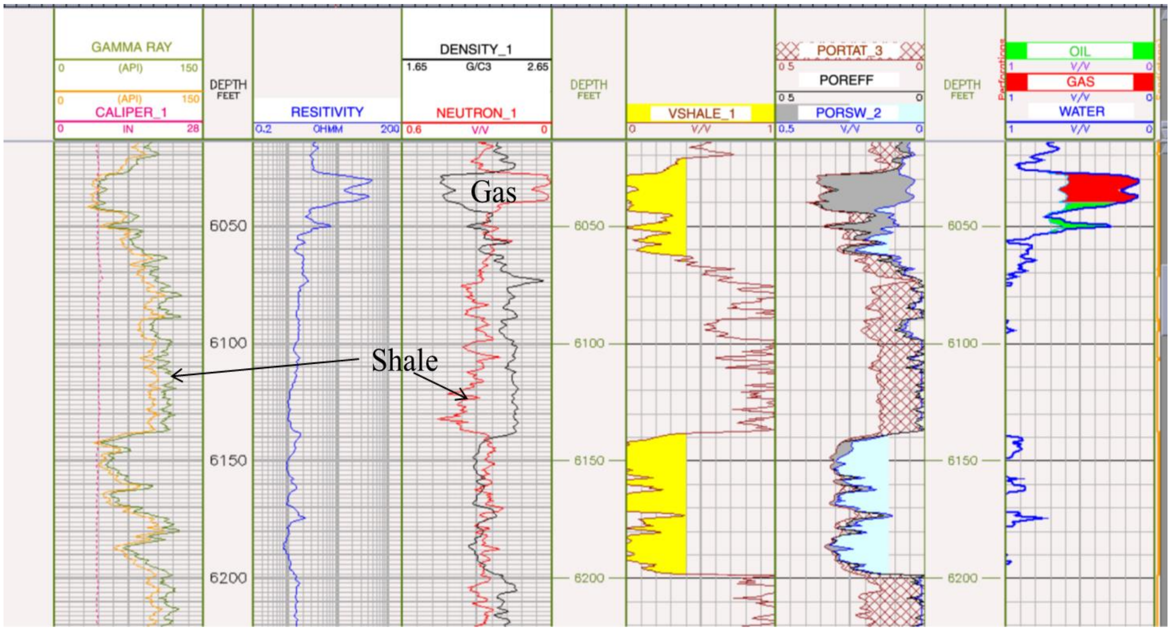

Figure 3 Reservoir characterization: Clay, lithology porosity, and saturation [Badruzzaman 2002]

It should be noted that the example in **Figure 3** illustrates a simple case where the hydrocarbon (gas in this case) is present in a relatively clean (low shale) zone of the formation and the shale zone is clearly delineated using the neutron/density separation in the opposite direction. It represents a vast number of producing fields. However, the approach would not do well in a gas-bearing reservoir with a high shale content because the gas- and shale-based density/neutron separations would coalesce. Here NMR or (n, ɣ) spectroscopy techniques will add value. As seen later NMR techniques are very useful in fluid typing while (n, ɣ) spectroscopy techniques can help determine the total organic carbon (TOC) directly [Akkurt 1997; Herron et al 2011].

Mineralogy using (n,ɣ) capture spectroscopy: These tools are based on a 16 Ci ^{241}Am-Be source and a large scintillation detector, typically, BGO. They allow computation of elemental yields from the (n,ɣ) capture spectra which are then converted to elemental concentration to determine the mineralogy [Herron and Herron 1996; Galford et al 2009]. **Appendix A** discusses this topic in more detail. Mineralogy is playing an important role in both shale reservoirs and formations where uncommon materials are present [Herron et al 2011]. For example, identification of iron, a heavier element than those present in standard reservoirs, helps to improve the accuracy of input parameters, such as the matrix density used to compute the porosity from the measured ^{137}Cs-based density [Ellis and Singer 2007]. As discussed later, D-T generator based (n,ɣ) spectroscopy tools which provide both the capture and inelastic spectra and thus additional information, such a direct measure of TOC, are beginning to replace the ^{241}Am-Be based mineralogy tools [Herron et al, 2011; Radtke et al 2012].

Response simulation techniques: Starting in the early 1980's advances in radiation transport modeling techniques and use of these techniques, in tandem with the availability of faster computers, have played a major role in both the development, calibration, and evaluation of conventional nuclear tools, significantly reducing the development cost and design-to-deployment duration [Ullo 1987; Badruzzaman 1991; Badruzzaman 2005]. Monte Carlo methods have been used primarily in view of their ability to represent the geometry and the physics almost exactly. Deterministic methods, which are more approximate, were used to a much lesser extent, mainly to gain insights in simpler geometries. Many of the basic methods and codes, but not all, were developed at Los Alamos and Oak Ridge National Labs. The Los Alamos Monte Carlo code, MCNP, has become the industry mainstay in nuclear tool response simulation [LANL 2003/2008]. Tool designers in major integrated service companies now routinely use the code to study new design concepts, optimize design and complement experiments to build a much larger calibration database than possible just with experiments. End-users, the oil companies, have used modeling to assess nuclear logging tools in complex realistic conditions to minimize the need for field trials and understand tool response in conditions where calibration data is minimal or non-existent [Day and Petler 1991; Badruzzaman et al 2002] .

Monte Carlo simulation has played a central role in developing and assessing the more complex generator-based tools. However, the public version of MCNP does not have the extent of detector response simulation capability that is needed for the variety of detector types that the industry uses or is developing. In addition, the public version also does not have an adequate capability to compute elemental yields from (n, ɣ) spectral data. Thus, various industry players developed in-house proprietary patches to incorporate these features for their applications. Developments of these features for incorporation in the public version of MCNP will be needed if the techniques are needed to help explore nuclear alternatives for a wider circle of players in a consistent manner

Small designers/service companies or oil companies do not use modeling. Perhaps, if they adopted use of modeling, they will be able progress alternatives in a more cost-effective manner while reducing design-to-deployment duration as integrated service companies have. However, these companies will likely need help in adopting modeling techniques.

Nonnuclear porosity/lithology techniques

Acoustic: Acoustic measurements use a transmitter-receiver system to record the compressional and shear wave velocities generated in the formation following insertion of an acoustic signal. These are related to the associated porosity and lithology [Ellis and Singer 2007]. These tools and their interpretation are discussed in more detail in **Appendix A.** There are several empirical correlations, based on the geological condition, to estimate these parameters. The transit time measured can be used to compute the porosity. The acoustic-based porosity is less accurate (2-4 pu) than density porosity. However, in some specific hole conditions, such as in severely deformed well bores, where nuclear-based porosities are inaccurate, acoustic porosity, appropriately compensated, remains unaffected by the deformity.

Figure 4 displays an example of this, adopted by Ellis and Singer (2007) from a paper by Timur (1987). The figure shows that the acoustic transit time (Track 7, right-most track) appears flat reflecting a near-constant porosity while the density and neutron logs in Track 3 and 5, respectively, appear inadequate over the interval a part of which is clearly sand (low GR). Density tool is shallow and sees mostly a low–density, namely the liquid in the deformity. Neutron is nearly constant below the shale zone but shows a spike in the interval, likely because the correction scheme was inadequate. The acoustic tool uses the so-called borehole compensation (BHC) method that utilizes multiple transmitters and receivers that compensate for the borehole irregularity [Ellis and Singer 2007].

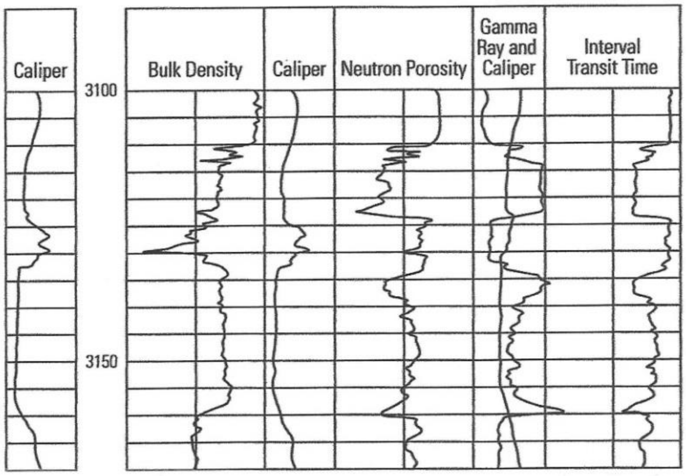

Figure 4 Acoustic, density neutron and GR logs in a well with approximately a 20 ft. interval of borehole irregularity, where the formation likely had caved in [Timur 1987]

In addition to filling in for nuclear logs in certain complex conditions, acoustic data supplies rock mechanical properties [Ellis and Singer 2007]. These properties are essential in understanding wellbore stability, rock anisotropy that may impact drilling, and fracture mechanisms, especially in unconventional reservoirs where fracturing (fracing) is needed for production. Nuclear methods cannot supply this.

NMR (Nuclear magnetic resonance): In this technique the protons (hydrogen nuclei) in liquids in the pore space are first polarized using a magnetic field. The polarized hydrogen nuclei are then modulated with a transverse RF field. The resulting RF field due to relaxation is measured by recording it with a receiving sensor (coil). The resultant polarization and relaxation times are measured to compute a lithology-independent liquid-filled porosity (in the traditional sense of being unaffected by dry clay), obtain a permeability estimate, and get a measure of the viscosity. The time constant associated with polarization is called the longitudinal time constant or T1[13]. The time constant, T2, is related to the dephasing of nuclear spins. Both T1 and T2 have been utilized to obtain the porosity. A third parameter, diffusion, can be related to the viscosity. A more rigorous description of the various parameters and their relationship to petrophysical parameters is given in **Appendix A**. NMR techniques are being used increasingly in fluid typing, something nuclear techniques are challenged to provide [Akkurt *et al* 1995; Akkurt *et al* 1998; Hurlimann *et al* 2002]. NMR logs, in conjunction with other logs, can help identify parameters that standard logs may not be able to do by themselves.

Figure 5 illustrates an interesting application, namely, how NMR logs can offer insights in a quick-look interpretation situation where full processing has not yet been done on standard logs and next steps need to be decided [Akkurt *et al* 2009]. The formation was a low-resistivity, low-contrast gas reservoir.

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[13] In the report T1 and T2, respectively, have been used interchangeably with T_1 and T_2.

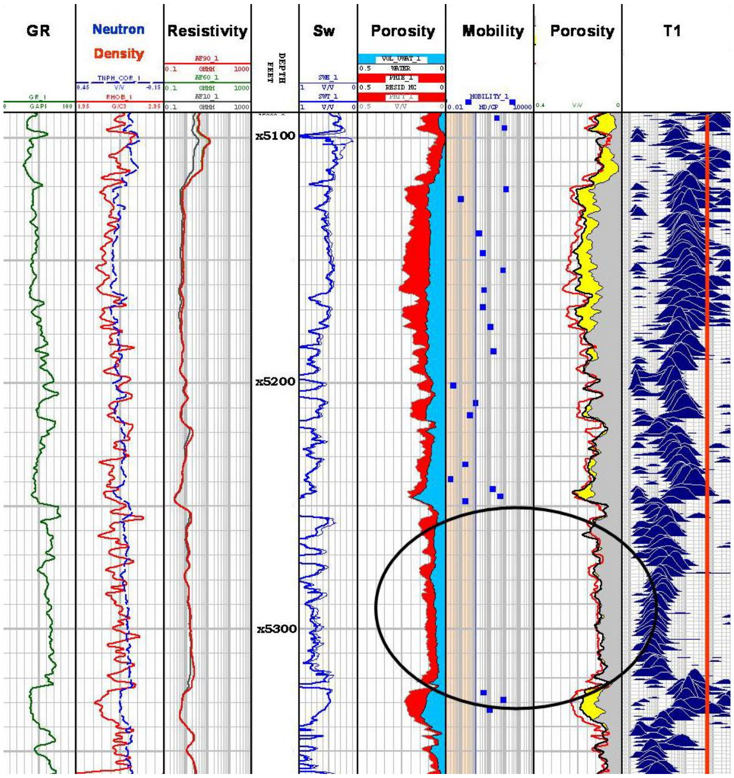

Figure 5. Various logs in a low-resistivity low-contrast gas reservoir [Akkurt *et al* 2009]

In the example, a quick-look was first done using the standard logs, namely, GR, density, neutron and resistivity. Most log nomenclature is obvious. Track 4 shows the quick-look water saturation (S_w) obtained using the resistivity (Track 3). The uncorrected density and neutron porosities are in Track 2. Fluid volume fractions in Track 5, obtained using the quick-look saturation and the quick-look porosities (from density and neutron shown in Track 2), predicts that the formation along the entire length of the well is gas-filled (red). Track 7 shows the NMR free-fluid (yellow) and bound-fluid porosity (grey) along with the quick-look porosity. NMR shows that that below about 5180 ft., there is no gas, except in a small zone towards the bottom of the well. The NMR data in the circled zone shows no gas while the quick-look had indicated otherwise.[14]

NMR T_1 data (Track 8) in **Figure 5** also helped to easily delineate the gas-bearing zone; prior experience in the field had indicated that in gas the T_1 should be more than 1 sec. Note that a regular and full processing of density, neutron and resistivity data would have arrived at the same conclusions which then would be confirmed with fluid testing. However, this example illustrates that a quick-look use of NMR data can help decide whether further processing or full fluid testing needs to proceed.

While the above example by Akkurt *et al* (2009) illustrated an interesting quick-look application of NMR supplementing standard logs, the authors also noted a number of challenges that have hindered the routine use (what they call ‘everyday’ use) of NMR logs. One key limitation they cite is the inability to operate wireline NMR tools at standard tool logging speeds of 1800 ft/hr. The logging speed of wireline NMR logging tools in practice is

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[14] Track 6 displays the fluid mobility obtained using a formation sampling device called formation tester. Absence of mobility data in circled zone reflects lack of pressure data which could not be taken due to the very low permeability [Akkurt et al 2009]. Discussion of this is beyond the scope of the present study.

much slower than this. There are two aspects to the slow logging speed of these tools, namely i) incomplete polarization at high speeds and ii) a higher resolution and better signal to noise with a slower logging speed . Several users have noted, in their input to the Scoping Study, that in their practice, wireline NMR tools are run slow, at ~200 ft/hr [Wendt 2015; Nikitin 2015].[15] Logging speed is not of an issue in LWD tools where tool movement rate is determined by the rate-of-penetration (ROP) of the drill-bit, typically at 150 ft/hr. Low signal/noise ratio (SNR) and shallow depth of investigation are other major limitations of current NMR tools. In current industry practice, NMR-supplied porosity has about 2 pu in error; however, it should be possible to improve it by increasing the signal/noise ratio, for example see [Sun 2015]. We discuss an R&D approach in the roadmap to achieve a better accuracy.

Akkurt *et al* (2009) further investigated what would be needed to achieve an order of magnitude improvement in NMR tool logging speed to make NMR tools replacement quality.[16] Their analysis indicated that NMR tools designed to achieve a logging speed of 1800 ft/hr would result in an unacceptably long and heavy tool. Hence, an important challenge to address would be to design next generation NMR tools with form factors (size and weight) that are practical with logging speeds demanded in standard wireline logging.

Combination of tools: Combinations of nuclear and non-nuclear methods allow identification of geological characteristics specific to complex unconventional reservoirs such as in shale reservoirs. **Figure 6** illustrates the interpretation of kerogen using of ^{137}Cs density and NMR logs [Herron *et al* 2011]. Kerogen is a mixture of organic chemical compounds. Its volume is used as a measure of hydrocarbons in shales. The separation of density porosity and the NMR porosity seen in the figure is the Kerogen porosity: $\phi_{\kappa} = \phi_D - \phi_{NMR}$. NMR sees only the liquid-filled porosity while density log sees both the liquid-filled and kerogen-filled porosity. The TOC which is a measure of hydrocarbon volume in shale is proportional to the Kerogen porosity. This example shows how multiple techniques can be used to understand the value of a reservoir, in this case using both density and NMR tools. We later illustrate this for a combination of density and acoustic tools.

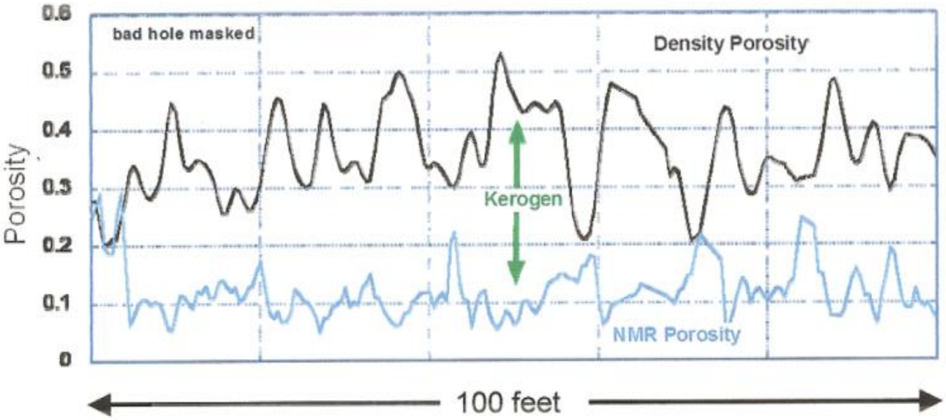

Figure 6. Kerogen fraction: Density porosity vs. Magnetic Resonance (NMR) porosity in Green River Formation [Herron *et al* 2011]

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[15] Some commercial NMR tools, such as MR Scanner from Schlumberger, cite a logging speed range of 250 ft/hr to 3600 ft/hr However, end user feedback did not validate this for full NMR. However, see Appendix A for additional discussion.

[16] This requirement was also pointed out by Ron Cherry of Halliburton in his input to the Scoping Study.

(n,ɣ) capture spectroscopy: In **Appendix A**, the complexity of utilizing (n,ɣ) capture spectral data to obtain mineralogical information is discussed. It requires use of closure relations, oxide models, and normalization to core. Application of (n,ɣ) spectroscopy is becoming essential in determining the TOC directly. ^{241}Am-Be based capture spectroscopy tools are limited in their inelastic gamma ray yields and would be hard-pressed to give a reasonable yield measurement of Carbon. However, Skelt (2011) with appropriate normalizations and empirical fitting procedures, was able to obtain a better correlation of Kerogen content in Green River shale reservoir than was obtained using other methods. **Figure 7** compares three methods, i) natural gamma ray spectroscopy that estimates the Uranium fraction in the rock, one of the early techniques for Kerogen quantification, ii) a combination of acoustic and density techniques, and iii) (n,ɣ) capture spectroscopy.

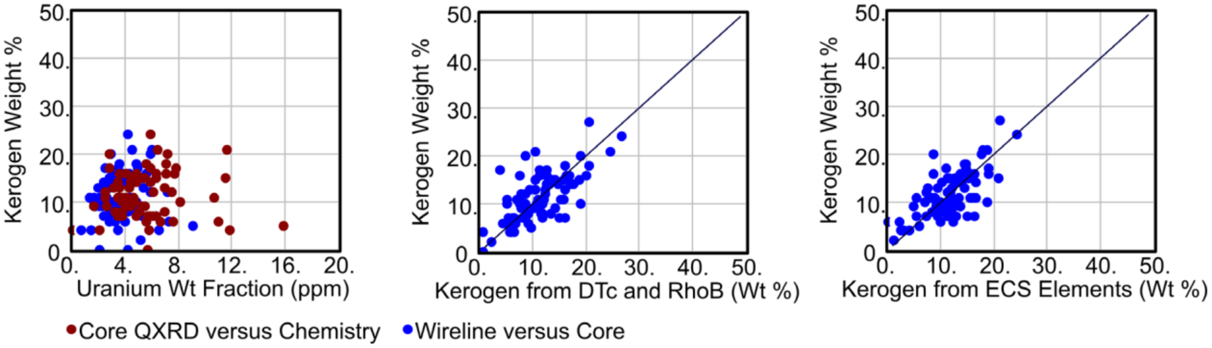

Figure 7. Kerogen Prediction in Green River Formation, Colorado [Skelt 2011].

From the left-most plot in in **Figure 7**, there appears to be a broad association with Uranium but no correlation was attempted. Correlation with conductivity, acoustic data (DTc) and bulk density (RHOB), shown in the middle plot, had an r^2=0.473 while that with elemental capture, shown on the right-most plot data, was r^2=0.541. The author also tested correlation with NMR data and other elements. The correlation of elemental capture spectroscopy shown in **Figure 7** was the best.

Radiation Transport Simulation: Use of Monte Carlo modeling is illustrated in examples discussed later.

Key determinants of adequacy of petrophysical parameters

Here we discuss key items that determine the adequacy of the predicted petrophysical parameters.

A. Logging protocols, data acquisition, calibration, and quality:

1. Logging suite:

In standard logging suites, tools are run in a string, the most common set of tools being an electrical tool and the two radionuclide tools (along with a natural GR detecting scintillator). The combination is called a Triple Combo. When an acoustic tool is added, the string is denoted as a Quad Combo. In many cases, such as in unconventional reservoirs where mineralogical information is important, (n,ɣ) spectroscopy tools are also run. NMR data are often acquired on a different run than with the standard logging suite. Scintillators detecting total natural GR are always included in tool string. The detectors for detecting the natural GR spectra are larger. It should be recognized that no single logging tool type gives a complete picture of the geology.

2. <u>Operation</u>:

Logging speed: This is determined by the precision desired, the signal/noise ratio, and ultimately the accuracy of the petrophysical parameters being determined. In conventional reservoirs the standard wireline logging tool suite, density, neutron, electrical, and GR tools are typically run at 1800 ft/hr with acceptable response.[17] [18] In the case of radionuclide tools, the radioactivity utilized in the source is a key determinant of the logging speed. The typical yields needed for the noted logging speed are, respectively, 10^{10} gamma rays/sec (ɣ/sec) and approximately 2×10^7 neutrons/second (n/s). Using lower activity would not allow an acceptable precision. Tools are primarily run coming out of the hole although sometimes data may also be acquired going down. Acoustic tools are typically run at the same logging speed as the standard logging suite.

Although some designers claim high logging speeds for NMR tools, industry practice indicates a lower speed. Two end-users of the technology, in their input to the Scoping Study, cited typical logging speed of about 200 ft/hr to obtain acceptable results [Wendt 2015; Nikitin 2015]. Akkurt *et al* (2009) cited incomplete polarization of the interrogated region as a major reason for the lower logging speed. Others would be the resolution required and the signal/noise ratio.

Logging speed is much less of an issue in logging-while-drilling where tool movement is determined by the rate of penetration (ROP) of the drill-bit as drilling proceeds. Typically, at approximately 150 ft/hr, the ROP is much slower than the typical logging speed of a wireline tool. This would allow i) a better statistical precision in nuclear tools using the same radiation source yields, ii) time for a more compete polarization with NMR tools, and ii) a better signal/noise ratio for all tools.

Tool positioning: Since nuclear tools have a relatively shallow depth-of-investigation (DOI), in vertical wells they are eccentered in the well to be in contact with the borehole wall. Density tools have a pad to maintain contact with borehole wall; the pad is of a material transparent to gamma rays. Wireline neutron tools are usually run with a bow-spring on the opposite side to push the tool up against the borehole wall to avoid a standoff that can severely affect the computed porosity.

Acoustic tools are centralized in the wellbore because only centered transmitters excite pure borehole modes (monopole, dipole, quadruple, etc.). In theory, eccentered acoustic transmitters excite all modes resulting in a superposition of modes, making it difficult to extract the correct P-wave velocity. The centralization works well in vertical wells but is challenged in high-angle/horizontal wells. Nuclear tools do not face this challenge.

As noted elsewhere, whether NMR tools are run centralized or eccentered, depends on the design and the zone being interrogated. Tools that investigate a volume are run centralized while tools sensing a radial point are run eccentered and padded, more like the density tool. Only Schlumberger's CMR shares the eccentered nature of density and neutron tools.

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[17] Some proponents of nuclear tools have claimed adequacy of faster logging speeds, but the industry practice, based on experience, has remained for these tools at 1800 ft/hr for conventional reservoirs.

[18] In unconventional reservoirs standard wireline logging tools are generally run slower, at 900 ft/hr.

3. <u>Wellbore effect - avoidance, mitigation, or correction</u>:

Mudcake: During drilling, mud is circulated to keep the drill-bit cool and maintain wellbore stability. A mudcake may form between the tool and the borehole wall and the density tool if the fluid in the mud is squeezed out as the tool is pushed up against the wall. Mudcakes with high-Z materials absorb gamma rays and thus can adversely impact the density tool response. There are several techniques to minimize this. These range from running a scraping mechanism to multi-parameter inversion in order to account for mudcake thickness, density, and photoelectric (PE) properties.

Neutron log corrections: The raw neutron data are corrected for borehole size, formation water salinity, mud properties, etc.

Invasion of drilling fluids: This can significantly impact shallow logs such as nuclear logs and even more so the shallower NMR log [Ellis and Singer 2007; Akkurt *et al* 2009]. If the invading fluid is similar to that in the pore space, ultimately, the apparent density or neutron response may not look different. For NMR this may be tricky since it would be polarizing the protons in the wrong liquid. However DOI focusing can possibly be used to address this problem. In LWD, the effect of invasion is generally lower since the data is acquired as the well is being drilled.

4. <u>Calibration</u>: Integrated service companies calibrate nuclear tools in their own specially constructed rock formations, called test pits, with multiple-hole sizes and with fluids in the pore space. They also occasionally calibrate the GR and neutron tools at the common calibration pits located on University of Houston campus, built over 50 years ago with funding from the American Petroleum Institute (API) and thus denoted as API pits. Small independent service companies, often with no calibration pits of their own, utilize these pits.[19]

5. <u>Job planning</u>: In order to obtain the best quality data, logging jobs have to be pre-planned starting with whether the well is an exploration, appraisal, development, or in-fill well. This will determine the type of logging tool that is used. Typically, in an exploration well, almost all types of tools are used to get the maximum amount and type of data to decide if well shows a promising presence of hydrocarbons to move on to the next phase, namely, to further appraise and then develop the field. However, if the geology is simple enough, the Triple combo may suffice. If one is exploring in unconventional reservoirs, where the Triple Combo will likely not suffice, one would add NMR, acoustic and (n,ɣ) spectroscopy tools. On the other hand, in-fill wells are often drilled in existing fields where cased-hole monitoring tools (usually specially designed small diameter D-T generator (n,ɣ) devices) have indicated presence of economic amounts of *remaining* hydrocarbon. One often but not always has modern open-hole data in these fields and thus may not require the full logging suite, or NMR, acoustic, or (n,ɣ) spectroscopy tools.

In job planning, one needs to account for the geology and special characteristics of each tool type and how it may behave in the particular geology. For example, presence of magnetite in the rock would affect an NMR log. A large amount of iron would impact the density log. The type of answers desired may also determine the type of tool to be used within a tool family. Since NMR is slated to predict multiple parameters, the choice of tool operation modes will depend on which parameter the user wants to focus on [Stambaugh *et al* 2000]. For example, for porosity in a low permeability formation such as a low-porosity gas sand, one may not need to

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[19] These pits provide a limited, but needed common calibration of standard nuclear tools across vendors important for quality control, especially when multiple service companies may be logging a field over time. In fact it is the radioactivity in the GR pit that defines the so-called API scale used in all GR tools. Unfortunately, soon these pits may cease to exist.

acquire a large number of echoes and may not need a long wait time (Tw), since the T2 would be low. On the other hand, in clastics (sand/shale) formations with large pores, carbonates in general, or light oil formations, where T2 is expected to be long, one would require a large number of echoes and a long Tw. Similarly, if one is using a D-T generator, pulse duration is determined by whether one would be obtaining the porosity or the thermal neutron decay constant to estimate the saturation. Long neutron pulse durations may cause activation and would determine the pulse gap. All of these will impact the logging speed. There may even be differences between wireline and LWD implementations. Radionuclide source tools do not have such constraints.

B. Benchmark: Core samples taken downhole using specialized coring methods are utilized to validate the log interpretation for porosity, saturation, and lithology. Acquiring and testing core samples require special care since the samples can be altered during, acquisition, handling, and preparation for analysis [Ellis and Singer 2007].

C. Interpretation:

1. External input: In all logging techniques, input of external parameters, often based on the geological condition, are required in addition to the basic data acquired and the various borehole and formation corrections that calibration conditions do not directly reflect. Often these external parameters are accounted for through correlations as in the cases of acoustic interpretation, or through additional measurements and judgement calls. For example, as shown in **Appendix A**, to construct porosity from the log-supplied formation bulk density, the rock matrix density and the fluid density are needed. The matrix density is known from core data or legacy field knowledge. The fluid density is usually measured from samples. For neutrons, one needs to convert the computed porosity to a specific matrix.

In the case of acoustic porosity from the measured average transit time in the formation, one needs to know the transit time in the matrix and the transit time in the fluid. Note the similarity with obtaining porosity from density.

Similarly, the accuracy of NMR-derived petrophysical properties depends on fluid and rock properties, but in a different way than the dependence of density-and neutron-based parameters. For example, NMR porosity is not impacted by dry clay, unlike the neutron porosity and is thus denoted as lithology-independent in the traditional sense. In general, NMR data interpretation utilizes several external quantities such as the hydrogen index, acquisition parameters such as wait time to achieve full polarization, Tw, processing modes, fluid cutoff, and binning. The issues related to the T_2 cutoff are discussed in **Appendix A.**

Thus, the accuracy of the external parameters will have an impact on the accuracy of the final petrophysical parameter computed.

2. Processing algorithms. Many of the algorithms to estimate petrophysical parameters from logging instrument data are empirical such as those in electrical, Acoustic and NMR techniques, and some are non-linear as in the case of NMR. (n,ɣ) techniques to obtain mineralogy require closure relations, often geological location-dependent, to obtain absolute concentrations from relative yields. Radionuclide-based algorithms are simpler.

3. Workflow: Since petrophysical parameters are interrelated, carefully constructed workflows are used to compute them using the log data. In recommending alternatives, it is important to understand the concept to appreciate how a given interpretation is arrived at. A typical workflow for conventional reservoirs is displayed in **Appendix B**. Here we illustrate the steps in a simplified version, namely that used in the log example in **Figure 3**.

While the visual inspection identified the shale, gas-sand and water-wet sands, quantifying the various parameters needed further processing using a workflow similar to those shown in **Appendix B.** Note that no acoustic or NMR logs were taken in this simple lithology and fluid conditions. Briefly, following workflow process was used.

