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A Green Alternative for Determination of Frac Height and Proppant Distribution

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Abstract

As regulations and public awareness regarding hydraulic fracture operations continue to change, it is important to continue to look for options to reduce risk to both the environment and personnel. Current fracture diagnostic technology uses radioactive materials which can pose a high risk from a health, safety and environment (HSE) perspective. Exposures to people and the environment to radioactive chemicals; and the potential to cause pollution or long term detrimental health problems, are great. A technology has been developed to allow fracture diagnostics to be performed with zero-risk to the environment and personnel.

The technology involves using Boron Carbide particles added to the frac slurry as a tag material. Boron Carbide is a ceramic compound that has a 75% abundance of Boron by weight and the same density as Silica. It is a compound that is chemically inert under typical conditions of hydraulic fracturing.

Because Boron is a neutron absorber, post-frac detection is accomplished by using a neutron device utilizing an Am-241Be sealed source which detects descending neutron and gamma count rates, as well as, capture gamma validation by energy discrimination across tagged intervals. This method will give both near and not near well bore dimension and provides Neutron-Neutron (N-N) and Neutron-Gamma (N-G) differences against initial base line reference data.

Field data and analysis of results are presented for a vertical coalbed methane well in Virginia as well as a horizontal Berea Sandstone well in Kentucky.

Use of Boron Carbide for Tracing Material

An effort is being made to eliminate the use of open source radiochemicals as tracer materials in various oilfield applications. These applications include the following:

- ✓ Tracing cement: Boron Carbide is definitive with respect to proving the presence of lightweight cement slurries (<1500 kg / m³) typically used for surface cement and remedial intervention.
- ✓ Tracing fluid placements in hydraulic fracturing operations.
- ✓ Production logging for proving casing integrity, material flow and velocity rates.
- ✓ Subsurface location of downhole jewelry such as float shoes, collars, etc.

The use of Boron Carbide (CB₄) has been patented for tracing the cement and hydraulic fracturing applications. CB₄ is a ceramic metalloid compound that has a 75% abundance of Boron by weight. It has a specific gravity of 2.5 g/ cm³ which is approximately the same as that of silica. Silica particulates are commonly used as proppants in fracturing operations or as an aggregate for mixing cement slurries. CB₄ particle sizing can be matched to that of those materials used in these operations (proppant, etc.) and because of its similar density, will travel at the same velocity as pumped fluids giving a homogenous distribution of the tracer throughout a fluid displacement. In the application for fracturing operations, where discrimination between stages is required, differences between N-N and N-G measurements can be used to distinguish between pad and proppant stages by comparing baseline reference data versus the placement of silica proppants and CB₄ tagged silica proppants. In other words, it is possible to look at multiple stages of a fracturing operation using the single CB₄ tracer. It is

preferable to have a baseline log reference using the same tool; however, not totally necessary if previous N-N and N-G formation data is available by using normalization log processing techniques. The technology relies on baseline reference data and comparisons to them. The technology can be proven with N-N response only and the use of a single detector neutron tool. The use of N-N, N-G logging tools can be used for more comprehensive log data such as near and not-near wellbore tag effects. The technology uses descending N-N neutron count rate as a primary measurement.

CB₄ is chemically inert and will not react with other chemicals. It has a few unique physical characteristics; in that it is one of only two elements that are neutron absorbers and it is the second hardest substance on the Moh's hardness scale, second only to diamonds. Boron captures a thermalized neutron (0.25 eV) and transmutes into Lithium under Alpha decay. Lithium does not pose an HSE risk. Boron has a capture Gamma energy of 0.48 MeV, which is ironically the same as the principal Gamma photon energy of iridium-192; the most common radioisotope currently used in oilfield tracing applications. The second neutron absorbing element is Cadmium. Cadmium is a heavy metal of a toxic nature. It is a carcinogen and its use as a tracer must be done with considerations made for potential personnel uptakes and burdens on the environment. Intrinsic Cadmium particles can be used with a comprehensive quality control program that shows efficiency of the particle containment system to give a level of confidence with respect to particle integrity in this regard.

