Low-field Magnetic Resonance in Harsh Environments

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Low-field nuclear magnetic resonance (NMR) is now a well-established measurement utilised in laboratory and logging environments for characterisation of porous media. NMR enables determination of porosity, fluid volumes and a qualitative estimation of permeability in complex geological environments. Considerable technological advances in the design of NMR instruments has already enabled complex measurements to be performed in a range of challenging environments, such as oil and gas reservoirs and Antarctic sea ice. This work examines extending NMR towards three applications with challenging operating and measurement conditions: (i) designing an NMR logging-while-drilling (LWD) tool to operate in hard rock iron ore mining, (ii) performing accurate quantitative characterisation in iron ore, and (iii) characterising water in space exploration.

NMR LWD is now an everyday service in the oil and gas industry, enabling real-time formation evaluation. Mineral exploration drilling is highly unfavourable to LWD due to the 'high' shocks and vibrations experienced. Designing an NMR LWD tool for such environments requires a detailed understanding of the impact of tool motion on NMR measurements during logging. This involves conducting electromagnetic simulations which quantify the magnetic fields generated by a logging tool, and subsequently introducing motion profiles within the relevant spin dynamic calculations [1]. Such simulations can then be used to optimise the design of the tool to be robust to tool motion. The critical design considerations are reducing the radial magnetic field gradient as well as the echo spacing in order to reduce the degree of signal attenuation due to motion.

NMR measurements of water within iron ore samples is complicated by the presence of high internal magnetic field gradients due to magnetic susceptibility differences at the ore–water interface. Advanced 2D relaxometry measurements can be used to quantify key material properties. We utilise Decay due to internal fields Carr-Purcell Meiboom-Gill (DDIF-CPMG) measurements to quantify 2D l_s-T_2 (where l_s is the pore length scale) which is subsequently used to quantify the surface relaxivity of samples. Multi-echo measurements (consecutive CPMG measurements at variable echo spacing) can then be used to determine T_2–g_{eff} (where g_{eff} is the effective internal gradients). A new method, called the multi-regime model, is used to model the diffusive NMR signal attenuation in internal gradients [2]. The multi-regime model is a key step in accurately segregating surface relaxation and diffusive relaxation in high susceptibility materials. This is crucial in accurately estimating properties such as pore size distributions and permeability in these iron ore samples.

Finally, we consider the application of NMR towards extra-terrestrial materials in consideration of using NMR for space exploration. This is achieved by conducting laboratory NMR measurements on Lunar and Martian regolith simulants [3]. DDIF-CPMG measurements are used to quantify the pore-size distributions. These measurements are translated to particle size distributions (using a simple pore-to-particle model) and validated against laser particle size analysis measurements. Multi-echo measurements are used to quantify water volumes as both clay-bound and inter-particle water. The NMR measured moisture content showed reasonably good agreement to corresponding gravimetric measurements used for validation. Finally, we discuss the implications of the current measurements for space exploration and the use of NMR to monitor plant growth in these simulants.

References: [1] K.T. O'Neill, Jnl Mag. Res., 337, 107167 (2022) [2] K.T. O'Neill, Geophys. Jnl Int., 232, 3, 2017 (2023) [3] K.T. O'Neill, ICARUS, 339, 115544 (2023).