Using Corona to test NMR response of iron ore chip samples

Mark Downey
Downey Data Analysis Pty Ltd
c/o Kazek Trofimczyk
BHP Iron Ore
mark.downey@bhp.com

Kazek Trofimczyk*
BHP Iron Ore
125 St George's Tce,
Perth, WA 6000
kazek.trofimczyk@bhp.com

SUMMARY

The application of Nuclear Magnetic Resonance (NMR) to investigate the distribution of moisture in materials has not normally been applied to iron ores due to the magnetic properties of iron. However recent test work on blast hole chip samples of iron ore using the very low field Corona system has shown that it is possible to obtain useful information on moisture content. Key to obtaining useful results has been operating the Corona with "burst-mode", replicating the style of data acquisition used in wireline NMR. The greatly increased signal-to-noise-ratio allowed for more robust inversions and more realistic representation of the moisture distribution in the samples being tested in a manageable time frame. This has allowed us to investigate the relationship between magnetic susceptibility and detected water content using the Corona.

Key words: Nuclear Magnetic Resonance, iron ore, Corona, signal to noise ratio, magnetic susceptibility.

INTRODUCTION

The development of NMR in general and wireline NMR in particular has depended on significant advances of the technology to be able to provide valuable insights into fluids distribution in porous media. The ability to not only measure the presence of fluids but also to be able to discriminate different fluids and formation permeability has meant that wireline and laboratory NMR are valued tools in exploration of oil and gas (Kleinberg, 2001). Furthermore, the development of slimhole tools for hydrological investigations has provided valuable tools for in-situ investigation of water and other resources (Walsh et al, 2013), and lead to an understanding of fluid characterisation in coal (Hopper et al, 2017). Application in iron ores is also under investigation (Parashar et al, 2015). The difficulty of using NMR in high iron content materials is well known (e.g. Keating and Knight, 2008) and is related to the magnetic properties of iron. Even "non-magnetic" hematite is paramagnetic and can influence measurements. Diffusion and other issues must also be taken into account. Recent work has shown that using very low field NMR can reduce the influence of magnetic mineralogies (Keating et al, 2015).

BHP Iron Ore has commenced a program investigating the suitability of NMR to rapidly measure water content and distribution in blast hole chip samples from its Yandi mine. Initially this involved laboratory measurements to determine whether such technology is applicable. Corona was chosen to test iron ore samples due to its specifically low-field operation (485kHz compared to conventional systems at 2000kHz) and relatively short echo time spacing of 0.2ms. Initial tests showed that the signal-to-noise-ratio (SNR) of the spin-echo decay curves was too low, leading to significant uncertainty in the inversion results. To improve signal-to-noise, we used a "burst mode" of acquisition to improve SNR and provide greater certainty in the inversion results. With the data acquired, we consider the relationship between magnetic susceptibility and the water content response of Corona.

METHOD

Dedicated laboratory space was allocated for Corona including a wooden table. This was to ensure that Corona was not affected by any nearby magnetically susceptible material that could affect the magnetic fields generated by Corona. A photograph of the setup is shown in Figure 1. Initially, we loaded samples into ~120ml plastic vials after tests confirmed the vials produced no NMR response. Later tests using PTFE containers confirmed the veracity of the initial results.

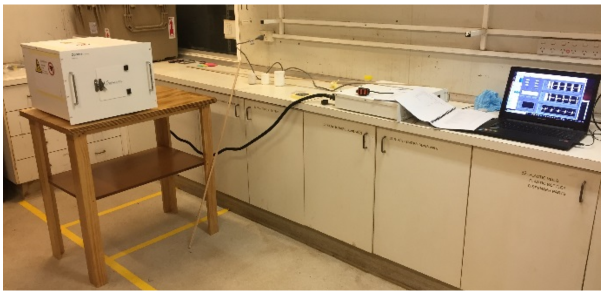

Figure 1. Arrangement of Corona, control unit and laptop for testing blast hole chip samples.

Prior to testing most iron ore samples we divided them into two, one for direct testing (denoted S1) and later addition of water from the as-received state and a twin sample of approximately the same mass (S2) for drying to estimate water content and later addition of water from the dry state. A 100% water filled vial was used to provide a calibration standard that was tested every day sample tests were run.

