Small-scale instrumentation for nuclear magnetic resonance of porous media

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Abstract. The investigation of fluids confined to porous media is the oldest topic of investigation with small-scale nuclear magnetic resonance (NMR) instruments, as such instruments are mobile and can be moved to the site of the object, such as the borehole of an oil well. While the analysis was originally restricted by the inferior homogeneity of the employed magnets to relaxation measurements, today, portable magnets are available for all types of NMR measurements concerning relaxometry, imaging and spectroscopy in two types of geometries. These geometries refer to closed magnets that surround the sample and open magnets, which are brought close to the object for measurement. The current state of the art of portable, small-scale NMR instruments is reviewed and recent applications of such instruments are featured. These include the porosity analysis and description of diesel particulate filters, the determination of the moisture content in walls from gray concrete, new approaches to analyze the pore space and moisture migration in soil, and the constitutional analysis of the mortar base of ancient wall paintings.

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1. Introduction

There are three main application areas of nuclear magnetic resonance (NMR). These are relaxometry, imaging and spectroscopy (figure 1). Each of them can be associated with at least one Nobel Prize and with distinct demands on magnetic field homogeneity. Hardly any field homogeneity is required for NMR relaxometry, which concerns the measurement of time-domain signals that bear information about relaxation and diffusion. NMR was discovered with inhomogeneous magnetic fields, and the study of relaxation times is one of the oldest subjects of NMR [1]. Probably the first commercially significant application was envisioned in well logging for the oil industry [2], but it took 50 years for the first successful commercial logging tool to be introduced [3, 4]. By using permanent magnets in well-logging tools [5], the sensitivity could be enhanced compared to the nuclear polarization in the earth’s magnetic field and the sensitive volume be positioned far enough away from the sensor surface in the stray field of the magnet that penetrates the borehole wall.

NMR imaging is extensively applied in diagnostic medicine [6], where it is known as magnetic resonance imaging (MRI). Other applications concern studies of chemical processes and materials [7, 8]. To encode position along the frequency axes of NMR spectra, MRI is preferably conducted in magnetic fields that vary linearly with position across the object. Typically, such fields are generated as the sum of two fields, a homogeneous field and a linearly space-dependent gradient field that can be turned on and off with gradients of well-defined strength and direction.

NMR spectroscopy is the most important method of molecular analysis in chemistry and the life sciences. It is best performed with magnetic fields that are highly homogeneous across the object, so that the small differences in the local fields that give rise to the chemical shift can be resolved [9, 10]. All three areas of application benefit from strong magnetic fields, as the detection sensitivity scales with the field strength in addition to the chemical shift dispersion in spectroscopy, which is crucial for separating the lines in crowded NMR spectra.

The standard measurement methods today are based on acquiring the NMR signal in the time domain in response to radio-frequency (rf) excitation impulses. The signals are then analyzed by Fourier or Laplace transformations depending on whether spectra and images or relaxation information are to be measured. Advanced measurement schemes produce...
There are three areas of application with different demands on magnetic field homogeneity. Relaxometry can be conducted in arbitrarily inhomogeneous fields, imaging is best performed in linearly space-dependent fields, and spectroscopy benefits from highly homogeneous fields. For each type of NMR analysis, there are particular instruments. In contrast to large-scale NMR, small-scale NMR works with closed magnets, where the sample rests inside and open magnets for nondestructive testing of large objects. Each type of analysis is associated with at least one Nobel prize.

Today, small and portable instruments are available for each of the three application areas. They are built from permanent magnets so that the magnetic field strengths are low, as in the earlier days of NMR. These low-field instruments come with two variants of magnets, open and closed magnets. Open magnets expose the object to their stray field and the NMR signal is acquired from a sensitive volume outside the magnet and inside the object. This principle has been pioneered in well-logging NMR and become popular for materials testing with the advent of the NMR-MOUSE. The stray field can be shaped locally to vary linearly across the sensitive volume so that it is suitable for imaging, and it can even be made homogeneous for single-sided spectroscopy. Stray-field NMR does not limit the size of the object, but has low sensitivity, as the sensitive volume is typically rather small. A large sensitive volume is obtained with homogeneous and weakly inhomogeneous fields inside closed magnets. Even when assembled from blocks of permanent magnets, the field inside can be shimmed to extreme homogeneity sufficient for chemical-shift resolved spectroscopy, although each magnet block is made with finite precision in the percent range and with local field variations due to the granular structure of the magnet material.

| Small-scale NMR | Large-scale NMR | Nobel prizes |
|-----------------|-----------------|--------------|
| Closed magnets  | Open magnets: NMR-MOUSE | 1952 Nobel prize in Physics: Edward Purcell, Felix Bloch 1962 Nobel prize in Chemistry: Richard Ernst 1977 Nobel prize in Chemistry: Kurt Wüthrich |
| Relaxometry     |                 | 2003 Nobel prize in medicine: Paul Lauterbur, Peter Mansfield 1999 Nobel prize in Chemistry: Paul Lauterbur 2003 Nobel prize in Chemistry: Peter Mansfield |
| Tomography      |                 | 1991 Nobel prize in Chemistry: Richard Ernst 2002 Nobel prize in Chemistry: Kurt Wüthrich |
| Spectroscopy    |                 | 2003 Nobel prize in medicine: Paul Lauterbur, Peter Mansfield 1999 Nobel prize in Chemistry: Richard Ernst 2003 Nobel prize in Chemistry: Peter Mansfield |

