Geophysical Logging to Assess Annular Seals in Groundwater Monitoring Wells at the Hanford Site – 14536

Rick McCain *, Paul Henwood *, Arron Pope *
* S.M. Stoller Corporation

ABSTRACT

Groundwater monitoring wells are an important component in any environmental program. A poorly constructed groundwater monitoring well may not provide adequate or representative water samples. Worse, the well itself may provide a channel for downward contaminant migration. Well completion forms and construction diagrams provide documentation on well screen, casing configuration, filter pack, and borehole seals, but this information can be impossible to independently verify. Once the well is completed, the only access for inspection is the well casing. Errors in the completion process or problems that have developed since the well was completed may be difficult to detect and assess.

Geophysical logging offers a means to evaluate the continuity and integrity of the annular seal, and to locate contacts between different materials through casing.

INTRODUCTION

Well construction techniques are discussed in a number of references [1, 2, 3]. Well completion forms and construction diagrams provide documentation on well screen, casing configuration, filter pack, and borehole seals, but once a groundwater monitoring well is completed, the only access for inspection of subsurface components is the well casing. The annular space between the well casing and borehole wall can provide a channel for vertical movement of water and/or contaminants unless it is properly sealed. In any casing and borehole system, there are several potential pathways for water and contaminants [2]:

- Through the sealing material itself
- Along the contact between the sealing material and the casing
- Through voids creating by “bridging” of the sealing material or caving of the formation material when the casing is withdrawn

If the sealing material is not properly formulated, or if it cracks or deteriorates after emplacement, the permeability in the vertical direction can be significant. Gaps between the sealing material and the casing can occur because of temperature changes during curing of the sealing material, shrinkage of the sealing material, or poor bonding between the sealing material and the casing. Incomplete filling of the annular space can occur because voids behind the casing are not adequately filled, the sealing material “bridges” during placement, or the surrounding formation material caves during casing withdrawal and blocks the placement of sealing material.

The most effective seals are obtained by using expanding materials that will not shrink away from the casing of the borehole wall after curing or setting. Bentonite, expanding neat cement or mixtures of cement and bentonite are the most effective. If the annulus is backfilled with any other material, such as drill cuttings, sand, or borrow material, a low-permeability seal cannot be assured and the borehole can act as a conduit for vertical migration. This is particularly a problem when drill cuttings are used, because recompacted drill cuttings typically have a higher permeability than the undisturbed formation materials from which they are derived [2].

In Washington State, the term "resource protection well" means monitoring wells, observation wells, piezometers, spill response wells, and cased geotechnical test borings. Wells must be constructed in such a manner as to prevent contamination of the samples, the sampled strata, and between aquifers and water bearing strata in accordance with chapter 173-160 WAC, "Minimum Standards for Construction And Maintenance of Water Wells." [4] In particular, WAC 173-160 requires that casing be installed within a borehole at least four inches larger in diameter, and that the annular space between the outside of the casing and the borehole wall from the monitoring interval to ground surface "shall be grouted with bentonite or cement-bentonite sealant" from the monitoring interval to ground surface.

Geophysical logging tools offer a means to assess the continuity and integrity of the borehole seal, and to locate contacts between different materials through casing. Christman et al [5], Wheaton and Bohman [6] and Yearsley, et al [7] provide reports of geophysical logs used to assess well completions and seals. These studies suggest that problems with annular well seals may be relatively common.

GEOPHYSICAL LOGGING METHODS FOR WELL COMPLETION ASSESSMENT

A wide variety of geophysical logging equipment is available and specialized logging systems have been developed in the petroleum industry to provide data on borehole seals, and the condition of casing or tubing. [8]. For example, the cement bond log was introduced in the mid-1950's and quickly accepted for evaluation of petroleum well completions. Data gained from this log led to significant improvements in oil well cementing techniques [9].

Other acoustic or electromagnetic logging tools are available for assessment of casing thickness or overall condition. For example, a borehole televiewer can be run in "casing thickness" mode. Pipe analysis logs use electromagnetic methods to assess casing quality and discriminate between internal and external defects. High-frequency eddy current tests detect flaws on the casing interior and magnetic flux leakage tests inspect the full casing thickness [10].