1. Clay volume, V_{clay}: It was first computed using natural GR utilizing an empirical algorithm with a field-specific adjustment. It was confirmed using the density-neutron separation (or its absence). The final clay (shale) volume was a weighted average of the two.

2. Primary lithology: The V_{clay}, from Step 1 was fed to the lithological information obtained from the ^{237}Cs-based PE (not shown) and the density, to construct the primary lithology. If acoustic data were taken, it could have been confirmatory. The lithology feeds into computing the porosity and saturation, and in making well placement decisions.

3. Porosity: Several approaches were possible depending on geological consideration, based on the lithology information in Step 2 above and the pore fluid. In the wet zones, it was computed directly from the ^{137}Cs-based density. In the gas-filled zone, a combination of density and neutron was used. A similar procedure can be used for light hydrocarbon zones which are not explicitly indicated as gas zones. Acoustic data, if taken, could have helped to validate. NMR would have been challenged in the gas but would have done well in the wet sand if the logging speed was not too high.

4. Water saturation (S_w): Feed the V_{clay}, lithology and porosity information to resistivity (or induction data) to compute water saturation. In an oil/water formation, oil saturation (S_o) =1-S_w.

5. Gas saturation (S_g): The V_{clay}, lithology, porosity and the resistivity data were utilized with appropriate correlations.

VII. Key Requirements for Alternative Technologies

These were determined from literature survey and responses to the Questionnaires provided to the industry players.

A. End-user Input: **Table 2** lists the responses from the end users of logging technologies, the oil companies. Briefly, we note the following from the Table.

1. Temperature, pressure condition and vibrations conditions the end-users operate in are harsh and vary widely.

2. In routine wireline applications, the logging speeds are 1800 ft/hr. Specialized tools such as (n,ɣ) spectroscopy and NMR tools demand slower speeds, at 400-600 ft/hr and 200 ft/hr, respectively. Thus, such data may be acquired as needed. Slow logging speeds drive up the rig time and mobilization cost. Also, waiting to acquire data may increase drilling fluid invasion into the formation causing problems for shallow measurements.

3. The density accuracy needs to be ± 0.015 g/cc resulting in no more than ± 1 pu error in porosity. In a 5-pu reservoir, that alone will result in a 20% error in the estimated hydrocarbon reserve volume. Much of world’s reservoirs have such low porosity. Consequently, such stringent porosity accuracy is demanded.

Table 2 Key Requirements for Alternatives Identified by End-users (Oil Companies)

Attribute		Requirement
Formation and borehole	Temperature	75^0 F- 500^0 F now, 600^0 F future
	Pressure	200-30,000 psia now, 40,000 psia in future
Borehole	Diameter	4-in- 12-1/4 in for most, actual drilled holes could be 36 in-50 in
	Mud	Fresh water or saltwater, up to 21 lb/gal, Likely loaded with barite
	Salinity	Fresh -300 kppm NaCl
Accuracy	Density	±.015 g/cc* or better- accuracy by ^{137}Cs density tool
	Porosity	Density porosity: varies on user:± 0.5-1 pu for some; 0-20 pu for others Neutron porosity:± 0.25 pu in low porosity
	Lithology	± 0.5 pu from neutron in 8-pu formation
Generator Operation	Working life	1000 hours
	Pulse shape	Square would be ideal- fast rise and shut-off times required
	Reliability	Ideally zero failure; failures can be costly, into millions of dollars, especially offshore with some rig costs at $1milion/day; spare generator recommended.
Data quality	Precision	As good as ^{241}Am-Be for neutron porosity; open-hole wireline data acquisition is at 1800 ft/hr, for standard logging suite, if replacement Density ±0.015 g/cc or better Neutron: 1.5 pu or better
Use Cost		Must not be significantly more than for use of radionuclide tools: Onshore example: $35k / job with density /neutron and $50k/per job with induction included; $150k/job for LWD Use cost is complex: will include rig time, decision time, personnel, cost of stuck tools, etc. Being able to log faster will be a cost saver. Lower logging speed than radionuclide sources is not acceptable for their replacement. If a generator can give multiple parameters simultaneously, as D-T possibly can, it could be a big a cost saver
Physics/interpretation Complexity		Radionuclide source physics is straight forward and interpretation simple with acceptable accuracy. But physics can be simple but implementation complex as in NMR which was not considered a replacement. Proposed alternatives are not as accurate: Either physics, interpretation, or both are complex.
Legacy Data compatibility	Desirability	Moderate to very high for some, including the largest public oil company. NMR and sonic may give accurate porosity in some cases, but ^{241}Am-Be neutron for lithology is irreplaceable
	Interest in big data analytics to achieve compatibility	Some are interested, but some claim they are not good enough; correlations will not suffice.

* Equivalent to 1 pu (actually 0.91 pu) error in porosity in a fluid-filled quartz formation with a matrix density 2.65 g/cc and fluid density of 1 g/cc.

4. The neutron porosity error window to obtain lithological information is very tight. Lithological information is critically important in accurately computing petrophysical parameters. Lithological information helps determine well placement and completion designs for safe operations and optimal production- the well has to be properly cased and cemented before the mud is withdrawn. Some well completions, especially offshore, can cost over $100 million. Recent incidents have indicated the cost of inappropriate well completion strategies.

5. End-users demand a fairly long generator life, ideally with zero failure. Cased-hole experience with generators indicates that D-T generators can last 1000 hours of operating life. In cased-hole logging, D-T tools are used for monitoring segments of the well. In open-hole wireline logging and LWD, logged intervals would generally be much longer and thus requirements will be more stringent. Note that radionuclide sources (used in wireline or LWD tools) would not fail in the sense a generator can fail. In off-shore operations, failure of neutron or (other radiation source generators) to be used as replacement would be catastrophic. For cased-hole logging, a spare D-T generator is recommended especially in off-shore applications

6. Logging costs are substantially higher offshore, rig time cost being a major component.

7. Users demand a more straight-forward interpretation. They do not view the currently proposed alternatives, whether nuclear-based, NMR or acoustic, to be sufficiently accurate.

8. Several end-users indicated that legacy data compatibility is essential.

B. Service Company/designers: The responses from service companies were similar in many aspects, different in others. Also, they were specifically asked about design requirements. The details of the feedback are given in **Appendix C**. Here we highlight the key points they made and compare those with end-user feedback.

Service companies/designers were queried on three broad areas: 1) Non-nuclear (acoustic and NMR) techniques that can compute porosity, 2) nuclear-based alternatives and 3) desired design attributes, including cost and design-to-deployment duration. All service companies utilize radionuclide-based tools.

1) Acoustic and NMR techniques:

i) Three of the six respondents indicated they supply (additional) service with both types of tool, one indicated use of only acoustic tools and one noted that they utilize neither. The three who indicated that they supply service with both acoustic and NMR were integrated service companies.

ii) None of the service companies, not even those who design and deploy service with acoustic and NMR tools viewed these techniques, individually or in combination, as complete replacement for nuclear techniques.

iii) For NMR, service company respondents noted that an order of magnitude improvement in the signal/noise ratio would be needed. This correlates to the order of magnitude increase in the wireline logging speed the end users indicated that would be needed for NMR tools.

iv) For NMR, suggestions made to gauge interest in higher frequency design, NMR spectroscopy, or imaging as is done in medical elicited the following responses.

a) Higher frequency would result in a very shallow depth of investigation that would increase the sensitivity to invasion and borehole conditions.

We note, however, that while there might be a concern that higher frequencies have lower depth of penetration due to absorption or attenuation, the focusing capability of shorter wavelength (i.e. high frequency) pulses, together with high SNR at these frequencies, more than compensates the attenuation loss associated with high frequencies. This is similar to microwave communications for long-range communications- although microwaves at higher frequencies encounter higher propagation attenuation, the directivity of a parabolic dish antenna allows longer range satellite communication at a lower power due to antenna directivity gain. Furthermore, the higher frequencies allow larger fractional bandwidth or wider band pulses that can be used for channel equalization and pulse coding for processing gain. However, these ideas need to be explored in the context of well logging applications.

b) Spectroscopy and imaging are also of interest, but a key respondent suggested that it would not improve porosity.

c) On the issue of rock connectivity using NMR, it was noted that connectivity is obtained using local knowledge; direct measure of connectivity with diffusion is unlikely to be commercial, although one service company claimed their tool does measure connectivity. These techniques do not address the issue of NMR not providing the bulk density needed for seismic and geotechnical applications.

2) <u>Nuclear-based alternatives</u>

i) ^{241}*<u>Am-Be Neutron Alternatives</u>:*

D-T Generators: Of the six respondents representing a broad spectrum of service companies/designers, only one integrated service company indicated that they have deployed D-T generator-based neutron porosity tools and another integrated service company noted that they have tested the technology but not deployed it. One medium service company indicated that they have used D-T neutron generators in cased holes.[20] The major reason for the not pursuing the technology, even by those who have the technical capability, is that the response does not look like ^{241}Am-Be response. It could be made to look like ^{241}Am-Be, as one medium service company noted, but it will be too expensive for small independents who do not have the needed technical or financial capabilities. Only the service company who has deployed D-T neutron porosity tools thought they can get better than ^{241}Am-Be porosity.

Other generators: Three of the six respondents indicated a general interest in other generators; two respondents were interested in DPF accelerator assuming the neutron yield is comparable to that from ^{241}Am-Be. One respondent expressed an interest in D-D and another in T-T if neutron yield can be increased significantly (by 2-3 orders of magnitude.) Three of the respondents expressed an interest in collaborating with national labs if advanced generators are pursued; another was not interested currently but did not rule it out. One respondent was skeptical about using two generators, DPF for porosity and D-T for spectroscopy, in the same tool, since that would likely compound problems with generator failures.

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[20] All integrated service companies provide dedicated cased-hole logging service using tools designed with D-T generators to monitor wells.

Note: As discussed elsewhere, challenges with pulsed operations of generators to increase their instantaneous counts was illustrated by one service company scientist.

ii) *^{137}Cs Density Alternatives*:

(n,ɣ) inelastic density: One integrated service company indicated they have deployed it for LWD applications. Two others indicated that they have tested it but did not pursue due to inadequate accuracy (.05 g/cc vs 0.015 g/cc for ^{137}Cs based density). Two service companies were directly negative.

LINAC X-ray Tool: Two thought this technology should be pursued. Others thought it would be too expensive.[21]

Mono-energetic photon generators: There was some interest, in principle.

iii) *^{241}Am-Be alternative for (n,ɣ) spectroscopy*: There appears to be a movement towards D-T generator-based spectroscopy tools in view of the ability of these to provide inelastic and capture data for a more complete determination of the mineralogy, especially the ability to directly quantify the TOC, an important parameter in unconventional reservoirs.[22] The advantage of using D-T generators is illustrated elsewhere in the report.

3) Desired Design and Associated Attributes

The service company/designer input indicated the following:

Nuclear generators

- Neutron yield should be ^{241}Am-Be equivalent (15 Ci) or better. The photon yield should be 10^{10}/sec at < 1 MeV. Neutron: for D-T it should be pulsed to take full advantage of high duty factor (10-50%). Photon generator would be run in CW mode..
- Service companies noted that the current regulatory regime for neutron generators is the same as that for radionuclide sources, despite the fact that they are safer than radionuclide logging sources. In other words, there is no regulatory relief for using a safer technology. Thus, there was no advantage for the customer from the regulatory perspective.

All tools:

- Tolerances: Temperature of 150-175^{o}C under normal operating conditions and pressure conditions of 20,000 psia or higher. Note that these are lower than the requirements identified by the end users.
- Shock and vibration tolerances have to be high; for example, in LWD 1000G shock and vibrations of 5-500 Hertz at 20 g rms.
- Total tool length should be less than 12 ft, and the tool outer diameters could range from 1.7 to 3.5 inches.
- Telemetry and calibration requirements would be as for current tools. Designers want no active cooling.

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[21] As discussed elsewhere in the report, an experimental LINAC-based density tool had been successfully tested in the mid-1980's but not commercialized. In a recent conversation with the Technical Lead of the Scoping Study, a representative of this designer indicated that LINAC-based tool may be difficult to utilize in LWD applications, even with modern hardware.

[22] Organic carbon is a direct measure of the hydrocarbon content.

- Corrections for various effects should be similar to those now. Both real-time and post-processed outputs, single and combinable across tools, should be possible.
- As for cost, one service company indicated that alternatives would be expensive, another indicated that a cost equivalent to current D-T tools would be acceptable, and two others, both small independents, indicated that the cost would be unaffordable.
- As for government support, smaller companies would clearly welcome it, one integrated service company was opposed, and response from two other integrated service companies was unclear.
- The response to the query on the acceptable design-to-deployment interval varied from 3 years to 10 years.

VIII. Tested Alternatives

VIII-A. General: We first summarize the industry response on their experience with techniques that have been tested with the potential of being alternatives to understand if they can be replacement. The input listed in **Table 3** indicates the following:

1. End users note that current NMR and acoustic tools do not provide the same porosity accuracy as radionuclide source tools, though it may be possible to improve it by alternative designs.[23]

2. Acoustic would provide limited lithology information and NMR being lithology-independent does not provide any lithology information. While NMR could provide a standalone measure of porosity, other sensors would be needed for lithology data and ties to seismic data that is needed for a complete field assessment.

3. NMR, acoustic and D-T nuclear tools will locate gas, but with varying degree of accuracy. Inelastic (n,ɣ) density sees deeper than ^{137}Cs in gas.

4. Only D-T tool is likely to supply mineralogy as do ^{241}Am-Be tools. Direct Kerogen quantification would be possible with a D-T tool if appropriate scintillators are included to record inelastic data.

5. None of the four potential replacement techniques (D-T neutron, NMR, acoustic, (n,ɣ) density) will resolve thin beds. Only a ^{137}Cs density tool does so as do dedicated imaging tools.

6. Only D-T neutron tool may address legacy data issues but that too with special processing.

7. Only a D-T generator tool that can provide multiple parameters may offer cost savings by limiting the use of multiple tools. However, accuracy issues should be noted.[24]

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[23] Significant signal/noise ratio improvements would be needed. Slower logging speeds make it even more difficult.

[24] A (D-^{7}Li), discussed later, can in theory lead to a multiple-parameter tool. But it will have significant neutron-yield, power-demand, and materials challenges.

Table 3. Summary of Input by end-users (oil companies) on performance of potential alternatives tested.

Parameter	**Acoustic**	**NMR**	**D-T Neutron**	**Inelastic (n,ɣ) density**
Porosity accuracy*	2-4 pu+	2 pu+ : can likely be improved	1 pu in many cases but with special design and processing Strongly affected by standoff. Exact accuracy is less important since only density porosity is used to estimate reserves.	2 pu in clean formations and 4.5 pu in shale under calibration; may be worse in certain field conditions. Accuracy will be difficult to improve
Lithology determination	Limited	No	Yes	Not clear
Mineralogy	No	No	Yes	Unlikely
Gas detection	Yes	Yes	Yes	Yes, greater DOI helps in vertical wells
Other: Thin-bed resolution	Difficult	No	No	No
Other: Kerogen in unconventional resources	No	Yes with density	Yes, if scintillators are also included.	No
Mitigate legacy data issue	No	No	Yes, with special processing	Limited, unlikely
Use cost savings	No	No	May be possible since D-T tools can supply multiple parameters simultaneously.	Not clear

VIII-B. Nuclear-based Alternatives

1.^{241} Am-Be source alternatives for neutron porosity: Two D-T neutron generator-based alternatives to ^{241}Am-Be based tools have been marketed by the same logging company, one for wireline logging and other for LWD [Mills *et al* 1988; Flanagan *et al* 1991; Scott *et al* 1994; Evans *et al* 2000]. In addition, ^{252}Cf which requires much lower radioactivity to provide the same order of magnitude neutron yield, has been tested over the years and an LWD tool was developed as ^{241}Am-Be replacement [Valant-Spaight *et al* 2006]. As with any nuclear tool, the performance of these tools will be determined by the source strength, the energy spectrum, design features, and the wellbore environment. The source strength in terms of neutrons/per sec (n/s) and also duty factor of a pulsed source will determine the statistical precision and the logging speed. At the base level with no borehole complexity, the porosity sensitivity is determined by the energy spectrum. Wellbore environments can distort the signal and thus will have to be corrected by using design features, algorithms, or both. We briefly examine this next.

(i) Source Spectrum Effect: **Figure 8** compares the ^{241}Am-Be source spectrum with those from ^{252}Cf and D-T, the two alternative sources implemented in actual logging tools.[25]

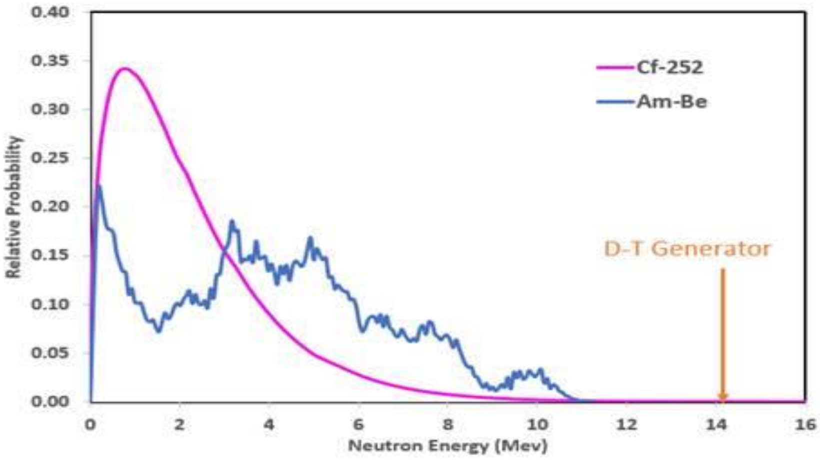

Figure 8 Neutron spectra of ^{241}Am-Be, ^{252}Cf and 14 MeV neutrons [Xu *et al* 2010]

In principle, when neutron sources are simply swapped in the same tool, ^{252}Cf-produced neutrons, due to their lower energy would exhibit higher porosity sensitivity. On the other hand, the 14-Mev D-T neutron source, being at a considerably higher energy than the peak energy of the ^{241}Am-Be spectrum, would exhibit a lower porosity sensitivity.

Figure 9 illustrates this for source energies displayed in **Figure 8,** based on modeling of tool response using a version of the Los Alamos Monte Carlo radiation transport code, MCNP (LANL 2003/2008) [Xu *et al* 2010]. Note that at most porosities of interest (i.e., below ~35 pu), the ^{252}Cf tool sensitivity would be similar (but not identical) to that from the ^{241}Am-Be tool while the differences are substantial for the D-T source tool.

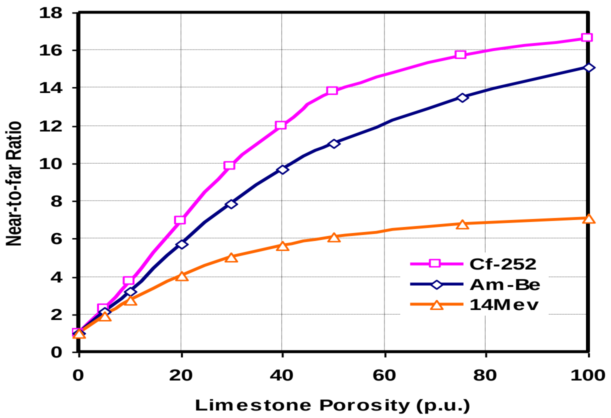

Figure 9. Near-to-far response to limestone porosity for ^{241}Am-Be, ^{252}Cf, and 14 MeV neutrons with a 6 ¾" tool. The ratios are normalized to unity for zero porosity [Xu *et al* 2010]

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[25] As noted elsewhere both sources were suggested for consideration as alternatives to ^{241}Am-Be source in the National Academies' Report [National Research Council 2008].

The resulting response and porosity differences would require renormalization or design changes to reproduce the ^{241}Am-Be like porosity. **Figure 10** displays the improvement in the sensitivity of the D-T tool response the authors achieved by adding 7 inches to the far detector [Xu *et al* 2010]. The maximum difference is less than 2 pu. Note, however, the shape change vs. porosity. The D-T tool which had consistently underestimated the porosity now shows an overestimation at lower porosity and crosses over to an underestimation at higher porosity. The actual impact of the shape change in field application needs to be examined further.

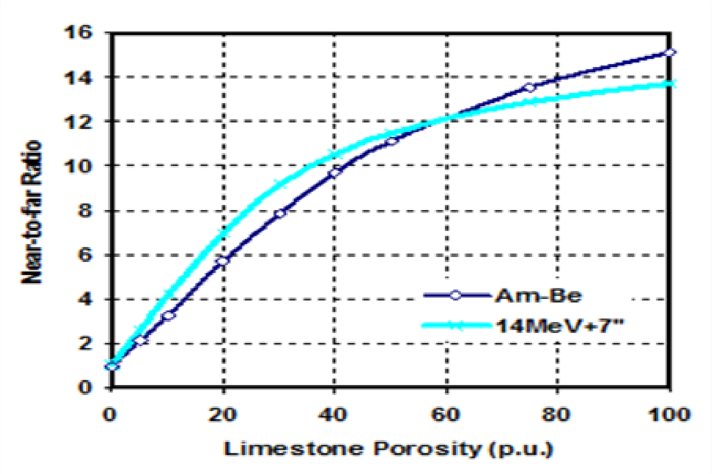

Figure 10. Neutron porosity response for a 14 MeV source with a 7" increase in far detector spacing as compared with ^{241}Am-Be at original spacing's. Ratios are normalized to unity at zero pu [Xu *et al* 2010]

While the above examples show an approach that may allow the porosity sensitivity of D-T source tool to approach the ^{241}Am-Be porosity tool, the change in the design made would result in a considerably longer tool. This is not always desirable from an operational perspective; longer tool strings may be difficult to maneuver, especially in high-angle wells.

(ii) Detected neutrons-a commercial wireline D-T neutron porosity tool: We noted elsewhere that with the ^{241}Am-Be tool, the total counts (epithermal + thermal) are utilized to construct the ratio porosity. The sensitivities noted for the other two sources in **Figure 9** also utilize this concept. However, the wireline D-T neutron porosity tool that was marketed utilized only the *epithermal* neutrons to interpret the porosity. One reason was to minimize the effect of thermal neutron absorbers that may be present in the geology. The designers also optimized the detector positions to minimize the effect of the lithology.

Figure 11 displays the log data from various tools including the D-T generator epithermal neutron porosity tool [Badruzzaman 2005]. The (epithermal) neutron porosity is displayed in Track 2 (from left) in both limestone units (APLU) and in sandstone units (APSC). The Track also displays the ^{137}Cs-based density (RHOB).

The spiky behavior of the neutron response is particularly noticeable in zones that are clearly identified from the GR log as clean sand (low GR in Track 1). The behavior was unexpected in view of the clear shale/sand delineation by the GR log, excellent hole conditions indicated by the caliper log (Track 1), the rather smooth density log (Track 2), especially in the sand zones , and the negligible density correction (DRHO) in Track 1. Even the acoustic logs in Track 3, which show a separation in shale, are fairly constant in the sand zone. So there should be no porosity spikes, especially in sand zones. If the neutron porosity traces in Track 2 are to be trusted, a geologist will likely interpret the GR-delineated sand zones as variable carbonate zones and the predicted grain densities would be different from those for sand as shown in Track 4. However, core data (not shown), the density response, and the associated geologist's years of knowledge of the formation all indicated that these zones must be clean sand.

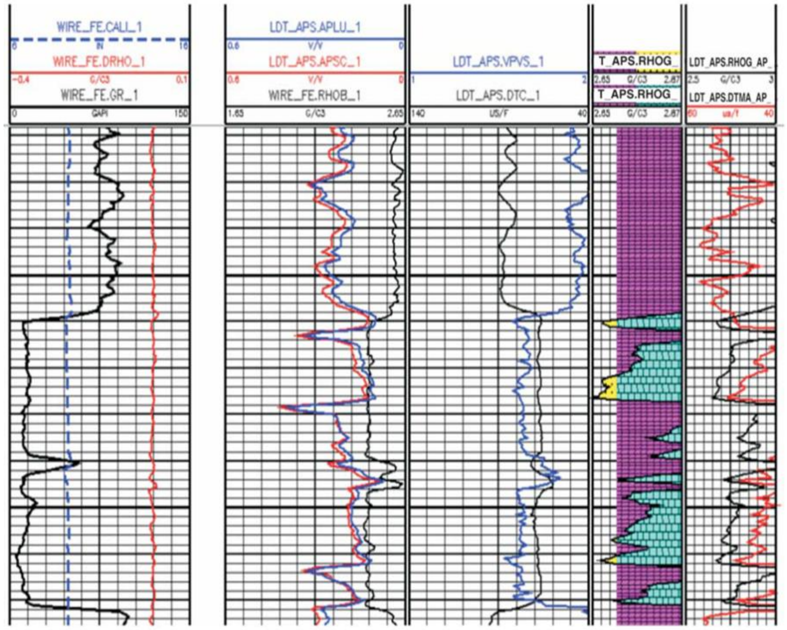

Figure 11. Porosity from wireline D-T source epithermal neutron tool in wet sandstone: In this tool only epithermal counts ratio was used [Badruzzaman 2005)

An examination of neutron response by modeling the behavior of epithermal neutrons indicated that the spikes most likely arose from water standoff, i.e., a water-filled gap between the tool and the borehole wall. It is well-known that such standoff has an inherently greater effect on epithermal neutrons; effect of standoff would be much less for the neutrons from the ^{241}Am-Be tools which are dominated by thermal neutrons. It was conjectured that the standoff arose from the difficulty in pushing the tool up against the borehole wall in the harsh operating conditions of this high-pressure, high temperature well. The standoff was not clearly known and thus it was not always possible to adequately correct for the standoff [Badruzzaman 2005].

The standoff effect on this wireline D-T tool could possibly be reduced by utilizing the total counts and not just epithermal counts. A few years later the service company reported standoff a correction [Fricke *et al* 2008]. However, experience has shown that this correction may not be adequate, especially if the standoff is large since the algorithm still utilizes epithermal counts to start the processing [Badruzzaman 2015].

(iii) Detected Neutrons- Commercial LWD D-T neutron Porosity Tool. This tool was reported by the same service company as the one that marketed its wireline counterpart [Evans *et al* 2000]. The tool performed reasonably well in predicting the neutron porosity [Flanagan *et al* 1991]. There are two likely reasons for this behavior. Firstly, unlike its wireline counterpart, this tool utilizes total counts which would be less affected by the standoff than this particular wireline tool was.[26] Secondly, being an LWD tool, its standoff is known by design and is usually small and

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[26] However, actual effects are more complex and beyond the scope of the present study.

is, thus, more easily correctable unless the tool rotates in an elliptical wellbore with a variable standoff. These two features allowed a reasonable performance by the LWD D-T neutron tool. These results show that, despite a lower porosity sensitivity to start with, a suitably designed D-T neutron tool utilizing total counts with an appropriate interpretation algorithm may be able to replace an ^{241}Am-Be tool in many cases. The industry is exploring other approaches and it is possible that for the near term D-T generator neutron porosity tools can significantly reduce the use of ^{241}Am-Be source neutron porosity tools, especially if adequate processing algorithms can be developed to address the spectral differences.

(iv) *Legacy neutron Data compatibility of D-T neutron porosity*: We noted that the basic spectrum difference of a D-T generator with ^{241}Am-Be sources will make the porosity sensitivity lower unless design changes are made, even if total counts are used. In addition, the field example cited indicated that use of epithermal neutron counts in the current wireline D-T tool may lead to erroneous results. In both cases, D-T neutron tools would not normally reproduce the legacy data. In order to address this, Fricke *et al* (2008) developed an involved algorithm that requires additional input. The algorithm takes the epithermal porosity and corrects it using density and thermal absorption coefficient while using the slowing down time to correct for any standoff. Field tests show that while the algorithm may reproduce the ^{241}Am-Be response where borehole conditions are benign, it will not suffice when standoff is significant [Badruzzaman 2015]. One main reason is the use of epithermal counts which are more severely affected by standoff than total or thermal counts; the slowing-down-time-based correction may not be able account for the large standoffs. The LWD tool which uses the total counts is likely to perform better. In LWD, the standoff effect on neutron tool is fixed, small, and well-calibrated unless one is in an elliptical borehole with variable standoff. However, correcting for such standoff would be difficult for any tool [Day and Petler 1991].

2. ^{137}Cs alternatives for density:

(i) LINAC density: One of the two switchable photon source alternatives tested to replace to ^{137}Cs for density was a LINAC X-ray wireline tool successfully tested in the 1980s but it was not commercialized [King *et al* 1987]. The tool showed a greater depth of investigation, somewhat lower density sensitivity, and difficulty in separating the photoelectric effect which affects the lithology sensitivity. While the tool was not commercialized, it demonstrated the feasibility of using a direct generator-based photon source to determine the density.

(ii) Inelastic (n,ɣ) density: The other ^{137}Cs alternative is an interpretation algorithm in a D-T generator LWD tool that utilizes the density signature in gamma-rays produced from inelastic interactions of high-energy neutrons [Evans *et al* 2000; Reichel *et al* 2012]. The concept was initially developed for density-through-casing as a density indicator in old wells with limited modern data [Wilson 1995; Badruzzaman 1998; Odom *et al* 1999; Neuman *et al* 1999]. The resultant density is denoted as inelastic (n,ɣ) density (INGD) or sourceless neutron gamma density (SNGD) by some. Since it is not a direct measure of the density, the cased-hole practitioners faced several challenges and had to develop several corrections to compute, what is essentially a pseudo-density, and thus more qualitative than quantitative. The INGD concept for use in LWD tool was proposed by Evans *et al* (2000) and its commercial version was reported by Reichel *et al* (2012). This is the only marketed INGD tool for reservoir characterization in open-hole logging. **Figure 12** displays the schematic of the LWD tool.

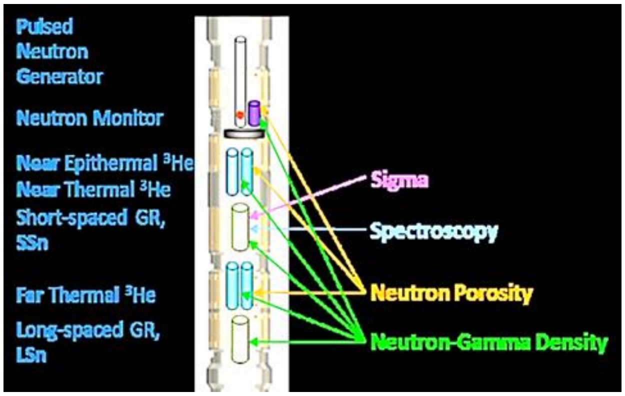

Figure 12: Schematic of a D-T Neutron Generator-Based Multiple Detector Multi-Parameter LWD Tool [Reichel *et al* 2012]

From the figure we note it is a multiple-parameter tool. Thus, in addition to INGD, it seeks to simultaneously provide the neutron porosity as noted in Evans *et al* (2000), the pulsed neutron capture decay constant, Sigma that can be used to compute the water saturation, and the (n,ɣ) capture spectroscopy data for determining mineralogy. Thus, it has multiple neutron and gamma detectors.