HSE Considerations

The CB₄ technology is not hazardous from a radiological perspective for surface handling procedures and can be easily handled using standard personal protective equipment (PPE) as specified on MSDS sheets for the tracer chemical. The use of CB₄ does not render any harmful byproducts in well flow back production. No federal licensing is required to use Boron, Cadmium or their compounds.

Economic Considerations

The use of CB₄ tracer materials can have some economic benefits to the operator during and after frac operation such as:

- ✓ Well flow back monitoring and the use of tanks for the retention of contaminated or radioactive tagged effluents is not required. This eliminates tank rentals and the cost of onsite personnel for extended periods of time.
- ✓ The cost of CB₄ tracer materials and services are equivalent or lower than costs associated with radioactive tracers.
- ✓ The CB₄ technology gives a permanent tracer signature on tagged wells that can be logged for years to come.
- ✓ The CB₄ technology mitigates risk and the potential liabilities from a legal perspective.

Measurement with Quad Neutron and its use for Fracturing Analysis

A specialized logging tool was used for evaluation of the test wells. The Quad Neutron utilizes a four detector array of electrically balanced N-G and N-N detectors. Using a combination of the data from these balanced detectors, the measurements are derived. The balanced array configuration reduces borehole effects and allows for acquisition of data through casing and pipe strings. Each detector is individually characterized to minimize detector errors and to equalize dead time compensation. Utilizing the four detectors in a balanced configuration virtually eliminates borehole, casing and cement effects and allows a very accurate formation porosity to be measured.

When using Boron Carbide as a primary tracing element, the Carbon serves as a thermalizer and Boron serves as an absorber. The absorption of a neutron by a Boron nuclide with subsequent radiation emission is not a repeated event. The abundance of Boron allows the measurement to be repeated numerous times. The Boron Carbide does not expire over time allowing the measurement to be done when the information is required.

The logging tool is able to perform a frac analysis due to the sensitivity of the balanced and calibrated reference detectors. The tool depends on the absolute value of the detector counts. Since each detector is calibrated and base-lined, small variations in porosity can be detected. It is from the ability to log these small variations that a frac trace can be developed. CB₄ influences the Neutron-Neutron field and the Neutron-Gamma field. For most formations the Neutron-Neutron field is larger than the Neutron-Gamma field, which also allows discrimination between near vs. far well bore tag placement.

For a CB₄ wellbore tracing during a frac operation an evaluation log with the logging tool is obtained before the fracturing to obtain neutron (N) and gamma (G) detector measurements. If this baseline log cannot be obtained, a synthetic baseline can be produced using a combination of neutron to neutron and/or neutron to gamma measurements.

During the fracturing operation, Boron Carbide is mixed at the blender into the proppant and is carried into the formation by the carrier fluid. The Boron Carbide is deposited alongside the proppant in the formation. After the fracturing operation, the well is logged a second time with the Quad Neutron tool.

Vertical Coalbed Methane Well Frac Analysis

Located in Russel County, Virginia, a vertical coalbed methane well was chosen for the first test of the CB₄ technology. Well total depth was 2,167 feet deep and was planned to be a six stage fracture treatment using baffles and perforations. Details of the treatment are listed below:

- ✓ Six stage 65Q N2-Foam frac treatment.
- ✓ Each stage treated with 17.5 mg/lb of Boron Carbide tag.
- ✓ Total proppant tagged in all stages 79,516 lbs.
- ✓ Average surface treating pressure 3,026 psi (all stages).
- ✓ 12/20 mesh proppant.
- ✓ Base log performed open hole with standard Compensated Neutron tool.
- ✓ After-treatment log performed with Quad Neutron tool (Figure 6).

The interpretation was done using open hole neutron data for the base pass and cased hole neutron for the evaluation pass. Ratio responses were used to detect the presence of the CB₄ tag. No radioisotope tags were used on this well.

