Methods to Identify Product Placement Behind Pipe
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EXECUTIVE SUMMARY

Petroleum Technology Alliance Canada (PTAC) has engaged InnoTech to determine what methods may be used to identify the placement of sealing products behind steel casing in wellbores, particularly during well remediation. Confirming the placement of these products provides an assessment of likelihood of hydraulic isolation in the annular area between casing and formations or the existing cement.

Well remediation is complex and many different repair methods may be deployed. Various types of wellbore evaluation tools have been developed to assess well integrity and to provide technical guidance for these operations. The vast majority of well interventions to restore hydraulic isolation behind casing has historically utilized oil well cement as a sealing product.

Due to some shortcomings of cement, new products have been undergoing development to address applications where traditional remedial cementing is not adequate. Operators want to know how effective these products are and to confirm the final placement behind casing.

A series of cased hole cement evaluation tools has been in service for many decades which are designed for assessing cement quality. This project examines how cement evaluation logs and other cased hole logging tools may be utilized to identify the placement of alternate products behind casing. These technologies are summarized as follows:

1. Temperature and passive noise logs.
2. Legacy cement bond logs (CBL) which utilize 3 and 5 foot receivers, and which are now also referenced as a type of cement evaluation logs.
3. Modern cement evaluation logs particularly high frequency sector and segmented tools.
4. Deploying gamma emitting tracers with the products and running spectral logs.
5. Deploying boron / borax with the products and running pulsed neutron logs.
6. Magnetic detection with electromagnetic pulse tools.

Many alternate products have a range of properties that can be tailored depending on the blend of components. In this report the properties of alternate products are discussed as much as practical with respect to the recommended operating ranges of the logging devices.

Guidelines for using the subject logging tools are included in this report and one device will not be suitable for all applications. In many instances it may be advisable to use more than one tool in a logging suite depending on the specific conditions and sealing product that is deployed. Whoever is planning the well intervention will determine the most cost-effective approach often with input from other technical experts.

The key recommendations which have resulted from this project are:

- The guidelines in this report should be provided to DACC of Energy Safety Canada for consideration in future updates to industry recommended practices (IRPs).
- Alternate products should be assessed for acoustic velocity, density and acoustic impedance of the product blends to determine their suitability of identifying placement with cement evaluation logs before the products are placed in the wellbore.

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1.0 INTRODUCTION

Approximately 460,000 wells have been drilled in Alberta since the 1880s. Technology, best practices, and rules related to well integrity, well remediation, well abandonment (closure), the environment and emissions have changed immensely over the last 130 years. Alberta currently has roughly 40,000 wells that are leaking to surface and about seven percent of new wells drilled in Alberta leak from the time they are drilled and completed.

Most wells in Alberta with surface casing vent flow (SCVF) or gas migration (GM) leak at very low rates. Some legacy wells which are not leaking to surface still require hydraulic isolation between porous formations in the wellbore. The AER has information which indicates that roughly 17% of wells that were repaired before abandonment end up leaking again in Alberta.

More than one formation in a wellbore may contribute to a leak and some porous formations may function as temporary 'storage' intervals. Consequently, the assessment and remediation action can be four dimensional, in other words it can change with time. It is critical to collect reliable data and to eliminate variables when conducting this work.

Cement has been an incredibly useful product in well construction and has excellent applications but remediation of wells with low leak rates is particularly challenging when using traditional cementing procedures. It is very difficult to pump a cement slurry containing particulate matter into a tiny fracture or channels where high-pressure gas can easily flow. Also, cement shrinks when set. Improved and cost-effective methods of repair work on leaking wells is critical for some well remediation operations.

A number of alternate sealing products have been developed for well remediation which have far superior properties to cement in specific applications. The use of these products has been emerging slowly, but some questions still need to be answered.

Energy Safety Canada with the drilling and completions committee (DACC) produce industry recommended practices (IRPs) which fill regulatory gaps and which provide valuable guidance to industry. IRP 26 *Wellbore Remediation,* has recently been sanctioned and this IRP has some information on the use of alternate products in well remediation.

PTAC and InnoTech can play important roles in deploying science, technology development and industry knowledge to field applications for the benefit of all Albertans. Emissions from leaking wells is a world-wide problem. Solutions developed in Alberta can be exported to create employment and expanded business for Albertans.

A second report called 'Drilling and Primary Cementing Best Practices for Well Integrity' has been provided as part of this PTAC project. In that report well integrity throughout the full well life cycle was discussed.

2.0 WELL AND AREA HISTORY

2.1 Well File Review

One of the most important steps in conducting a well remediation in a cost effective and safe manner is to ensure that all relevant data is utilized. These records range from original drilling and cementing activity to workovers, including all intervention work to the current time. The well integrity status of a well can be four dimensional and change over time.

ESC IRPs 25 *Primary Cementing* was published in 2017 by DACC of Energy Safety Canada and a new IRPs 26 *Wellbore Remediation* has been sanctioned. IRP 27 *Well Abandonment* is expected to be released soon. These IRPs provide excellent guidance for utilizing the available information and best practices related to well integrity.

When a SCVF or GM leak is clearly understood with variables minimized, the chances of planning and executing a successful intervention are much higher. Selection of the optimal repair method and sealing products is part of the process. This includes identifying where hydraulic isolation is required and after the intervention confirming if sealing materials were placed as designed.

2.2 Area Review and Experience

Local knowledge and field experience are very valuable when filling information gaps and eliminating confusing variables during the planning and execution of well intervention work, especially well remediation.

It is critical to communicate with local service providers and it is often very helpful to investigate what other producers have learned when conducting similar work in the area. Regulators do not require all well intervention details to be digitally reported. Sometimes key information is not readily available to the public.

Companies often learn techniques which are not reported or shared in technical reports and presentations. Frequently the learnings are lost when personnel change positions, however the local field personnel usually remain and can be an excellent source of information.

When there is uncertainty regarding the rules related to the use of alternate products in well remediation, producers / licensees may be reluctant to disclose their successes in writing. It is important to encourage open communication as well integrity should not be a competitive activity among producers.