In order to obtain a quantitative (n,ɣ) density, the authors utilized a detailed customized modeling of tool response using Los Alamos Monte Carlo radiation transport code, MCNP (LANL 2003/2008), to overcome many of the challenges noted in the cased-hole renditions of the technique. After experimenting with many interpretation concepts, such as the use of the ratio of long- and short-spaced (LS and SS) inelastic gamma-ray counts to arrive at response-to-density algorithm , the authors settled on the following formulation where they express the intensity in the long-spaced (LS) detector as

$$I_{LS} \sim Sn * f_1 f_2 .. \exp(-g\mu_c x) ,$$

where *Sn* is the neutron source strength, f_1, f_2, ... are correction factors needed to account for the effect of neutrons, and the parameter *g* is needed to accurately account for the gamma transport in the presence of neutrons. The correction factors are determined utilizing Monte Carlo simulation and normalization to experiments. Contrast the above equation with the simple intensity equation, Eq. A-I.1, noted in **Appendix A**, for the ^{137}Cs source gamma-ray intensity that depends only on photon physics and does not require correction factors noted in the equation above.

By using the above approach, Reichel *et al* (2012) were able to overcome many of the challenges in the cased-hole renditions of INGD. The tool showed a greater depth of investigation than a ^{137}Cs tool would. However, despite the gains, their INGD exhibited a number of shortcomings, including a poorer accuracy versus the ^{137}Cs-based density tool. In clean formations, the accuracy was 0.025 g/cc vs. 0.015 g/cc, and in shale-type formations it was 0.045 g/cc vs. 0.015 g/cc. The resultant porosity accuracy would be 2-pu and over 4-pu, respectively, and thus would be generally unacceptable. The accuracy was even poorer in certain field conditions (by as much as 0.2 g/cc) [del Angel *et al* 2014].

A modeling assessment of the physics basis of INGD vs. photon-based density from ^{237}Cs gamma rays or LINAC X-rays, using the MCNP code, revealed that the LINAC X-rays should give a reasonable density as was obtained by King *et al* (1987) but the INGD errors would be much larger and complex [Badruzzaman 2014]. The greater errors in INGD arise from its origin in the coupled neutron-photon physics involved and resulting competing effects of photon production vs. transport, dominated by hydrogen. **Figure 13** illustrates one of the main issues identified from the modeling by computing the gamma flux at different locations in a sphere of formation material with a 14-MeV neutron source at the center. The source is turned on at t=0. The figure displays photon flux/time vs. time at the same location under two formation-fluid conditions, dry and wet (pore-space filled with water), the average density of the two formations were identical (2.115 g/cc).

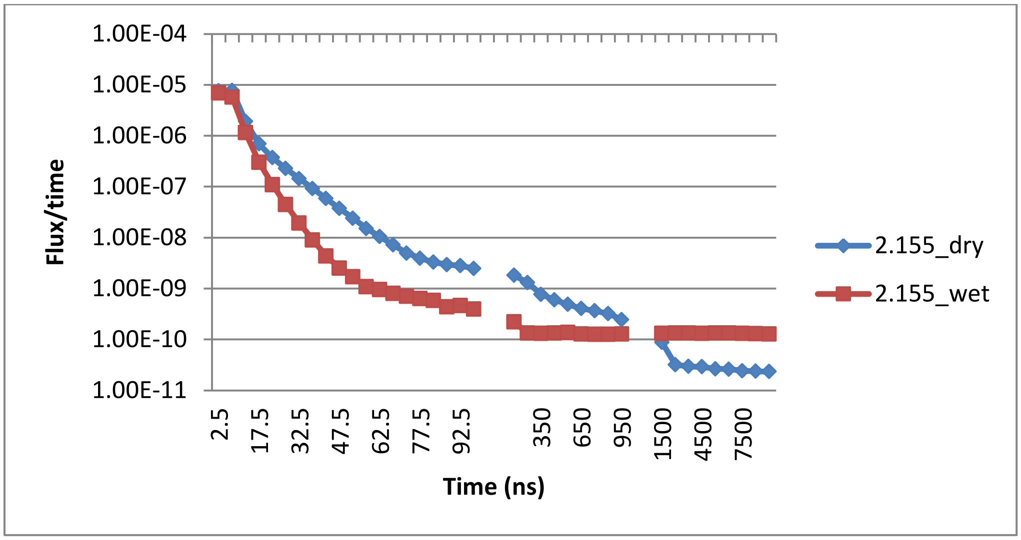

Figure 13: Induced photon flux/time at 14 inches of a spherical formation with 14 MeV Neutron source at the center of the sphere in an t=0 [Badruzzaman 2014]

The following is noted from the figure:

Despite the density being identical, the two fluid conditions display different responses, in what appears to be three temporal zones with distinct response behavior:

a. In the less than 100 nanosecond (ns) time frame where inelastic signal dominates, the wet formation has lower counts. This is due to the neutron spectra being softer, vs. that in the dry formation, caused by the presence of hydrogen (in the water,) thereby reducing the inelastic gamma-ray production vs. the dry formation; inelastic reactions are threshold reactions. Clearly, this effect will not arise in ^{137}Cs gamma source or LINAC X-ray source tools. Those are based entirely on photon physics. This explains the complex behaviors seen in cased-hole implementation of the technique [Wilson 1995; Badruzzaman 1998; Odom *et al* 1999; Neuman *et al* 1999].

b. The time zone in the low several hundred nanoseconds appears to be a transition zone where inelastic photons continue to decline, capture photons are created, and down-scattered gamma rays begin to arrive. If data are recorded in this time zone, complex corrections will be needed to separate out the inelastic counts to compute a density.

c. Finally, in the microsecond zone, inelastic gamma rays would be almost non-existent, there will be additional down-scattered gamma rays reflecting a Compton effect, but capture gamma rays will dominate. Thus, to use the gamma rays in that time zone for density, capture subtraction would be needed and gamma transport will need to be modeled carefully.

Further analysis showed that the above effects are compounded when the source is left on for a few microseconds, as would be in a tool. Also, it was seen that the effects would be location-dependent.

Additional issues, such as causes of poorer accuracy seen in shales vs. clean formations by Reichel *et al* (2012) are discussed by Badruzzaman (2014). In general, the INGD technique involves coupled neutron-photon physics with several complex and competing effects.

In contrast to the above, the photon-based density from either ^{137}Cs gammas or LINAC X-rays is entirely from Compton physics which is fairly simple. No photon production or capture correction issues are involved [Badruzzaman 2014]. Despite these challenges, Reichel *et al* (2012) demonstrated that INGD *can* give a quantitative density, though inherently a less accurate one. Thus, with more testing, the INGD *may* in some cases be a substitute, albeit a considerably less accurate one, in conditions where the ^{137}Cs-based density cannot be obtained, the caveats of coupled physics can be addressed sufficiently, or a stringent accuracy may not be needed.

3. Advanced (n,ɣ) spectroscopy for mineralogy: D-T generator (n,ɣ) spectroscopy tools are already beginning to replace ^{241}Am-Be based spectroscopy tools in determining mineralogy [Pemper *et al* 2006; Herron *et al* 2011, Radtke *et al* 2012]. The advantage D-T generator (n,ɣ) spectroscopy tools offer over ^{241}Am-Be-based tools is their generation of recordable inelastic gamma rays, in addition to capture gamma rays, to allow detection of key elements that only inelastic collisions can detect, such as Carbon and Potassium. Inelastic reactions also allow a direct measure of Aluminum a key indicator of shales, and also give a clearer determination of Magnesium, the key element in dolomite ($MgCO_3CaCO_3$).

We illustrate the advantage of D-T based (n,ɣ) spectroscopy in estimating TOC by revisiting the example in **Figure 6** and noting the example in **Figure 7**. The example in **Figure 6** from Herron *et al* (2011) illustrated a method to accomplish this using a combination of density and NMR logs. **Figure 7** displayed a couple of other approaches, one based on a combination of resistivity, acoustic and density techniques and the other using elemental capture spectroscopy [Skelt 2011]. Accuracy of the combination of methods may be affected by inaccuracy of mineral density, presence of gas which will affect density, acoustic, and NMR, and non-inclusion of all of the clay-bound water in the NMR signal, as may happen in gas shale. The Green river formation had almost no gas and thus the NMR technique worked well. This may not be true in other formations, especially in gas-bearing shales and thus the use of an (n,ɣ) spectroscopy-based approach to obtain the TOC directly, without having to infer it from a combination of techniques, is being explored with increasing frequency. However, since capture spectra by itself cannot infer Carbon directly, this technique would also be limited.

Thus, D-T based (n,ɣ) spectroscopy tools utilizing both capture and inelastic spectra offer an advantage over both the combination techniques and the capture spectroscopy technique alone. The premise is that the inelastic data will provide the total Carbon (inorganic + organic) directly in addition to other parameters. The capture data does not provide Carbon but can delineate many other minerals that can be used to infer the inorganic Carbon content. **Figure 14** illustrates the approach and advantage of inelastic data.

The authors utilized the following steps in the interpretation.

a. The (n,ɣ)-based Elemental Capture Spectroscopy (ECS) tool, noted in Herron and Herron (1996) was used to obtain clay minerals, inorganic Carbon, etc. Inorganic Carbon is shown in Track 2. ECS does not give Carbon gamma rays since the tool uses the ^{241}Am-Be neutron source- most of neutron energy is at or below the Carbon inelastic threshold. Special algorithms and core normalization (red dots) were used to obtain the other parameters shown.

b. The D-T generator-based saturation monitoring tool, RST-A (Roscoe *et al* 1993) was then used to demonstrate the value of a D-T-based (n, ɣ) spectroscopy tool to obtain the total Carbon (left-most track), Oxygen, etc., directly.

c. The organic Carbon volume is obtained by subtracting the inorganic Carbon from ECS from the total Carbon from RST-A (n,ɣ)

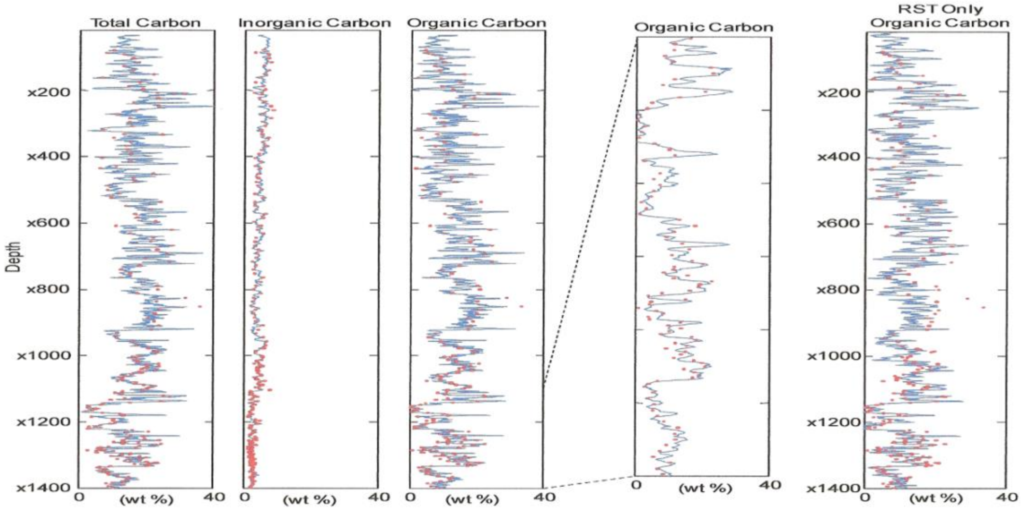

Figure 14: Total carbon, inorganic carbon, and total organic carbon (TOC) in Green River from an (n,ɣ) spectroscopy tool [Herron et al 2011]. Inorganic carbon arises from calcite ($CaCO_3$), dolomite ($CaCO_3$MgCO3), nahcolite ($NaHCO_3$)

The authors then obtained both total and inorganic carbon directly from the D-T-based tool RST-A to compute the organic Carbon content since the tool records both inelastic and capture data. This is demonstrated in the right-most track of **Figure 14** which shows the organic Carbon from RST-A data only. While the results appear reasonable compared to that in Track 2, it is clear that they are more noisy. The RST-A is a small tool (1-11/16 inch outer diameter) designed for running through tubing in cased-hole applications and is not optimal for open-hole applications.

Having demonstrated the advantage of D-T source for (n,ɣ) spectroscopy, the service company recently reported a dedicated D-T generator-based (n,ɣ) spectroscopy tool developed to replace the ECS. The new tool consists of a D-T generator that produces more neutrons/sec (capable of 3x10^{8} n/s) than previous generation of their generators and a single crystal of $LaBr_3$ [Radtke *et al* 2012]. $LaBr_3$ has a much better energy and timing resolution than the gadolinium orthosilicate (GSO) detector used in RST-A or Bismuth germinate (BGO) crystal generally used in other (n,ɣ) spectroscopy tools. Radtke *et al* (2012) note its superior performance, but the logging speed the tool is slated to operate at is 600 ft/hr versus the 1800 ft/hr the capture-only spectroscopy tool, ECS, operates in. This arises from the need to accommodate the relatively lower inelastic gamma counts vs. capture counts.

4. Multiple-parameter Nuclear Tools**:** The above discussion of enhanced (n,ɣ) spectroscopy and previously of neutron porosity, each using a D-T generator tool but, separately, point to the possibility that if appropriately designed, a single D-T neutron tool can provide both the neutron porosity and mineralogy information. This is illustrated for LWD by the design depicted in **Figure 12** that already can supply multiple parameters, including the neutron porosity, capture decay constant to compute water saturation, (n,ɣ) capture spectra, and (n,ɣ) density, admittedly at present a less accurate measure of the density. Several industry respondents indicated an interest in such a multiple parameter tool for wireline application.

VIII-C. Tested Acoustic:

The design of acoustic logging tools involves a multidisciplinary activity that encompasses a range of fields including basic wave propagation theory, sensor and instrumentation, and data interpretation. Over the past three decades, resulting from numerous theoretical studies and analysis of field logging data, the industry has a much better understanding of acoustic wave propagation in different formations and downhole acoustic measurements. Also thanks to much faster instruments and powerful acoustic sources, modern acoustic logging tools provide a longer range, shorter logging time, higher resolution, and better accuracy. Modern acoustic logging techniques are comparable to or can assist with nuclear logging techniques in many applications, including:

- Determination of porosity in porous rocks from compressional velocity or the combination of compressional and shear velocities (details in **Appendix A**);
- Stoneley wave-derived permeability in porous rocks for the detection of fractures, vugs[27], and bed boundaries and the measurement of fracture permeability;
- In-situ determination of compressional and shear-wave velocities, which are useful in the interpretation and calibration of hole-to surface measurements, hole-to-hole seismic tomography, and surface seismic data;
- Lithology correlation between holes using logs of compressional and shear velocities;
- Compressional and shear slowness or their ratio can be combined with data from a density-logging tool to determine formation mechanical properties (details in **Appendix A**);
- Primary means for the evaluating the mechanical integrity and quality of the cement bond.

Three tested modern acoustic logging techniques are presented next as examples of well-logging applications. We had noted one example previously.

Acoustic Primary and Secondary Porosity Measurements

The porosity of a formation can be estimated from acoustic, density, neutron, or NMR log. Using any single logging tool, the porosity is calculated from relations between the values of the rock formation and the pore fluid or gas. To correct for lithology effects in a complex formation, a combination of these logs is then used or rescales need to be conducted [Doveton 1999]. Neutron and density logs respond to overall pores, i.e. pores of all sizes. On the other hand, acoustic log measures waveform travelling through formation and borehole wall that are free from fracture and vugs. Hence, acoustic log is more sensitive to the primary porosity (inter-particle porosity) and less to the secondary porosity caused by fractures and/or vugs. For example, in the case of gas-filled porosity, the acoustic-neutron cross-plot in **Figure 15** shows porosity measurements resulting from neutron-density and acoustic logs in a Pennsylvanian section in Mesa Leathersland. The tracks of both logs are close (within around 3%

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[27] Small- to medium-sized cavities in the rock.

porosity) here and in the Sniabar limestone, but are quit apart (15-25% porosity) in the Bethany Falls limestone zone. More details of acoustic porosity measurement can be found in **Appendix A.**

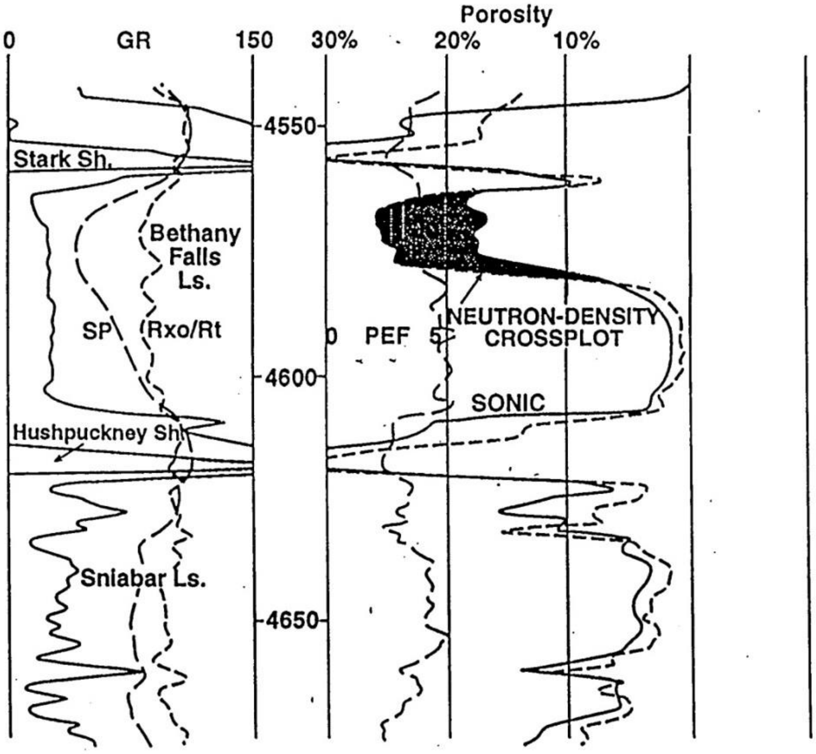

Figure 15. Neutron-density (dashed line) and acoustic (solid line) porosity logs [Doveton 1999]

Acoustic Hydrocarbon Identification

In order to confirm the conclusions from standard logs, a common practice for hydrocarbon identification uses wireline formation testers either by measuring fluid-pressure gradient and density or taking oil/water/gas samples from the invaded zone for sophisticated chemical analysis on surface. The operation of wireline formation testers is neither cheap nor without risk of tool sticking. An alternative and more efficient practice is applying the acoustic technique used for porosity logging. According to Snell's law, less acoustic energy transmits from solid formation into gas or fluid media. Also, compressional wave propagates much slower in gas and fluid, which do not carry shear waves. A sudden loss of acoustic intensity or reduction of compressional velocity may indicate gas-filled pore space. Compressional velocity is different in different hydrocarbon gases. Thus, V_p/V_s ratio offers a quick-look indicator to distinguish between reservoir fluids and is especially effective in identifying light hydrocarbon gases.

Figure 16 shows a log cross-plot for gas identification. The changes of Δt_c, Δt_s , *and* V_p/V_s ratio (1st and 3rd tracks) can be used as quick-look indicators. In the case of gas-filled porosity, the acoustic-neutron cross-plot can be useful for this purpose because neutron porosity is lower than acoustic porosity in gas zones. **Figure 17** presents a cross-plot of shear slowness vs. V_p/V_s serving as a quick-look hydrocarbon indicator. For a formation with known V_s, V_p/V_s ratio drops, i.e., compressional-slowness travel time (Δt_c) increases where the rock pore space is occupied by more compressible gas [Fertl 1981]. These two figures (especially **Figure 16**) show that acoustic technique is able to distinguish between oil and water. Between them the difference of acoustic impedance is 12-25%. Their viscosity and attenuation are also very different. The differences are even larger for water vs. pressurized gas.

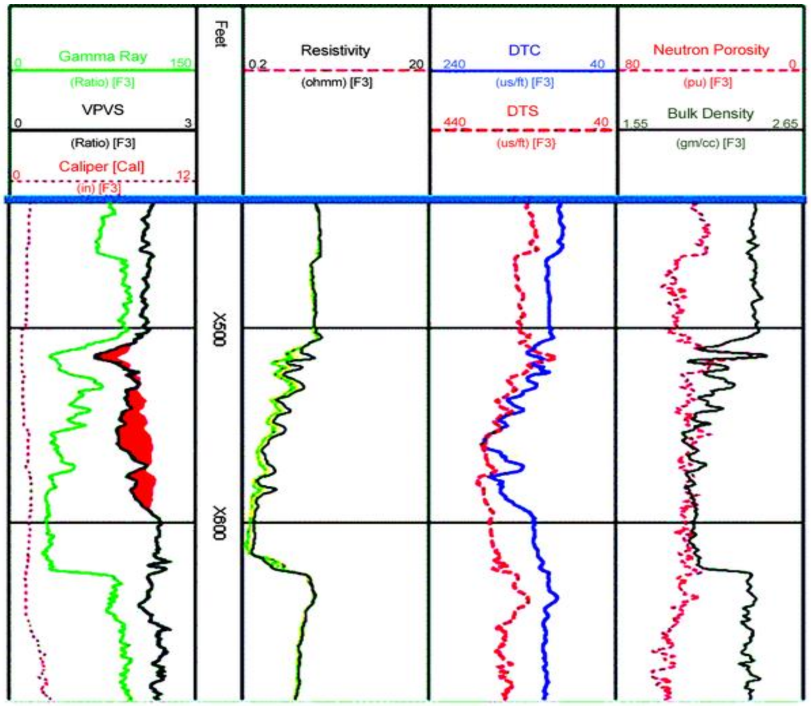

Figure 16. Logging cross-plot for gas identification. Adopted from http://petrowiki.org/Fluid_identification_and_characterization- identified as a Baker Atlas figure.

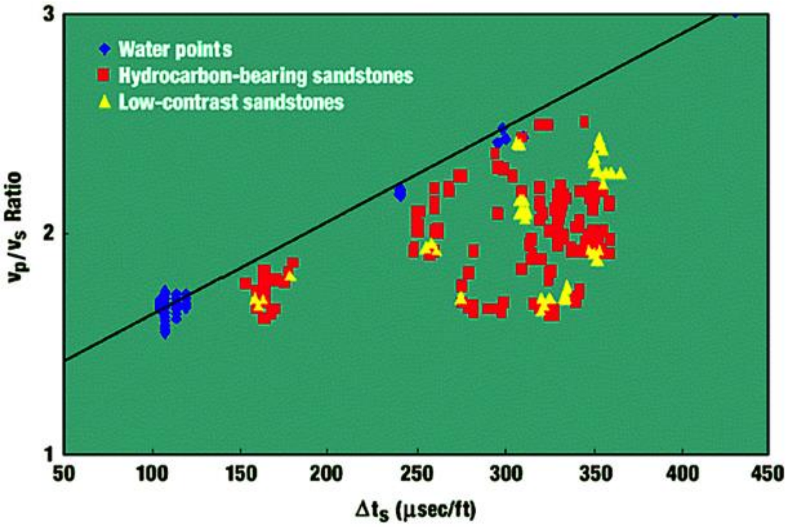

Figure 17. Cross-plot of shear slowness vs. V_p/V_s serves as a quick-look hydrocarbon indicator. Adopted from http://petrowiki.org/Fluid_identification_and_characterization- identified as a Baker Atlas figure.

__Acoustic-derived Permeability__: It has been reported that the velocity (travel time) and attenuation (central frequency shift) of Stoneley wave are sensitive to formation and fracture permeability, particularly at low frequencies [Paillet and Cheng 1991]. By comparing acoustic log data and synthetic modeling, Stoneley permeability is determined by calculating its travel-time delay and frequency shift. Stoneley-wave velocity decreases, and its attenuation increases, as permeability increases. Stoneley-wave reflection, together with an increase in compressional slowness or a decrease in the V_p/V_s ratio, can identify a gas-bearing zone [Tang and Patterson 2001].

Figure 18 shows that the permeability measured by Stoneley wave compares well with the measurements of core analysis and NMR logs (3rd track) [Geerits *et al* 1999; also, see Tang *et al* 1998]. In the presence of gas, Stoneley permeability may be overestimated because of decreased fluid viscosity and compressibility, and NMR permeability may be underestimated because of a decreased hydrogen index. They would be complementary to each other because of the nature of their response behavior, i.e. Stoneley wave measures total permeability and NMR measures vuggy permeability. The combination of these two techniques would improve the capability of acoustic gas detection and identification.

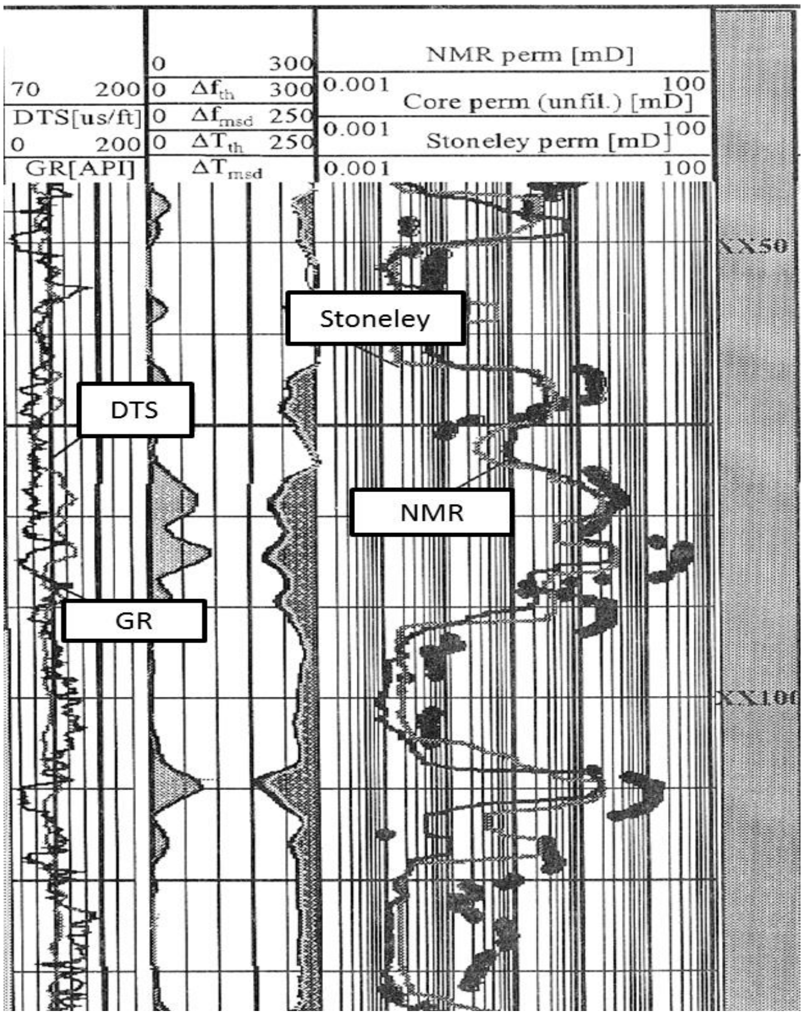

Figure 18. Cross-plot of NMR-, core-, and Stoneley-permeability [Adapted from Geerits *et al* 1999]

VIII-D. Tested NMR

Fluid Typing

Historically, detecting fluid types has involved using standard logs, GR to delineate sand vs. shale, neutron/density cross plot to delineate liquid vs. gas, and resistivity to differentiate water vs. hydrocarbon. In more complex reservoirs where subtle changes in fluid types may occur, such as those with thin beds, and variations in (dissolved) gas to oil ratio in the liquid, oil density, or water saturation, these techniques often are inconclusive, and formation pressure tester tool is used to measure the pressure gradient and take fluid samples to delineate fluid types. However, in some cases the latter techniques can be unusable or the pressure gradient method may result in an erroneous conclusion. NMR fluid typing has proved invaluable as illustrated by the next two examples.

Gulf of Mexico:
This example is from a paper by Akkurt et al (1997) that reports on the analysis of a deep-water turbidite field in the Gulf of Mexico, where the main pay horizon is a highly laminated formation, a very shaly sand zone where hydrocarbon fluid typing using conventional logging techniques was problematic due to presence of shale laminae. Resistivity- based water saturation models failed due to the highly laminated nature of the formation while the density/neutron separation technique to locate gas would not work in a gas-bearing high-shale reservoirs, as noted elsewhere in the present report. The authors note that pressure gradient techniques, which are primarily used, though applicable in this field, was not utilized due to operational constraints. The authors employed a time-domain analysis of NMR data acquired using dual wait times. NMR is unaffected by shale and gave a clear determination of fluid contacts and establish hydrocarbon fluid types in the three-well field development program.

Nigeria:
This example is taken from a paper by Spears and Saha (2005). Here the formation was complex with gas, oil, and water present, unexpectedly, within different portions of the reservoirs. It was found that, often, conventional logs were inconclusive and needed corroboration, the pressure gradient method-based conclusions were erroneous, and down-hole fluid sampling was problematic for a variety of reasons. The NMR-based diffusion-T_2 (D-T_2) cross-plot technique clearly established the fluid types. We illustrate this citing two case studies reported by Spears and Saha (2005). Conventional logs were acquired in the logging-while-drilling (LWD) mode and the NMR tool was then inserted to make stationary[28] measurements in the wireline mode in zones where conventional data appeared problematic.

Case Study 1**. Figure 19** displays the conventional logs and the NMR D-T_2 cross-plot image from NMR data acquired in the sand (low GR in Track 1) zone marked A. Note that the low resistivity (Track 5) indicates the sand zone to be water-bearing. The neutron-density (Track 4) was ambiguous. The pressure gradient technique had definitively concluded that the zone was oil-bearing. However, the D-T2 cross-plot interpreted the zone to be water-bearing corroborating the resistivity. Fluid sampling that followed definitively established this zone to be water-bearing.

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[28] Newer NMR tools are run continuously but at a significantly lower speed than conventional wireline tools. However, now LWD NMR tools have been developed.