The cased hole neutron porosity response was normalized to the open hole neutron porosity and the differences analyzed. The presence of the CB₄ tag should decrease the neutron count rate which should result in an increased porosity change. The initial analysis was performed on this premise and the results analyzed. The results were reverse to expectation. Possible explanation is that the coal porosity is already very high and that the introduction of CB₄ and sand into the coal matrix actually decreases the porosity response relative to the original neutron porosity response. The analysis was then redone on this premise and the results matched expectations. Analysis results compared well against offset wells traced with radio isotopes (Figure 1). Summary of each stage is presented below and shown in Figures 2-3.

Stage 1: Three perforated intervals were treated in stage 1. The bottom interval was not accessible due to high plug back. Of the two remaining intervals, the uppermost interval took the majority of the frac as indicated by the log. The frac also appears to have travelled 2 feet upwards from the perforations. The other interval had a small change in nuclear response but this was below the statistical cut-off used for the analysis.

Stage 2: Two perforated intervals were treated in this stage. Similar to the first stage the uppermost interval received the majority of the frac. The lower interval interpretation may be suspect due to the poor open hole neutron response thru this coal. The lower interval looks to be the cleaner of the two coals yet open hole neutron hangs back at lower porosity than would normally be expected.

Stage 3: Five intervals were treated in this interval over a span of 325 ft. All intervals except the second highest interval were treated successfully with the lower most and upper most intervals receiving the majority of the frac. Analysis response at 1553 and 1565 are anomalous and are due to changes in the nuclear environment between the open hole and the cased hole neutron log.

Stage 4: Three intervals were treated in this interval. All intervals were treated successfully. The upper two intervals indicate that the frac may have some communication between them.

Stage 5: Four intervals were treated in this interval, with the majority of the treatment occurring in the lower interval. The lower interval has the largest nuclear change in the wellbore. This type of nuclear change was also noted on a previous well treated with CB₄ tracer. Again, some anomalous responses are being seen outside of the perforated intervals.

Stage 6: Three intervals were treated in this interval. All three were successfully treated. The middle zone shows some of the frac travelled approximately two feet below the perforations.

Although radioisotopes are easier to trace in such an environment, the HSE risks can limit their use. The methodology of introducing a non-radioactive tag, such as CB₄, and comparing open hole neutron against cased hole neutron logs does work as demonstrated above. Errors in the method can be reduced by performing a base log immediately prior to the fracture treatment, to minimize changes in the nuclear environment.

Horizontal Berea Sandstone WellFrac Analysis

Located in Pike County, Kentucky, a horizontal Berea Sanstone well was chosen for another test of the CB₄ technology. Well total depth was 7,309 feet deep and was planned to be a twelve stage fracture treatment using an open hole packer system. Only the final stage of the treatment was selected to place tracer material to allow for logging operations without the requirement of drilling out the frac ports. Other details of the treatment are listed below:

- ✓ 12 stage 85Q N2-Foam frac treatment.
- ✓ Each stage treated with 34.0 mg/lb of Boron Carbide tag in addition to Iridium-192 radioactive tracer material (21 mCi) for direct comparison purposes (Figure 4).
- ✓ Total proppant tagged in 42,615 lbs (final stage only).
- ✓ Average treating pressure 4,264 psi.
- ✓ 20/40 mesh proppant.
- ✓ Base log and post-frac logs performed with Quad Neutron tool.
- ✓ Logs conveyed in horizontal section via 2-1/8" wireline tractor (Figure 7).

The following interpretation was done using a cased hole Quad Neutron log for the base pass and the evaluation pass. Single detector Neutron-Neutron and Neutron-Gamma responses were used to detect the presence of the CB₄ tag. This well also had Iridium 192 pumped for direct comparison purposes with the CB₄ tracer.

One stage was fractured thru an openhole packer completion. The initial phase of the frac was not tagged allowing the annulus to pressure up, breakdown the formation, and to establish a steady slurry injection rate. This prevents contamination of the annular space with the tagged material which allows for better fracture analysis. Tag concentrations remained constant throughout the tagging exercise while the proppant concentration increased.