The gamma density log uses a radioactive source (typically Cs-137). Gammas from the source are subject to Compton scattering within the formation, and some are scattered back to one or more detectors in the sonde. The count rate at the detector can be related to the bulk density. Although it is generally considered to be an open-hole log, the gamma density log has been successfully used to assess seal materials around casing [7].

HANFORD GEOPHYSICAL LOGGING CONDITIONS

At the Hanford Site, geologic conditions consist of unconsolidated flood deposits overlying poorly consolidated fluvial deposits. Depth to groundwater varies. In the Central Plateau area where most of the waste sites are located, the groundwater level is typically 200 to 300 ft (61 to 91 m) below ground surface. These conditions require that practically all boreholes be cased. In normal practice, the well is drilled to total depth using one or more temporary casing strings in a "telescoping" manner. Geophysical logs, generally high-resolution spectral gamma and neutron moisture, may be run in each casing string to detect any manmade radionuclides and to provide data for stratigraphic correlation. The well is completed with a screen and sandpack at the monitoring interval and borehole seal material is placed into the annular space as the temporary casings are withdrawn.

Since borehole materials are closer to the detector, they tend to have a significant effect and will generally dominate log response. It stands to reason that log response should be relatively uniform and consistent when borehole materials are consistent. In the case of an annular seal, variations in log response may be indicative of variations in the quality or consistency of the seal. Both gamma and neutron moisture logs show promise for assessment of annual material in completed monitoring wells.

Gamma Logs

In uncontaminated sediments, gamma activity originates from potassium (radioactive K-40 comprises 0.0117% of all potassium); uranium and thorium. Gammas emitted by radioactive decay in the material surrounding the borehole travel though the formation, annular material, casing, borehole fluid, and the sonde housing to be detected. Assuming the formation is not contaminated, gammas from the annular seal material will dominate detector response. In contaminated intervals, at least some of the gammas from the formation material may “shine through” the annular seal and casing. If a gamma log is available from prior to the start of well completion activities, it is possible to identify those intervals or points where gamma activity from the formation may contribute to perturbations or irregularities in the gamma log collected during completion. Lower than usual gamma activity may indicate possible voids behind casing and special attention should be provided to these intervals during completion.

Total gamma or gross gamma logs count gamma activity without regard to energy level. These logs provide a gross indication of bed boundaries and/or the presence of gamma-emitting contaminants, but they provide no radionuclide identification. They may be useful in identifying voids or washouts, and discriminating between sandpack and bentonite or concrete.

In spectral gamma logging, a gamma energy spectrum is collected at each point. Conventional spectral gamma logs typically employ low-resolution detectors such as sodium iodide (NaI) or bismuth germanate (BGO). These are sensitive and rugged, but they lack sufficient energy resolution to identify specific gamma energies. High-resolution spectral gamma logs utilize cryogenically cooled high-purity germanium (HPGe) detectors to collect gamma energy spectra with a very good energy resolution that allows characteristic gamma emissions from both manmade and naturally occurring radionuclides to be identified and assayed.

Variations in the relative amounts of potassium, uranium and thorium provide information on the composition of the surrounding material. Potassium and thorium content can be used to identify clay minerals in petroleum logging. The thorium-potassium ratio can be associated with specific clay minerals. Chart CP-19 [11] provides thorium-potassium ratios for common clay minerals. Montmorillonite is the primary mineral constituent of bentonite. For montmorillonite, the thorium-potassium ratio is approximately 12. This is stated in terms of ppm Th and w% total potassium. When both Th-232 and K-40 are reported in terms of pCi/g or Bq/g, the equivalent ratio would be about 0.16.