3.0 ACOUSTIC AND TEMPERATURE LOGGING

3.1 TRADITIONAL DEPLOYMENT OF PASSIVE ACOUSTIC AND TEMPERATURE LOGS

Two primary challenges in conducting remediation of leaking wells are identifying the formation sources of the leaks and selecting the optimal locations in the wellbore to conduct the operation to restore hydraulic isolation. A common practice is to run cased hole sound and temperature logging tools to help addresses these issues. All logging tools are calibrated and recorded to well depth and can be correlated to formation tops.

Passive acoustic logs are designed to detect the sound of fluid (liquids or gas) movement behind the pipe. These are not to be confused with other types of acoustic logs which are utilized for evaluating the cement behind casing and these are addressed later in this report under cement evaluation logging.

The temperature log measures a temperature profile of the wellbore and displays the temperature variance from the expected background profile. A temperature shift can result from fluid movement sourced from a formation at a different depth or from fluids pumped into the wellbore. When gas is flowing behind casing, a drop in the temperature profile is commonly observed due to the Joule Thompson effect (JT) of the flowing gas expanding from a restricted area to a larger area.

Deploying these logging tools before and after a well intervention can help identify the relative degree of hydraulic isolation (stopping the flow) that has occurred from placement of the sealing product.

Advanced logging devices, particularly those using fiberoptic technology or advanced spectral noise tools combined with powerful computation abilities, continue to expand their application scope. When a dynamic profile of fluid flow outside of the casing may be interpreted, it helps assess the leak sources, the storage effects, the optimal approach for intervention and the results of a remediation attempt.

Because of the number of variables involved in well remediation, careful selection and deployment of other cased hole technologies besides acoustic and temperature logging will usually help reduce costs, minimize variable and improve outcomes.

3.2 IDENTIFYING PRODUCTS WITH EXOTHERMIC REACTION

Temperature logging after conventional cementing is a common procedure used to locate a cement top behind casing if the cement top has not been observed at surface. With primary cementing, the maximum heat evolution will typically occur 8-10 hours after hydration and a temperature log run 8-24 hours after hydration may enable the cement top to be identified.

Temperature logs may be run sooner than 8 hours after cementing by running two logs at different time intervals, typically within a couple hours of cementing. Smaller temperature changes are observed in the beginning stages of the exothermic event that identify cement placement. This may be particularly useful with concentric casing strings where cement evaluation logs are not effective to determine cement placement. This is in part possible when using modern hi-res RST platinum temperature probes.

When highly exothermic products such as resins are squeezed behind casing, a temperature log may identify where the top of the sealant is located behind the casing provided the logging is conducted while the material is still reacting and provided that enough product has been placed. As with cement placement, a procedure can be deployed to help identify the placement of the alternate product when concentric casing strings are in place.

This method of detecting product placement is widely understood. However, caution must be taken to ensure that the product and the volume of product placed will produce enough heat energy to be detected by the temperature log of choice. If the size of the leak pathway is unknown, it is advisable to estimate the size or capacity of the flow path before placing the sealant. This may be possible by perforating through casing and establishing a feed rate (injection rate) with clean water into the leak pathway, by running a cement evaluation log which produces an image of the cement outside of the casing or by other means.

For exothermic reactions, a temperature log on its own will not provide sufficient information to confirm if the sealing product has achieved hydraulic isolation in the wellbore. Advanced cement evaluation tools, which provide an image of the cement or sealant behind casing, run before and after the squeeze can provide additional information.

4.0 CEMENT EVALUATION LOGGING

4.1 Background and Applications

Cement bond logs or CBLs have been used for many decades to provide an assessment of cement quality between steel casing and the rock face in a wellbore. These are logging tools that transmit an acoustic signal into the casing and then measure the amplitude of the return signal at the tool receivers. Casing in contact with the cement sheath will have lower amplitude reflections, or more attenuation, and the signal will die out faster than with casing that is not 'bonded'. Casing that is not in contact with cement will 'ring' like a bell from the induced acoustic energy.

A cement bond log refers to the bond between casing, cement and formation, derived from the first arrival of amplitude back to the receiver and also the analysis of the full acoustic waveform through observation of the variable density log (VDL).

A 'bond index' is used to identify the relative quality of the casing to cement bond at a point in the wellbore. The bond index is a ratio of the acoustic attenuation at this point divided by the attenuation at a point in the wellbore where the bond is interpreted as being very good. API 10TR1 advises against using Bond Index. The technology in modern segmented tools supersedes the concept and some experts believe a bond index should be used with caution.

These tools typically have the capacity of VDL which uses the amplitude and frequency characteristics of the full waveform. The VDL log provides an indication of the degree of cement contact to the formation. This is derived from a 5 ft (far) receiver that allows for shear wave identification within the waveform which is a typical result of formation response of the acoustic signal. A poor contact, or bond, of cement to formation is a common cause of the loss of hydraulic isolation behind casing.

No logging tool can directly measure the ability of cement to provide zonal isolation to stop fluid flow behind the casing, but acoustic logs can help confirm cement placement outside the casing and provide insight into the likelihood of zonal isolation. This technology has undergone tremendous advancement over many decades, resulting in the current suite of tools now referred to as cement evaluation logs.

In IRP 25, *Primary Cementing*, (https://www.energysafetycanada.com/_Resources/DACC-IRP-Volumes/DACC-IRP-VOLUME-25-PRIMARY-CEMENTING) Section 10.2, Cement Log Evaluation, is an excellent source of current information related to cement evaluation logging.

Cement evaluation tools are often classified according to the frequency of the sound waves they employ. The two classifications are sonic (low frequency) and ultrasonic (high frequency).

Sonic and low-ultrasonic evaluation tools:

- CBL – Cement Bond Log; typical frequency range of 20-30 KHz with one transmitter and one or two omni-directional receivers
- CBT – Compensated cement bond log; similar to CBL but with two transmitters and three receivers. Typical output of attenuation as opposed to amplitude

- SBL – Sector bond log; similar to the CBL but with the addition of an additional receiver with 6-12 sectors that are directionally focused to provide phased sectors of acoustic response. Intended to identify channels.
- SBT – Segmented bond tools; a pad tool with multiple arms that typically has a transmitter and receiver on each pad and arranged to detect a matrix of attenuation. Often combined with a 5ft (far) receiver as well to capture VDL for detection of bond to formation.