Before and after Neutron-Neutron and Neutron-Gamma responses were compared. Post frac responses were normalized to the pre frac responses in the upper logged interval as shown on the log. SNG represents Short Neutron-Gamma and SNN represents Short Neutron-Neutron. The NNTag represents the Neutron-Neutron change and the NGTag represents the Neutron-Gamma change. Log results are shown in Figure 6.

Before and after gamma ray (GR) responses are also presented. Large changes in GR are due to the radioactive tag presence. Minor changes may be attributed to changes in fluid density in the casing and/or the annulus.

The initial analysis was done looking for descending count rates on both Neutron-Gamma and Neutron-Neutron as a result of the CB₄ presence. From the log it is apparent that there is a uniform decrease on both measurements from the top packer to the frac port. This would indicate a uniform distribution throughout this interval and without a fracture, which is unlikely. Why the decrease in count rates? The base log was performed with nitrogen in the annulus while the evaluation pass was assumed to be natural gas and/or residual nitrogen foam. The increase in hydrogen from the gas and the nitrogen would naturally decrease the count rates on both measurements. The uniformity of the change also suggests that no fracture was initiated throughout this upper section. This uniformity does not exist in the lower section indicating that fractures had occurred in this interval.

The analysis was then done looking for increases in Neutron-Neutron and Neutron-Gamma. These differences are plotted as NNTag and NGTag. Both the NNTag and NGTag indicate that the tagged part of the frac treatment occurred below the frac port at 4,030 feet with the majority of the treatment occurring at approximately 4065 feet. This is in agreement with the increase in gamma ray due to the Iridium 192. Notable differences include responses around 3870 feet, 4150 feet and the gradation from the frac port to the peak response at 4,065 feet.

The response at 3,870 feet appeared on both the NGTag and NNTag. This also coincides with the largest GR change above the top packer. We are not sure why there would be a nuclear change here but would have to rule it out as a fractured interval because of the lack of the traceability from the frac port to this point. The response is approximately 15 feet from the top packer.

Similarly the response at 4,150 feet appears approximately 15 feet from the bottom packer. It can be argued that this interval was due to fracturing operations because there is traceability to the frac port. The gamma response does not support this however, which would suggest that this is anomalous similar to the response at 3,870 feet.

The last notable difference is the gradation response on the NGTag and NNTag to the maximum peak at 4,065 feet. This would be expected considering that the tagging exercise was conducted to the end of the frac. There is a break in the NNTag at 4,040 feet that does not exist in the NGTag. There are other incidents of similar response. 4,070 feet is another example of this. This may be the influence of the CB₄ tag on the Neutron-Neutron counts while the NGTag is being influenced by the

gamma energy of the Iridium 192. This may also be a function of the changing concentration ration between the tag and proppant. Referring to the GR response, there is no gradation between the frac port and the fracture with the Iridium 192. One reason may be that the tagging exercise was cut short with the Iridium 192 to try and avoid contamination inside the pipe and to surface.

In general the entire fracture path is in agreement between the two tracers. The use of the radio isotope certainly is an easier method of determination but poses HSE risks. The use of the CB₄ tracer appears to have altered the response thru the fracture interval but is unclear in this example. This was the first time that CB₄ was used in an openhole packer completion system with a nitrogen based frac strategy. Future plans are to continue observing the appearance of the anomalous responses above the packer assemblies, to maintain a constant concentration ratio between tag and proppant and to alternate between pad and proppant tagging between stages to confirm packer isolation.

Conclusions

With increasing regulations and heightened public awareness of oilfield operations, specifically hydraulic fracturing, the use of Boron Carbide for a tracing material eliminates the HSE and political concerns that are attached to the use of radioactive materials. While this paper references only a small subset of test data, it has been illustrated that Boron Carbide can be used to achieve results to evaluate proppant distribution and frac height.