CALIBRATION

In the absence of magnetic influences, the NMR amplitude response (arbitrary units au) should be linear with the mass of water. Initially, we ran a series of tests using different masses of water to determine the scale factor for the Corona. The results (Figure 2) confirmed Corona provided good linearity of response to mass of water present and a scale factor of 0.222 au/g.

INITIAL RESULTS AND DISCUSSION

Our initial tests using the as-received samples were not encouraging. The primary reason for this was that many of the as-received samples had dried to less than 5% by mass water content; dried samples expectedly showed little response. The addition of 5% by mass of water (~9g) resulted in a measurable, but sometimes variable, response. An example of the response of sample 786B_S1 is shown in Figure 3.

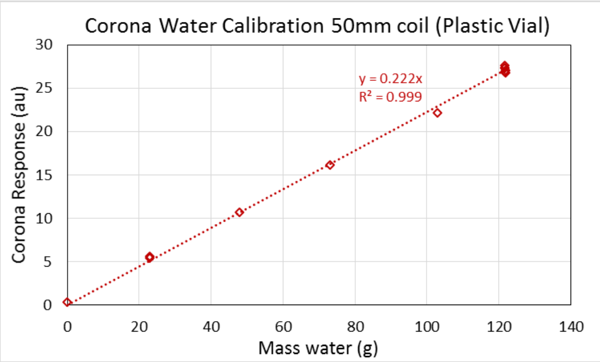

Figure 2. Calibration of Corona showing good linear response to mass of water present.

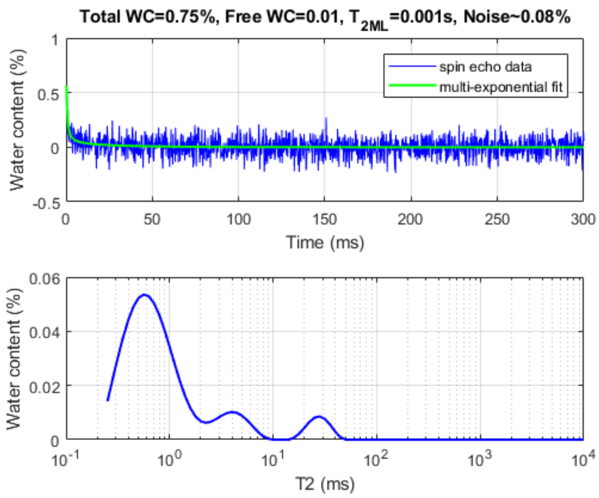

Figure 3. Corona results for sample 786B_S1, 9g water added; the twin dried sample indicated ~4g of water was present in the as-received sample. Top: spin-echo decay data from 200 repeat scans. Bottom: Inversion of data into T2 domain.

Considering higher water content, and in order to determine whether the scale factor varies between the water sample and other geologic samples, we added known quantities of water to our samples and ran tests with Corona. In addition to the iron ore samples, we also considered a sample of clean sand. Results for the response of the clean sand and iron ore sample 786B_S1 with varied mass water added are shown in Figure 4. For the clean sand sample, the scale factor is the same as for water. For this iron ore sample, however, the scale factor dropped by approximately 75%. We note that at very low water content in the iron ore sample the values deviated from a linear trend. As water content becomes very low, the total signal amplitude gets very small and the decay time gets shorter, resulting in poorer sensitivity and more variance.

Another point to note in Figure 4 is that when water is added it is gradually drawn into micro-pores over time. These results indicate the Corona is not adequately measuring water adsorbed in these micro-pores at very low water content. This issue is exacerbated in high magnetic susceptible materials such as iron ore (Grombacher et al, 2016).