Ultrasonic evaluation tools:

- Ultrasonic imaging tools (USIT)
- Circumferential acoustic scanning tool (CAST-V)
- UltraSonic Radial Scanner (URS)
- Isolation scanner
- Magnetic resonance

A new type of cement evaluation tool has recently been developed which uses electromagnetic acoustic transducer (EMAT) technology to induce wave movement into steel casing without an acoustic source. The EMAT tool allegedly has superior performance with light weight cement and with foam cement. It apparently does not require the casing to contain fluids or a pressure pass to assess a micro-annulus.

Cement evaluation logs were originally designed around the acoustic properties of oil well cement, steel casing, rock formations and wellbore fluids. The key property of the materials is acoustic impedance which is the result of multiplying density and acoustic velocity. It is expressed as Z (acoustic impedance) = ρ (density kg/m^3) x V (acoustic velocity m/s).

The SI unit of acoustic impedance is the pascal second per cubic meter (Pa·s/m^3) or the rayl per square meter (rayl/m^2). A rayl equals Pa·s/m. In cement evaluation logging the measurement used for acoustic impedance is referred to as Mega Rayl (MRayl).

Oil well cement has a range of acoustic impedance from a little over 1 to ~ 5.5 MRayl. Figure 1 from Schlumberger below illustrates the acoustic impedance range of some other wellbore fluids relative to cement.

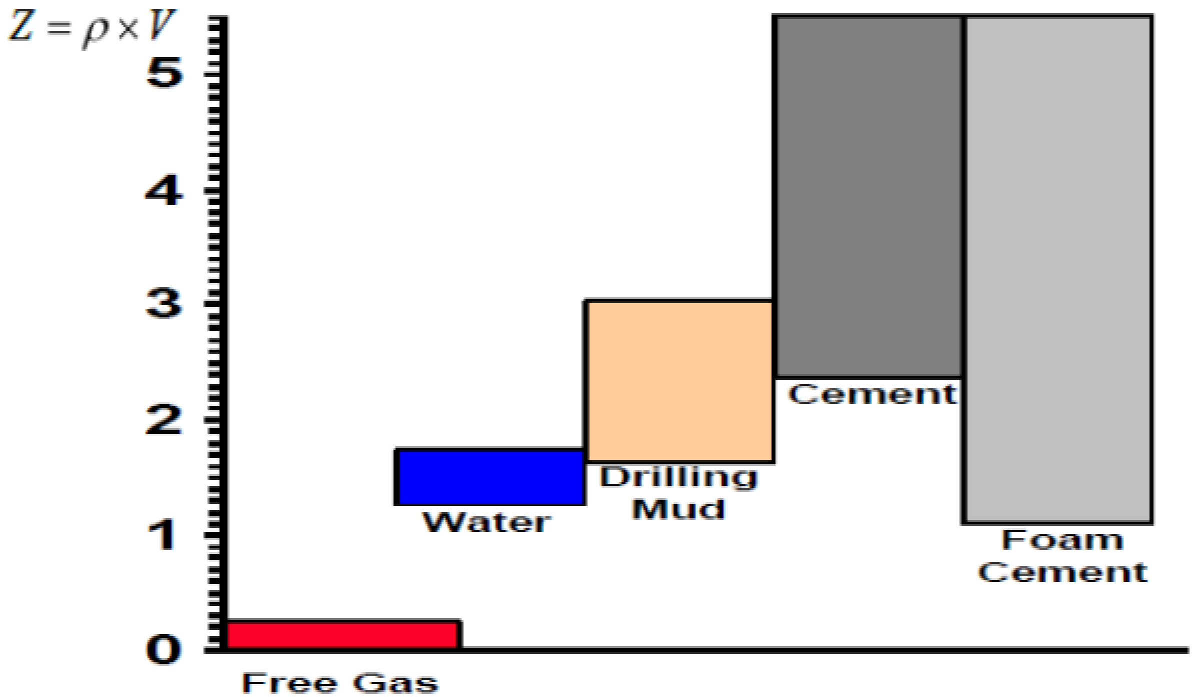

Figure 1 – Acoustic Impedance Chart from Schlumberger Oilfield Services Company

Alternate products that have an acoustic impedance within the same range as oil well cement may be detected and evaluated in a similar same manner as cement when placed behind casing. Because alternate products can be blended with a wide variety of components, it is recommended that the acoustic impedance be determined for each blend that is pumped when the placement may need to be identified with cement evaluation tools. It is important to know if the acoustic impedance is outside of the normal range for cement and having an accurate value will provide guidance for interpreting cement evaluation logs.

Some alternate products have higher elasticity than cement resulting in a higher attenuation or impediment of wave propagation when assessing with cement evaluation logging. An enhanced method of interpreting cement evaluation logs has been developed when this type of product is placed behind casing.

A paper presented at the Society of Petrophysicists and Well Log Analysts (SPWLA) 55th Annual Logging Symposium in May 2014 outlined an interpretation procedure for high elasticity products. The authors were I. Foinini, G. Frisch and P. Jones and the paper was titled Successful Identification And Bond Assessment of Epoxy-Based Resin Cement Behind Production Casing: Integrating Cementing Technology With New Log Interpretation Methodology To provide An Innovative Well Integrity Solution.

Some key information in this document that may help identify the placement of alternate products is as follows:

- Ultrasonic tools can identify the presence of resins when casing coupling exists but are unable to determine annular volume or formation bond.

- The novel method combines visual and analytical interpretation of sonic and ultrasonic data sets by mean of cross plot correlations to determine unique product characteristics in a multiple slurry system.
- The types of cross plots that were utilized were (1) average amplitude vs average acoustic impedance and (2) average acoustic impedance vs average derivative of acoustic impedance.
- CBL information on its own is likely not effective enough in determining the presence and bonding of some resins.