References

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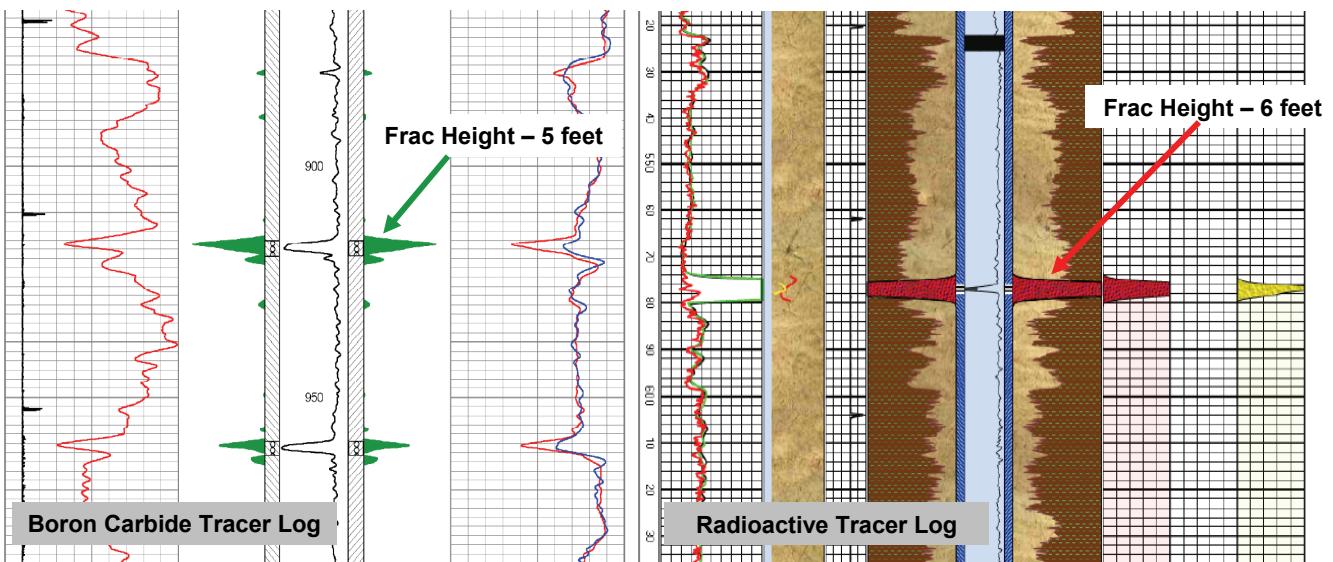


Figure 1 - Comparison of Boron Carbide with iridium 192.