Neutron Moisture Log

The neutron moisture log uses a small (1.85 MBq) americium-beryllium (AmBe) neutron source to bombard the formation around the borehole with “fast” neutrons. These are scattered and moderated in the formation and reflected back to a thermal neutron detector a short distance above the AmBe source. Within geologic media, neutrons are most likely to be scattered and slowed by collisions with hydrogen atoms, and the count rate at the detector is an indication of the volumetric hydrogen content in the surrounding material. Since most of the hydrogen is likely present as a component of water, the neutron count rate can be related to volumetric water content. Neutron scattering is unaffected by the state of the water, so the neutron moisture log responds equally well to “free” water in the pore space, as it does to “bound” water in clay minerals or water of hydration in grout or cement.

Neutron moisture logs are relatively unaffected by steel casing, but very sensitive to borehole diameter. The log cannot be run below water level in the borehole. Neutron moisture logs can be run in boreholes as small as 1.5 inches in diameter. For borehole diameters greater than 12 inches, neutron log response may be very weak. Voids or washouts behind the casing will also cause a weak response.

For most vadose zone soils at Hanford, moisture contents are generally less than 5 vol %. Portland cement typically includes about 15 to 20 vol % moisture after setting. Even “dry” bentonite contains at least 10% moisture and it will absorb significantly more. Since the annular seal material lies between the sonde and the formation material it will tend to dominate neutron log response. Assuming a uniform annular seal, one would expect the neutron log response to be relatively high and consistent over the sealed interval. This leads to the concept of a “grout line”, meaning a relatively high response value indicative of an intact annular seal. Significant reductions in neutron log response relative to the grout line may be an indication of voids, caves, or other features that compromise seal integrity. Where bentonite has been placed “dry” a significant increase in neutron moisture log counts over the grout line could be an indication that water is reaching the borehole (and being absorbed by the annular bentonite).

In contrast to the seal material, the sandpack generally consists of clean silica sand, with relatively little capacity to “hold” water. Where the sandpack extends above the groundwater level, the contrast in neutron log response between the sand and the overlying cement or bentonite seal will result in a significant difference in count rates. A sharp inflection on the log should exist at the contact between the sand and bentonite if materials are properly placed. A more gradual inflection might suggest mixing of the completion materials.

RESULTS

Recently, a well was logged with both high-resolution spectral gamma and neutron moisture to investigate casing corrosion. A borehole video survey was also performed. Well completion details and the video survey were depth-adjusted and compared to spectral gamma and neutron moisture data. Figure 1 shows gamma and neutron moisture logs compared to borehole completion details. For this well, there appears to be little or no correlation between Th/K ratio and the nature of the annular material. However, Th-232 concentrations greater than 0.7 pCi/g (0.026 Bq/g) appear to be diagnostic of bentonite. Th-232 values less than 0.7 pCi/g (0.026 Bq/g) indicate either cement or sandpack. K-40 values greater than 9 pCi/g (0.33 Bq/g) indicate sandpack, while K-40 values less than 8 pCi/g (0.3 Bq/g) indicate cement.

The neutron log also correlates well to the annular seal. Above 263 ft (80.1 m), the neutron moisture count rate is relatively high and consistent, with some variation, around a value of about 500 cps.