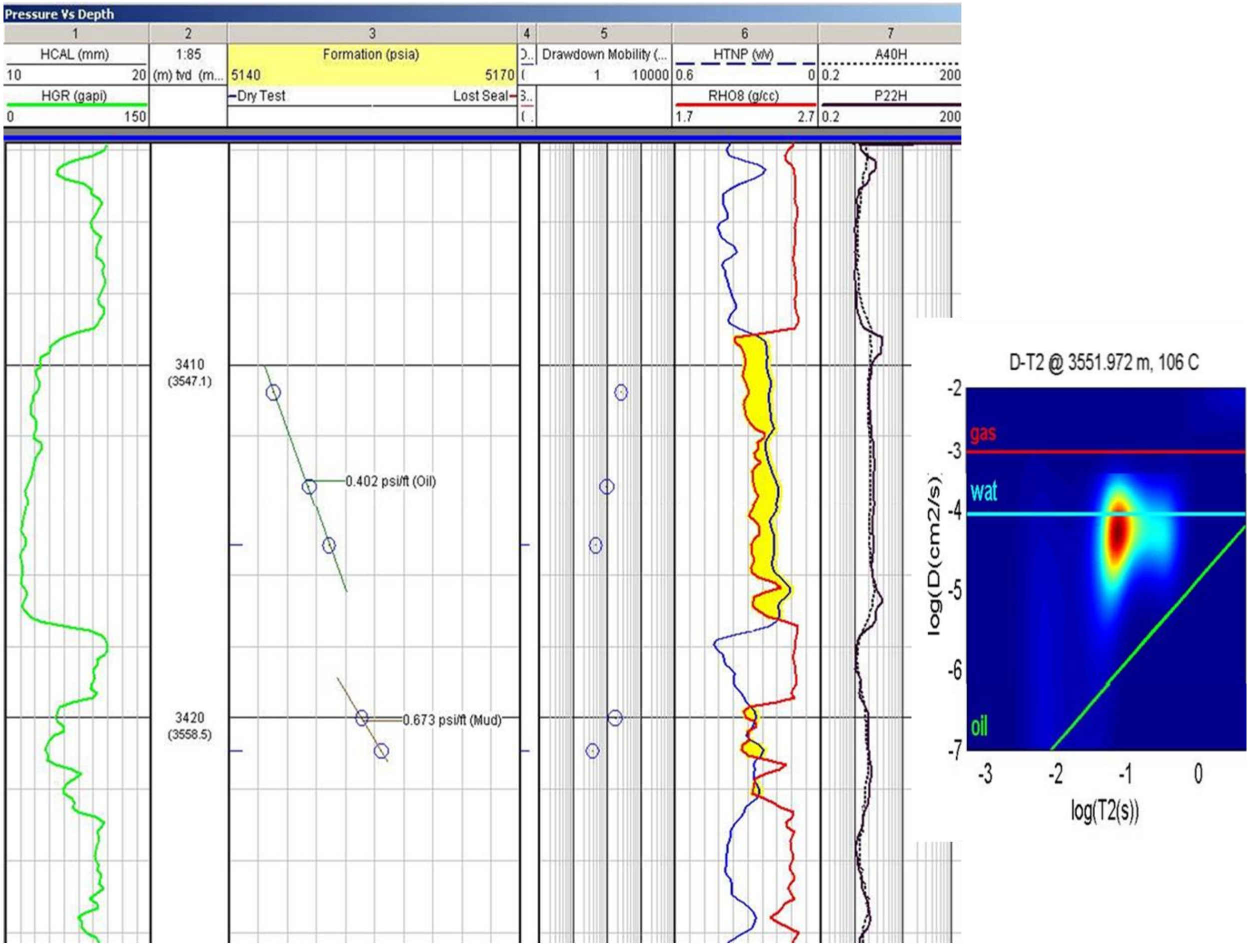

Figure 19. Case Study 1 of Spears and Saha (2005). Log traces from left to right are GR, formation pressure and gradient, mobility, neutron-density, and resistivity. Green arrow indicates the depth at which stationary NMR data was acquired. NMR D-T_2 map is on the right.

Case Study 2*:* **Figure 20** displays the conventional logs where neutron-density separation and crossover had identified the fluid types to be dry gas, and possibly oil mixed with gas but with a low degree of confidence. Pressure gradient tests had indicated the sand contained dry gas. NMR D-T_2 image indicates that the fluid type is more complex. The NMR station data at 3999m (top lobe) is clearly gas as the neutron-density would also conclude. Fluid sampling corroborated this. The two NMR stations at 4010m and 4013m indicate that the fluid is oil with a high GOR (i.e., high fraction of dissolved gas) firming up the somewhat weaker neutron-density conclusion.

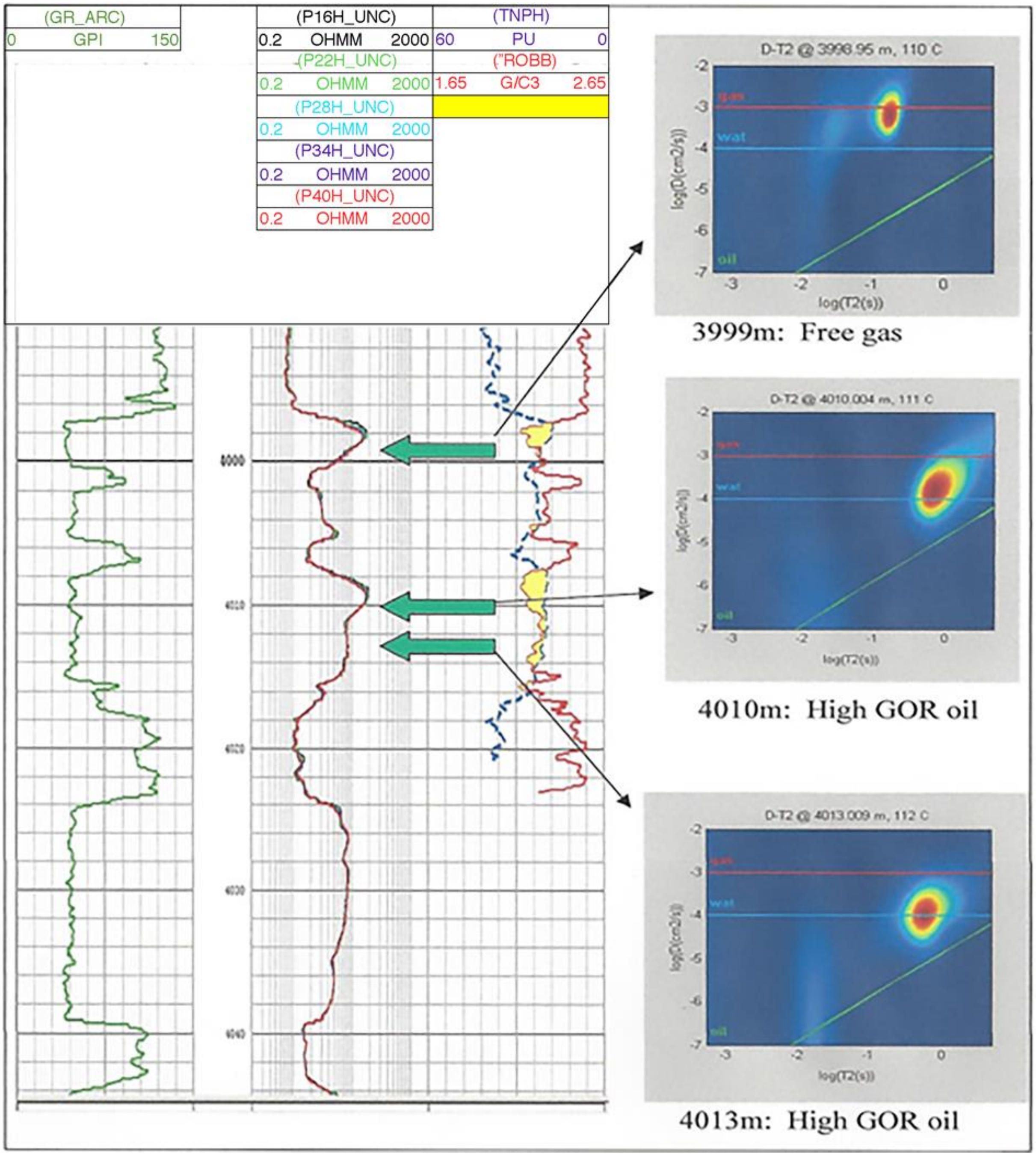

Figure 20. Case Study 2 of Spears and Saha (2005). Conventional triple-combo LWD log- traces from left to right are GR, resistivity, and neutron-density, respectively. Green arrows indicate the depths at which stationary NMR data were acquired. NMR D-T_2 maps are on the right. Resolution of track legends enhanced for clarity.

The authors urged caution that in the pressure-temperature domain of phase change where the variation between volatile oil and gas condensate can be subtle, NMR data may not be able to sufficiently resolve the difference between high GOR oil vs. gas condensate, as would be the case with neutron-density. However, NMR data in their tests had clearly established the presence or absence of dry gas.

NMR Porosity

It is noted in **Appendix A** and in the body of the report that in computing the porosity from the bulk density from the ^{137}Cs tool, the matrix density will be an input paramter. On the otherhand, NMR porosity is generally lithology-independent in the traditional sense and thus one will be able to determine the porosity without the matrix information. This is illustrated by **Figure 21** that compares NMR porosity and density porosity with the correct matrix input [Freedman 2006]. NMR porosity, as expected, was insensitive to matrix properties. This would offer a particular advantage in formations with mixed lithologies.[29]

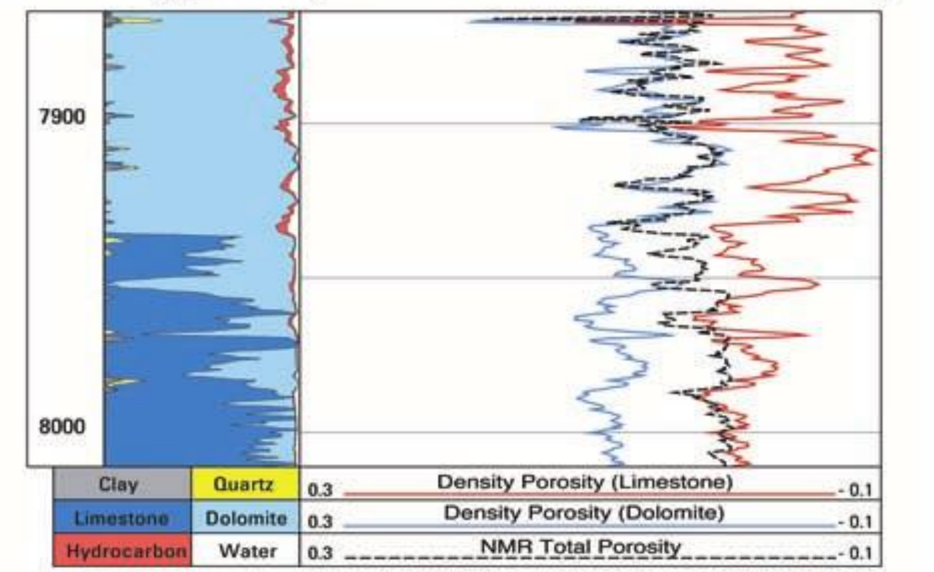

Figure 21. Lithology-independent NMR Total Porosity [Freedman 2006]

NMR Permeability

Although we previously indicated that a permeability indication may be obtained using acoustic logs, in general permeability cannot be determined using standard logging techniques. Traditionally, permeability is determined using core data. In many formations, one then may be able to construct porosity-permeability transforms for the formation. On the other hand, we note in **Appendix A** that NMR data can be used to estimate permeability and cite two empirical relations used in the industry to estimate the permeability using NMR. These depend on porosity. **Figure 22** below adopted from Luthi (2001) shows that NMR permeability was in excellent agreement with core-derived permeability (black circles).

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[29] This example is not intended to suggest that lithological information is not important but demonstrate that NMR can offer an advantage in determining porosity without having to know matrix properties. Lithological information is important on its own right such in making well placement, completion, and later in production decisions.

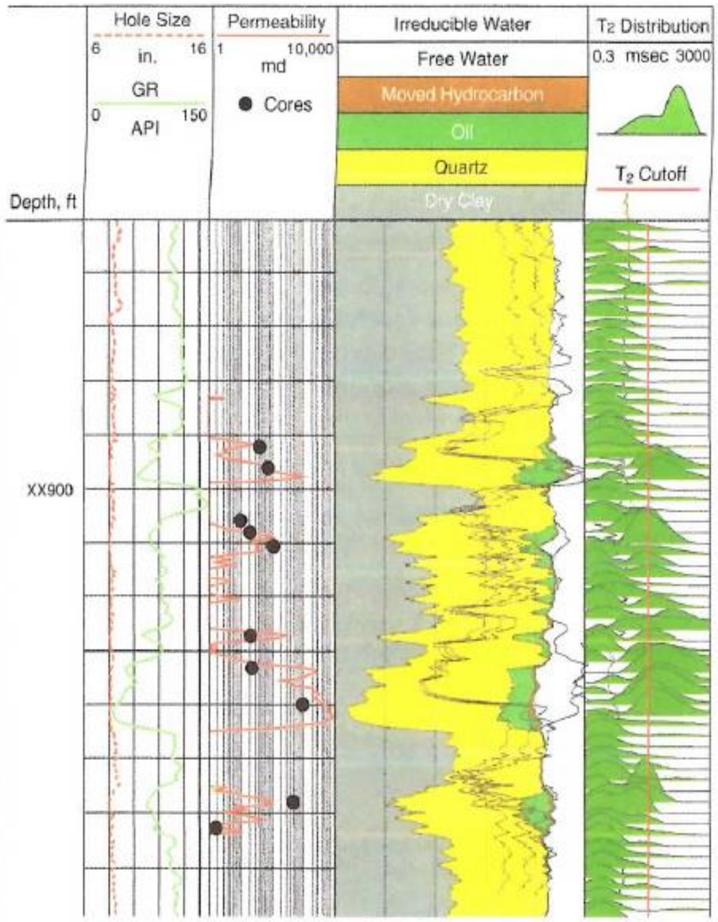

Figure 22. NMR-estimated vs. Core-derived permeability [Luthi 2001]

Effect of Paramagnetic Materials on NMR logs

We noted the value NMR logs add in obtaining petrophysical parameters where conventional logs either are not applicable or inconclusive. However, as we discuss in **Appendix A**, the physics-to-geological interpretation of NMR depends on properties of liquids and rocks in the formation, as with the other physics-based techniques discussed in the report, and the effect can be detrimental to the results expected; this must be understood to improve the quality of the answers. For NMR, as noted later in this Section and in **Appendix A**, presence of paramagnetic materials can have such an effect on T2.

Rueslatten *et al* (1998) studied this in a North Sea oil-sand reservoir with porosities ranging from 25 pu to 35 pu where standard NMR techniques are expected to do well. However, they found that presence of high contents of paramagnetic glauconite and chlorite had a significant adverse effect on the NMR-predicted parameters including porosity; the porosity-permeability correlation was poor. The error in porosity would arise from an inappropriate T2 cutoff. They performed a detailed study using NMR log data, special core analysis using x-ray diffraction (XRD), and laboratory NMR measurements to understand effects on estimated porosity, irreducible water saturation, permeability, etc. Core analysis indicated that the glauconite and chlorite contents varied and it is the chlorite-rich zones that had the most adverse effect.

Figure 23 displays the glauconite and chlorite percentages difference between NMR T2-derived porosity and core porosity**.** From the figure the authors noted that the porosity difference had no correlation with the glauconite content and but had a broad correlation with chlorite content; the maximum porosity error was 7.5 pu. In view of the 4th power of porosity in the permeability relations cited in **Appendix A**, this error would have a significant impact. For log data, authors ended up using the density porosity in permeability equations.

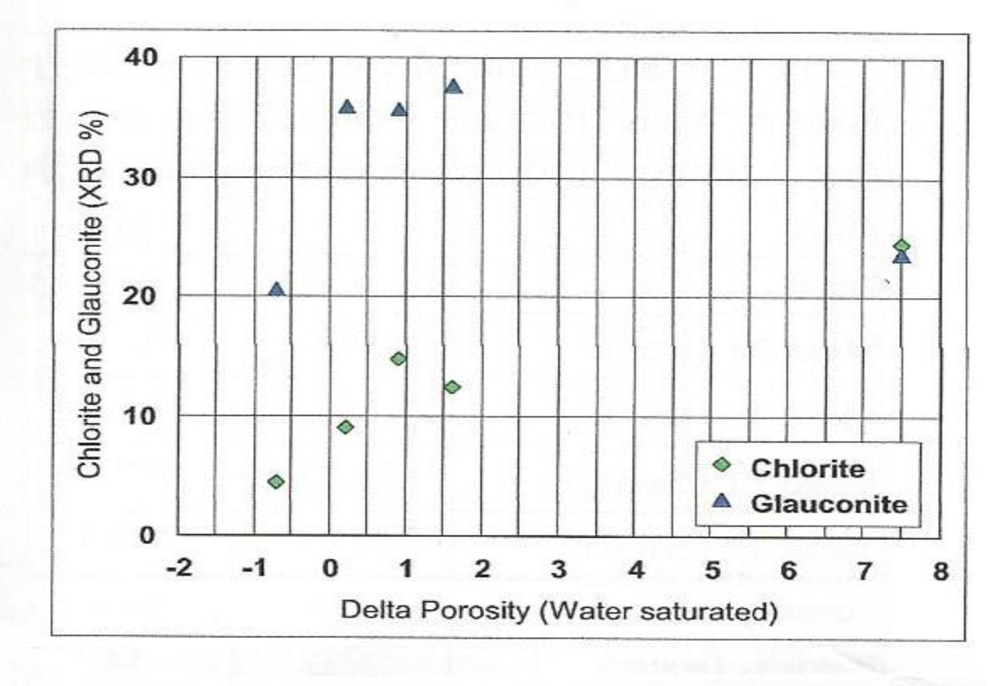

Figure 23. Chlorite and glauconite content vs. difference between NMR porosity and core porosity [Rueslatten *et al* 1998]

From further examination of core and lab NMR data, the authors recognized that fine-grained chlorite was affecting a much larger surface area inducing magnetic gradients on the pore level, thereby shortening the T2 relaxation times. The sand-grain sized glauconite, on the other hand, affects a much smaller surface area and thus does not affect the T2 relaxation significantly. However, this led to an interesting situation. The SWirr, the irreducible water saturation, needed a higher T2 cutoff vs. that for chlorite since both glauconite and chlorite affect it. Only chlorite affects the permeability.

IX. Untested Promising Alternatives

IX-A. Nuclear-based Proposed Techniques

D-D and T-T generators*:* Los Alamos studied a variety of neutron generator concepts [Dale 2013]. Among these were the D-D generator that produces 2.45 MeV neutrons and the T-T generator that produces a neutron spectrum similar to that from a ^{241}Am-Be source. **Figure 24** displays these against ^{241}Am-Be, ^{252}Cf, and D-T neutron distribution**.**

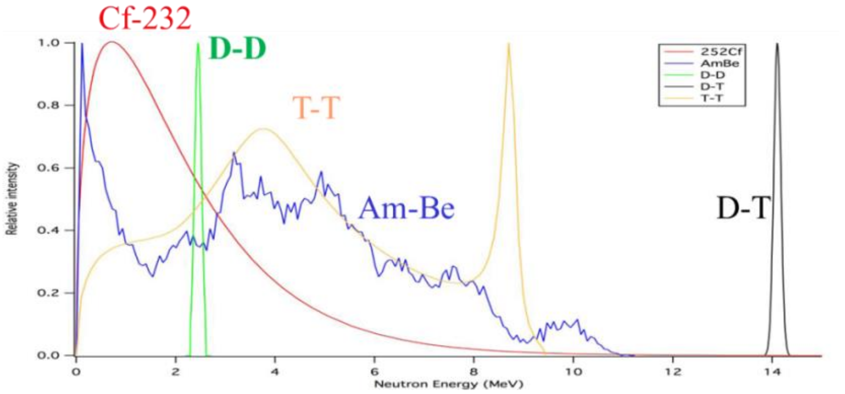

Figure 24. Neutron source spectra from D-D and T-T generators vs. spectra from ^{241}Am-Be, ^{252}Cf-152 and D-T sources (Data Courtesy of Dr. Jim Rutledge, LANL, presented at a Teleconference with oil industry, May 2011; Also reported in Dale 2013)

Simulations of porosity sensitivity of a conceptual borehole tool were performed using the Los Alamos Monte Carlo code MCNP and the following conclusions were reached:

D-D generator: Since the energy (2.45 MeV) of emitted neutrons from a D-D generator is lower than the average energy of ^{241}Am-Be neutrons, and much lower than the energy of the D-T neutrons, a tool with a D-D source would result in a porosity sensitivity that is greater than with ^{241}Am-Be sources and significantly greater than from a D-T generator tool. This was verified by MCNP simulation studies by Rutledge (2011) and Chen *et al* (2012).

T-T generator: Since the neutron spectrum from the T-T generator is similar to that of the ^{241}Am-Be source, the porosity sensitivity would be similar as verified by Rutledge (2011).

Despite their advantageous porosity sensitivity, these sources in their current state are unlikely to be replacement for ^{241} Am-Be as illustrated in **Table 4**.

Table 4. Neutron Spectra and Yields
(Courtesy of Dr. Jim Rutledge, LANL, presented at a Teleconference with oil industry, May 2011)

Neutron Source	Nominal Yield	Yield
Am-Be	3x10^{6} n/s/Ci	1.87 x10^{7} n/s
Cf-252	1.87 x10^{7} n/s	6.7x10^{7} n/s
D-T	4x10^{11} n/s/mA	1x10^{8} n/s
D-D	4x10^{9} n/s/mA	1x10^{6} n/s
T-T	8x10^{9} n/s/mA	2x10^{6} n/s

The data in **Table 4** indicate that both D-D and T-T generators yield about 50-fold fewer neutrons/second. This would make the logging speed unacceptably slow. Research is underway to increase the neutron yield. However, the 2.45 MeV D-D neutrons will make production of 4.44 MeV carbon inelastic gamma rays, and hence identification of Carbon, impossible. Quantifying Carbon and delineating organic vs. inorganic Carbon is critically important, especially in unconventional reservoirs. A T-T generator could add even more tritium to the system than a D-T generator logging tool would likely add. Tritium is radioactive and thus, in principle, would defeat the objective of eliminating radionuclide sources.

The neutron yield from ^{252}Cf source would be acceptable. However, it is still a radionuclide source. In addition, it has several other limitations. Due to its short half-life (2.65 years vs. 432 years for ^{241}Am), the initial radioactivity would be higher than nominal to allow operation for an acceptable time frame, the tool will have to recalibrated often, the source will have to be replaced more often, and there will be more sources to be replaced in the same period of time.

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α-Be DPF generator: The dense plasma focus (DPF) is a compact accelerator that has been demonstrated to accelerate ions to multiple MeV while only requiring a few kV of voltage [Schmidt *et al,* 2012]. A team at Lawrence Livermore National Laboratory (LLNL) is currently evaluating the feasibility of using this device to accelerate alpha particles (helium) into a beryllium target, effectively mimicking the ^{241}Am-Be neutron spectrum. The DPF alpha particle spectrum is not mono-energetic so it does not exactly reproduce the Am-Be neutron spectrum. However, due to the high Q of the α-Be reaction, the energy spectrum is not highly dependent on incident energy. Thus, from modeling studies, the DPF-generated neutron spectrum is predicted to be quite similar to that of ^{241}Am-Be as shown in **Figure 25**.

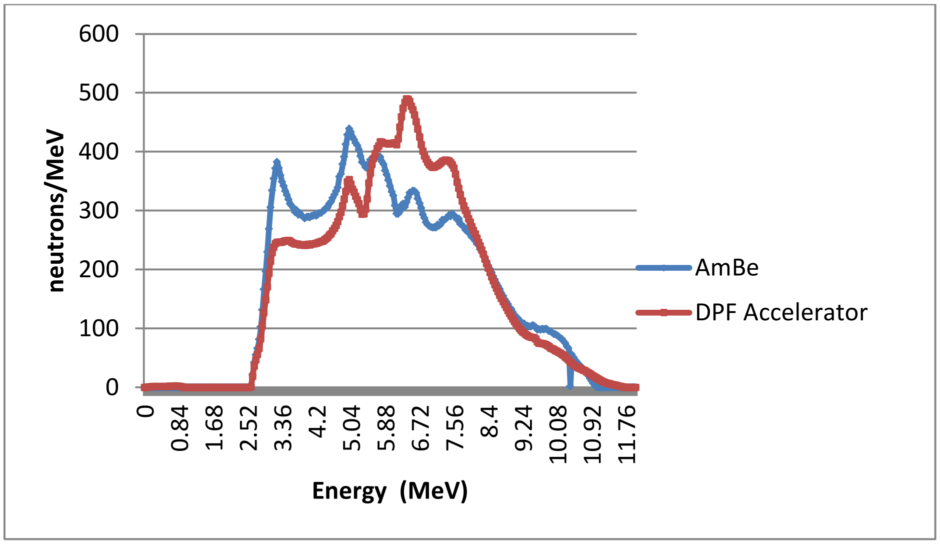

Figure 25. ^{241}Am-Be Vs. Dense Plasma Focus Accelerator Neutron Spectra from Theory [Schmidt *et al* 2012]

Figure 26 compares porosity response using a DPF, D-D, and D-T generator obtained using the Monte Carlo code MCNP. Not surprisingly, the expected response vs. porosity obtained with the DPF source shows a porosity sensitivity that is almost identical to that with an Am-Be source. Kinematic modeling indicates that the neutron yield would be a bit lower than ^{241}Am-Be but of the same order of magnitude. Thus, in principle, the DPF generator can be an ^{241}Am-Be replacement provided it can survive the harsh logging environment noted elsewhere in the report and can provide a sufficient neutron yield.[30]

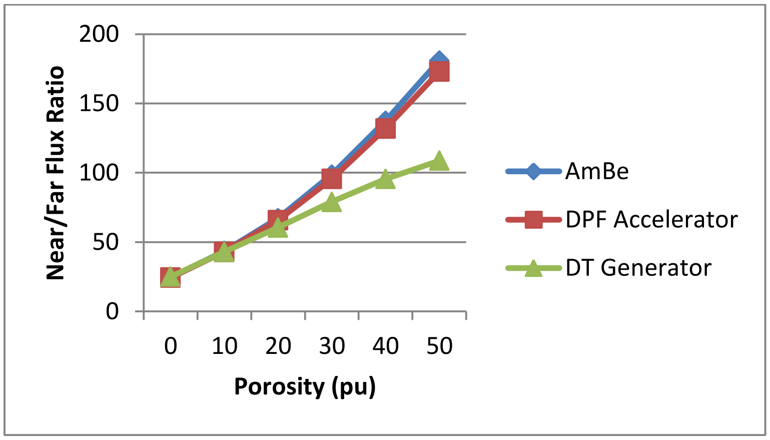

Figure 26. Porosity Sensitivity in Spherical Formation Model. Near and Far locations are a 10 inches and 22 inches respectively [Badruzzaman, to be published]

Other neutron generators: There are several low cross section and thus low-yield neutron generator concepts that have been considered. For example, there is currently an SBIR project underway to study design ideas using the D-^{7}Li nuclear reaction. **Figure 27** displays the spectrum.

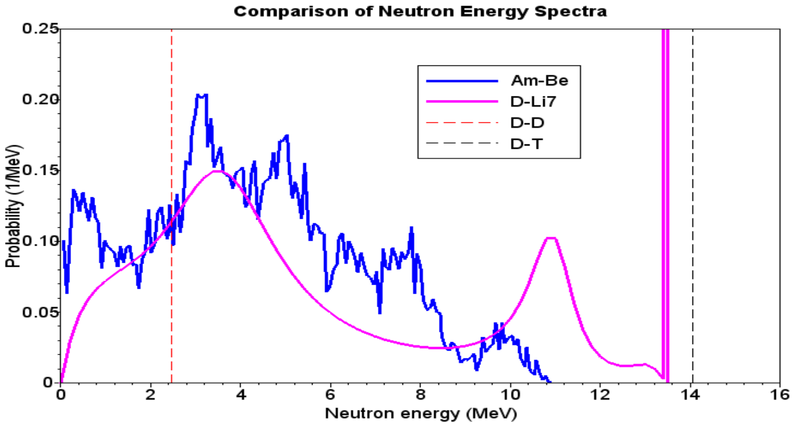

Figure 27. Neutron spectrum from ^{7}Li(d,n)^{9}Be, D-D, D-T, and ^{241}Am-Be.
[Plot Courtesy of Matt Coventry of Starfire Industries using available data, Aug 30, 2015]
The data for D-D and D-T reactions is from Bosch & Hale, Nucl. Fusion **v32** (1992) p611-631.

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[30] DPF accelerator has generated some interest among small service companies, provided it becomes application ready at a reasonable cost. They do not need NMR, use acoustic on a limited basis, and have no love for D-T for porosity since its porosity response needs adjusting and they have no technical capability to do that, They think they do not need mineralogy in the simple geology they operate in. So anything that looks close to ^{241}Am-Be will be very welcome. Of course, it needs to work in real world. They operate onshore and do not do LWD and thus do not have the extreme conditions. This is a part of the Industry Landscape discussion noted in the report.

The similarity of the D-^{7}Li spectra to the Am-Be spectra indicates that porosity response of a tool with this source is expected to be similar to that from and thus offer an advantage over D-T. This was verified via Monte Carlo simulation of porosity sensitivity (not reported here) using MCNP on a simple formation model. In addition to the advantage in computing the porosity, the 13.3 MeV line would allow generation of inelastic gamma rays from reactions of high energy neutrons as do neutrons from a D-T source, but without Tritium. This will, in principle, allow inelastic- and capture-based mineralogy similar to those from recently-developed D-T-based spectroscopy tool. On the other hand, the D-^{7}Li concept faces several technical obstacles. One of them would be the low neutron yield in view of the low cross-sections, illustrated in the following table.

Table 5. Reaction cross sections vs. voltage from various neutron generators.
(Ion *Beam Handbook for Material Analysis*, Editors: J.W. Mayer and E. Rimini,
Academic Press, Inc., New York, NY, 1977.)