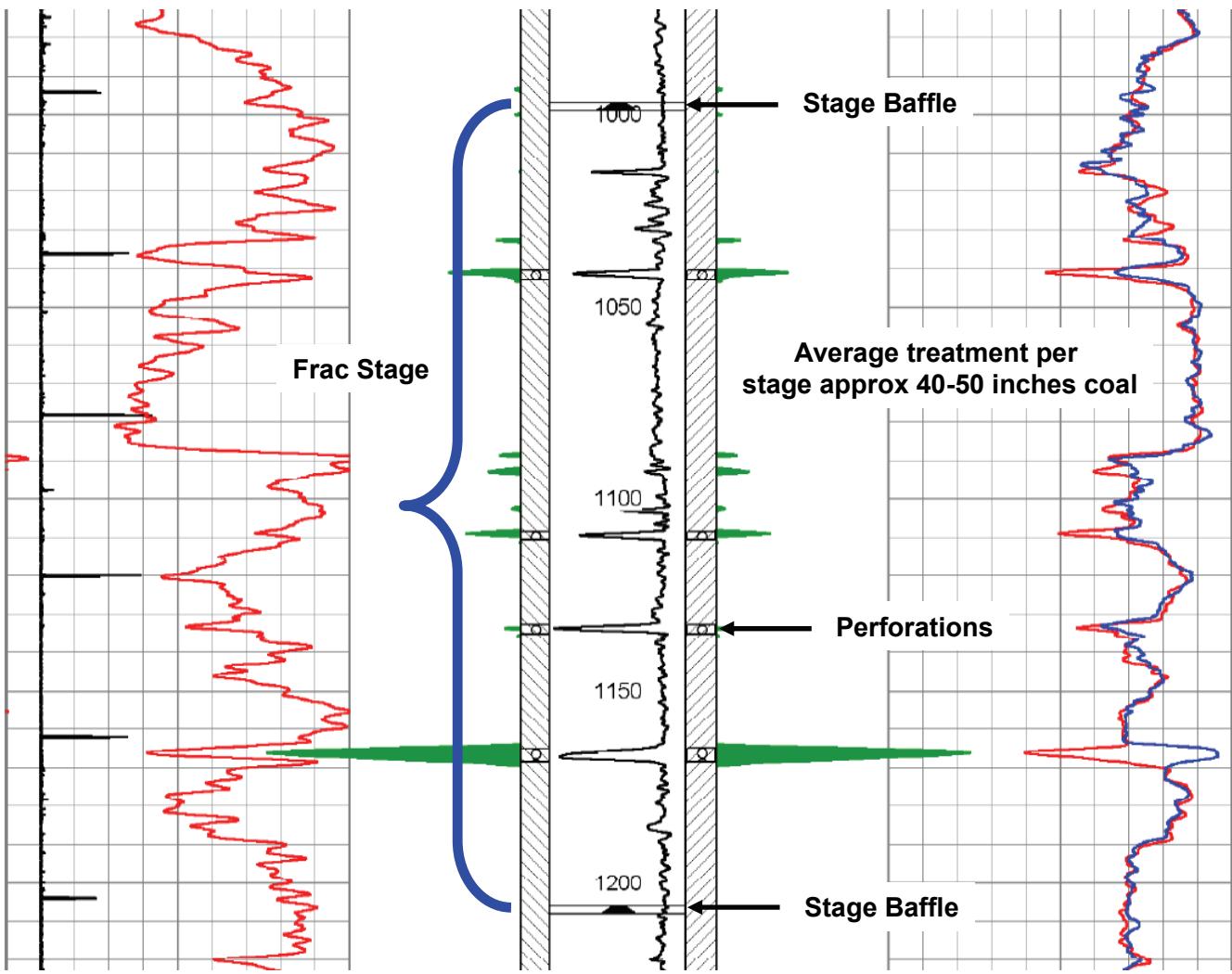


Figure 2 – Distribution of Boron Carbide Tracer in Frac Stage of Coalbed Methane Well in Virginia.