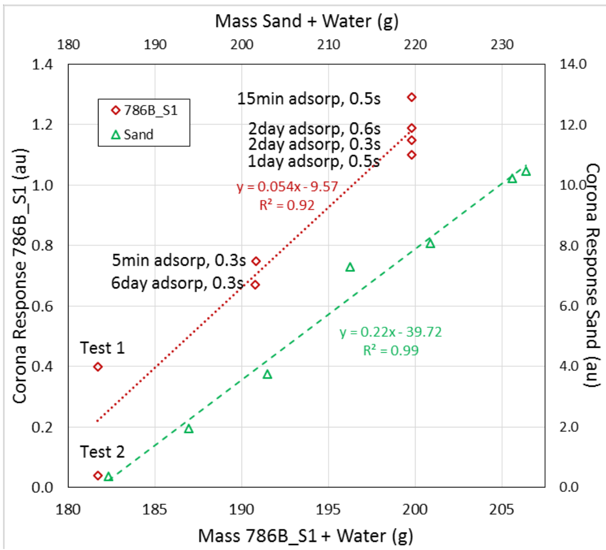

Figure 4. Example of initial Corona results, sample 786B_S1 and clean sand (note different scales for display purposes). For sample 786B_S1, tests were conducted either minutes or days following addition of water, to examine effects of adsorption. Test 1 and Test 2 were on the as-received 786B_S1 which had ~4ml of water present. All tests used 200 repeat scans. For clean sand, results were from 30 repeat scans at different quantities of water over a few hours as adsorption was not an issue. The slope of each line of best fit represents the Corona scale factor.

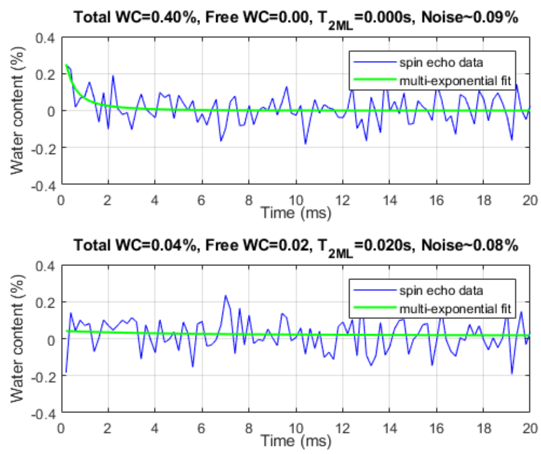

Figure 5. Corona results for sample 786B_S1, as-received sample showing impact of noise on inversion. Top: spin-echo decay data from 200 repeat scans of Test 1. Bottom: spin-echo decay data from 200 repeat scans of Test 2.

ALTERNATIVE APPROACH

The variation in repeat tests, examples of which are Test 1 and Test 2 in Figure 5, are a direct consequence of too low SNR in the recorded spin-echo data. A typical approach to improve

SNR is to increase the number of scans. However, a consequence of increasing the number of scans is that time of acquisition increases accordingly. An alternative approach is to increase the SNR where it is needed at early time rather than for the full record, in an approach used in wireline NMR often known as “burst-mode”. In this approach for each full scan, a large number of much shorter scans with short polarization times are recorded (e.g. Prammer et al, 1998). In the short polarization time scans, the mobile water is not fully polarized, however the data can be corrected or inverted to account for the under-polarization. The result is a measurement with improved SNR for short signal components and robust quantification of both short and long signal components.

To investigate improvements to SNR we carried out tests on sample 784B using a manual burst-mode approach. For a duty cycle of 25% (scan time as a percentage of scan plus polarization times), 2000 scans of 0.02s is 160s and 100 scans of 2s is 800s. The addition of data processing overheads in Corona increased the total scan times to ~400s and ~1200s, respectively. The roughly 66% increase in time to 1600s, excluding additional data handling, resulted in a SNR improvement in early time of approximately $\sqrt{2000/100} = 4.5$ times. Without burst-mode such an increase in SNR would have required approximately $1200*4.5^2 \sim 24000$s or over 6 hours. The results are shown in Figure 6. As expected, the much larger number of scans provided significant improvement in SNR at early time. The inversion is more robust than for the single polarization time approach without requiring a very large increase in acquisition time.

MAGNETIC SUSCEPTIBILITY

With the combined method available we proceeded to complete testing of the blast hole chip samples. We tested a range of samples having a range of magnetic susceptibilities. We then compared the Corona scale factors obtained from these results against magnetic susceptibility (Figure 7).