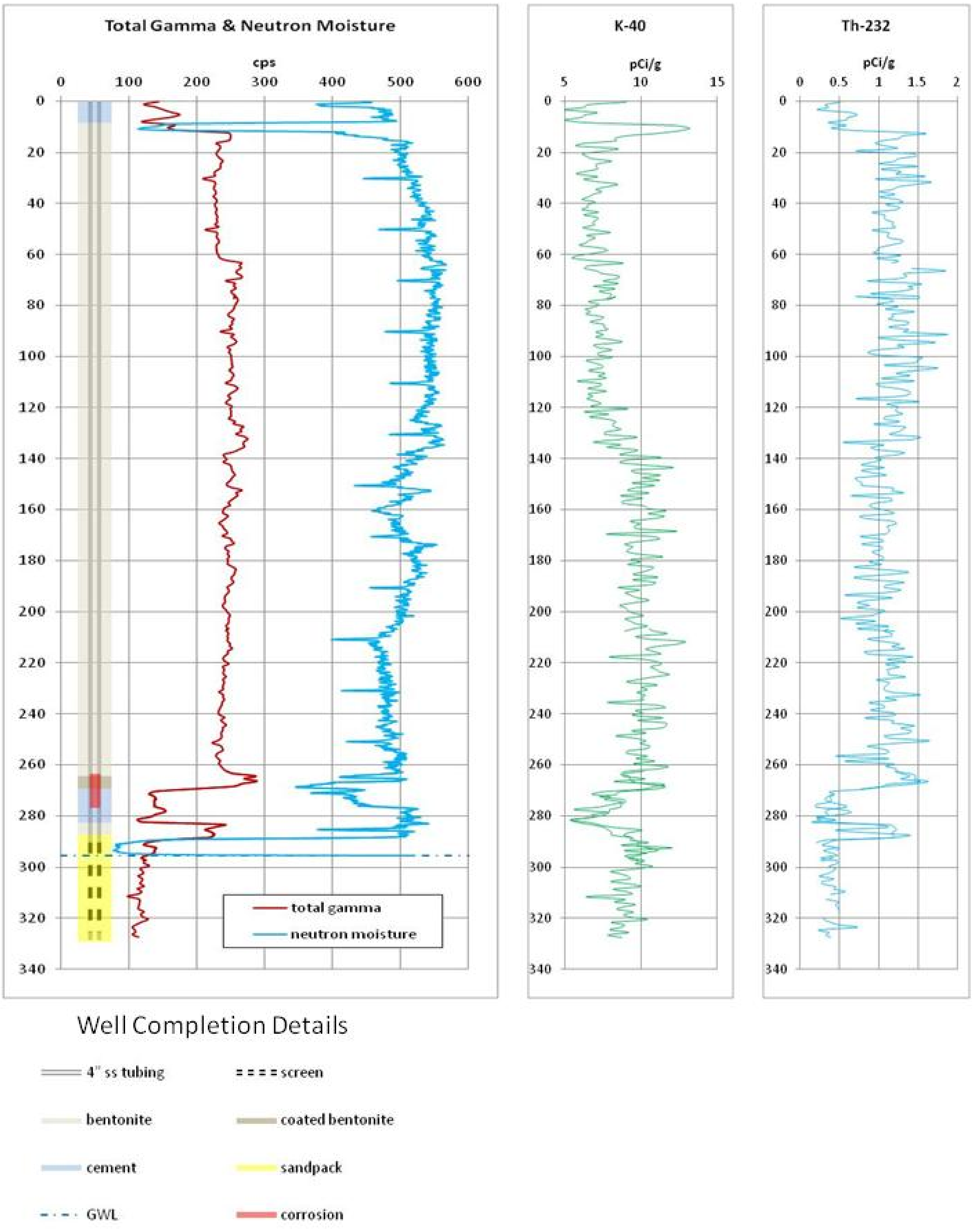

Figure 1 Gamma & Neutron Logs in Well With Casing Corrosion

Between 263 and 277 ft (80.1 and 84.4 m), the neutron count rate drops to between 350 and 450 cps: this is interpreted as evidence of a “poor annular seal” in this interval. In the borehole video survey, casing corrosion is first observed at 263 ft (80.1 m).

At 289 ft (88.1 m), the neutron count rate abruptly drops from about 500 cps to 100 cps. This is interpreted as the contact between the sandpack and the bentonite. On the well summary sheet, the top of the sandpack is reported to be at 287.5 ft (87.63 m)depth. It appears the contact is 1.5 ft (0.46 m) lower than the depth reported when the well was completed in 2008. No log was run to confirm the contact in 2008, so it is possible that the depth of the contact was incorrectly reported on the borehole summary sheet. From the borehole camera survey, the top of the screen is known to be at 290.3 ft (88.48 m) depth. It is possible that the sandpack is compacting over time, and the overlying bentonite pellets are falling down to fill the gap. The drop in count rates at 285.5 ft (87.02 m) is interpreted as evidence of a possible small void at the top of the seal.