The most technically advanced cement evaluation tools can provide additional information and are recommended when attempting to identify the placement of alternate products. Segmented (SBT) and Sector (SBL) cement evaluation logs are designed to identify channeling in the annular area (a cement map around the casing). An ultrasonic tool design may be the best option. These tools are referenced in this report and additional information is available in IRP 25. Ultrasonic cement evaluation tools should not be confused with ultrasonic casing inspection which have significant differences in focal distance and responses.

Good cement evaluation logging results are not a guarantee of zonal isolation. Tiny channels within the cement sheath and pathways at the cement formation interface may not be identified with current technology.

4.2 Sector Logs (SBL)

An SBL log is designed to provide a number of outputs and this tool has the ability to identify channels where cementing, or hydraulic isolation, may not exist in the wellbore. It utilizes multiple directional receivers with each receiver-transmitter pair contacting a portion of the casing. Wellbore fluids and materials can make interpretation complex when using these tools.

When some of these tools are properly calibrated, they may be able to identify the presence of gas or air behind casing. This will be observed by amplitudes that are higher than expected for unbonded casing with liquid behind it, which is what most CBL charts will present as "Free Pipe".

4.3 High Frequency Segmented Logs (SBT)

A six-arm high frequency, SBT is generally considered one of the most advanced cement evaluation tools. This tool provides a 360 degree display of the cement quality around the outside of the casing. The tool pads make direct contact with the casing and the impact of tool decentralization is minimized.

The acoustic impedance (related to the compressive strength) of the material in the annulus is determined by analyzing a portion of the received waveform. The strength of the measurement is in the high spatial resolution which can help in identifying narrow cement channels. A relatively low sensitivity of the ultrasonic tools to wet micro-annulus can aid in the bond interpretation in the absence of a pressure pass. Characteristic patterns in the cement log image can identify the location of casing centralizers and also yield qualitative indications of casing centralization.

4.4 ULTRASONIC EVALUATION TOOLS

Ultrasonic bond logging tools are used for both cement and casing evaluation. These tools typically use a single rotating transducer as both an emitter and receiver of an ultrasonic signal.

With respect to cement evaluation, the acoustic impedance of the material in the annulus is determined by analyzing a portion of the received waveform (determined by the form of the resonance). The high spatial resolution can help identify narrow cement channels. A relatively low sensitivity of the ultrasonic tools to wet micro annulus can aid in the bond interpretation in the absence of a pressure pass. Patterns in the cement log image can identify the location of casing centralizers and can also yield qualitative indications of casing centralization.

In a typical ultrasonic log display, two-dimensional images of cement coverage around the pipe circumference may be shown as either a raw image without interpretation of material type or with a colour coding that differentiates solids from liquid or gas based on acoustic impedance thresholds or cut-offs. These images indicate the following:

- Intervals of continuous cement coverage without evidence of channeling suggest possible isolation.
- Low acoustic impedance, de-bonded or contaminated cement can sometimes be detected using variance based techniques that compare the acoustic impedance of each data point with surrounding data. The assumption is that solids typically show greater variability in acoustic properties than do liquids. Individual service companies implement variance based processing in different ways.

Flexural mode is a variant of ultrasonic bond measurements that incorporates the conventional pulse-echo ultrasonic mode with a second mode that imparts a flexural wave into the casing. By comparing to a laboratory database of acoustic impedance and flexural attenuation, the interpretation can be enhanced for light weight and contaminated cement. It is anticipated that this technique can also be applied to alternate products with a density or acoustic impedance similar to light weight cement.

Echoes reflecting from the cement-formation interface can often be detected which provide information about the conditions out to the formation or inner wall of a second casing string. These echoes are referred to as third interface echoes (TIE). TIE applications are used to identify casing position within the hole and the velocity profile of the annular material.

Casing corrosion can impact the ultrasonic cement map. Areas of extensive pitting corrosion will disperse the ultrasonic energy resulting in a noisy cement image.

Some ultrasonic tools can also be used for casing evaluation but with different settings for the focal range. The primary outputs of ultrasonic tools when used for this purpose are as follows :

- Inner casing wall condition (qualitatively inferred by the amplitude of the initial echo)
- Inner casing radius (determined by the two-way transit time)
- Wall thickness (derived from the frequency of resonance)

5.0 GAMMA EMMITTING TRACERS & SPECTRAL LOGGING

5.1 GAMMA EMITTING TRACERS

The use of gamma emitting (GE) tracers with spectral gamma ray (SGR) logging tools is an established technology practice for identifying the placement of injection fluids, fracture proppant and cement in wellbores.

In a cased hole environment, the SGR is used to assess the placement and effectiveness of well stimulation operations and sand control operations, by monitoring GE tracers that are injected with the proppant. Common GE tracers include Iridium 192, Scandium 46, and Antimony 124. These isotopes also have characteristic gamma energies in the 0.1 MeV to 3 MeV range. Tool designers have indicated that it may be possible to extend the range of the SGR to 10MeV if alternate isotopes were to be used other than the common GE tracers.

Appendix A contains a recommended practice with considerable detail for the use of GE tracers and identifying the placement of these tracers using spectral gamma ray logging. The recommended practice includes safe procedures for utilizing GE tracers.