Energy (keV)	**^{7}Li(d,n)^{9}Be** (mb)	**D-D** (mb)	**D-T** (mb)
100	0.5	18	3000
200	15	40	4000
300	50	50	2500
600	500	80	750

Note that at 100 keV the D-^{7}Li reaction will have about four orders of magnitude lower cross section relative to D-T. The D-D will be about 166-fold lower. Even at 200 keV, the D-^{7}Li cross section is over two orders of magnitude lower, and D-D will be an order of magnitude lower. At significantly higher voltage where the D-T performance is noticeable degraded, the D-^{7}Li cross would appear comparable. Thus, the neutron yield and hence the logging speed using a D-^{7}Li reaction neutron source will unlikely be acceptable.[31]

It should also be noted that lithium is a difficult target material since it is “soft” and has a low melting point. As a result, one must generally use a lithium compound which will further reduce the yield. The D-^{7}Li reaction simultaneously produces 12, 14, 15, and 17 MeV gamma-rays which may or may not be a problem for neutron logging, but may raise issues with gamma or X-ray based density logging.

Power Requirement

Table 6 below displays the beam power that would be required for D-D, D-T, T-T and D-^{7}Li neutron generators to produce 2x10^7 neutrons/second which would approximate the neutron yield from an ^{241}Am-Be well logging source.

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[31] The values in the table above are point cross sections. The actual neutron producing cross section must take into account the integral of the cross section curve since the incoming ions slowdown in the target. While the point cross-section for D-D is 166x less than D-T at 100kV, the actual integrated cross section would make D-D about 100x less than D-T.

Table 6. Beam Power Needed by D-T, D-D, T-T and D-^{7}Li neutron generators to Produce 2 x10^7 n/s[32]

Incident Particle Energy (keV)	**Beam Power (W) Needed to Produce 2 x 10^7 n/s**			
	D-T	D-D	T-T	D-^{7}Li
100	0.03	8	5	1
150	0.02	5	3	1
200	0.02	4	2	1

It is clear that other generators would require significantly higher power than a D-T generator to produce the same neutron yield as that from an ^{241}Am-Be logging source.

A Comment on Detection Calorimetry

Several of the proposed radiation generator concepts have very low yield. One concept some have suggested is to pulse the source. When one of the designer's nuclear expert was queried if the idea would work in logging tools, he noted that the concept may cause issues as quoted below [Stoller 2015]:

"1. For the proposed pulsed sources it is unlikely to see a duty factor >0.1%.
2. If you are counting pulses at an average of 50 kHz in a density tool with a radioisotope source (i.e. 100% duty cycle) and you provide the same average number of gamma rays with a pulsed source with a duty cycle of (optimistically) 1%, your instantaneous count rate has just gone up by a factor 100. Your counting electronics will not be able to count individual pulses or barely. One needs to resort (as it was done 30 years ago) to total charge measurements and give up on spectroscopy and traditional PE. (see e.g. US9008969[33])
3. For a thermal neutron measurement the problem is similar. The thermalization and diffusion will spread out the pulse but at early times after the burst a neutron measurement may need to rely on a total current measurement. This should work but changes the tool and detector (or at least detector electronics) design. Capture spectroscopy (like ECS) will not be possible given the excessive count rates. (Note that Litho Scanner[34] runs at about 2.5 MHz during the burst with a duty cycle of about 20% using a very fast scintillator, NaI is 10 times slower).

I am not saying it is impossible to use pulsed sources, but any program looking at pulsed sources needs to consider detection (calorimetry) as well."

X. Non-technical Roadblocks

In **Section V** we noted the diversity and complexity of the petroleum industry landscape. These include, size of various players, business drivers, international vs. domestic presence, technology needs, financial resources, and

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[32] D-T, and D-D yields derived from Shope, L. A., "Theoretical Thick Target Yields for the D-D, D-T, and T-D Nuclear Reactions Using the Metal Occluders Ti and Er and Energies up to 300 keV," Report SC-TM-66-247, Sandia National Laboratories, Albuquerque, N.M. (1966). T-T yields are derived from the same reference and Stefano Atzeni and Jurgen Meyer-ter-Vehn, The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter, Oxford University Press, USA, 2004. D-7Li yields derived from Chichester, D.L., "Production and Applications of Neutrons Using Particle Accelerators", Idaho National Laboratory Report INL/EXT-09-17312, November, 2009.

[33] Stoller C and Phillip OG, 2015, Pulsed x-ray signal processing, US patent 9008969.

[34] This is their D-T generator based n-gamma spectroscopy tool [Radtke et al 2012].

internal R&D capabilities. The industry landscape in the US is particularly complex with a mix of small oil companies operating in simpler conditions and major oil companies operating off-shore or in unconventional reservoirs. As we noted in **Section V**, nearly 70% of the logging service is provided by small independents that get their technology from third-party suppliers. They have limited financial resources and no R&D capability. These will be major non-technical road-blocks against consideration of alternatives by a large segment of the domestic petroleum industry. These entities will need financial and R&D support.

In fact, cost of service using new and complex technologies such generator-based nuclear tools or NMR will be high for all, especially if these techniques do not perform as well as radionuclide tools. The current industry downturn, worst in nearly three decades, has resulted in, thousands of layoffs and cancellation of large projects, such those offshore or in the Arctic, by some major oil companies.

At this point all proposed alternatives need further development to be of replacement quality. These and non-technical roadblocks noted above call for a collaborative approach to engage key players from the industry to develop a roadmap. In the next section we identify technology development needs that will have to be sorted before such a roadmap can be developed.

XI. Advanced Technology R&D Requirements

XI-A **<u>General</u>**: The study shows that all alternative techniques or proposed technologies would need enhancements in hardware, simulation techniques and processing software. In addition, a systematic assessment of existing data can help identify areas of further research. We discuss requirements in these areas for each alternative technology.

XI-B. <u>Alternative Nuclear</u>

- A systematic assessment of existing field data from proposed alternatives to identify improvement needs.
- Continued assessment of tested alternative technologies to overcome or significantly reduce their identified shortcomings.
- A systematic assessment of untested but promising alternatives identified in the report
- The above will entail the exploration of following hardware and software technologies.
    - Direct photon generators, with sufficient photon yield, that will survive the harsh logging conditions, with a long operating life and low failure rate.
    - Longer operating and low failure rate neutron generators with sufficient neutron yield that will survive harsh logging conditions.
    - Robust scintillators that can sufficiently resolve the photon spectra.
    - A neutron detector that can provide direct neutron spectrum measurement. Currently, He-3 used in neutron porosity tools either measures the total counts or the epithermal counts by filtering out the thermal counts. (n,ɣ) reactions provide an indirect indication of the spectral effect but in complex borehole conditions, the neutron effect and the derivative photon effect may not be identical in complex boreholes [Badruzzaman *et al* 2007].
    - Advances in current tool response simulation codes to compute the detector response for the variety logging tool detectors being developed and to simulate (n,ɣ) spectroscopy adequately.
    - Advanced processing and filtering techniques for the spectral data that can be noisy.

  - Use of modern data-mining techniques to extract additional information and that too at various depths-of-investigation.

XI-C. Acoustic

Near-term R&D Areas

- Continuing developments in tool hardware, including acoustic sources (monopole, dipole, and quadrupole), data acquisition (DAQ) system, and signal processing, to enhance signal-to-noise ratio (SNR) and penetration depth;
- Conducting a comprehensive literature search on types of acoustic/ultrasonic waves propagating in various borehole and formation conditions to gain a more comprehensive understanding of acoustic propagation in well logging in order to design an acoustic tool that provides a better waveform quality and reduces the complexity of sonic logging;
- Continuing developments in interpretation techniques to expand the utility of these logs in formation evaluation and completion (fracture) design and evaluation;
- Improve acoustic tools for gas-filled shaly, low porosity formation “unconventional reservoirs”; and
- Use of tool/technique combinations (such as acoustics with NMR) to increase accuracy and capability, minimize logging trips, and thus preserve maximum borehole stability.

Advanced Acoustic Tool Requirements

- High-temperature (>320°C) acoustic sources with high power output (>10 MPa acoustic pressure) to produce high-fidelity wideband waveforms and dispersion curves.
- Multiple transmitter and receiver array to provide axial, azimuthal, and radial information
- Accurate data correlation with the formation so that interpretation would be less dependent on previously acquired formation information prior to data analysis for LWD or MWD applications
- Faster logging speed (>3,500 ft/h): Conventional acoustic logs use monopole source and only measure slowness of P-wave. Modern full waveform acoustic logs (FWAL) use new dipole or quadrupole sources and are capable of providing information, including P-, S-, and Stoneley waves, which can be transformed to additional seismic and lithologic properties of a formation. Typical logging speed of a borehole compensated (BHC) tool is 5,000 ft/h. Currently, the logging speed of the state-of-the-art FWAL is about 1,800 ft/hr, i.e. ~1/3 of the speed of BHC.
- More predictable and less complex acoustics.
- Enhanced measurements and characterization of cased bore-wall logging
- Higher imaging resolution for near-wall evaluation and NDE of wall/case
- Extremely rugged electronic package for harsh well logging environment, such as high pressure, high temperature, high flow rate, and muddy formation.
- Automated acoustic logging system and simplified data interpretation for a more user friendly acoustic logging tool

XI-D NMR

Near-term R&D Areas

- Improved signal processing and optimization techniques for inversion.
- Differential spectral algorithm for higher resolution distributions on T2.
- Theoretical analysis of frequency dependency for SNR and depth of penetration.
- Similar to acoustics: continuing developments in interpretation techniques to expand the utility of these logs in formation evaluation and completion (fracture) design and evaluation;
- Improve customization of NMR for challenging areas such as carbonate formations.
- Use of tool/technique combinations (such as acoustics with NMR) to increase accuracy and capability, minimize logging trips, and thus preserve maximum borehole stability.

Advanced NMR Tool Requirements

- Higher frequency NMR for better SNR through focusing and greater depth of investigation.
- NMR receiver components with higher sensitivity and better filtering and adaptive signal processing for removal of ringing.
- Multiple transmitter and receiver array to provide multi-static high-resolution and improved SNR measurements.
- Automated optimization of polarization and number of echoes for improved relation time constant measurements.
- Improved statistical analysis for threshold determination.
- Faster logging speed (> 2000 ft/h) even for fluid typing.
- Automated NMR logging interpretation software
- Reduced cost of NMR hardware and software.

XII. A Suggested Roadmap

XII-A. General

- Industry and DOE explore a phased, diverse, and collaborative approach to advance technology.
- DOE use a multi-pronged strategy to promote consideration of alternatives. These should include non-technical and technical components, as noted next.
- The government should take a broad synergistic view of source risk mitigation where alternatives would be one component of an approach that would also likely include regulations, enhanced security regimes, tighter international and in-house industry protocols, and source monitoring using tagging methods that are under development. Continuously reassess security profiles in US vs. non-US to finetune the approach.

- Non-technical
    - Pay attention to industry landscape.
    - Use business drivers, technology needs, and potential for additional info with alternatives as incentives for change, not just the issue of security.
    - Organize a working or experts group of key industry players- large and small, third party

  - tool/source vendors, etc., explore ideas in this report and elsewhere to move forward.
  - Explore collaboration with industry. The small players will require funding & R&D support.
  - Continue outreach to with relevant professional societies, such as SPWLA, AESC, and SPE.

- Technical
  - Explore the recommendations on each technology in **Section XI,** with a roadmap identified for each in the following sections.
  - Continue to directly support technology development/ assessment: nuclear, non-nuclear, and combination of approaches.

XII-B. Alternative Nuclear Technology Roadmap

i) Density

For density, two areas need to be further explored:

a. Direct density: Conclusively establish if direct photon generators such as LINAC's, betatron or mon-energetic photon generators would be feasible in a logging tool. In particular, revisit a LINAC X-ray technique that was successfully demonstrated in the 1980's, but not commercialized, to see if its limitations can be overcome. Areas to study would be more compact designs, lower power requirement and tool weight that were challenges for the experimental tool.

b. (n,ɣ) density: Laboratory, theoretical analysis, and some field data have concluded that this technique would not be as accurate as the ^{137}Cs density. However, it will be useful where ^{137}Cs tools are unavailable or in cases where the accuracy requirements are not as stringent, such as in scoping measurements. Perform a systematic study of the available field data in a diverse set of field conditions, in conjunction with tool response simulation, to determine the conditions where the method will offer acceptable answers or where additional developments are needed in the processing algorithms to improve the quality of density prediction.

(ii) Neutron Porosity

There are two options that can be examined here.

a. Tested generators: Since D-T generator-based neutron porosity tools have shown some promise, especially in LWD, but may require more complex design features, examine processing techniques that may allow estimation of the apparent porosity in close proximity to that from Am-Be sources.

b. Untested but promising generators: Examine the potential for improving neutron porosity prediction in low porosity. Continue to study the DPF generator to validate its potential to generate an Am-Be-like spectrum with neutron yields comparable to those from Am-Be sources, while surviving in the harsh logging environment. D-D generators appear attractive if their neutron yields can be increased by at least an order of magnitude. The D-^{7}Li technique will require more effort to overcome its inherent limitations of low cross section and poorer quality target material. Continue to explore other innovative neutron source technologies.

(iii) (n, ɣ) spectroscopy

Industry is migrating to D-T based tools which provide both inelastic and capture spectra to construct the mineralogy. A D-^{7}Li tool with sufficient neutron yield can supply similar data but without tritium. The drawbacks of the technology are due to lower neutron production cross section at lower power and poorer quality target material. If tritium is a major issue, this technique (or other similar technologies) should be further explored.

(iv) Multiple parameter "super" tool

Separate D-T generator tools have been tested to obtain the neutron porosity and determine the mineralogy, while a D-T based LWD tool has demonstrated the feasibility of obtaining simultaneous multiple parameters using a single tool. Whether the latter can be duplicated with a wireline tool where wellbore environment is different, should be examined using tool response simulation. A (D-^{7}Li)-based tool, in principle, will be able to similarly provide multiple parameters and that too without tritium, but its significantly lower generation cross section and poorer target quality will have to be mitigated.

(v) Advanced detection and source technologies

These will be beyond those noted previously.

a. Assess advanced neutron detection technology that can replace He-3 and can possibly supply neutron spectra directly.
b. Assess the tolerances of the advanced photon detector technologies that have been proposed.
c. Industry should continue to follow developments of advanced sources at national labs while the labs should take into account, a priori, issues of appropriateness in logging conditions, if such applications are desired.

(vi) *Advanced tool response simulation techniques*

Enhanced detector response capability and an adequate algorithm to compute elemental yields from (n,ɣ) spectral data from both inelastic and capture reactions need to be included in the public version Los Alamos Monte Carlo code MCNP; the code has become mainstay in full nuclear tool response simulation.

(vii) Advanced processing techniques

We noted that (n,ɣ) spectroscopy to construct mineralogy requires closure relations which are geological location dependent and require normalization to core. Much of the data may have significant uncertainty due to insufficient mineral concentration or overlap of spectral data, for example. More robust error minimization and filtering techniques and use of more sophisticated closure relations are needed.

XII-C. Acoustic Technology Roadmap

Hardware Improvements

Improvements in tool hardware are needed, especially to enhance signal-to-noise ratio (SNR) and penetration depth for both conventional and unconventional multiphase reservoir applications. Some development needs are

- High temperature transducers, and multiple transmitter and receiver array. Transducers to be used for deep sea or geothermal applications may need to be operated above 320°C, compared to 240°C for most onshore oil logging tools.
- Enhance and develop acoustic sources (monopole, dipole, and quadrupole) to generate different acoustic waves in various formations and to deliver higher power for greater penetration and better SNR.
- Development of faster multi-channel data acquisition (DAQ) system for transducer array application and faster logging speed (>3,500 ft/h), especially for LWD and MWD applications. Typical logging speed of a borehole compensated (BHC) tool is 5,000 ft/h, and a neutron log is ~2,000 ft/h. Currently, the logging speed of the state-of-the-art wireline logging is at about 1,800 ft/hr, i.e., ~1/3 of the speed of BHC.
- Development of low noise acoustic waveguide for high-temperature and deep-depth applications, especially acoustic tools for gas-filled shaly, low porosity formation "unconventional reservoirs."
- Developments of LWD, MWD, and LWC (Logging-while-Coring) tools for future logging applications to reduce cost and to assure borehole safety.

Modeling and Signal Processing Developments

Acoustic waveforms are complex but contain information about rock formation that needs a more thorough study. A better understanding of wave propagation would provide better logging accuracy and media identification. Within the full waveform, there are many parameters and factors that can be used. The industry is using mainly just the velocity or slowness. Even velocity calculation needs to be rescaled or correlated for different formations. Developments of modeling algorithms and signal processing techniques are needed for a better understanding of acoustic propagation to achieve real-time automated data interpretation, improvement of empirical relations between field data and model results, and design of new and more powerful acoustic excitation sources. Some development needs are

- Development of higher resolution acoustic imaging techniques to improve reservoir modeling and simulation.
- Establishment of theoretical models for better understanding of acoustic propagation to achieve real-time automated data interpretation.
- Development of 3D anisotropy algorithms to assist waveform analysis and to expand logs data interpretation in formation evaluation.
- Achieving a more comprehensive understanding of propagation of various waves, monopole, dipole, and quadruple, to design an acoustic tool that would produce better waveform quality and reduce the complexity of sonic logging.
- Development of advanced signal processing techniques, such as statistical linear regression model, for better interpretation of formation and fracture evaluation.

Enhanced measurement designs

- *In-situ* well experiments for acoustic modeling and simulation validation and verification (V&V)
- Use of tool/technique combinations (such as acoustics with NMR) by correlating outputs and identifying unique capability of each tool to increase measurement accuracy and prediction capability, minimize logging trips, and thus preserve maximum borehole stability
- Improve acoustic tools for gas-filled shaly, low porosity formation "unconventional reservoirs"; one possible approach is to develop a gas-filled waveguide for better acoustic impedance match.

- Analysis and comparison of information acquired from acoustic tools and other techniques (radiation and none-radiation) through existing published data from industries and/or downhole experiments.

Beside capability and accuracy, the major issues of replacing nuclear logging tools are cost and complexity of acoustic tools. The cost includes cost of equipment, training, and maintenance. The complexity is from the nature of acoustic waveforms, equipment operation, and data interpretation. These might just enough to drive the industry, especially small logging companies, away from using alternative non-radiation logging tools.

XII-D. NMR Roadmap

- Work with industry on real data for improved methods of NMR inversion techniques.
- Analysis and comparison of information acquired from NMR tools and other techniques (radiation, acoustics, and other non-radiation logs) through existing data from industries and/or downhole experiments
- More comprehensive understanding of faster real-time, automated data interpretation technique improvements.
- Development of higher resolution NMR imaging techniques to improve reservoir modeling and simulation
- Approaches to cost reduction.
- Development of 3D NMR imaging to expand logs data interpretation in formation evaluation.
- Use of tool/technique combinations (such as acoustics with NMR) to increase accuracy and capability
- Developments of advanced LWD, MWD, and LWC (Logging-while-Coring) for the future logging applications to reduce cost and to assure borehole safety.
- Continuing developments in tool hardware to enhance signal-to-noise ratio (SNR) and penetration depth
- Improving NMR algorithms for "unconventional reservoirs."
- Use of tool/technique combinations (such as acoustics with NMR) to increase accuracy and capability, minimize logging trips, and thus preserve maximum borehole stability.

Acknowledgement

The Scoping Study Team gratefully acknowledges the feedback and input they received from the following individuals both through the two questionnaires the Study Team had solicited input on and in the form of e-mails, letters, and pointers to published reference material. Most supplied their feedback and input on their own recognizance as designers or expert end-users while a number, as noted, did it on behalf of their organization or company.

A. Questionnaire feedback

Oil companies:

Dale Fitz, Senior Technical Consultant at a major international oil company (IOC)
Shouxiang Ma, Senior Petrophysical Consultant at a major non-US oil company
John Nieto, Executive Vice President, Subsurface, Canbriam Energy, and former Chief Petrophysicists at a major IOC
Anton Nikitin, R&D Petrophysicist at a major IOC and a former designer
Boqin Sun, Senior Consulting Research Scientist at a major IOC and a former designer
Jerome Truax, Petrophysicist, Linn Energy, and a former designer
Brett Wendt, VP Technology, Soc. Petrophysicists & Well Log Analysts and a senior Petrophysics at a major IOC
Adrian Zett, Consulting Petrophysicist at a major IOC

Designers/ Service Companies:

Larry Albert, VP, Allied-Horizontal Wireline Services
Gary Fisher, Division Manager, Pioneer Energy Services
Ron Cherry, Strategic Business Manager, Wireline, Halliburton
Medhat Michael, VP Engineering, Weatherford
Chris Stoller, Scientific Advisor, Schlumberger

B. E-mails, letters, and reference pointers:

Larry Cavanna, Managing Director of a small independent service company
Kenny Jordan, Executive Director, Assoc. Energy Service Companies-AESC
David Kennedy, Outgoing president, SPWLA
Mahendran Relton, VP Engineering, Probe Technologies
Kaveri Ray, Advisor, Deepwater RSC of an integrated service company
Winston Seaman: An AESC member and a petrophysicist formerly at several service and oil companies

The Scoping Study Team thanks Arden Dougan of NNSA for the gentle guidance and the NNSA and the DOE for supporting the work

Nomenclature/Acronyms

AESC: Association of Energy Service Companies
Am-Be: Americium-Beryllium
API: American Petroleum Institute
BGO: Bismuth germinate (Bismuth germanium oxide)
CBL: Cement bond logging
D-D: Deuterium-Deuterium
D-Li7: Deuterium-Lithium7
DOE: Department of Energy
DOI: Depth of investigation
DPF: Dense Plasma Focus
D-T: Deuterium-Tritium
ECS: Elemental captures spectroscopy (tool)
GR: Gamma ray (denotes naturally-occurring gamma rays
GSO: gadolinium orthosilicate
IOC: International oil company
INGD: Inelastic neutron-gamma density; also denoted as sourceless n-gamma density (SNGD) by some.
LS: Long-spaced
LWD: Logging-while-drilling
LWC: Logging-while-coring
NMR: Nuclear magnetic resonance
NNSA: National Nuclear Security Administration
(n,ɣ): Neutron-gamma
pu: Porosity unit
R&D: Research and development
RDD: Radiological dispersal device
ROP: Rate of penetration
SNR: Signal/noise ratio
SP: Spontaneous potential
SPE: Society of Petroleum Engineers
SPWLA: Society of Petrophysicists and Well Log Analysts
SS: Short-spaced
S_w: Water Saturation
TOC: Total organic carbon
T-T: Tritium-Tritium

References

AESC 2015, Letters to Scoping Study Team from Kenneth Jordan, Executive Director of Assoc. of Energy Service Companies, August 31 and from Mahendran Relton, VP of Engineering, Probe Technologies, Fort Worth, TX., July 15, illustrate the concerns.

Aitken JD, Adolph R, Evans M, Wijeyesekera N, McGowan R, Mackay D, 2002, "Radiation Sources in Drilling Tools: Comprehensive Risk Analysis in the Design, Deployment and Operation of LWD Tool, SPE 73896, SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration, Kuala Lumpur, Malaysia, March 20-22.

Akkurt R, Vinegar HJ, Tutunjian PN, and Guillory AJ, 1995, NMR Logging of Natural Gas Reservoirs, paper N, 36th SPWLA Annual Logging Symposium.

Akkurt R, Moore MA, Freeman JJ, 1997, Impact of NMR in the Development of A Deepwater Turbidite Field, in: Proc: SPWLA 38th Annual Logging Symposium, June 15-18.

Akkurt R, Mardon D, Gardner JS., Marschall D, and Solanet F, 1998, Enhanced Diffusion: Expanding the Range of NMR Direct Hydrocarbon-Typing Applications, paper GG, 39th SPWLA Annual Logging Symposium.

Akkurt R, Kersey D, Zainalabedin K, 2009, Towards Everyday-NMR: An Operator's Perspective, *Petrophysics*, **50** (6), p495-510.

Allen D, et al, 1988, Probing for permeability—An introduction of measurements, *The Technical Review*, v. 36, no. 1, p. 6–20.

Archie GE, 1942, The electrical resistivity log as an aid to determining some reservoir characteristics, Pet. Trans, AIME 146: 54-62.

Arns CH, 2004, A comparison of pore size distributions derived by NMR and X-ray-CT techniques. Phys A 339:159–165.

Badruzzaman A, 1991, Computational Methods in Nuclear Geophysics, Prog. in Nuclear Energy, **25**, p265.

Badruzzaman A, 1998, Multidetector Pulsed-Neutron Through tubing Cased-Hole Density Measurement Sonde, U.S. Patent No. 5,825,024, October 20.

Badruzzaman A, 2002, Tutorial on Nuclear Logging – A Subsurface Measurement Technology, Proc. 12th Biennial American Nuclear Society RPSD Topical Meeting, April 15-18, 2002, Santa Fe, NM.

Badruzzaman A, Badruzzaman T, Nguyen PT, and Zalan TA, 2002, Oil Field Applications of Nuclear Modeling, Proc. 12th Biennial American Nuclear Society RPSD Topical Meeting, April 15-18, 2002, Santa Fe, NM.

Badruzzaman A, 2005, Nuclear Logging Technology, Present and Future-An Operating Company Perspective, Petrophysics, **46**, No. 3, 220-236.

Badruzzaman A, Logan JP, Bean C, Adeyemo AO, Zalan TA, Barnes D, Platt C, 2007, "Is Accurate Gas/Steam Determination Behind Pipe Feasible with Pulsed Neutron Measurements?" SPE 110098, in Proc. SPE Asia Pacific Oil & Gas Conf., Jakarta, Indonesia, 30 October – 1 November 1. Society of Petroleum Engineers.

Badruzzaman A, Barnes S, Bair F, and Grice K, 2009, Radioactive Sources in Petroleum Industry: Applications, Concerns and Alternatives, Paper SPE-123593, presented at the SPE Asia Pacific Health, Safety, Security, and Environment Conference and Exhibition, Jakarta, Indonesia, 4-6 August. Society of Petroleum Engineers.

Badruzzaman A, 2014, An Assessment of Fundamentals of Nuclear-based Alternatives to Conventional Chemical Source Bulk Density Measurement, Petrophysics, **55**, 5, 415-434.

Badruzzaman A, 2015, Alternative Nuclear-based Technologies to Mitigate Risks of Radionuclide Well Logging Sources: Their advantages and challenges, a 2014-2015 SPWLA Distinguished Speaker Lecture, Soc. of Petrophysicists and Well Log Analysts, Houston, TX.

Baker Atlas –Petrowiki, 2015, http://petrowiki.org/Porosity_evaluation_with_acoustic_logging

Banavar JR, and Schwartz LM, 1987, Magnetic resonance as a probe of permeability in porous media, Physical Review Letters, v. 58, no. 14, p. 1411–1414.

Bigelow EL, 1990, Cement Evaluation, pp. 1-142. Houston: Atlas Wireline Services.

Biot MA, 1956a, "Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid: I. Low Frequency Range, JASA 28, pp. 68-178.

Biot MA, 1956b, Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid: II. High-Frequency Range, JASA 28, pp. 179-191.

Bond LJ, Denslow KM, Griffin GW, Dale GE, Harris RV, Moran TL, Sheen DM, Schenkel T, 2011, Evaluation of Non-Nuclear Techniques for Well Logging: Technology Evaluation, PNNL-19867, Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830, Pacific Northwest National Laboratory

Brown RJS and Neuman, CH, 1982. The Nuclear Magnetism Log--A Guide For Field Use. The Log Analyst 23 (5): 4. SPWLA-1982-vXXIIIn5a1

Chabot L, et al., 2002, "Single-well Imaging Using Full Waveform Sonic Data," CREWES Research Report, Volume 14.

Chen AX, Antolak AJ, Leung, K-N, 2012, Electronic neutron sources for compensated porosity well logging, Nuclear Instruments and Methods in Physics Research A, 684, 52–56.

Chen AX, Antolak AJ., Leung K-N, Raber TN, and Morse DH, 2013, Pulsed Pyroelectric Crystal-Powered Gamma Source, in Applications of Accelerators in Research and Industry, AIP Conference Proceedings 1525, 720.

Coates GR, Xiao L, Prammer MG, 1999, NMR Logging principles and applications, Halliburton Energy Services, Houston, TX.

Coates R, Kane M, Chang C, Esmersoy C, Fukuhara M, and Yamamoto H, 2000, Single-well sonic imaging: High-definition reservoir cross-sections from horizontal wells, SPE Paper 65457.

Crain ER, 2000, Crain's Petrophysical Handbook, 3rd edition, Rocky Mountain House, AB : Spectrum 2000 Mindware Publisher.

Crain ER, 2004, How Many Acoustic Waves Can Dance On The Head Of A Sonic Log, Canadian Logging Society: pp10-16.

Dale GE, 2013, Piezoelectric Transformer Neutron Generator (PTNG) Neutron Source for Well Logging, LA10-FY10-117-PD13, Final report, Los Alamos National Laboratory

Day SNJ, and Petler JS, 1991, "Tool Motion and Borehole Environment Effects on MWD Neutron Porosity

Measurements," Paper A, SPWLA Annual Symposium.

del Angel JG., Zuniga JA, Martinez M, Gremillion J, Godinez A, Bonnigue P, Barajas CI, and Villanueva H, 2014, "The Use of New Generation of LWD Technology to Efficiently Log and Evaluate The Cretaceous Carbonates of the Ku Maloob Zaap Field in the Gulf of Mexico," SPWL 55th Annual Symposium, Abu Dhabi, UAE, May 18-22. Paper J.

Doveton JH, 1999, Basics of Oil & Gas Log Analysis, Kansas Geological Survey.

Dunn K-J, Bergman DJ, LaTorraca GA, 2002, Nuclear Magnetic Resonance: Petrophysical and logging applications, Pergamon, NY.

Dvorkin J and Nur A, 1998, Time-Average Equation Revisited, Geophysics, **63**(2), pp. 460–464.

Ellis DV, 1987, Well Logging for Earth Scientists, Elsevier, New York, ISBN 0-444-01180-3.

Ellis DV and Singer JM, 2007, Well Logging for Earth Scientists, Second Edition, Springer, Dordrecht, The Netherlands, ISBN 978-4020-3738-2

Evans M, Adolph R, Vilde L, Morris C, Fissler P, Sloan W, Grau J, Lieberman A, Zeigler W, Loomis WA, Yonezawa T, Sugimura Y, Seki H, Misawa RM, Holenka J, Borkowski N, Dasgupta T, Borkowski D, 2000, A sourceless alternative to conventional LWD nuclear logging, SPE 62982, in Proc. SPE Annual Technical Conference and Exhibition, Dallas, TX, 3-4 October.