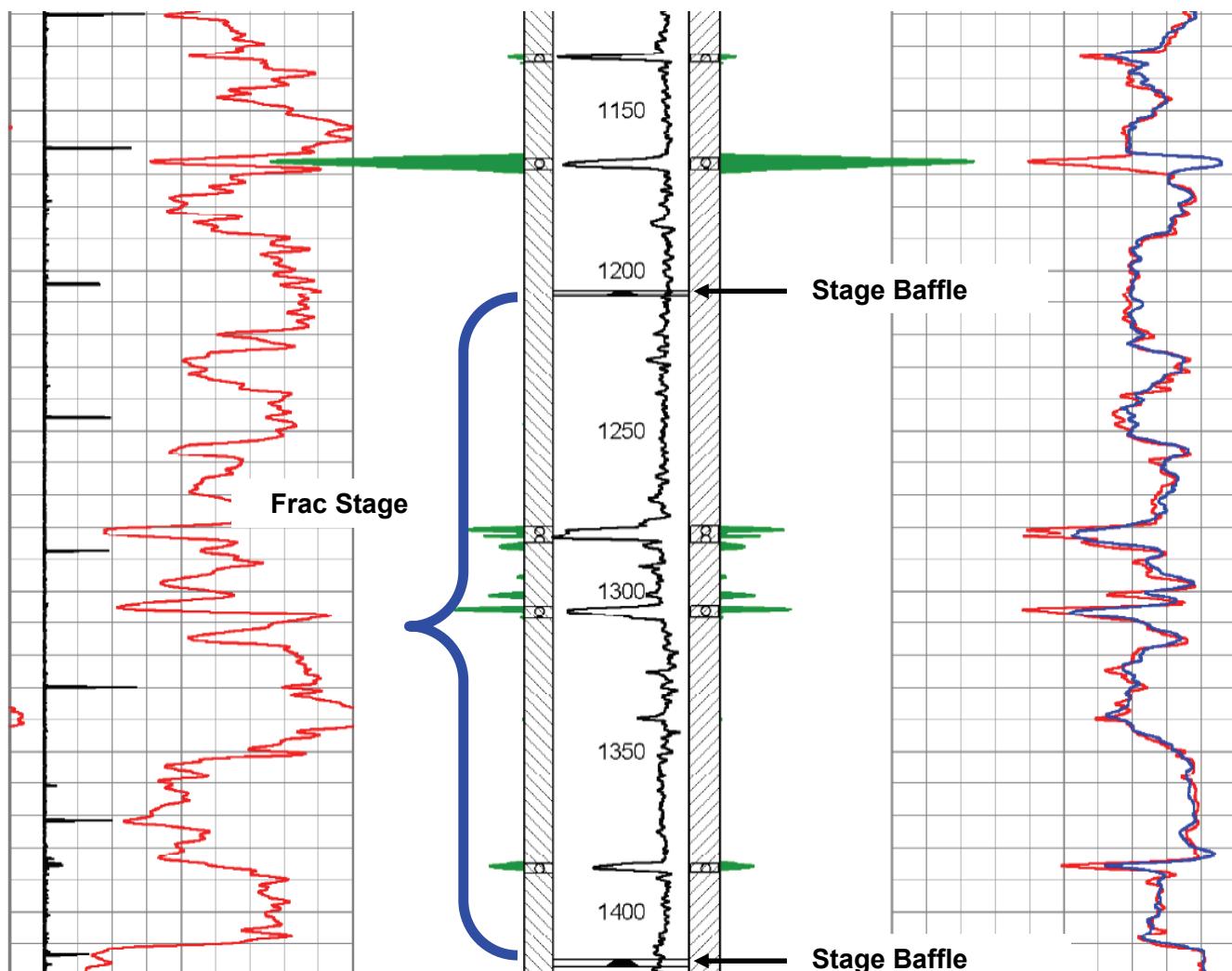


Figure 3 – Distribution of Boron Carbide Tracer in Frac Stage of Coalbed Methane Well in Virginia.



Figure 4 – Introduction of Boron Carbide during Frac Stage of Berea Sandstone well in Kentucky.