From Figure 7 it is apparent that the magnetic susceptibility of iron ores has a strong influence on the ability of Corona to estimate total water content. For our sample set our Lower Channel Iron Deposit (LCID) samples all had low magnetic susceptibilities and scale factors ranged from 0.20 to 0.22, very close to the normal scale factor. On the other hand our Upper Channel Iron Deposit (UCID) samples had a wide range of magnetic susceptibilities and consequently scale factors ranged from 0.04 to 0.22. Overall, for samples with magnetic susceptibility below 10^-3 SI, the scale factor did not require adjustment, but the magnetic susceptibility has a significant effect up to 10^-2 SI and a very significant effect above that. Thus it would appear that Corona measurements can be used to estimate moisture content for samples with susceptibility below 10^-3 SI. For higher susceptibility samples, knowledge of the magnetic susceptibility might be used to scale Corona measurements to also provide good estimates of total water content.

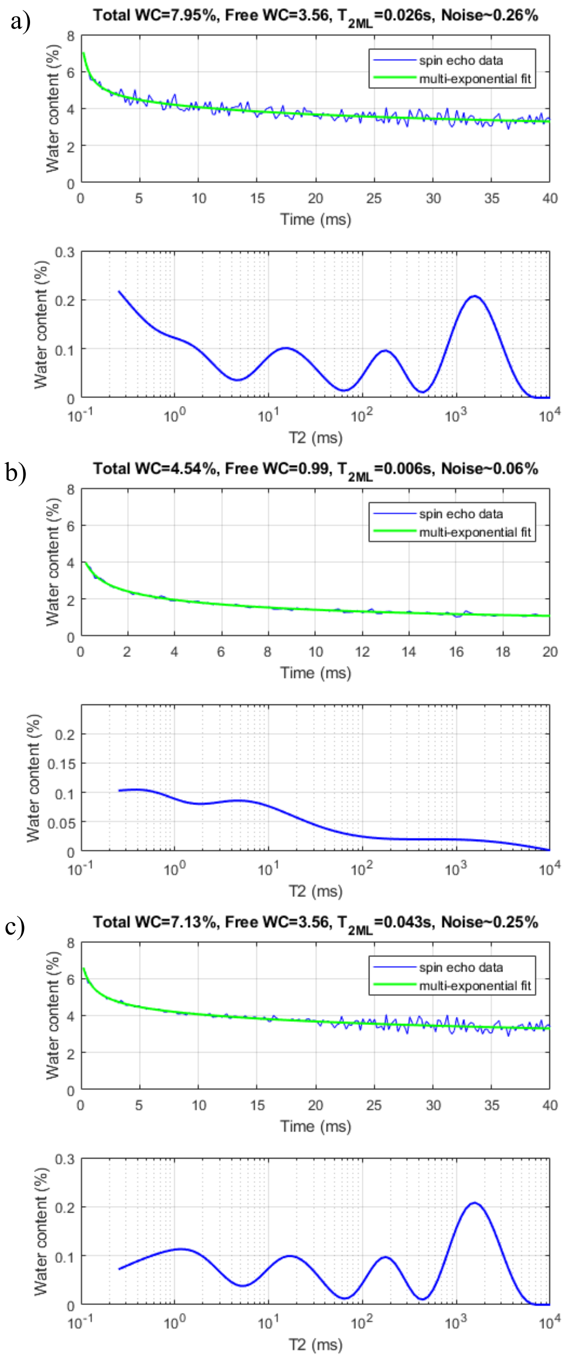

Figure 6. Corona spin-echo decay data and T2 inversions from sample 784B for: a) 100 scans, 2s decay; b) for 2000 scans of 0.02s decay; and c) combined. Both a) and c) are truncated to 40ms for comparison. The short scan and polarization time leads to partial polarization and lower free water response, but provides significant improvement in SNR.

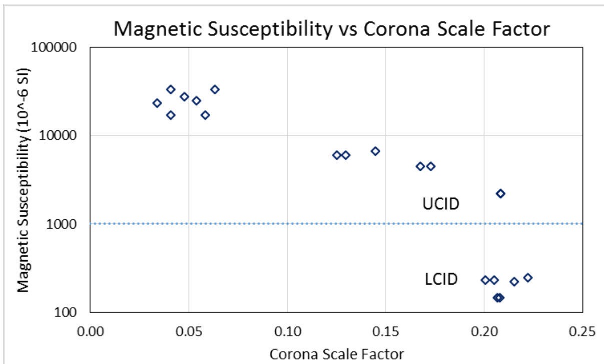

Figure 7. Corona scale factor for a range of samples having different magnetic susceptibilities.