Fertl WH, 1981, Openhole Crossplot Concepts A Powerful Technique in Well Log Analysis, *J. Pet. Technol.,* **33**(3), pp. 535-549. SPE-8115-PA.

Flanagan WD, Bramblett RL, Galford JE, Hertzog RC, Plasek RE, and Oleson JR, 1991, A New Generation Nuclear Logging System, Paper Y, *Transactions, SPWLA32nd Annual Logging Symposium*, Midland, Texas, USA, 16-19 June.

Foley I, Farooqui SA, Kleinberg RL,1996, Effect of paramagnetic ions on nmr relaxation of fluids at solid surfaces. J Magn Reson, Ser A 123:95–104

Freedman R, 2006, Advances in NMR Logging, Journal of Petroleum Technology, P60, January.

Freedman R and Heaton N, 2004, Fluid Characterization using Nuclear Magnetic Resonance Logging, Petrophysics, Vol 45 No 3, p241-250.

Fricke S, Madio DP, Adolph B, Evans M, Leveridge R, 2008, "Thermal Neutron Porosity using Pulsed Neutron Measurements," in Trans. SPWLA 49th Annual Symposium, Edinburgh, Scotland, May 25-28, Paper L

Galford J et al, 2009 A new neutron-induced gamma ray spectroscopy tool for geochemical logging, Trans. 50th SPWLA Annual Logging Symposium, 21-24 June, The Woodlands, TX. Paper X. Also see SPE 123992, 2008, by the same authors.

Geerits TW et al, 1999, Comparison Between Stoneley, NMR, and Core-Derived Permeabilities, Trans. 40th SPWLA Annual Logging Symposium , Oslo, Norway, May 30-June 3, Paper TT.

Gilchrist WA, Inanc F, Roberts L, 2011, Nuclear Source Replacement- Promises and Pitfalls, Trans. 51st Annual Symposium of the Soc. of Petrophysicists and Well Log Analysts, Colorado Springs, CO, May 14-18. Paper KKK.

Graham WL et al, 1997. Cement Evaluation and Casing Inspection With Advanced Ultrasonic Scanning Methods, *the SPE Annual Technical Conference and Exhibition*, San Antonio, Texas, SPE-38651-MS.

Grau JA, Schweitzer JS, Ellis DV, Herzog RC, 1989, A geological model for gamma-ray spectroscopy logging measurements, Nuclear Geophysics, Vol. 3, no. 4, p 351-359.

Griffin JW, Moran TL, and Bond, LJ, 2010, Radiation Source Replacement Workshop, PNNL-20102, Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830, Pacific Northwest National Laboratory

Hearn G, 2014, Search and Recovery Efforts by the State of Texas to Locate Missing Radioactive Sources, a Presentation at WINS Workshop on Security of Radionuclide Sources Used for Radiography and Well Logging, Paris France, April 9-10.

Hearst JR, Nelson PH, and Paillet FL, 2000, *Acoustic Logging, Well Logging for Physical Properties*, 2nd edition, Chap. 8, pp. 257–303, New York City: Wiley and Sons Inc.

Herron SL and Herron MH, 1996, Quantitative Lithology: An Application for Open- and Cased-hole Spectroscopy, in Trans. SPWLA 37th Annual Logging Symposium, Paper E.

Herron MM, Grau JA, Herron SL, Kleinberg RL, Machlus M, Reeder SL, Vissapargada B, Burnham AK, Day RL, Allix P, 2011, Total Organic Carbon and Formation Evaluation with Wireline Logs in Green River Oil Shale, SPE Paper 147184, IN: Proc. SPE Annual Technical Conference and Exhibition, Denver, CO, 30 October- 2 November.

Hill AD, 1990, Cement-Quality Logging, *Production Logging—Theoretical and Interpretative Elements*, Vol. 14, pp. 123-140, Richardson, Texas: Monograph Series, SPE.

Hurlimann MD, Venkataramanan L, Flaum C, Speier P, Karmonik C, Freedman R, and Heaton N, 2002, Diffusion-Editing: New NMR Measurement of Saturation and Pore Geometry, paper FFF, 43rd SPWLA Annual Logging Symposium.

IAEA, 2002, “Inadequate Control of World’s Radioactive Sources,” IAEA Press Release 2002/09, International Atomic Energy Agency, Vienna, Austria, June 24.

IAEA 2003, Categorization of radioactive sources, IAEA-TECDOC-1344, Revision of IAEA-TECDOC-1191, International Atomic Agency, Vienna, Austria, July.

IAEA, 2012, Radiation Protection and Safety in Well Logging, a draft source handling (unpublished, under review)

Jackson JA, 1984, Nuclear magnetic well logging, The Log Analyst 25 (5), 16-30.

Johnson DE and Pile KE, 2006. *Well Logging in Nontechnical Language, 2nd Ed.*, PennWell Corp., Tulsa, Oklahoma.

Johnson R, 2014, Mobile Source Threat and Vulnerability Environment, a Presentation at WINS Workshop on Security of Radionuclide Sources Used for Radiography and Well Logging, Paris France, April 9-10.

Jordan K and Fisher G, 2014, Wireline Unit Market Survey Results and Possible Impact of Chemical Source Replacement, presentation at the SPWLA Nuclear SIG Technical Meeting, Houston, TX. October 9.

Jutten J and Morriss SL, 1990, Cement Job Evaluation, *Well Cementing*, EB Nelson ed., Ch. 16, Amsterdam: Elsevier, *Developments in Petroleum Science* No. 28.

King III G, Bramblett RL, Becker AJ, Corris GW, and Boyce JR, 1987, “Density Logging Using An Electron Linear Accelerator as the X-Ray Source,” Nuclear Instruments and Methods in Physics Research B24/25, 990-994.

Kleinberg RL, 2001, NMR Logging in Schlumberger. Concepts Magn Reson 13(6) 396-403.

Krief M, et al., 1990, A New Petrophysical Interpretation Using the Velocities of P and S Waves (Full Waveform Sonic). The Log Analyst, 31(6), pp. 355–369.

Lake LW, 2007, Petroleum Engineering Handbook, Volumes I-VII, Society of Petroleum Engineers.

LANL, 2003/2008, MCNP-A General Monte Carlo N-Particle Transport Code, Version 5, LA-UR-03-1987, Los Alamos National Laboratory, Los Alamos, NM. Published on April 24, 2003 and revised February 1, 2008.

LaTorraca GA, Dunn KJ, Bergman DJ, 1995, Magnetic Susceptibility contrast effects on NMR T2 logging, SPWLA 36th Annual Logging Symposium, Paris, June 26-29

Lo S, Hirasaki G, House W, and Kobayashi R, 2002, Mixing rules and correlations of NMR relaxation time with viscosity, diffusivity, and gas/oil ratio of methane/hydrocarbon mixtures: *SPE Journal*, vol. 7, no. 1, p. 24–34.

Luthi SM, 2001, Geological Well Logs, p. 179.

Mavko G, Mukerji T, and Dvorkin J, 1998, The Rock Physics Handbook—Tools for Seismic Analysis in Porous Media, pp. 1-329, Cambridge, England: Cambridge University Press.

Medlin WL and Alhllall KA, 1992, Shear-Wave Porosity Logging in Sands, SPE Form Eval., 7(1), pp. 106-112.

Mills WR, Allen LL, and Stromswold DC, 1988, Pulsed neutron porosity logging based on epithermal neutron die-away, Nuclear Geophysics, vol. 2, no. 2, p. 81–83.

Mishra UC and Pradhan AS, 1997, Proceedings of an International Conference Goiania, Brazil
26-31 October http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/008/30008035.pdf#page=179

National Research Council, 2008, Radiation Source Use and Replacement, National Academy of Sciences, Washington, D.C: https://www.nap.edu/catalog/11976/radiation-source-use-and-replacement-abbreviated-version

Neuman CH, Sullivan MJ, and Belanger DL, 1999, An Investigation of Density Derived from Pulsed Neutron Capture Measurements, SPE 56647, in Proc. of SPE Annual Technical Conference and Exhibition, Houston, TX., 3-6 October.

Nikitin A, 2015, Input through personal communication to A Badruzzaman, July-Sept.

NRC, 1987, 10 CFR Part 39, "LICENSES AND RADIATION SAFETY REQUIREMENTS FOR WELL LOGGING," US Nuclear Regulatory Commission, 52 FR 8225, March 17, and various subsequent amendments.

NRC, 1991, 10CFR 50 Part 20- Standards for Protection against Radiation, US Nuclear Regulatory Commission, Washington DC.

NRC, 2006, "AGREEMENT STATE REPORT – WELL LOGGING SOURCE DAMAGED," Event Number: 42891, CA Report Number: 100706, a report from State of California to US Nuclear Regulatory Commission, October 8.

Odom RC, Streeter RW, Wilson RD, 1999, Formation density measurements utilizing pulse neutrons, US Patent 5,900,627, April 4.

Paillet FL and Cheng CH, 1991, *Acoustic Waves in Boreholes*, pp. 1–264, Boca Raton, Florida: CRC Press.

Parthasarathy K, 2013, https://ksparthasarathy.wordpress.com/2013/05/09/recovery-of-radioactive-sources-from-coovum-river-while/

Partyka GA, et al., 2000, Upscaling Petrophysical Properties to the Seismic Scale, *the 2000 Exposition and 17th Annual Meeting of the Society of Exploration Geophysicists, Calgary, Canada.*

Pemper R, Sommer A, Guo P, Jacobi D, Longo, J, Bliven S, Rodriguez E, Mendez F, and Han X, 2006, A new pulsed neutron sonde for derivation of formation lithology and mineralogy, SPE 102770, In: Proc. SPE Annual Technical Conference and Exhibition, 24-27 September.

Pickett GR, 1963, Acoustic Character logs and their characteristics in formation evaluation, Journal of Petroleum Technology, 15, 650-667.

Pittman ED, 1992, Relationship of porosity and permeability to various parameters derived from mercury injection-capillary pressure curves for sandstone, *AAPG Bulletin*, v. **76**, no. 2, p. 191–198.

Radtke RJ, Lorente M, Adolph B, Berheide, M, Fricke, S, Grau, J, Herron, S, Horkowitz, J, Jorion, B, Madio, D, May D, Miles, J, Perkins, L, Phillip, O, Roscoe, B, Rose, D, Stoller C, 2012, A New Capture and Inelastic Spectroscopy Tool Takes Geochemical Logging to Next Level, In: Proc. 53rd SPWLA Annual Symposium, Cartagena, Columbia, June 16-20.

Raymer LL, Hunt ER, and Gardner JS, 1980, An Improved Sonic Transit Time-to-Porosity Transform, paper P, Trans., 1980 Annual Logging Symposium, SPWLA, pp. 1–12.

Reichel N, Evans M, Allioli F, Mauborgne M-L, Nicoletti L, Haranger F, Laporte N, Stoller C, Cretoiu V, Hehiawy E-El, and Rabrei R, 2012, Neutron-Gamma Density (NGD): Principles, Field Test Results and Log Quality Control of a Radioisotope-free Bulk Density Measurement, in: Proc. SPWLA 53rd Annual Symposium, Cartagena, Colombia, June 16-20, 2012. Paper GGG.

Rueslåtten H et al, 1998, NMR STUDIES OF AN IRON-RICH SANDSTONE, http://www.ux.uis.no/~s-skj/ipt/Proceedings/SCA.1987-2004/1-SCA1998-21.pdf

Roscoe B, Stoller, CA, Adolph, RA, Cheesborough JC, Hall JS, McKeon DC, Pitman D, Seeman B, Thomas SR, 1991, A New Through-tubing Oil-saturation Measurement System, Paper 21413, presented at the International Artic Technology Conference, Anchorage, Alaska, May 29-31 1991,

Rouillac D, 1994, *Cement Evaluation Logging Handbook*, pp. 1-176. Paris: Editions Technip.

Rutledge J, 2011, LANL, presentation at a Teleconference with oil industry, May.

Schmidt A, Tang V, and Welch D, 2012, Fully Kinetic Simulations of Dense Plasma Focus Z-Pinch Devices. Physical Review Letters, 109(20): p. 205003.

Scott HD, Wright PD, Thornton JL., Olsen J-R., Hertzog RC, McKeon D, DasGupta T, and Albertin IJ, 1994, “Response of a multidetector pulsed neutron porosity tool,” paper J, in 35th Annual Logging Symposium Transactions: Society of Professional Well Log Analysts.

Singer J et al, 1997, Fast NMR logging for bound fluid and permeability, paper YY, 38th Annual SPWLA Logging Symposium Transactions. Society of Professional Well Log Analysts.

Skelt C, 2011, Petrophysical Analysis of the Green River Formation, Colorado- a Case Study in Oil Shale Formation Evaluation, Petrophysics, Vol. **52**, No. 5. pp.331-343.

Song YQ, 2013, Magnetic resonance of porous media (MRPM): a perspective. J Magn Reson 229:12–24

Spears RW and Saha S, 2005, Improved Fluid Typing with NMR, Paper FFF In: Trans. SPWLA 46th Annual Logging Symposium, June 26-29

Stambaugh B, Svor R, Globe M, 2000, Quality Control of NMR Logs, SPE 63212, In: Proc. SPE Annual Technical Conference and Exhibition, Dallas, TX, 1-4 October, Society of Petroleum Engineers.

Straley C, Morris CE, Kenyon WE, Howard JJ, 1991, NMR in partially saturated rocks: laboratory insights on free fluid index and comparison with borehole logs, Trans SPWLA 32nd Annual Logging Symposium, paper CC.

Stoller C, 2015, Input to the Scoping Study Team, June.

Sun B, 2015, E-mail to A. Badruzzaman, January 21.

Tang XM, Altunbay M, and Shorey D, 1998, Joint Interpretation of Formation Permeability from Wireline Acoustic NMR, and Image Log Data, paper KK, Trans., 1998 SPWLA Annual Logging Symposium, SPWLA, pp. 1–13.

Tang XM and Patterson D, 2001, Detecting Thin Gas Beds in Formations Using Stoneley Wave Reflection and High-Resolution Slowness Measurements, paper OO. Trans., 2001 SPWLA Annual Logging Symposium, SPWLA, pp. 1–14.

Tang, X-M and Cheng A, 2004, Quantitative Borehole Acoustic Methods, *Handbook of Geophysical Exploration, Seismic Exploration*, Vol. 24. Oxford, England: Pergamon Press (Elsevier).

Timur A, 1968, An investigation of permeability, porosity and residual water saturation for sandstone reservoirs, The Log Analyst, 9(4), 8-17

Timur A, 1987, Acoustic logging. In: Bradley H (editor) petroleum production handbook, Society of Petroleum Engineers, Dallas, TX.

Ullo JJ, 1986, Use of multidimensional transport methodology on nuclear logging problems, Nucl. Sci. Eng., **92**, p228.

Valant-Spaight B, Han W, Guo W, and Schultz W,2006 "Field Examples with a Slim LWD Density/Neutron Instrument Containing a Californium-252 Neutron Source and Three Neutron Detectors," in Proc. 47th SPWLA Annual Logging Symposium. Paper CCC.

Wendt B, 2015, E-mail to A. Badruzzaman, September 30. Wendt is Vice-president of Technology, Soc. of Petrophysicists and Log Analysts, Houston, TX, September 30.

Westphal H, Surholt I, Kiesel C, Thern H, and Kruspe T, 2005, NMR Measurements in Carbonate Rocks: Problems and an Approach to a Solution, Pure and Applied Geophysics, **162**, 549-570, Berhauser Verlag, Basel.

Wilson RD, 1995, "Bulk Density Logging with High-Energy Gammas Produced by Fast Neutron Reactions With Formation Oxygen Atoms," Paper NSS11-01, Trans. IEEE Nuclear Science Symposium, San Francisco, CA, October 21-28.

Wylie MRJ, Gregory AR, Gardener LW, 1956, Elastic wave velocities in heterogeneous and porous media, Geophysics, 21 (1), 41-70.

Xu L, Schultz W, Huiszoon C, 2010, A Comprehensive Investigation of Source Effects on Neutron Porosity Response for Logging-While-Drilling Measurements, Petrophysics, Vol. **51**, No. 3, p185-198, June.

Appendix A

Well Logging Measurements and Tools: A Summary

Here we briefly discuss key logging tools and their interpretation. An expose can be found in Ellis and Singer, 2007.

I. Radionuclide-based Techniques

I-1. Natural Gamma Ray (GR): Total and Spectral

Most logging tool strings contain what are referred to as gamma ray 'tools.' These are nothing more than single scintillation counters used to record gamma rays originating from naturally-occurring radioisotopes in the formation, Potassium (^{40}K), Thorium (^{232}Th), and Uranium (^{238}U). K and Th are correlated to clay minerals. U is correlated to the organic matter. Thus, total GR counts are low in sand and high in clays/shales and the clay volume can be computed from the difference in GR readings. However, it is not a linear relationship and depends on the clay type and other lithological factors. There are several correlations that can be used to compute the clay volume.

In addition to recoding the total GR counts, the detector can also record the gamma-ray spectra from the three naturally occurring radioisotopes, K at 1.46 MeV, Th at 2.62 MeV and U at 1.76 MeV, by placing energy bins around these energies. K, Th, and U concentration can be estimated from the data using appropriate correlations. Since the statistical errors of the spectral data are greater, larger detectors than those for recording total GR are utilized. Delineation of U is important since it is not correlated to clay minerals. Sometimes delineating K from Th is needed since some non-clay rocks such as feldspars which may also contain potassium.

I-2. Cs-137-based Formation Density

Figure A-I.1 displays a typical dual-detector density tool. Such tools typically have a 2-3 Ci ^{137}Cs source emitting 662 keV gamma rays and two scintillators, usually NaI. The spectra and total gamma ray intensity are recorded. The physics involved are Compton scattering at higher energies (approximately above 250 keV) and the photoelectric effect at lower energies. In each detector, the intensity in the Compton window, in a simplified model is given by

$$I \sim I_0 \exp(-\mu_c x)\,, \qquad \text{(A-I.1)}$$

where x is the source-detector spacing and μ_c is the Compton scattering attenuation coefficient given by

$$\mu_c = \rho_B A_v \frac{Z}{A} \sigma_c\,. \qquad \text{(A-I.2)}$$

In Eq. (A-2), ρ_B is the average formation density, also known as the bulk density (and hence the subscript 'B') and A_v is the Avogadro's number, a constant. The ratio Z/A is approximately ½ except for hydrogen and thus is a near-constant. σ_c is the microscopic Compton cross section. Thus, in principle, by recording the intensity to compute the attenuation coefficient and then inverting Eq. (A-I.2) one can obtain the bulk density, ρ_B. The bulk density is related to the porosity, φ as follows:

$$\rho_B = (1-\varphi)\,\rho_{matrix} + \varphi\,\rho_{fluid}. \qquad \text{(A-I.3)}$$

Thus, the density information comes from the Compton scattering.

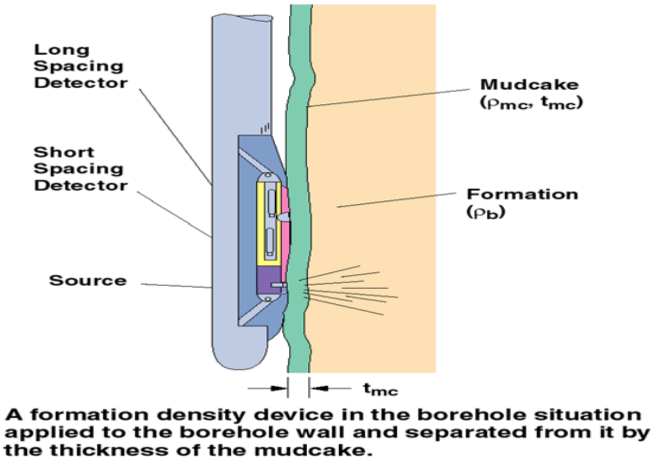


Figure A-I.1. A ^{137}Cs source density-PE tool [Adapted from Ellis 1987]

The photoelectric effect is related to the Z of the formation and thus is a lithology indicator. Consequently, the intensity in the photoelectric range is used to estimate the so-called photoelectric factor (PEF) as a lithology indicator. The actual processing is more complicated, with borehole and other effects that need to be corrected for. **Figure A-I.1**, illustrates one such effect, namely the mudcake that may be formed when the tool is pushed up against the borehole wall and the solid matter in the mud forms a 'cake' of finite thickness on the wall when the liquid is squeezed out of the mud that is circulated while drilling to keep the drill-bit cool and maintain hydrostatic pressure, and thus the borehole stability. The density of mudcake and its thickness need to be corrected for. In high-pressure formations, the mudcake may be loaded with Barite, which due to its very high Z can prevent gamma rays reaching the formation from the source in sufficient numbers.

I-3. Neutron Porosity

Figure A-I.2 displays the schematic of a dual-detector neutron porosity tool.

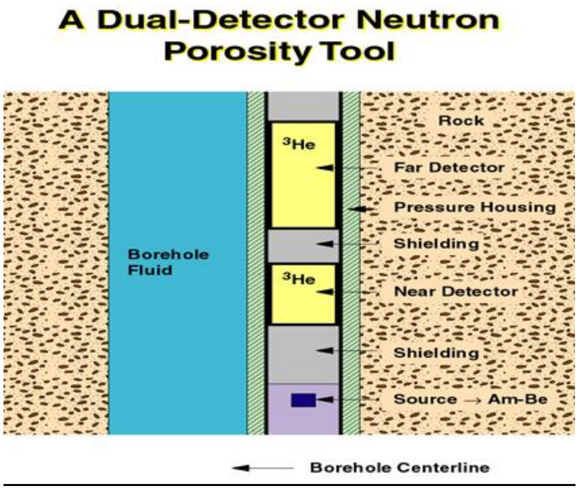


Figure A-I.2. Schematic of a Dual-detector Neutron Porosity Tool [Badruzzaman 2002]

The ratio of near detector counts to far detector counts (N/F ratio) can be shown to be related to the slowing down or the migration length which are related to the porosity for a given lithology. Thus, in the processing, the N/F ratio is constructed, the slowing down or migration length corresponding to this ratio is obtained from the transform table for the tool, and this parameter, for the given lithology, is used to estimate the so-called neutron porosity. There are several corrections that need to be applied relative to the calibration conditions for the tool. These include the borehole size, salinity, temperature, any standoff that may arise between the tool and borehole wall despite efforts to maintain a zero standoff by pushing the tool up against the wall using a bow-spring.

I-4. <u>(n,ɣ) capture spectroscopy and mineralogy</u>

(n,ɣ) spectroscopy logs for open-hole applications were first introduced by Grau et in 1989 and an ^{241}Am-Be source (n,ɣ) capture spectroscopy tool with a single-detector crystal and a definitive interpretation process was deployed in the field in the mid-1990's. As its name implies, the tool records the spectrum of gamma rays produced from capture of low-energy neutrons. **Figure A-I.3** displays one such tool. Note that it uses a BGO crystal. Thus, a thermal flask (dewar) is needed at temperatures above 80 deg F.

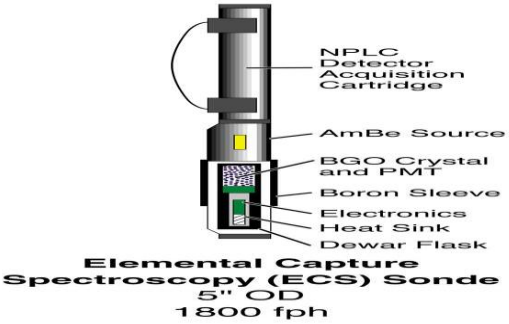


Figure A-I.3. An (n,ɣ) capture spectroscopy tool [Figure courtesy of Schlumberger]

The measurement-to-mineralogy interpretation is broadly done as follows.

1. <u>Physics</u>: Record capture-produced gamma rays and construct relative elemental yields.

2. <u>Closure Model</u>: Obtain dry elemental weight percent (wt.%) of a subset of elements, such as Si, Ca, Fe, S, Ti, Gd

3. <u>Mineralogy</u>: Use the dry wt.% computed in step 2 to construct minerals fitting to mineralogy/lithology model generated from a "large" core data base. One can construct Clay, Sand, Carbonate, Evaporite/ Pyrite at the wellsite. Aluminum, a key parameter in clay, cannot be obtained using the ^{241}Am-Be source tools and is thus emulated using additional closure-type empirical relations. More detailed mineralogy requires an involved processing at the expert level. The technique cannot provide Carbon or Potassium and is poor in providing Magnesium, another key element. As discussed elsewhere, new D-T generator-based tools with the ability to produce both inelastic and capture gamma rays and utilizing scintillators with better energy and time resolutions are beginning to address the latter issues.

Actual implementation of the (n,ɣ) techniques to obtain mineralogy is complicated. Closure models would depend on the lithology. In clastics, a simple closure model assumes that principal earth elements are present as oxides (SiO_2, Al_2O_3, Fe_2O_3, Na_2O, K_2O, CaO, MgO, TiO_2, MnO, etc.). The oxide ratios from this description is then used to establish the association of Oxygen atoms with the other elements such as Potassium (K), Aluminum (Al), Silicon (Si), etc., in a given mineral, such as $KAlSi_3O_8$ (orthoclase), for example, to construct its amount. Note that eight Oxygen atoms are associated with orthoclase as seen from the formula. In carbonates, the associations would be with $CaCO_3$ and $MgCO_3$. Such associations become more complicated in the presence of the same element in multiple minerals simultaneously. Also, spectral data may show signals from trace elements deemed unimportant and often these have to be excluded in a consistent manner.

Tool designers often propose that the mineralogy can be used to perform 'improved' petrophysical analysis. These would include adjusting various petrophysical parameters calculated using other methods, such as neutron, density, and total porosity, irreducible water saturation (Swirr), permeability and grain density for input to density porosity, to reflect the mineralogical interpretation. While these adjusted parameters may be internally consistent, they may be inaccurate as end-users have noted [Skelt 2011]. In fact, Skelt in the reference cited, notes the following:

i) Since the spectral data gives relative elemental yields only, transforming them to elemental concentrations or mass fractions requires some knowledge of the mineralogy itself.

ii) Closure models used may introduce differences between core and log-derived mass fractions. Closure models used in the two types of data need to be reconciled.

iii) Even if the core and log-derived results agree, unless the closure models themselves are appropriate, one may obtain useless results. Closure models normalize a given target parameter, say the sum of oxide volumes from different minerals, to unity, but errors in the individual components, or elimination of elements that have a larger contribution than deemed appropriate may cause considerable errors.

The above discussion of designer optimism vs. user experience is present in all logging technology design to implementation, particularly with inversion techniques that rely on multiple adjustment parameters, 'knobs ' as practitioners refers to.

II. Acoustic Well Logging Techniques

II-1. <u>General</u>: Since the introduction for well logging in 1950's, acoustic techniques have been widely used for various logging applications, among them including evaluating reservoirs, selecting well locations, designing completions, increasing hydrocarbon recovery, and cement evaluation. The deployment of acoustic logging tools involves a multidisciplinary activity that encompasses a range of fields including basic wave propagation theory, sensor and instrumentation design, and data interpretation. Over the past three decades, resulting from numerous theoretical studies and analysis of field logging data, the industry has much better understanding of acoustic wave propagation in different formations and downhole acoustic measurements. Also, thanks to much faster instruments and powerful acoustic sensors, the modern acoustic logging tools provide longer range, shorter logging time, higher resolution, and better accuracy. The acoustic logging tools also can reduce exploration and production risks. **Figure A-II.1** shows the different geophysical acoustic techniques and their ranges [Chabot *et al* 2002; Coates *et al* 2000]. Applications of the acoustic well logging to specific disciplines are summarized in **Table A-II.1** [Lake 2007].

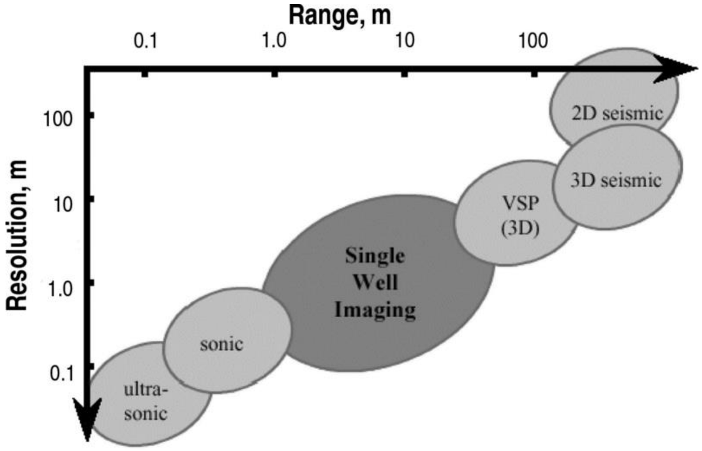
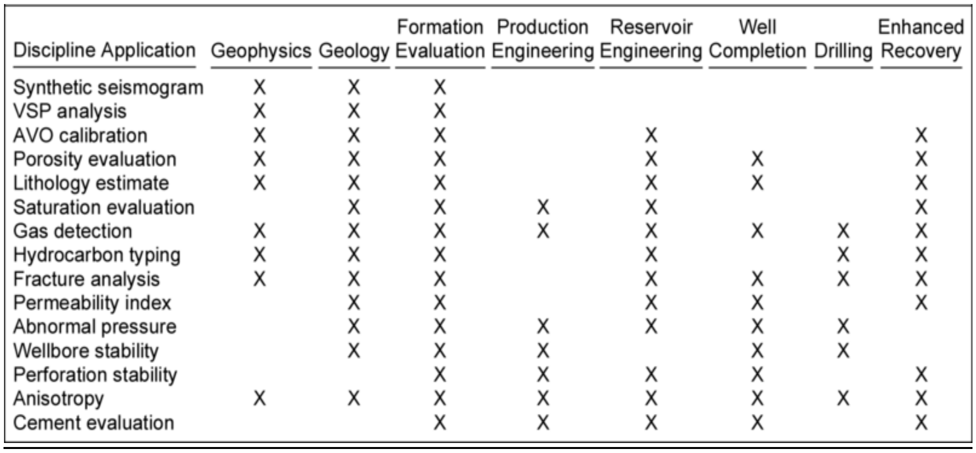


Figure A-II.1: Geophysical Acoustic Techniques and Ranges [Chabot et al 2002; Coates et al 2000]

Table A-II.1: Applications of acoustic well logging to specific disciplines [Lake 2007]



Discipline Application	Geophysics	Geology	Formation Evaluation	Production Engineering	Reservoir Engineering	Well Completion	Drilling	Enhanced Recovery
Synthetic seismogram	X	X	X					
VSP analysis	X	X	X					
AVO calibration	X	X	X		X			X
Porosity evaluation	X	X	X		X	X		X
Lithology estimate	X	X	X		X	X		X
Saturation evaluation		X	X	X	X			X
Gas detection	X	X	X	X	X	X	X	X
Hydrocarbon typing	X	X	X		X		X	X
Fracture analysis	X	X	X		X	X	X	X
Permeability index		X	X		X	X		X
Abnormal pressure		X	X	X	X	X	X	
Wellbore stability		X	X	X		X	X	
Perforation stability			X	X	X	X		X
Anisotropy	X	X	X	X	X	X	X	X
Cement evaluation			X	X	X	X		X

VSP: Vertical Seismic Profiling. AVO: Amplitude Variation with Offset

II-2. Basics of Acoustic Logging

Today, acoustic logging, including surface seismic methods and borehole logging, comes in different forms and has become an integral part of well logging to provide mechanical properties of rock formation. The principles of acoustic logging are based on the theory of acoustic wave propagation in an elastic medium [Tang and Cheng 2004; Hearst *et al* 2000; Mavko *et al* 1998; Paillet and Cheng 1991]. The theory predicts the acoustic waves propagate through the formation and/or borehole. Snell's law explains how the acoustic wave behaves at a boundary separating different formations and/or borehole.