In another well shown in Figure 2, a neutron moisture log was run over a borehole interval where a problem with the annular seal was suspected. During well completion, both the casing and tremie pipe became “stuck” and it was suspected that completion materials might not exist in this depth interval. The neutron moisture log showed a significant drop in count rates between approximately 196 and 248 ft (59.7 and 75.6 m), which is interpreted as an absence of cement in this interval. The neutron log provided supporting information for a variance request.

CONCLUSIONS AND RECOMMENDATIONS

Well completion assessment should begin with an evaluation of logs acquired before completion materials are introduced. Comparison of gamma and moisture logs may indicate possible voids behind the casing and depth intervals of relatively high moisture or perched water. Generally, voids behind casing are indicated where moisture and gamma count rates are low and inconsistent with the geologist’s visual inspection of sediments at the same depth. A void can also be indicated by apparent low moisture response and relatively high gamma activity that is caused by radon collecting in the void space. The well site geologist and driller should plan for extra care in completion activities within suspect intervals.

Borehole completion reports and “as-built” diagrams provide a representation of the well configuration. However, it is difficult to independently verify the accuracy of the information. Moreover, it is possible that the configuration may change over time (e.g. compaction of sandpack, or development of voids in the annular seal) such that the well becomes unsuitable for its intended purpose. Geophysical logging offers a means to assess well completion details from inside the casing. Both the spectral gamma log and the neutron moisture log have application to well inspection, particularly with respect to evaluating the integrity of the annular seal material in the vadose zone.

When problems occur during well completion, spectral gamma logging or neutron moisture logging can be used to provide information for proper completion, or to support a variance on completion requirements. In critical wells, consideration should be given to running logs during the completion process to assure that materials are correctly placed before the next step. This would be particularly useful after placement of the filter pack (sandpack) to assure that it is at the proper depth and thickness. For wells scheduled for decommissioning, spectral gamma and neutron moisture logging can be used to determine depths of casing strings and the general nature and condition of annular material.