The recommended practice has focused on products from one supplier with proven safe procedures that do not result in radioactive contamination. The supplier manufactures GE tracer materials which are contained in ceramic beads. The ceramic beads vary in size and density and contain three different isotopes scandium, iridium and antimony. The names and properties of the GE tracer beads are listed below:

Low Density ZERO WASH

ZEROWASH		SG	API Mesh	Microns	Inches	Millimeters
Low Density	LD-SC	1.25	70-140 (100)	106 - 210	0.0083 – 0.0029	0.105 – 0.21
Low Density	LD-IR	1.25	70-140 (100)	106 - 210	0.0083 – 0.0029	0.105 – 0.21

2 Isotopes. Scandium and Iridium
Crush Resistance Strength. 41.37 MPa (6,000 psi)

ZERO WASH

ZERO WASH	Isotope	SG	Mesh	Microns	Inches	Millimeters
	SC	2.65	40 - 70	425 -210	0.016 – 0.0083	0.425 – 0.210
	IR	2.65	40 – 70	425 -210	0.016 – 0.0083	0.425 – 0.210
	SB	2.65	40 - 70	425 -210	0.016 – 0.0083	0.425 – 0.210

3 isotopes. Scandium, Iridium and Antimony
Crush Resistance Strength – 68.95 MPa (10,000 psi)

A consideration for using this product as a GE tracer to identify the placement of an alternate product as a sealant between casing and formation is the size of the ceramic beads and the annular area where the alternate product needs to be placed. This issue may be de-risked before attempting to place the product by establishing an injection feed rate into the area where the product is to be placed and or by running an ultrasonic cement evaluation log which provides 360 degree image of the cement outside of the casing.

If the particulate size of the GE tracer remains a concern, another method of identifying the placement of the sealing product should be considered. Similarly, if the alternate sealing product contains particulate matter and if injection capacity is a concern, a product which does not contain particulate matter should be considered.

The overall program should be reviewed with the GE service provider to ensure the best chance of success for identify the placement of alternate products.

5.2 Spectral Logs

An SGR logging tool is a downhole digital pulse height spectrum analyzer. This tool has been designed to measure both naturally occurring radioactive isotopes and common GE tracers used for fracture monitoring and other application.

Some naturally occurring radioactive isotopes such as potassium, uranium- radium series, and thorium series have characteristic gamma ray energies in the 0.1 MeV to 3.0 MeV range. Logging with SGR and analyzing the acquired spectrums also provides a method for improved through casing formation evaluation of shales, sandstones, carbonates, dolomites, etc. versus using the gross counts from a traditional gamma ray tool.

Conventional gamma ray logging tools do not have the sensitivity to identify trace amounts of the GE material and cannot differentiate between the three different types of GE tracers.

As indicated in Appendix A, the recommended practice is for using GE tracers and SGR logging from one service provider. Three different isotopes can be utilized in three different fluid blends. The Spectral logging tool is designed to identify the location of each isotope individually when blended with wellbore materials.

The half-life of these three GE tracers ranges from about 60 days to 83 days. It is important to plan Spectral logging within a few months of placing the product to ensure that the GE tracer material can be detected. If the logging time will be more than one month, the service provider should be notified so that the concentration of tracers can potentially be increased.

6.0 PULSED NEUTRON LOGGING & BORON - BORAX

6.1 Theory and Case Studies

There are two types of pulse neutron logging (PNL) tools, the pulse neutron/neutron (PNN) and the pulse neutron/gamma (PNG) tool. Most modern PNL tools have both PNN and PNG capabilities. PNN and PNG tools rely on very different responses. This section is mostly about PNG capable tools because tools with only PNN capability do not provide a gamma density response.

PNL logs are designed to generate a burst of high energy neutrons, or fast neutrons, which penetrate into the wellbore materials and rock formations. Thermal neutrons are then created from elastic and inelastic collisions with atomic nuclei in these materials. The PNN logging tool measures the rate of capture of thermal neutrons returning from the wellbore materials and the rock formations.

The capture of a thermal neutron normally results in the emission of one or more gamma rays and the gamma response is detected with PNG tools. These gamma rays are counted with PNG tools within specified time gates following the neutron burst. This count rate is inversely proportional to the thermal neutron capture cross section represented by the symbol sigma (∑).

The following table provides general information on PNG tools.

TABLE 3D.1—SELECTION OF COMMON NUCLEAR-LOGGING TOOLS: HOW THEY WORK AND WHAT LOG ANALYSTS REALLY WANT FROM THEM TO DESCRIBE HYDROCARBON RESERVOIRS

Tool	Physics Exploited	Reads	Desired Information
Gamma ray	Natural gamma rays	Gamma ray counts, K-U-Th counts	Clay type and bedding
Gamma density	Gamma ray scattering	Bulk Compton cross section	Formation density, porosity
Neutron porosity	Neutron slowing	Migration length	Porosity, lithology
Pulsed neutron	Neutron lifetime	Bulk capture cross section	S_w, porosity
Carbon/oxygen, geochemical	Neutron-induced gamma ray	Elemental count rates	S_0, lithology

https://petrowiki.spe.org/PEH:Nuclear_Logging

PNL logs (both PNN & PNG) typically have the following display channels correlated to the well depth:

- Formation Sigma ∑
- Far Counts (FAR)
- Near Counts (NEAR)
- Inelastic Counts (INEL)
- Diffusion Corrected Porosity (TPHI)
- Borehole ∑ (SIBH) when available

The various PNL outputs can be used to identify the presence of a channel, a gas oil contact, gas in the wellbore or formation and changes in wellbore fluids.

A larger sigma equates to a higher probability of neutron capture from a mineral or substance. Some minerals like borax have a very high sigma and can be used as a tracer material when injecting fluids into a formation or behind casing.

Borax is a readily available and naturally occurring mineral which contains boron. Boron contains two naturally occurring isotopes, boron 10 and boron 11. Boron 10 has an extraordinarily high sigma value of 3836 which is orders of magnitude larger than most isotopes.

An SPE paper # 25383 titled 'Channel Detection Using Pulsed Neutron Logging in a Borax Solution' was presented in 1993 by F. S. Sommer and D. P. Jenkins. This paper documented several case studies in the Alaska Prudhoe Bay oilfield in which borax was used as a tracer with PNL in dozens of wells. In Prudhoe Bay the operators selected this method to identify channels in the primary cement, leaking packers and leaking perforations that had been squeezed off.

Borax was also chosen because of its low cost, ease of handling, compatibility with the formations and safe use with onsite personnel. Borax has many common uses such as in water softeners and borax is normally available as a powder. In SPE 25383 and the Prudhoe Bay examples, borax was stated as being mixed at a ratio of 20 kg/m^3 (7 pounds/bbl.) in salt water and pumped with conventional oilfield equipment.