An acoustic logging tool, in general, consists of an acoustic source at one end and a receiver or an array of receivers at another end of the tool with predefined distances. Whether being used for wireline logging or for LWD, the logging tools are designed to measure one or more of the following properties:

- TOF (time-of-flight)
- Intensity (amplitude)

- Attenuation (amplitude attenuation)
- Dispersion (Frequency)
- Scattering
- Particle Displacement

The travel times (TOF) of refracted waves propagating through the formation are then used to calculate the acoustic-wave velocities or speed-of-sound (SOS). An acoustic logging tool records composite waveform signals containing different acoustic waves. The primary acoustic waves of well logging are classified according to the direction of particle displacement with respect to the direction of wave propagation, in order of arrival, as either:

- Compressional (Longitudinal, pressure) waves,
- Shear (Transverse) waves, or
  Stoneley (Tube) waves

A schematic diagram of a typical acoustic log, shown in **Figure A-II.2**, depicts different acoustic waves and their traveling paths [Crain 2000]. The amplitudes of acoustic waveforms are recorded as a function of time. The compressional wave (P-wave) has the fastest speed of these three waveforms and is least affected by faults, unconsolidated formations, and borehole fluids. The shear waves (S-wave) are generated either directly from the wave refraction or indirectly induced from acoustic mode conversion. The Stoneley waves are guided waves that propagate in the annulus between the logging tool and along the borehole wall/fluid interface and are the slowest among these three primary acoustic waveforms [Crain 2004]. The Stoneley waves have no cut-off frequency and exhibit a very mild dispersion, which is related to formation rock properties.

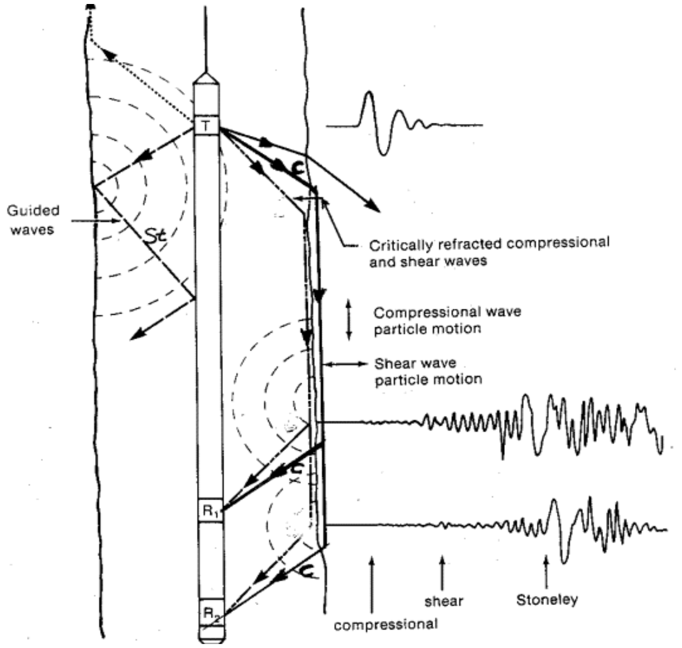


Figure A-II.2 Various acoustic waveforms for borehole logging [Crain 2000]

Figure A-II.3 shows the generalized acoustic waveforms of “slow” and “fast” formations received by an acoustic logging tool [Lake 2007]. **Figure A-II.3** also demonstrates that, in general, the amplitude of compression wave is larger than that of the shear wave in “slow” formation, and vice versa for “fast” formation.

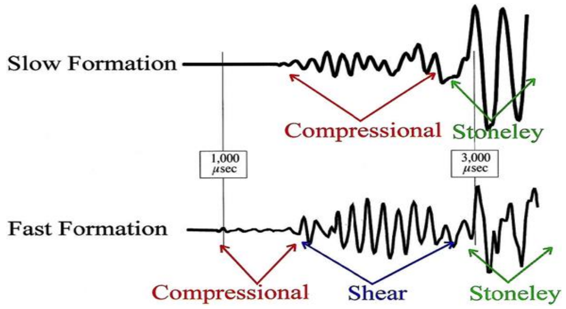


Figure A-II.3. Acoustic waveforms of "slow" and "fast" formations received by an acoustic logging tool [Lake 2007]

An acoustic-log measurement generates well-log scale images or cross plots between acoustic and petrophysical properties, generally including sound velocities and Vp/Vs ratio versus calibrated well-log derived petrophysical properties, such as water saturation, volume of shale or porosity. Sometimes, the acoustic impedance, which equals formation density times the sound velocity, is displayed. Depending on the types of acoustic-wave propagation, acoustic logging data is generally classified as transmission or reflection mode. Operating under the transmission mode, acoustic pulses are transmitted in short bursts within frequency range of 20 kHz. The reflection mode is usually operated at a frequency of ~500 kHz and it is difficult to determine the value of the shear slowness. **Figure A-II.4** shows an example of acoustic logging data of lithology (1st track: Lith), water saturation (2nd track: Sw), resistance (3rd track: Res), and acoustic velocities and acoustic impedance (4th track: Acoustic) [Partyka 2000].

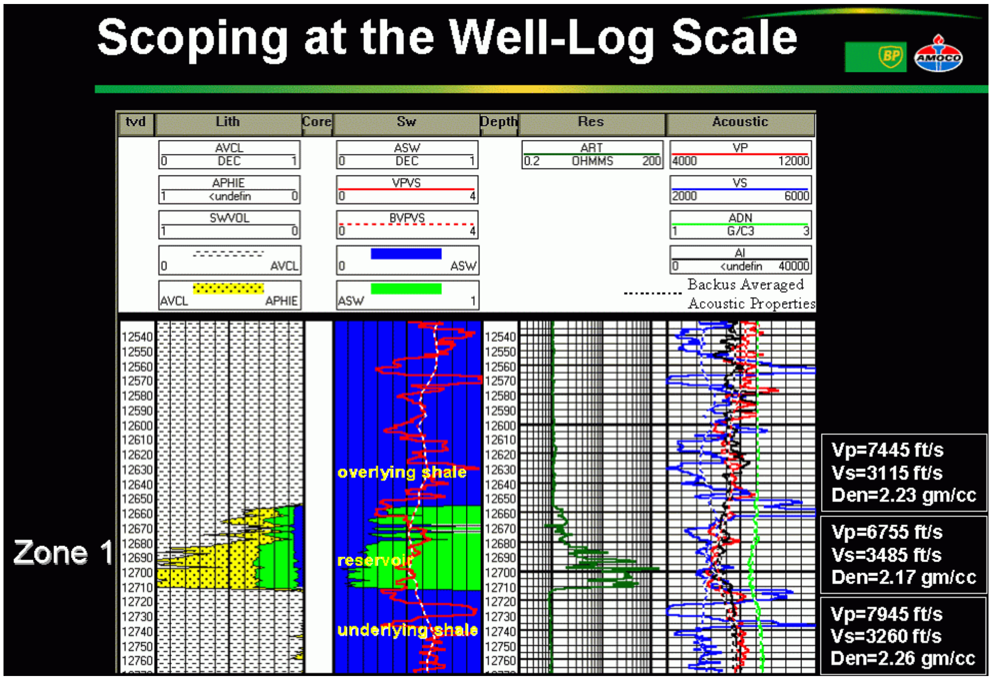


Figure A-II.4. An example of logging data of lithology, water saturation, resistance, and sound velocities [Partyka 2000]

II-3. Acoustic Logging for Mechanical (Elastic) Properties

Acoustic-wave velocities (slowness's) are a function of lithology, rock or clay formation, porosity, pore composition and pressure, and temperature. Acoustic-wave velocities (slowness's) are intimately connected to density and elastic constants of the rock formation and can be related to rock elastic properties through three constants of:

- Proportionality
- Elastic moduli (e.g., Young's, shear, and bulk)
- Poisson's ratio

The measurement and determination of mechanical (elastic) properties is based on the assumptions that rocks behave elastically and are isotropic. However, in practical, neither of these assumptions is actually true because formations are often anisotropic and not elastic due to porosity, fracture, water/gas content, pressure, and some other factors. Generally, S-wave logging is rare and shear wave velocity can be estimated if the P-wave velocity is known. For different formations, the velocity relation between P- and S-wave, then, also have to be adjusted. **Table A-II.2** summarizes the relations of compressional and shear velocities for common sandstone formations. Since density and the elastic properties vary with porosity, then so do acoustic velocities; a log of acoustic velocity or travel time (slowness) could be used to predict porosity or for gas identification.

Table A-II.2 Summary of the relations of compressional and shear velocities for sandstones.

V_P and V_S Relation	Rock Formation
Pickett	
$V_S = 0.866\ V_p - 1.16$	Sandstone
$V_S = 0.526\ V_p$	Limestone
$V_S = 0.555\ V_p$	Dolomite
Castagna, Batxle, and Eastwood	
$V_S = 0.862\ V_p - 1.17$	Mudrock Line
$V_S = 0.667\ V_p$	Dry
Greenberg and Castagna	
$V_S = -0.02180\ V_P^2 - 0.9629\ V_P - 1.0828$	Sandstone
$V_S = -0.02280\ V_P^2 - 0.9139\ V_P - 1.1347$	Shale
$V_S = -0.00271\ V_P^2 - 0.4727\ V_P - 0.2138$	Limestone
$V_S = -0.00984\ V_P^2 - 0.6036\ V_P - 0.0217$	Dolomite
Krief et al.	
$V_S^2 = 0.45\ V_P^2 - 1.59 + \ 1.32/V_P^2$	
Freund	
$V_S = 0.763\ V_p - 0.603$	

Currently, quadrupole sources have been developed and have the best possibility to provide energy to the formation while avoiding exciting the drill. Measurements of either type have applications in both open and cased holes. Acoustic well logging provides acoustic measurements in all borehole mud types (but not in air- or foam-filled boreholes) in vertical, deviated, and horizontal wells, in both open and cased hole. Over the years, because of the development of modern acoustic logging tools, the depth of penetration through mud has improved from less than a foot to up to ten feet of penetration by putting the source in direct contact with the mud and running at lower frequencies.

II-4. Acoustic Porosity

If pockets in porous formation are filled with fluid, acoustic logging tools can be used for porosity measurement because the sound velocity of compressional wave in fluid is less than the velocity in rock. The waves are transmitted by both the rock matrix and the fluid in the pore pocket. The travel time or sound velocity is affected by lithology, confining pore pressure, rock matrix, and fluid in the pockets. For consolidated and compacted formations such as sandstone, compressional acoustic velocity often has a good correlation with porosity. If the compressional acoustic velocity the rock matrix (V_M) and fluids (V_f) are known, the fractional porosity of the rock ($\emptyset$) can be estimated by an empirical relationship, known as Wyllie time-average equations in terms of velocity and travel time respectively [Wyllie *et al* 1956]:

$$\frac{1}{V_p} = \frac{\emptyset}{V_f} + \frac{1-\emptyset}{V_M}, \qquad \text{(A-II.1)}$$

$$\Delta t_p = \emptyset\, \Delta t_f + (1-\emptyset)\Delta t_M \text{ , or} \qquad \text{(A-II.2)}$$

$$\emptyset = \frac{\Delta t_p - \Delta t_M}{\Delta t_f - \Delta t_M}, \qquad \text{(A-II-3)}$$

where V_p: compressional acoustic velocity of the formation (ft/μsec)
Δt_p: acoustic transient time in the formation (μsec/ft)
Δt_f: acoustic transient time in the fluid (μsec/ft)
Δt_M: acoustic transient time in the rock matrix (μsec/ft)

Fluid type becomes more of a concern when oil-based mud (OBM) is used if the formation of interest is not invaded or if invasion is very shallow. The lithology must be known or estimated in order to select the appropriate matrix velocity. In poorly consolidated or unconsolidated rocks, correction is necessary for the estimation of porosity. To correct for observed anomalies and shortcomings of the Wyllie time-average equation, in 1980, a new empirical transform, known as the Raymer-Hunt-Gardner equation, based on field observations of transit time versus porosity was introduced. The equation provides good transit time-porosity correlations over a wide range of porosities, especially for clean sandstones and carbonates [Raymer *et al* 1980].

$$\emptyset_{log} = -\alpha - [\alpha^2 + \frac{\Delta t_M}{\Delta t_{log}} - 1], \qquad \text{(A-II.4)}$$

where $\alpha = (\Delta t_M / 2\Delta t_f) - 1$.

Figure A-II.5, as an example, shows the acoustic porosity of sandstone matrix estimated from the Wyllie and Raymer velocity-porosity relationships [Baker Atlas - Petrowiki 2015]. The results show that Wyllie equation over-estimates the acoustic porosity in sandstones in which the acoustic transient times of adjacent shale exceed 100 µsec/ft.

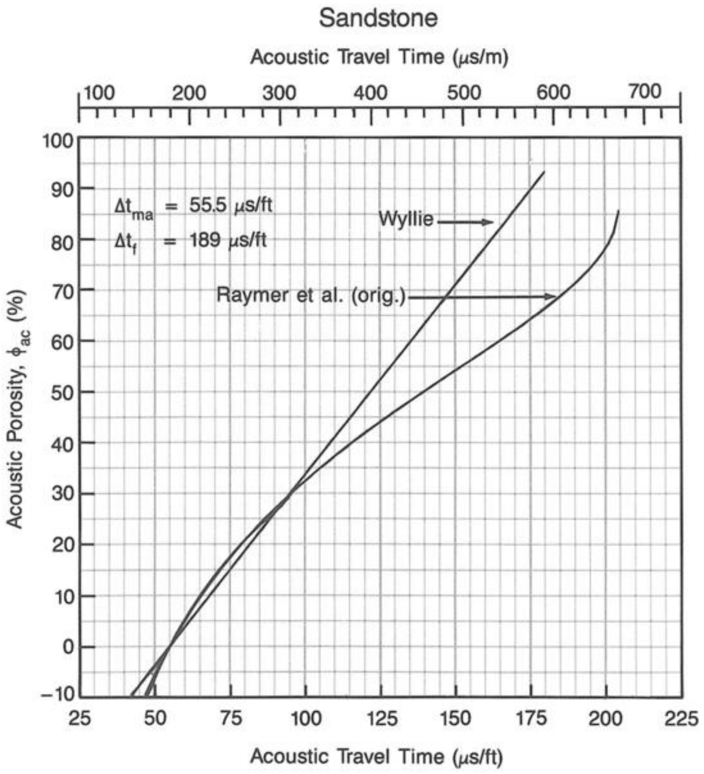


Figure A-II.5. An example of logging data of lithology, water saturation, resistance, and sound velocities [Baker Atlas- Petrowiki 2015].

However, neither of the empirical velocity/porosity transforms may be adequate for high-porosity, unconsolidated, and uncemented (slow) rocks [Dvorkin and Nur 1998]. In shaly formations, the sonic porosity must also be corrected for the presence of shale [Johnson and Pile 2006]. Based on field measurements, the following modified empirical transforms of transit time and porosity were proposed to provide superior transit time - porosity correlation for common sandstone formations: [Raymer *et al* 1980]

$$V_P = (1 - \emptyset)^2\, V_M + \emptyset V_f \qquad \emptyset < 0.37 \qquad \text{(A-II.5)}$$

$$V_P = (1 - \emptyset)^2\, V_M + \emptyset V_f \qquad 0.37 < \emptyset < 0.47 \qquad \text{(A-II.6)}$$

$$\frac{1}{V_P^2} = \frac{\rho\emptyset}{\rho_f V_f^2} + \frac{\rho(1-\emptyset)}{\rho V_M^2} \qquad \emptyset > 0.47 \qquad \text{(A-II.7)}$$

Shear velocity is also used for acoustic porosity evaluation, especially for fast formations, in a similar manner as described above for compressional velocity [Medlin and Alhllall 1992]. Compared to compressional velocity, shear velocity generally is more sensitive to porosity, insensitive to gas effects, and less affected by borehole washout. The combination of compressional and shear slowness can provide an enhanced porosity determination [Krief *et al* 1990]. Also, it is more manageable because porosity evaluation can be conducted in cased hole using dipole tools or, in some cases, monopole-array tools. Biot proposed a relationship of acoustic porosity, compressional and shear velocities, and rock and fluid densities [Biot 1956a, b]. The proposed relationship enables transit interval times and compressional and shear velocities to be estimated on the basis of lithology and porosity solution from well-logging data, even when acoustic logs are not available.

Beside lithology and rock matrix, acoustic porosity measurement is affected also by other factors, such as confining, clay content, pore pressure, and fluid in the pockets. For more accurate measurement or prediction, over the years, the velocity-porosity-lithology relations of different rock formations have been investigated and validated with field data. **Table A-II.3** gives a summary of velocity-porosity-clay content relations for common sandstone formations. If the formation velocities are known, these types of relations are very useful to provide the overall clay effects and the relation of compressional to shear velocity (Vp/Vs ratio), which is a critical lithology indicator.

Table A-II.3 Summary of velocity-porosity-clay content relations for sandstones.

P-Wave Velocity	S-Wave Velocity
Tosaya $V_P = (1-\emptyset)^2\, V_M + \emptyset V_f$	$V_S = 3.7 - 6.3\,\emptyset - 2.1\,C$
Dominico $\frac{1}{V_p} = 0.163 + 0.365\,\emptyset$	$\frac{1}{V_S} = 0.224 + 0.889\,\emptyset$
Costagna, Batzle, and Eastwood $V_P = 5.81 - 9.42\,\emptyset - 2.21\,C$	$V_S = 3.89 - 7.07\,\emptyset - 2.04\,C$
Han, Nur, and Morgan $V_P = 5.59 - 6.93\,\emptyset - 2.18\,C$	$V_S = 3.52 - 7.07\,\emptyset - 1.89\,C$
Eberhart-Phillips, Han, and Zoback $V_P = 5.77 - 6.94\,\emptyset - 1.73\,C^{1/2} + 0.446\,C$	$V_S = 3.70 - 4.94\,\emptyset - 1.57\,C^{1/2} + 0.361\,P$

where C: fractional clay content

V_f: compressional velocity of the fluid (km/sec)

P_e: effective pressure (MPa)

$P = P_e - e^{-16.7P_e}$.

II-5. Energy Sources for Acoustic Well Logs

Based on the excitation direction, there are three types of acoustic energy sources, monopole, dipole, and quadrupole, used for acoustic well logs. **Figure A-II.6** illustrates the excitation direction of the three acoustic energy source types. The use of a specific source type depends on required acoustic waves for a specific application. Some modern acoustic logging tools may use more than one source type to generate multiple types of waves for different rock formations or the measurement of multiple parameters.

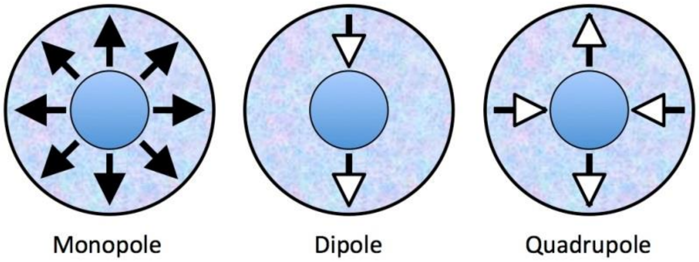


Figure A-II.6. Acoustic energy source types.

(i) Monopole Source

A monopole source consists of a piezoelectric element that is polarized in a way to generate acoustic energy in all directions radially from the tool axis. This is the most common acoustic energy source used to generate compressional wave for acoustic wireline well logs. The P-wave reaches the rock formation at a critical angle and is refracted so that it travels parallel to the borehole inside the rock formation. The refracted wave is then refracted back to the borehole and strike an array of receivers with predefined separation distances. The formation slowness is calculated from the differences of travel time to reach these receivers. In certain formations, such as “fast”, S-wave or Stoneley wave is generated due to mode conversion.

(ii) Dipole Source

Different from monopole sources, a dipole source generates unidirectional acoustic energy rather than radially. Compressional wave generated by dipole sources in the formation usually is very weak and hard to detect except in large boreholes or very slow formations. Within either a slow or fast formation, these sources are used to generate strong shear waves, or so-called flexural waves, along borehole wall.

Modern open-hole sonic logging tools may carry both monopole and dipole sources and receivers so that compressional and shear waves are both generated and recorded in slow and fast formations. To avoid interference with each other, these two sources usually are fired alternately [Crain 2004]. Also, modern crossed-dipole logging tools consist two sets of dipole sources set orthogonally, with corresponding dipole receivers to record shear data in two directions in the rock formation. The ratio of these two resulting acoustic velocities is used as a measure of acoustic anisotropy in the formation. This is an important property in formation stress analysis, hydraulic fracture design, fractured reservoir description, and tectonic studies.

(iii) Quadrupole Source

Currently, quadrupole sources, developed similar to dipole sources, are used to generate asymmetric pressure waves. They have the best possibility to provide energy to the formation while avoiding exciting the drill. They are more suited to the logging-while-drilling (LWD) environment and have shown some success in measuring shear velocity. It has been demonstrated that the use of quadrupole source provides direct shear slowness measurements, using slowness-time-coherency (STC) method, in extremely slow formations. This employment minimizes or eliminates the need for large dispersion corrections typical for LWD dipole acoustic tools.

II-6. Acoustic Evaluation of Cement Bond

Acoustic logs provide the primary means for the evaluation of cement bond [Bigelow 1990; Hill 1990; Jutten and Morriss 1990; Rouillac 1994]. Acoustic-based cement-bond evaluation tools consist of a pair or an array of transmitters and receivers. For a good bounding, i.e. good acoustic coupling, between cement/casing/formation, acoustic energy would transmit into formation and is rapidly attenuated. However, for partial bond or free pipe, the energy is reflected back from poor bonding and received by the receivers. The tools measure velocity, intensity, and attenuation of the compressional wave. Conventional cement bond logging (CBL) tools provide omnidirectional measurements, while the newer radial cement-evaluation tools provide azimuthally sensitive measurements for channel evaluation. Modern acoustic tools can evaluate cement-bond quality as well as casing integrity simultaneously. For example, Halliburton's Circumferential Acoustic Scanning Tool-Visualization version (CAST-V™) allows separate or simultaneous casing inspection and cement evaluation [Graham *et al* 1997]. This tool can also operate in open hole as a formation imager.

Figure A-II.7 shows a CAST-V data image of casing inspection. The casing-evaluation presentation includes casing ovality, eccentricity, hole deviation, and gamma ray in Track 1. In this case, the eccentricity comprises both tool and casing eccentricity resulting from formation movement (salt flow). Track 2 shows a cross-sectional presentation of the pipe shape. Track 3 shows a cross-section of the pipe wall. Track 4 provides the average, minimum, and maximum values of the pipe radius that is shown in Track 5. Track 6 provides the average, minimum, and maximum values of the pipe thickness that is the image shown in Track 7, where red indicates pipe thinning and blue indicates pipe thickening.

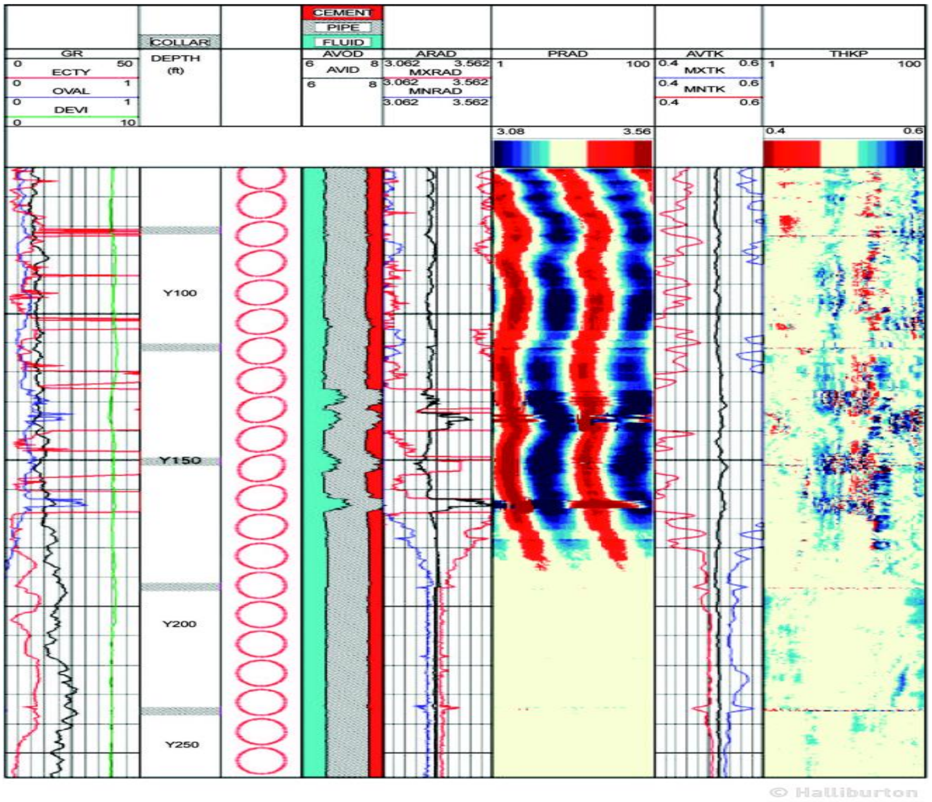


Figure A-II.7. Image of casing inspection using CAST-V™ [A Halliburton figure –see http://petrowiki.org/Casing_inspection_logs]

III. NMR in Well Logging

III-1. Introduction

NMR technology in well-logging is based on the response of hydrogen nuclei to magnetic and RF field excitations. The first generation NMR tools, until the early 1990s, were based on the relatively weak magnetic field of the earth. For these early NMR tools, the borehole signal from the hydrogen had to be suppressed by magnetite mud doping. The second-generation NMR tools are based on the "inside-out" design pioneered by Jasper Jackson of a DOE National Laboratory (LANL) [Jackson 1984]. The static magnetic fields of modern NMR tools are 1000 times greater, or about 0.055 Tesla. For these new NMR tools, magnetite doping is not required. As the NMR signals are related to the strength of the magnetic field, the second generation NMR logging tools can obtain several petro-physical parameters described very briefly in this section [Songs YQ 2013].

III-2. Measurement Principles of NMR and Well-Logging Parameters

It is useful to examine the NMR measurement process by considering the sensor timing diagram shown in **Figure A-III.1** below. The strong static magnetic field polarizes the hydrogen nuclei for a duration of time T_w, followed by transverse RF field, and then followed by a train of 180 phase-shifted RF pulses at the spin-echo time intervals T_e. The polarization time constant, T_1 and the relaxation time constant T_2 are then used to determine the petrophysical parameters.

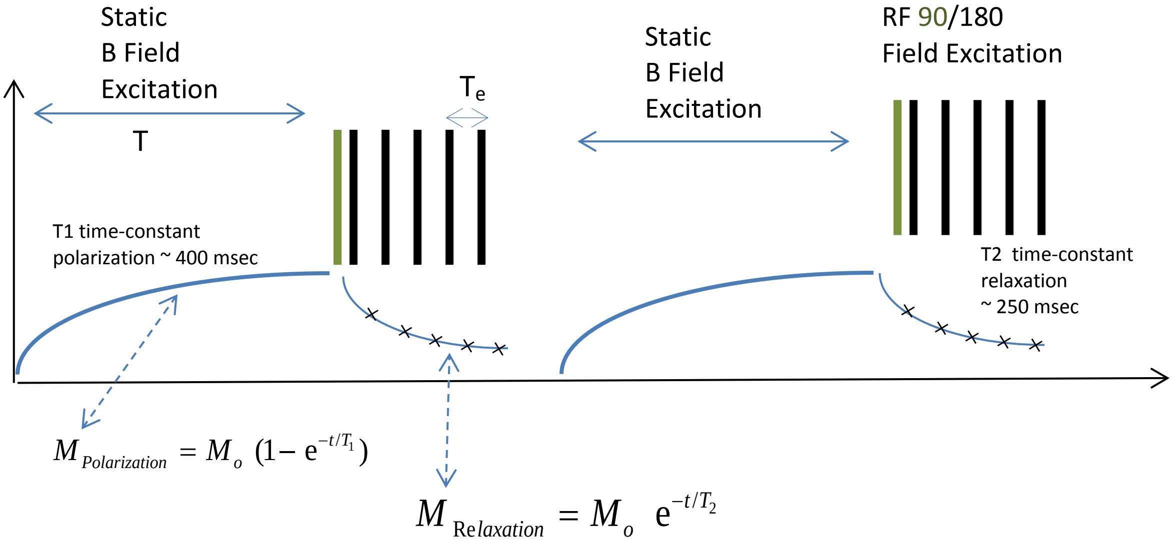


Figure A-III.1: NMR signal measurements require excitation with both static magnetic field and transverse directional RF pulses, and recoded at intermediate interval points the induced field due to nuclei polarization and relaxation**.**

<u>T_1 time Constant</u>. In order to measure the NMR signal, the first step consists of magnetizing or aligning the hydrogen nuclei of the formation fluids by applying a strong static magnetic field into the rock formation. The time required for this alignment of the hydrogen nuclei is called the longitudinal or the spin-lattice relaxation time, T_1. The NMR signal due to the induced polarization can be written as

$$M(t_W) = \Phi[1 - e^{-t_W/T_1}]$$

(A-III.1)

where M(tw) = NMR magnetization signal, Φ is a measure of porosity, t_W is the wait time or exposure time for polarization, and T_1 is the time constant for proton alignment, which for water is about 3 seconds at room temperature. During logging, when capillary- and clay-bound are being estimated, the polarization or relaxation times can be very short and logging speeds relatively very high vs. full NMR logging (Singer *et al*, 1997). In well-logging, a distribution of T_1 is a measure to describe the magnetization process, and the measured distributions can be used to identify the hydrocarbon composition. For example, the logarithm of the mean of the T_1 distribution, $P(T_1)$, is inversely proportional to viscosity of crude oils. The porosity and fluid types and volume also determine the net magnetization as a function of the time for polarization referred to as the wait time Tw.