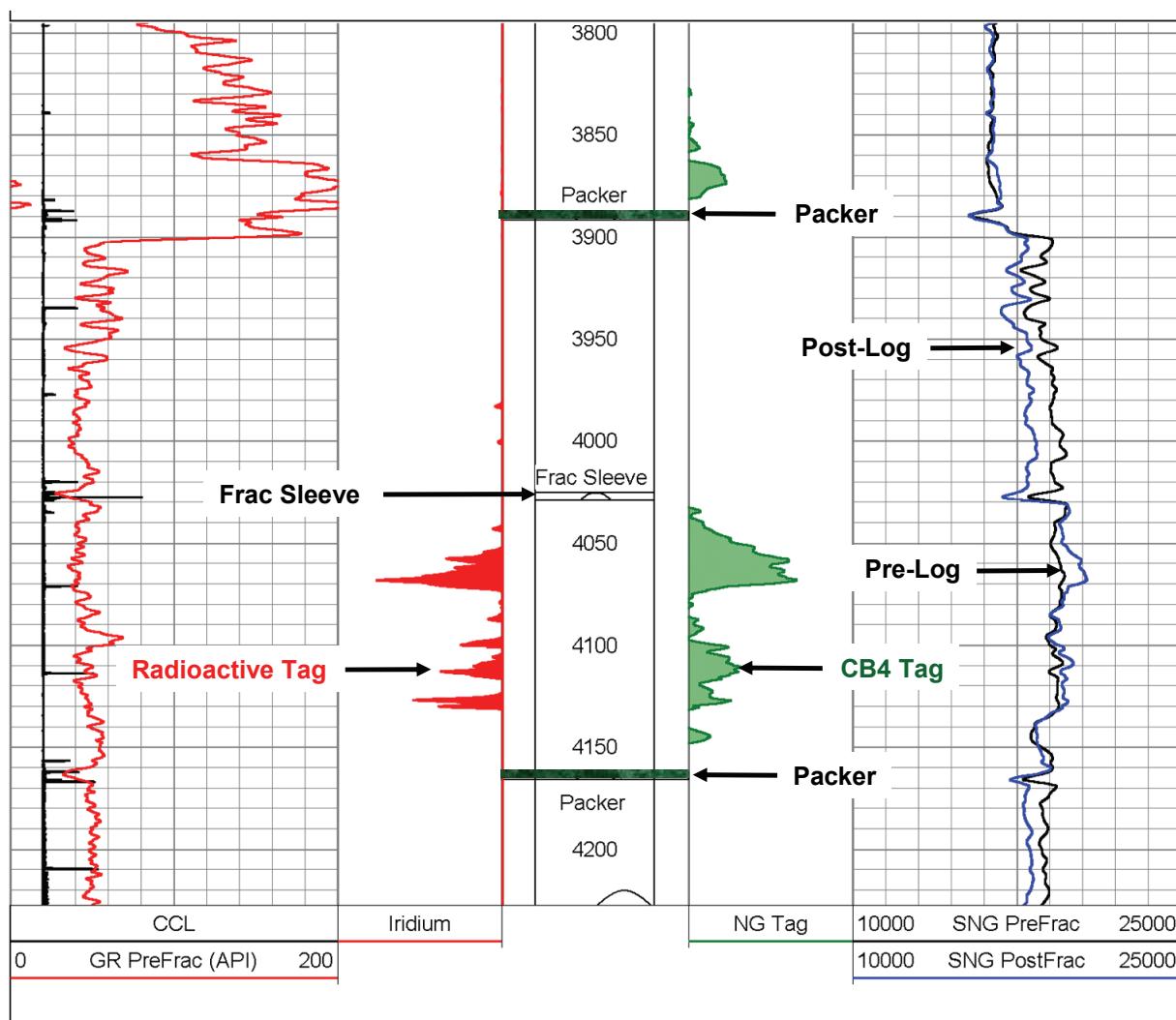


Figure 5 – Distribution of CB₄ and Ir-192 Tracers in Frac Stage of Berea Sandstone well in Kentucky.

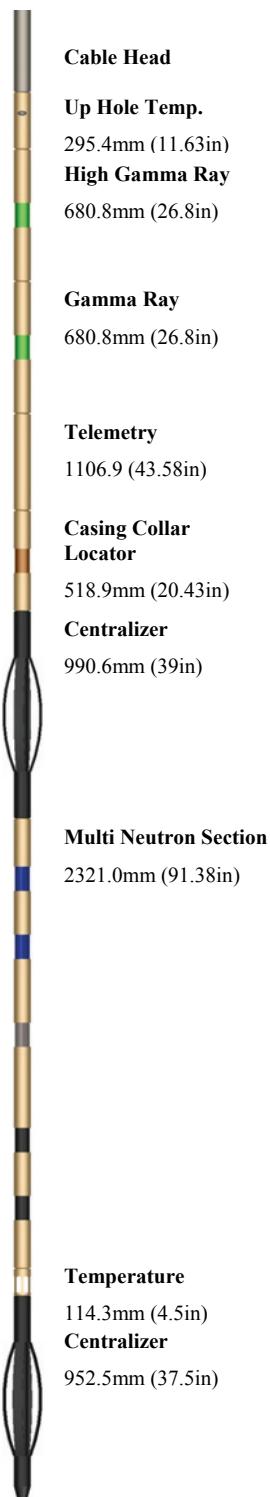


Figure 7 – Wireline tractor tool used for deployment of logging tools in horizontal portion of Berea well.

Figure 6 – Tool diagram for Quad Neutron device.