CONCLUSIONS

While obtaining reasonable NMR response on samples of iron ore is a difficult problem to tackle, we have shown that Corona can be used on blast hole chip samples with some success. However, several issues have been identified that require a more flexible approach. These issues include:

i) The high susceptibility of some iron ores is affecting the response of Corona. However, it appears that knowledge of magnetic susceptibility may be sufficient to scale the response to provide reasonably good estimates of total water content.
ii) As water is adsorbed into the micro-pore spaces it can no longer be detected by Corona, presumably due to the very short relaxation time of the adsorbed relative to the echo spacing 200µs. This is typically a characteristic of water adsorbed in clays and shales, but it appears that the iron is lowering the surface relaxation time, causing a "contraction" in the T2 domain. While typical blast hole chip samples do not normally have water added the issue shows that there remain a percentage of moisture that is currently undetectable by Corona. We expect further investigation will help quantify this effect.
iii) Generally, the reduced response of the iron ore also lowers the SNR. At early time the lower SNR results in greater uncertainty in estimating the total water content and distribution. The use of the burst-mode approach appears to be a means of providing greater SNR without requiring significantly greater recording time.

While some issues remain to be resolved we expect that Corona will be a useful tool in understanding water content and distribution in further investigation of blast hole chip samples. However, detection of water residing in micro-pores in iron ore requires improved understanding of the relaxation behaviour or the adsorbed water and perhaps a reduction in the echo spacing.

ACKNOWLEDGEMENTS

We would like to thank BHP for permission to publish these result. We also wish to thank Bureau Veritas for assistance with laboratory facilities, Hamed Sediqi for assistance with gathering the bulk of the experimental data and Vista Clara for providing updated software and support to allow us to complete this investigation in a timely fashion. We also wish to thank Elliot Grunewald for helpful suggestions in preparing this paper.

REFERENCES

Grombacher, D., Fay, E., Nordin, M., and Knight, R., 2016, The impact of pore-scale magnetic field inhomogeneity on the shape of the nuclear magnetic resonance time distribution, Geophysics, 81, (5), EN43-EN55. DOI:10.1190/geo20125-0466.1

Hopper, T., Summers, S., Birt, B., and Mandal, S., 2017, Borehole magnetic resonance in coal seams: Symposium on the Application of Geophysics to Engineering and Environmental Problems, 276 – 279.

Keating, K., Grunewald, E. D., and Walsh, D. O., 2015, A Laboratory Study to Determine the Effect of Field Strength and Magnetic Susceptibility on the NMR Estimated Water Content in Unconsolidated Sediments: American Geophysical Union, Fall Meeting 2015, abstract id. NS52A-05

Keating, K., and Knight, R., 2008, A laboratory study of the effect of magnetite on NMR relaxation rates: Journal of Applied Geophysics, 66, 188-196.

Kleinberg, R.L., 2001, NMR well logging at Schlumberger: Concepts in Magnetic Resonance 13, (6), 396 – 403. DOI:10.1002/cmr.1026.

Parashar, D., Fridjonsson, E.O., Carroll, M., Johns, M., and Hopper, T., 2015, NMR on iron rich core and cuttings – the importance of short TEs: ASEG 24th Geophysical Conference and Exhibition, February, Perth. Extended Abstracts.

Prammer, M., Bouton, R.N., Chandler, E.D., Drack, M.N, and Miller, M.N, 1998, A New Multiband Generation of NMR Logging Tools: Society of Petroleum Engineers Annual Technical Conference and Exhibition, New Orleans, U.S.A., paper SPE 49011.

Walsh, D., Turner, P., Grunewald, E., Zhnag, H., Butler, J.J.Jr., Reboulet, E., Knobbe, S., Christy, T., Lane, J.W.Jr., Johnson, C.D, Munday, T., and Fitzpatrick, A. 2013, A small-diameter NMR logging tool for groundwater investigations: Ground Water, 51, 914-926. DOI:10.1111/gwat.12024.