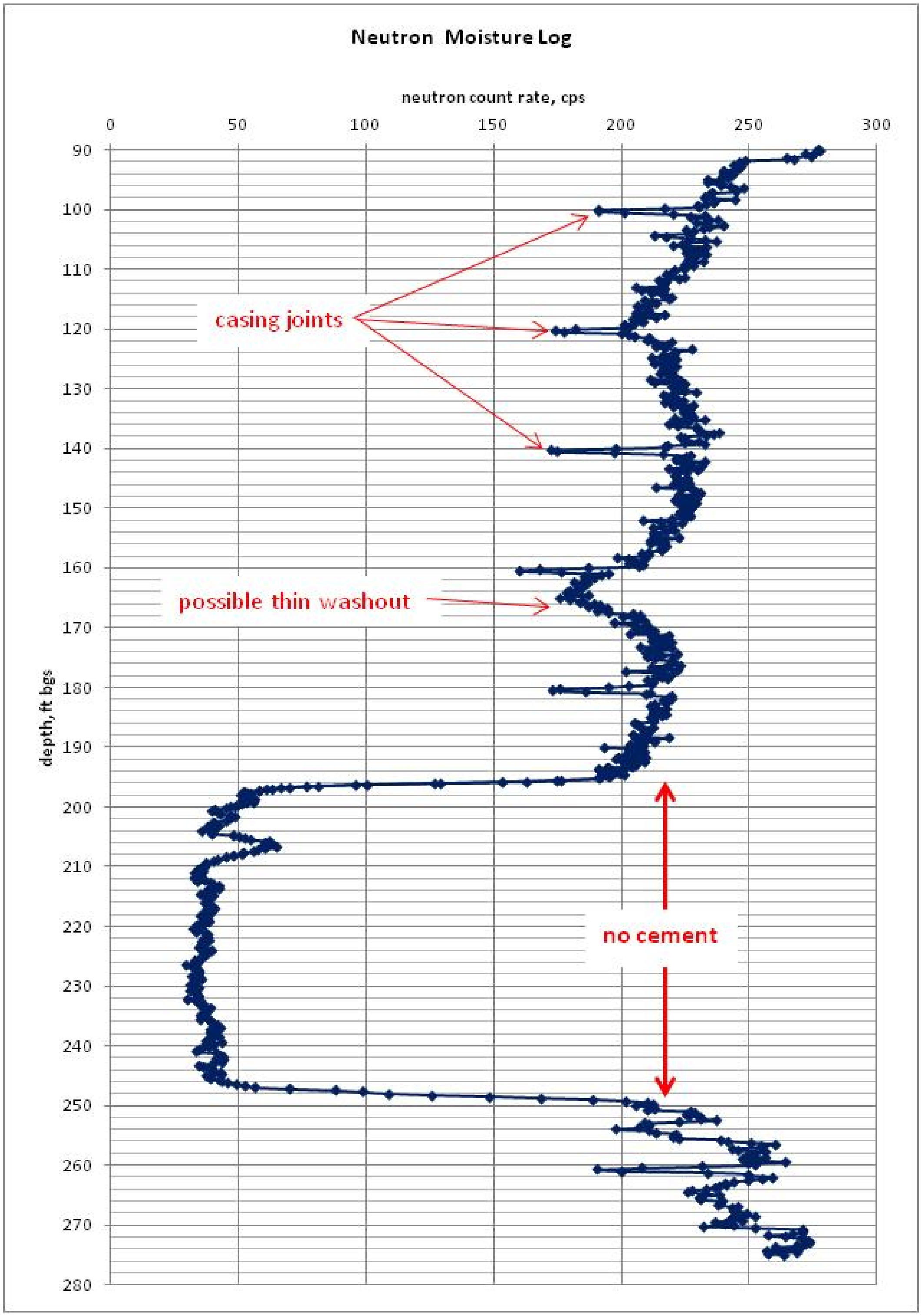

Figure 2 Neutron Log Showing Void In Annular Cement

REFERENCES

1 DRISCOLL, F.G. 1986. Groundwater and Wells, 2nd Edition. Johnson Division, St Paul, Mn

2 ALLER, L., T.W. BENNETT, G. HACKETT, R.J. PETTY, J.H. LEHR, H. SEDORIS, and D.M. NIELSEN. 1989. Handbook of Suggested Practices for the Design and Installation of Ground Water Monitoring Wells. National Water Well Association, Dublin, OH

3 ECOLOGY, 1990. Ground Water Monitoring Guidance for Solid Waste Facilities. Pub 90-04, Solid and Hazardous Waste Program, Washington State Department of Ecology, Mar 1990

4 WAC 173-160. 2008. Minimum Standards for Construction and Maintenance of Wells, Washington Administrative Code. WAC 173-160. Available at: http://apps.leg.wa.gov/WAC/default.aspx?cite=173-160 (July 23, 2013)

5 CHRISTMAN, M.C., C.H. BENSON and T.B. EDIL, 2002. Geophysical Study of Annular Well Seals. Ground Water Monitoring and Remediation, v 22 , n 3, Summer 2002, pp 104-112

6 WHEATON, J. and B. BOHMAN, 1999. Geophysical Investigations of Cased Well Completions. Ground Water Monitoring and Remediation, Winter, 1999, pp 143-151

7 YEARSLEY, E.N., R. E. CROWDER and L. A. IRONS. 1991. Monitoring Well Completion Evaluation with Borehole Geophysical Density Logging. Ground Water Monitoring and Remediation, Winter 1991, pp 103-111

8 SCHLUMBERGER, 1989. Cased Hole Log Interpretation Principles/Applications. Schlumberger Educational Services, Houston, Texas

9 MCGHEE, B.F. and H.L. VACCA. 1980. Guidelines for Improving Monitoring of Cementing Operations. Paper V, Proc 21st Annual Logging Symposium, Lafayette, La, July 8-11, 1980, Society of Professional Well Log Analysts, Houston, Tx

10 CRAIN, E.R. 2010. Crain's Petrophysical Handbook Available at http://spec2000.net/01-index.htm

11 SCHLUMBERGER, 1989. Log Interpretation Charts. Schlumberger Educational Services, Houston, Texas