The assessment of hydraulic isolation in the Prudhoe Bay wells utilized saline water containing borax tracer as a transient fluid. Adjustments were made on the log interpretations for fluid containing the tracer which remained inside of the casing.

The SPE authors noted the importance of pretesting the borax solution with formation brines and surface solutions to minimize the risk of potential incompatibilities. It was determined that an insoluble precipitate, sodium borate, could form when borax was mixed with seawater. This issue was resolved by using fresh water and the water was also heated to 27 to 33 ^{o}C to ensure complete solubility of the borax.

It was also determined through core testing that boron adsorption could occur with the borate ion substituting for alumina and silica in the formation rock. This could have a longer term impact on future neutron logging interpretation as the boron which has been introduced may increase the measured return of neutrons and gamma rays when neutron logging.

Several other findings from this SPE paper are referenced with respect to using borax and PNL for identifying the placement of alternate products.

6.2 Applications With Placement of Alternate Products

When borax and PNL is under consideration for tracing the placement of alternate products in the annular area between casing and formation rock there are a number of variables to assess. It is important to discuss the plan with logging service providers to ensure that the service providers PNL tool is appropriate and has the necessary outputs.

Some other application considerations are as follows:

- Ensure that borax is compatible with the alternate product blend that is planned to be used as a sealant.
- Ensure that borax is compatible with the formation brine and rock, particularly if the sealant will be placed across a formation that is needed for production or injection.
- It may be necessary to estimate the size and geometry of the leak pathway and the concentration of borax that can be mixed in with the alternate product to ensure that enough volume can be placed to be detected with the PNL tool.
- Natural gas has a significant impact on the neutron log interpretation due to an increase in inelastic counts. It is advisable to circulate the well over to water before PNL to eliminate the variable of gas in the casing.
- It is recommended to run a baseline PNL before squeezing the alternate product containing borax behind casing or into a porous formation, then run the PNL after the product is placed and set.
- It is recommended that that no fluids containing borax remain inside of the casing when logging to ensure that a high sigma response is only from outside of the casing.

7.0 OTHER TECHNOLOGIES

7.1 MAGNETIC DETECTION LOGGING

There are several types of magnetic detection logging tools that may be utilized for detection of material placement using magnetic principles.

Electromagnetic pulse tools (EMT) are likely the most cost-effective option . There are several variations with the two prominent ones being the pad style Magnetic Thickness (MTT) and the Electromagnetic Pulse (EMT). These tools may be able to detect both ferrous materials as well as materials with magnetic fields. They work on the basis of generating a magnetic pulse and then looking for the magnetic field interruptions during a decay period.

Magnetic flux leakage (MFL) tools are pad style and rely on magnetic saturation of the pipe which in turn will "leak" magnetism (flux) which will then indicate a loss of metal (i.e. corrosion). Although a MFL is good for identifying corrosion, these tools may not be ideal for seeing the increase of magnetism or ferrous materials for the desired detection of cement alternatives.

Magnetic resonance imaging (MRI) tools are typically an open hole technology used to identify changes and properties of lithology and may be effective. These tools may be cost prohibitive for this application.

7.2 SEALED SOURCE NUCLEAR LOGGING TOOLS

Some examples of sealed source nuclear logging tools are CHAT and Quad Neutron tools which may have the ability to measure the annular material density. CHAT does this to a certain degree with a "cement" curve. Further technology development is required to apply these tools for the purpose of identifying the placement of alternate products behind casing.

8.0 ACKNOWLEDGEMENTS

I thank my career colleagues who have been part of my career journey. You have shared your expertise in production operations, reservoir development, drilling, completions, well workovers and closure and in other operational. Some of that skill is included in this report in some way.

Two industry experts have contributed to this report. As indicated in the report, Ian McConnell provided a 'best practice' on the use of gamma emitting tracers and spectral logging. Stephen Wierenga, a cased hole logging expert, provided valuable input overall into this study.

Steve has been in the Cased-Hole Wireline services sector of the Oil & Gas industry since 1991 with several cased hole wireline service companies, Steve held multiple roles in technical logging services with a focus on Well Integrity logging, including cement and casing integrity as well logging for annular gas flow detection. Steve's roles in specialty logging services included both operations and technical sales until 2016. He then started his consulting business, "That Wireline Guy". He currently provides technical training, operations support and log analysis specializing in well integrity tools supporting operations in both on shore North American and abroad. In his spare time, he also maintains a small Geo-Logging service specializing in Water Well and Mineral logging operations in Western Canada. Steve is currently based in Calgary, Alberta.

Ian McConnell is associated with the Envision Group International via his consulting company *Energy37 Consulting Inc*. His focus is on capital sourcing, leadership training, team development, strategy consulting, strategy alignment and training, organizational development, ESG training, AI implementation, technical and procedural writing, mentorship, SECOR & COR certification, change management and HSE manual writing/support. Ian assists in sales for completions diagnostics and discussions for Qualified Environmental Trust applications. Ian was on the PSAC board and proposed the Area Based Closure concept to the Alberta government and served on the committee for the more efficient decommissioning of oil and gas assets. Ian represented PSAC in the development of Industry Recommended Practice (IRP) 26 *Wellbore Remediation* and was Co-Chair of IRP 27 *Wellbore Decommissioning*.

Ian started in the oil and gas industry with Nowsco Well Service Canada and worked in Canada, USA, Europe, Africa and the middle east. His experience included fabrication/installation of Zone 2 classification offshore equipment for the decommissioning of the first subsea wells in the North Sea. He worked as a special advisor to a project for the UK government Dept. of British Nuclear Fuels Ltd. (BNFL) regarding deep well repository planning and design.

Ian was the project manager for well control planning and field execution of the 6th largest global blowout and five other well control situations. Ian then joined a downhole tool and chemical company working in Canada, USA and Venezuela in sales and later as Operations Manager Western Hemisphere. He joined Core Lab as the Canadian manager for Completions Diagnostics division, and later as the VP Corporate Business Development for Canada.