T_2 Time Constant: Modern NMR tools measure the relaxation time, T_2, known as the transverse relaxation time, or the spin-spin relaxation time, and these measurements are used to estimate a distribution, $P(T_2)$. To measure T_2 distributions, following a polarization, a train of RF pulses is applied and the resulting decay rates between these pulses (i.e. echo amplitudes) are used to determine of the transverse magnetization produced by the RF pulses. Typically, the pulse repetition frequency for the echo pulses is several mega-hertz.

The total porosity is actually proportional to the area under the T_2 distribution. T_2 distributions can also be used to estimate the pore-size distributions and the molecular composition of crude oils [Coates *et al* 1999; Arns 2004]. There are at least three mechanisms that are related to T_2 distributions: (1) bulk relaxation; (2) surface or wetting-phase relaxation; and (3) diffusion (D) relaxation. Since the echo spacing of the RF pulses can be changed, these parameters can be estimated by varying the echo pulse repetition frequencies. **Figure A-III.2** below illustrates the non-linear optimization problem that allows one to decompose the measured signal into its components discussed below.

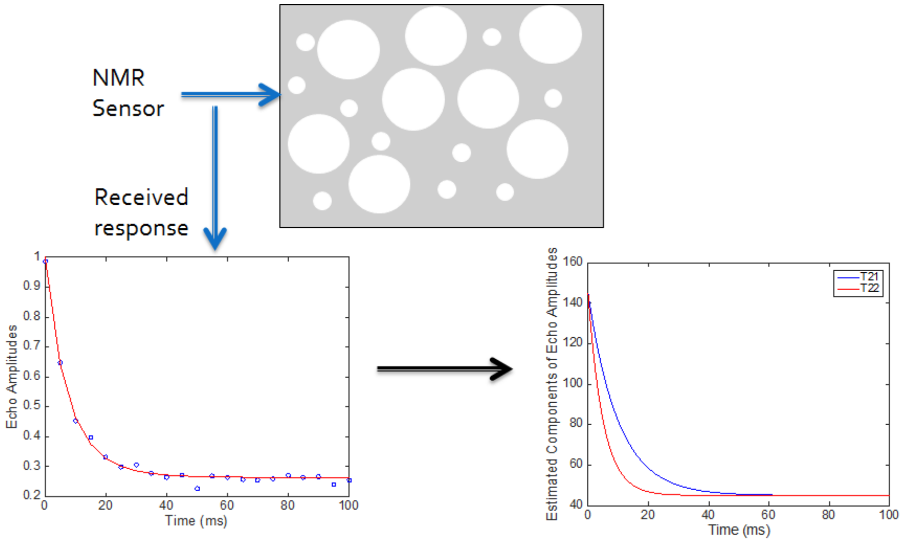


Figure A-III.2: In NMR inversion, the received response is decomposed into components by non-linear inversion and modeling

After T_2 distributions are estimated (see **Figure A-III.3** below), the water saturation characteristics of rocks can be decomposed into bound and free water using empirically derived partitions on $P(T_2)$ as the T_2 distribution reflects the porosity bins. Freedman (2006) reports that for sandstones, a T_2 cutoff of 33 msec separates bound water from the free water. Of course, there are important calibration issues for such thresholding operations. A detailed discussion is given by Freedman (2006).

Others have reported that for carbonates the T_2 cutoff is much larger (Westphal *et al* 2005) and these large T_2 values might make it more difficult determine a threshold cutoff value for T_2.

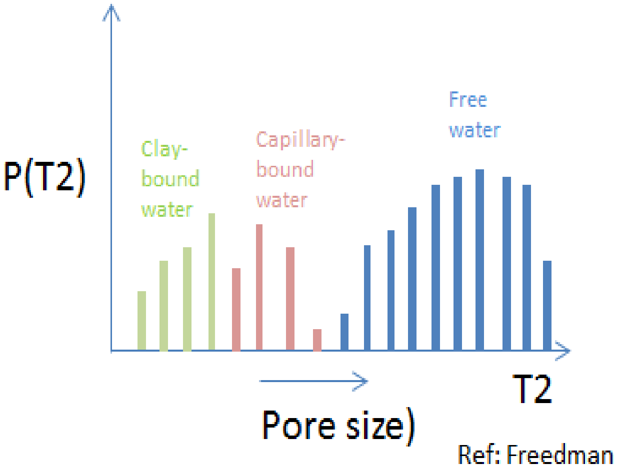


Figure A-III.3: An example partitioning of T_2 distribution for water saturated sandstone into bound and free water.

As discussed by many authors, a number of parameters can be derived from T_2 distributions. The key task is to define the threshold cut-off regions of T_2 axis, as shown in **FigureA-III.4**. Note that the measured time-constant is a bulk relaxation time and is sensitive to viscosity and temperature. For porous rock, the time constant is dependent on the ratio of the volume over surface of the pores in the rock. In summary, T is inversely proportional to surface relaxation ρ of the rock:

$$\frac{1}{T} = \rho \left(\frac{S}{V}\right)_{pore} \qquad \text{(A-III.2)}$$

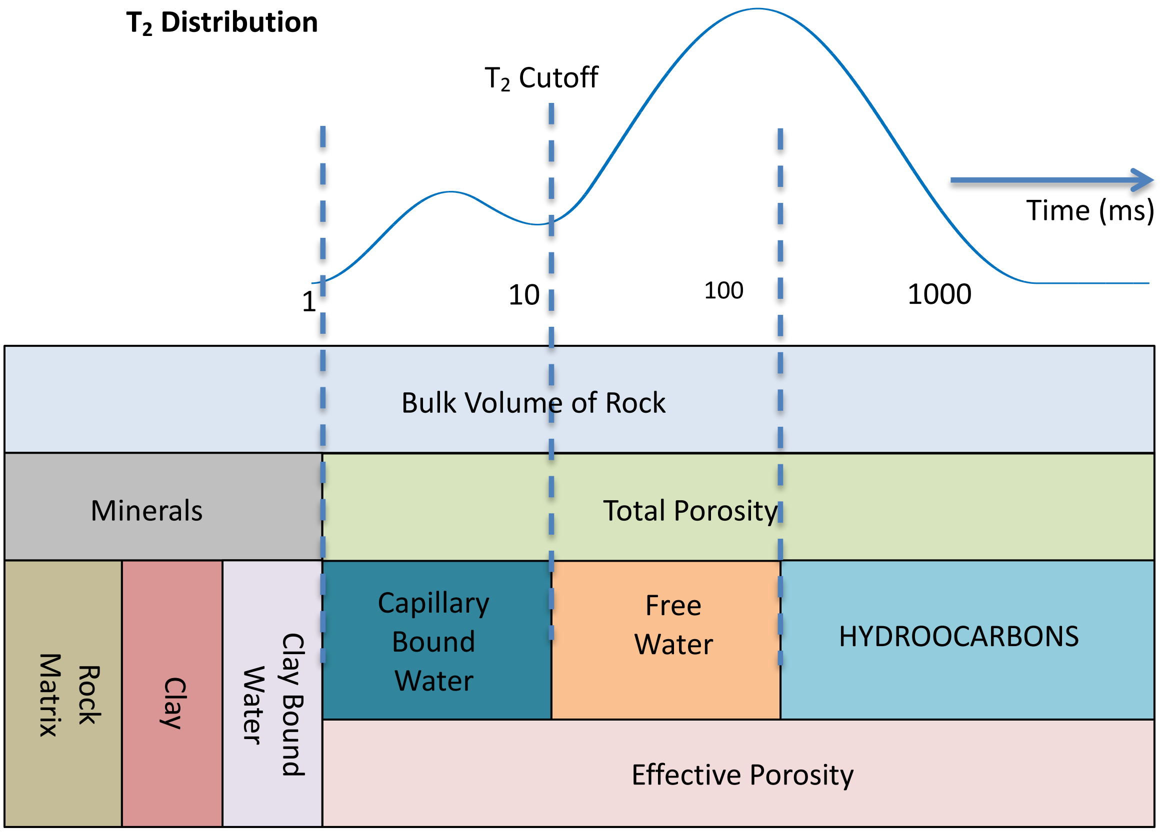


Figure A-III.4: An illustration on how T_2 distribution on porosity can be mapped onto various petro-physical parameters

From the above relationship of the relaxation time constant, and surface relaxivity (23 um/s for sandstone, 5 um/s for dolomite, and 3 um/s limestone) the pore throat size can be determined. While NMR is sensitive to <u>bulk porosity</u>, the measured signal is also sensitive also to pore sizes, and thus to the microscopic textural characteristics of rocks. NMR is also used to determine the amount of bound water and estimate rock permeability.

The other main NMR-derived parameters include permeability (K) and various fluid saturation parameters [Banavar and Schwartz 1987; Allen *et al* 1988; Pittman 1992]. Permeability (K) is a dynamic characteristic; so empirical relationships estimate this parameter. Some of the well-known empirical relations are given below.

$Timur / Coates:$

$$K \propto \Theta_{NMR}^{4} \left(\frac{FFI}{BVI} \right)^{2}$$

$SDR:$

$$K \propto \Theta_{NMR}^{4} \ (T_{2\log})^{2}$$ (A-III.3a) and (A-III.3b)

where FFI/BVI is the ratio of the free and bound fluid index obtained from the distribution of the estimated relaxation distributions, P(T). Note that since these relations are empirically derived, the exponents, in general can be different from the values cited for them. One approach to estimate FFI/BVI is shown below. Integral over short and longer relaxation time distributions are used to derive the required parameters.

$$\frac{FFI}{BVI} = \frac{\sum_{32,\ldots,\infty ms} P(T_2)}{Max\{\phi_{NMR}, \sum_{4,\ldots,16\mathrm{ms}} P(T_2)\}} \qquad \text{(A-III.4)}$$

For formations such as carbonates and sandstone reservoirs, the pore size distribution might be quite much more complex as there are multiple pore sizes or vugs in such formations. When T_2 distributions are directly related to pore-size distribution, this more simplistic interpretation could lead to errors in T_2 cutoff points, and thus could also lead to inaccurate estimates of permeability. However, significant progress has recently been reported to address these types of problems and solution have been developed using differential spectral methods that utilize multiple wait and echo times, and also multiple frequencies to obtain very high resolution and high SNR distributions.

Diffusion: Molecular diffusion also plays an important role in the analysis of NMR signals. Typical values of rock surface relaxation is about 5 μ m /s in sandstones to about 1.7 μ m /s in carbonates. In fact, NMR is routinely used to further distinguish the various relaxation times, including bulk relaxation, surface relaxation and diffusion relaxation, and the measured total relaxation time is the harmonic mean:

$$\frac{1}{T_{relaxation}} = \frac{1}{T_{Bulk}} + \frac{1}{T_{Surface}} + \frac{1}{T_{Diffusion}} \qquad \text{(A-III.5)}$$

Multiple wait times are used to compute what is known as differential spectrum to perform diffusion contrast into its components and derive very high resolution viscosity and even pore-size distributions. Viscosities are computed using empirical relationships that relates T_2 distributions, $P(T_2)$, to viscosities of crude oils. For example, the viscosity, η, is estimated by the relationship [Freedman and Heaton 2004]:

$$\eta \propto \frac{Temperature}{T_2^{Log-mean}\, F(gas/oil\ ratio)} \qquad \text{(A-III.6)}$$

where the function F(gas/oil) is described in detail by Lo *et al* (2002).

Finally, diffusivity versus T_2 can provide valuable information in oil/gas exploration, as illustrated in **Figure A-III.5** below.

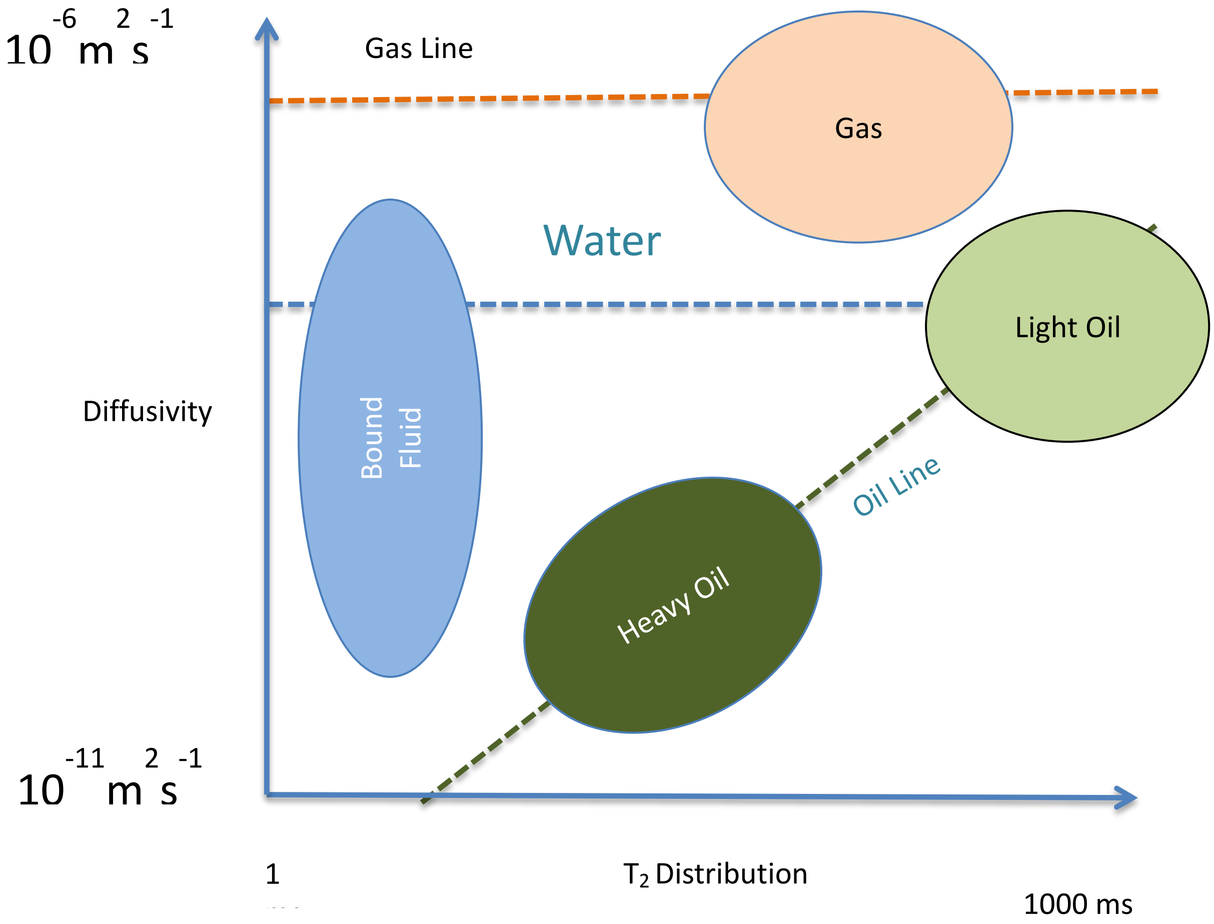


Figure A-III.5: T_2 distribution versus diffusivity can be used to discriminate the fluid using NMR analysis, a process known as fluid typing.

In an example in the main body of the report, we illustrate the use of molecular diffusion to resolve subtle differences in fluid types in complex conditions that conventional logs or even NMR T_2 distribution may not be able to resolve, and where standard formation pressure gradient and fluid testing method, which are generally robust fluid typing methods, are difficult to apply. For NMR T_2 distribution, the difficulty arises from the inability to always separate oil from salt water in partially saturated formations as crude oil and gas make NMR response complex. The difference in the NMR-supplied diffusion coefficients of oil, gas, and water are distinct and can be used to resolve fluid types.

Effect of paramagnetic minerals on T_2: We noted that NMR porosity is lithology-independent in the traditional sense that it is not affected by dry clay type. However, we also noted that the T_2 cutoff input in determining porosity differs between clastic and carbonate rocks. In addition, presence of paramagnetic minerals in the reservoir rocks can alter the T_2 [LaToracca *et al* 1995; Foley *et al* 1996]. In addition, as noted previously, work by Rueslatten *et al* (1998) showed that presence in the reservoir rock of certain clay types, depending on their grain size, can alter the T_2 and lead to erroneous porosity values and thus an inaccurate permeability estimation. This arises from a pore-size paramagnetic material adding a magnetic gradient term to the $1/T_2$ equation noted above.

III-3. Commercial NMR Tools

Some of the most useful NMR tool includes the Schlumberger's Combinable Magnetic Resonance tool (CMR) (Kleinberg 2001) and NUMAR's Magnetic Resonance Imager Log (MRIL, now part of Halliburton) (Coates *et al.*, 1999). We discuss the difference among these different NMR tools in the following.

First-Generation NMR Tools . As mentioned earlier, the first generation NMR logging tools, used between 1960 and 1994, were based on Earth's magnetic field and measured free-induction decay; polarization was achieved by direct currents through coils. For these instruments, polarization was time-consuming, and the 0.5 gauss Earth's magnetic field resulted in low SNR data. A detailed discussion of this tool is given by Brown and Neuman (1982);

Pulsed RF NMR Tools**.** The pulsed RF NMR tools are also referred to as "inside-out" NMR designs, as "inside" coil interrogates the "outside" formation rock, a design that is inverse of laboratory NMR designs. The borehole diameter limits the size and strength of the permanent magnet, and hence these borehole NMR tools operate at relatively low frequencies, less than 2 MHz; the first generation NMR tools operated only at around 2 KHz. To improve the SNR, pulsed NMR employs thousands of echo's and uses stacking methods to improve the SNR. One of the most distinct differences between the first and the second generation NMR tools is that the latter introduced the T_2 relaxation time as the primary measurement and therefore allowed faster logging speeds.

Other features include: (i) use of lower power by employing stronger permanent magnets; (ii) ability to focus at some distance, up to 4.5 inches beyond the borehole wall, and thus also avoiding mud signals; (iii) ability to control both resonance at Larmor frequency and also pulse duration for porosity and fluid-typing measurements. There are other variations in wireline NMR tools. The MRIL is a centralized device, whereas, Schlumberger's CMR and Baker-Hughes' MReX require contact with the borehole wall. Modern NMR logging tools operate at several frequencies, with lower frequencies having deeper depth of investigation (DOI) into the formation, and also allow multiple echo trains using multiple values for wait times, T_w, and echo intervals, T_e, for faster T_1 acquisition times. This allows both logging speeds to be optimized and invasion effects to be minimized. The CMR Plus has increased logging speeds utilizing 30" magnets and below 6" of the measurement RF antenna. This tool also pre-polarizes for increased logging speeds and improved resolution at short T_2 for clay-bound water. MREL Prime also has multiple frequencies of operation that increase logging speeds and discriminate rock properties at different depths of investigation.

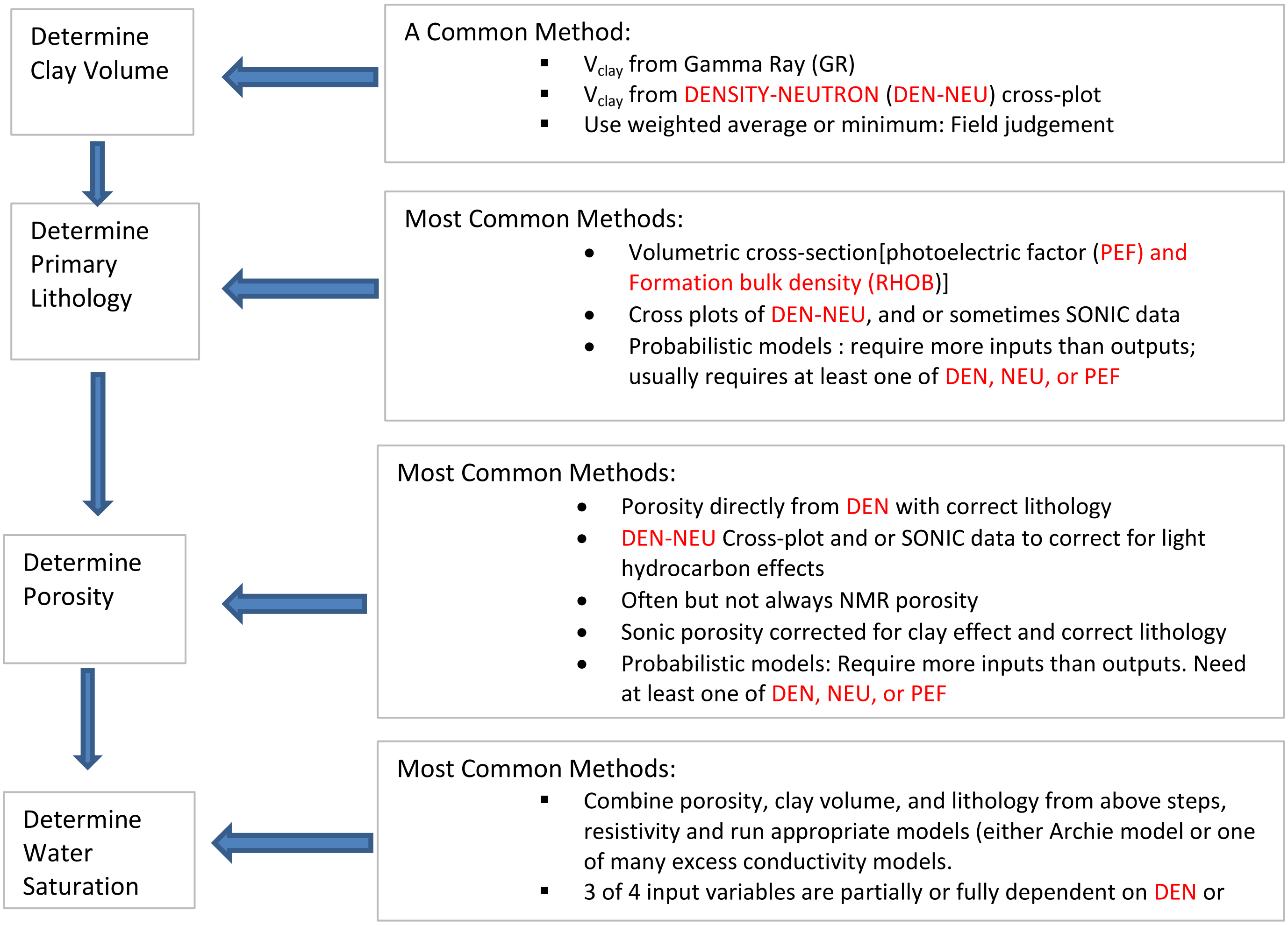
Appendix B

Typical Petrophysical Workflows Utilizing Log Data

B-1. A Conventional Workflow

Figure B-1. A Typical Conventional Petrophysical Workflow (primarily in big oil companies)

Courtesy of Brett Wendt, VP of Technology, Soc. Petrophysicists and Well Log Analysts (SPWLA)



Determine Clay Volume

A Common Method:

- V_{clay} from Gamma Ray (GR)
- V_{clay} from DENSITY-NEUTRON (DEN-NEU) cross-plot
- Use weighted average or minimum: Field judgement

Determine Primary Lithology

Most Common Methods:

- Volumetric cross-section[photoelectric factor (PEF) and Formation bulk density (RHOB)]
- Cross plots of DEN-NEU, and or sometimes SONIC data
- Probabilistic models : require more inputs than outputs; usually requires at least one of DEN, NEU, or PEF

Determine Porosity

Most Common Methods:

- Porosity directly from DEN with correct lithology
- DEN-NEU Cross-plot and or SONIC data to correct for light hydrocarbon effects
- Often but not always NMR porosity
- Sonic porosity corrected for clay effect and correct lithology
- Probabilistic models: Require more inputs than outputs. Need at least one of DEN, NEU, or PEF

Determine Water Saturation

Most Common Methods:

- Combine porosity, clay volume, and lithology from above steps, resistivity and run appropriate models (either Archie model or one of many excess conductivity models.
- 3 of 4 input variables are partially or fully dependent on DEN or

Note: For porosity In a gas zone, a combination of DEN and NEU is typically used.

B-2. Unconventional Workflow: This includes use of U concentration from spectral GR tools and mineralogy from (n,ɣ) spectroscopy tools

Appendix C

Service company/designer Feedback

Table C-1

Service Company/ designer feedback on acoustic and NMR Techniques

Nonnuclear in general (NMR/Acoustic)	NMR/Acoustic service supplier?	Both: 3 Sonic only: 1 Neither:1
	View NMR or Acoustic as Am-Be/Cs137 replacement?	No: All
	Other non-nuclear as replacement?	No: All
	Limitations	Both minimal lithology info Vertical resolution and logging speed NMR: Washout tolerance, order of magnitude slower wireline logging speed (due to incomplete polarization) vs. nuclear; cost Sonic: Empirical porosity transforms, poor response
	Combination of these techniques as accurate as nuclear?	No; not always.
NMR, specifically	Tools used	CMR -1, MRIL-1, spectrometers -1 None-2
	Improving signal/noise ratio sought? If yes, would higher frequency w/ filtering and echo cancellation help	Yes, but need order of magnitude improvement Filtering is used; high frequency means very shallow DOI-increased sensitivity to invasion and borehole conditions
	NMR spectroscopy or imaging of interest?	interesting
	Current NMR tool does rock and pore-space connectivity?	Connectivity done through local knowledge-direct measure w/ NMR diffusion unlikely to be commercial. May add application, does not address lack of bulk density needed for seismic and geomechanics applications. One tool claims to do connectivity

Table C-2

Service Company/designer feedback on nuclear-based alternatives

Neutron Porosity	D-T generators	Deployed or plan to deploy such tools?	Deployed -1, Tested-1, only in cased hole -1, No -2
		Limitations to overcome to compute porosity	Differ from Am-Be response: All, except 1 -Loss of sensitivity at high porosity -Need measurements compatible with thermal neutron porosity (Am-Be porosity) - Does not look like Am-Be Can be made to look like Am-Be, but would be expensive for independents that do most of US land-based logging; prefer Cf-252. Reliability and service life are concerns but this company thinks they can get Am-Be equivalent or better answer
		(n,ɣ) spectroscopy-advantage?	Inelastic in addition to capture. Inelastic a direct measure of carbon and K two important elements; clearer Mg
	Other generators: D-D, T-T, DPF, etc.	Interest?	Yes in general-3, DPF-2, D-D-1 if counts up, T-T-1, Don't know-1 Not likely-1: D-D may give porosity but not inelastic (n,ɣ) spectroscopy. Pulsed nature of DPF is major drawback-no other advantages than its Am-Be-like neutron spectrum-likely fewer legacy data issues
		If yes, desired design attributes?	Neutron yield needs to be Am-Be level, up 2-3 orders for D-D
		If yes, interest in collaborating with national labs?	Yes-3 Not likely, but do not rule out-1 N/A-1
Density	LINAC	Do you see a LINAC replacing ^{137}Cs?	No-2; tool expensive Yes-1 Yes-1, if ^{137}Cs-like density possible, but unlikely; PE information difficult to extract
		If yes, Limitations	Too expensive; size, power consumption, duty cycle, reliability
	Inelastic (n,ɣ) density	Tested or deployed	Deployed-1(LWD) Tested but not deployed-1 Tested-1, but 0.05 g/cc error vs. 0.015 for ^{137}Cs No-2
		If yes, challenges?	Not accurate enough, do not provide PE and borehole images Accurate neutron transport correction and good borehole corrections required
	Other photon generators [like (d, nɣ) Be-9]	Interest, if counts increase?	Yes-3 Yes-1, but pulsed operation introduces additional significant complication on detector side No-1: Too expensive
		If yes, national lab collaboration?	Yes-3 Unlikely but not excluded-1

Table C-3

Designer Input on Desired Design Attributes, Cost Tolerance, and design-deployment Duration

Design Attributes	Nuclear generator tools	Neutron/Photon yield	Neutron: Am-Be equivalent (15 Ci) or better Photon: < 1 MeV, 10^{10}/sec
		Generator operation mode	Neutron: pulsed for D-T to take full advantage- Duty factor 10%-50% Photon: CW; will require 20% or higher duty cycle to simplify acquisition and reduce development cost
	General	Temperature tolerance	150 deg C-175 deg C (under normal operating conditions.)
		Pressure tolerance	20,000 psia or higher
		Shock	LWD: 1000G, 1 ms half sine, 1000 shocks per axis Wireline: 40G, 11 ms 20 shock per X/Y axis and 40 shocks z axis
		Vibration	LWD: Random vibration 5 to 500 Hz, 20 g rms, X, Y and Z axis, 4 hrs. per axis Wireline: Random vibration 5 to 500 Hz, 7.5 g rms, X, Y, and Z axis, 2 hours per axis
		Power requirements	< 50 watts -1 < 500 watts -1 100 watts – 1
		Tool size	Length: < 12 ft up to 6 ft more for generator and electronics Diameter: Varied- 3.5 in-1.7 in – 1 Weight: N/A
		Telemetry	No different requirement, wireline, mudpulse or EM
		Heat removal requirement?	Prefer no active cooling; none
		Other: Regulatory regime	Generators are safe, but regulations for their life cycle handling requirements, storage, shipment, abandonment are the same as those of radionuclide sources. Regulatory regime does not recognize difference between generators and chemical sources. Abandonment rules, unless differentiated, offer no benefit to customer
		Calibration	Unchanged. All safety issues must be resolved a priori; can be handled using current facilities (integrated service companies)
		Interpretation complexity	No issue if spectrum similar to Am-Be Corrections required for wellbore and formation variability, in-situ interpretation and iteration required during acquisition
		Post-processing requirements?	Real-time output, but also ability to post-process, especially if multiple parameters and combination with other tools if needed
Cost to design, test, and deploy		Insurmountable in your org?	No answer -1; High-1; Unaffordable-2; Similar to current D-T – 1; development cost due to special handling required of generators. Manufacturing cost similar to Am-Be but more than ^{252}Cf
		If yes, would you accept government support?	No-1; yes-1 (in conjunction with their tool suppliers); Not possible to answer now-1; No answer -1
Duration of Concept-to-deployment		3-10 years. Up to 10 years acceptable	

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