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9.0 APPENDIX A – RECOMMENDED PRACTICE FOR GAMMA EMITTING TRACERS AND SPECTRAL GR LOGGING

This recommended practice was developed by Ian McConnell (ian.mcconnell@energy37.ca) an independent world expert on gamma emitting (GE) tracers and gamma ray (GR) Spectral logging utilized for the purposes of tracing materials injected into wellbores. It is based on deploying the technology of the only known full service provider of non-contaminating gamma emitting tracer products and a Spectral gamma ray logging tool to detect the placement of the gamma emitting tracers in the wellbore.

This recommended practice is also supported by the following Society of Petroleum Engineers (SPE) papers:

- SPE 17962. A Relative Distance Indicator from Gamma Ray Spectroscopy Measurements with Radioactive Tracers.
- SPE-77442. A Practical Guide to Tracer Diagnostics.
- SPE-31105. Measuring Hydraulic Fracture Width Behind Casing using Radioactive Proppant.

Introduction:

The use of gamma emitting tracers is proven technology in identifying the placement of fluids and materials in a wellbore. Areas of accepted use to date include the following applications:

1. Fracture stimulation and identifying the placement of proppants in a wellbore.
2. AER Directive 51 *Injection and Disposal wells,* to confirm hydraulic isolation when converting a producing well to an injector well.
3. Primary Cementing to confirm placement of a specific slurry or a cement slurry lost to fluid thief zones during drilling and/or cementing operations.
4. Remedial Cementing to confirmation of thief zone(s) and final placement of cement slurry.

In order for this technology to be successful, it requires the following properties:

- A gamma emitting radioactive energy source.
- A GE source with a reasonable "half-life" duration of approximately 60 – 85 days.
- Be non-contaminating leaving no residual radiation. The recommended practice utilizes ceramic beads with the GE material contained inside the bead. Only the outside of the bead will contact any surface area and the carrier fluids and other materials do not become radioactive. The radiation travels with the impregnated ceramic bead.
- Utilize a purpose-built Spectral gamma ray logging tool that can distinguish isotopes and their location in the annulus, including the relative distance (near vs far) from the outer casing. A traditional gamma log is inadequate due to the low radiation levels in the wellbore annulus from the GE tracer and the non-spectral nature of a gross gamma tool.

GE Tracing Materials:

The only known global source of gamma emitting and non-contaminating patented tracer material is ProTechnics Div. of Core Lab. The marketing name of the tracer product is "ZeroWash" as the product does not wash off fracturing proppant.

The three tracer products are contained in ceramic beads in which three different heavy metal flakes are impregnated into a ceramic slurry forming ceramic beads. The impregnated beads are irradiated in nuclear reactors to commence the emitting of gamma radiation. The only location of radiation is where the ceramic beads are located / placed. The carrying fluids and other materials do not become radioactive.

There are other tracing materials with radioactive coatings that can be placed on sand grains. When crushed, or when the coating is abraded off the sand, a radioactive signature remains wherever the sand grain as been. Many coatings will also soften in the presence of chloride ions resulting in a radioactive signature left on pumps, treating lines, downhole tubulars and wellbore fluids.

Safety Training & Exposure:
The Canadian Nuclear Safety Committee (CNSC) issues an operating license to any company that uses/handles gamma emitting isotopes based on approved and audited shop and field operations safety programs. ProTechnics trained technicians are authorized to handle / use these isotopes and Spectral logging tools.

The level of external radiation from these GE tracers is extremely low. Ingestion of the isotopes is the greatest hazard for radiation exposure to the public and tracer technicians. To reach the "body burden limit", a maximum annual radiation dose allowance, a person would need to ingest 22 kilograms of iridium isotope on one occasion. The ZEROWASH beads are too large to pass through the olfactory channel and as such cannot enter the body through the nose. The only method of internal consumption is through the mouth.

Planning the Well Intervention:
1. Define the purpose of the wellbore treatment including the objectives and information that is to be acquired from the operation.
2. Identify the anticipated product / fluid injection rate and pressure including the expected pressure stability / volatility.
3. Determine the expected volume and density of the injected fluids / materials.
4. Plan the time interval between AP fluid injection and logging the well.
5. Ensure there is access to the wellhead for a slick line or braided line operation. Select the wireline company with a contact name and number and review the planned operation with them.
6. Construct a current down hole diagram including; tubulars, deviation, perforated interval(s), packers, any wellbore restrictions etc.

Equipment and Material Required For Well Treatment:
1. High pressure down hole injection pump, usually a cement or acid mobile pump unit.
2. Access to the suction side of the injection pump for adding tracer beads into the injected fluids or products.
3. Hammer union connections where the "injection stinger" can be attached to the suction side of the high-pressure pump.
4. A volume of product or fluid to be traced.

5. A slick line unit when Spectral GR logging operations are required.

ProTechnics to Provide on Location for Tracing Operation:

1. CNSC federal license, copy to operate anywhere on land or seas of Canada.
2. Functioning Ludlum radiation survey meter.
3. Gamma emitting non-contaminating ZERO WASH isotopes.
4. Trained and certified tracing technician and ancillary lead-lined transportation overpack containing isotope storage cannisters, peristaltic injection pump and hoses, PPE, and ancillary safety equipment and signage.

ProTechnics to Provide on Location for Logging Operation:

5. CNSC federal license, copy to operate anywhere on land or seas of Canada.
6. Functioning Ludlum radiation survey meter.
7. Spectral Gamma Ray memory logging tool and backup tool.
8. Trained and certified logging technician with ancillary portable field office truck, software, PPE, and ancillary safety equipment and signage.
9. Radio communication with back up (when required) between wireline operator and logging operator.

Equipment To Be Provided by Well Operator:

1. Service rig or coil rig if required.
2. Any tubing and down hole tools / equipment required for injection.
3. High pressure down hole injection pump (cementing or acid unit) with an associated treating line to wellhead.
4. Product and fluid mixing materials and equipment to perform blending operations.
5. A slickline or braided line truck when logging operations are required. A braided line truck may be used if already on location. Slickline unit is normally used to control costs.
6. A backhoe should it be necessary to construct an earthen barrier for disposal of fluid or material containing GE tracers. This may be required if all of the product containing GE tracers was not squeezed behind casing resulting in product containing GE tracers still in the wellbore tubulars. Approval by the CNSC is not required for any burial operation and is included in the ProTechnics operating license. Burial of isotope residue on location is the preferred CNSC method of disposal due to the non-contaminating nature of the ZERO WASH tracer material.

Typical Job Procedure for Tracer Injection:

1. Perform safety meeting with all personnel on location using check list.
2. Perform pre-job radiation survey of downhole high pressure pump using Ludlum survey instrument.
3. Pre-injection survey of wellhead and area around the wellhead using Ludlum survey instrument.
4. Confirm and /or establish downhole injection rate using high pressure down hole pump to confirm and verify that the injection rate is acceptable for the operation.
5. Determine product and fluid injection volume.

6. Determine how many isotopes to use based on job size, injection rate, fluid type, information to be gathered. Up to three different isotope types can be selected for different fluid blends.
7. Set-up barrier signage from truck, mixing area, tracer injection & pumping area to restrict access.
8. Set-up injection pump and injection hose/stinger assembly to suction manifold of down hole pump. Be aware of pipes, cables set up by service company, observe caution tape if present. Run injection hose out of travel path. Follow 'as low as reasonably achievable' (ALARA) risk procedures.
9. Mix tracer in special gelled carrier fluid in tracer pump reservoir, in restricted area.
10. Upon commencement of pumping fluid and product, inject tracer(s) at pre-determined concentration into flow line, continuing to monitor injection rate of AP fluid to maintain tracer injection concentration.
11. Flush injection pump and injection hose after injection of traced fluid downhole.
12. Once downhole injection is complete, rig down high-pressure pump injection stinger, injection hose, injection pump.
13. Perform post-job radiation survey of mix area, down hole pumps, surface lines, downhole high-pressure pump, wellhead and surrounding area. If radiation is found in suction area of down hole pump, physically remove radiation material with adhesive tape or other material. Place any beads recovered in waste bag in lead lined transportation overpack.
14. If any volume of traced AP fluid ends up on surface for whatever reason, the CNSC recommended method of disposal is that the fluid or material containing beads of isotope be placed in an earth barrier (pit) below ground with a minimum of one meter of dirt on top of the burial location. IMPORTANT TO UNDERSTAND: The fluid or product itself is not radioactive, it is the ZERO WASH beads in the fluid which is emitting radiation. If the beads can be removed from the fluid / product, the radioactivity stays with the beads and the fluid is left "clean".

Typical Job Procedure for Logging Operation:

1. Perform safety meeting with all personnel on location using check list. Wear PPE.
2. Perform radiation survey of wellhead and surrounding area.
3. Place safety barrier signs in working area to restrict access.
4. Program memory logging tool.
5. Rig up memory logging tool and encoder to slickline/wireline or braided line unit. Run cables such that they do not become a trip hazard. Choose a clear path to wireline unit. Make sure brake is set on wireline drum before connecting the memory logging tool.
6. Communicate encoder attachment with wireline unit operator.
7. Rig into wellhead.
8. Confirm radio communication with wireline unit.
9. Run in hole to top-end depth of logging interval.
10. The logging interval is dependent on a number of variables of individual well conditions and historical primary cementing placement interval operations.
11. A minimum logging interval is 150 meters above and 50 meters below the targeted product placement interval or the tool hold-up depth if less than 50 meters.

12. Logged interval can be affected, but not limited to, any of the following well history and/or conditions, which may change the recommended logged interval. As the number of variables increases, the logged interval should be reviewed and possibly increased due to the potential vertical "travel" increase vs the designed/expected placement location risk.
    a. Well age / history. The older a well is, the higher the risk of poor hydraulic isolation due to original cement slurry quality and the condition of existing cement.
    b. Primary initial cement placement and top of cement. Upper intervals were sometimes not isolated at time of primary cementing resulting in potential crossflow.
    c. Cement slurry design including dispersant and fluid loss additives (if used). Without fluid loss additives and dispersants to increase the efficacy of the fluid loss, the potential for slurry "free water" increases and therefore channel development.
    d. Preflush volume / plus surfactant water-wetting agent (if used) efficacy with drilling mud removal before pumping primary cement. If the preflush / surfactant mix has not removed the drilling fluids and the film of drilling mud from both the casing and the formation surface contact area (filter cake); with a resulting a water wet formation contact, hydraulic isolation may not have been achieved.
    e. Casing centralization and wellbore deviation. Slant wells will have the highest potential for channel leakage as the free water will travel to the high side of the wellbore and the slant angle creates the pathway for leakage. Most slant wells are shallow and the production casing primary cement slurry was neat cement (no additives). This potentially results in a high free water cement slurry environment. This is conducive to creating a channel on the top side of a deviated wellbore.
    f. Wellbore stability / hole conditions at time of primary cement job. Thief zones and wash outs create areas of instability and therefore increased risk of lack of hydraulic isolation.
    g. Total interval to be covered with product. The larger the interval to be covered, the greater the risk of incomplete coverage or thief zone(s).
    h. Volume of fluid and product to be pumped. The larger the volume, the greater the chance of breaking down an existing stable zone and / or fluid channeling.
    i. Product and fluid injection circulating rate and pressure. Low and stable injection pressure suggests ease of flow placement in the annulus, and therefore potentially less potential for channeling.
    j. Unknown wellbore conditions.
13. Perform duplicate logging runs at 6 m/minute logging speed.
14. Pull out of hole. Lay down tool string and detach tool string from slickline/wireline.
15. Download data from memory tool; confirm data quality is good.
16. **NOTE:** If initial data download indicates the traced AP fluid material interval has not been completely covered, an additional logging run, above or below the annular interval is recommended, in order to determine the total AP fluid injected placement interval.

17. If initial data suggested AP fluid interval has been completely logged successful, send raw data to the processing center.

Review Processed log data allowing ~2 days for initial processed spectral gamma ray log.