Figure 1. Instruments for small-scale NMR and for large-scale NMR. There are multidimensional data sets that transform into multidimensional distributions of frequencies, positions equivalent to images, and relaxation times as well as combinations thereof.
Figure 2. NMR magnets from permanent magnet materials. (a) Halbach magnet constructed from trapezoidal magnet blocks with gaps between them in which magnetic plates are moved in and out to shim the field. Typical field strengths are 0.5 T for imaging and 1 T for spectroscopy. (b) Stray-field magnets for nondestructive testing of large objects. The classical design of the NMR-MOUSE® derives from a u-shaped magnet. The signal is collected from a thin sensitive slice above the sensor surface. By changing the distance between the sensor and the object, depth profiles or 1D images are acquired. (c) The design of the NMR-MOUSE® is similar to that of well-logging sensors. It has been reduced to cylinder shape with a 5 cm outer diameter to serve as a logging tool that slides along tubes in the ground and measures soil moisture.

2. Principles of open and closed magnets for mobile nuclear magnetic resonance (NMR)

Following Klaus Halbach, a closed magnet with zero stray field outside and a comparatively homogeneous field inside that is transverse to the cylinder axis can be constructed from individual blocks of permanent magnets [20]. Such a Halbach magnet is composed of several rings with discrete magnet elements. The blocks in each ring are magnetized so that the magnetization rotates by $4\pi$ when scaling the circumference of the ring by $2\pi$ (figure 2(a)). The distance between the rings is adjusted to achieve axial field homogeneity. A very effective way to shim the field in the cross-sectional plane of each ring consists of sliding rectangular magnet blocks in and out in narrow gaps between the main magnet elements in the ring. Different displacement patterns correspond to correction terms of different order spherical harmonic functions [19]. In this way, excellent homogeneity can be achieved, which, for example, is good for imaging applications.
enough to resolve the small splitting from the indirect coupling in ethanol in a volume of 1 cm$^3$ at 0.5 T in a desktop magnet for imaging small objects like mice.

Stray-field NMR magnets are designed in such a way that the field outside the magnet is used for the NMR measurement. There are two general approaches to build such magnets: the stray field can be oriented essentially parallel or perpendicular to the sensor surface [16]. The first one is preferable, as the rf stray field that needs to be perpendicular to the stray field of the magnet can be generated by simple wire loops which serve better in delineating the sensitive volume. The most simple stray-field sensor then is a u-shaped magnet (figure 2(b)) with the rf coil centered in the magnet gap. The stray field of such a magnet can be shimmmed to provide a constant gradient of chosen strength within the sensitive volume in a direction perpendicular to the sensor surface, including a field with zero gradient sufficiently homogeneous for chemical shift resolved $^1$H NMR spectroscopy [18]. A particular geometry is that which provides a thin sensitive slice in a plane parallel to the sensor surface at a given distance, such as 3, 5, 20 or 25 mm. This geometry is used in the profile NMR-MOUSE® [21], which is mounted on a computer-controlled positioning device that changes the distance between the sensor and the object and moves the sensitive slice through the object to acquire depth profiles of parameters typically extracted from multi-echo decays (CPMG according to Carr, Purcell, Meiboom and Gill) signals [16].

The types of sensors most important for the studies of porous media are the Halbach magnet for relaxometry, which does not require extensive shimming, the profile NMR-MOUSE for relaxometry and depth profiling, and the logging tool already well established in the well-logging industry. Such a logging tool has already been miniaturized to diameters less than 2 mm for use as a vascular endoscope [22]. Both 2 and 5 cm diameter versions reminiscent of the Halliburton concept have been built for studying soil moisture (figure 2(c)) by sliding the sensor along plastic tubes installed in the ground [23, 24].

3. Soil moisture

A detailed knowledge about the content, location and migration of moisture in soil is of utmost importance to maintain fresh-water sources, to optimize the growth conditions of plants for food and biomass, and to understand climate and weather patterns. Logging moisture similar to oil with tools sliding along the bore holes appears simple, but is challenged by the lack of shielding from electromagnetic noise in the partially water-saturated vadose zone of the upper few meters of the earth’s surface. Furthermore, the simple relationship between the relaxation time and pore radius [4], which is fundamental to logging fluid-saturated oil wells, no longer applies to partially fluid-saturated porous media. This situation calls for extensive laboratory studies of soil samples. These can be performed with closed magnets with moderate field homogeneity sufficient to excite the whole sample volume with a single rf pulse. In such studies, field-cycling techniques are employed to learn about the dispersion of longitudinal relaxation times at low-field strength given the polarization and detection sensitivity at the elevated field strength [25]. More detailed information can be derived from two-dimensional (2D) relaxation maps [13, 14], which, for the sake of saving measurement time, are preferentially performed with CPMG detection of the transverse relaxation, which is hard to measure at variable field strength in field-cycling experiments.

Transport phenomena are studied best by experiments, which include a time lag during which molecules may move, for example, by incoherent thermal motion or external pressure.
differences across the object. Diffusive displacement is best studied in fields with well-defined gradient strength using time-invariant and pulsed gradient fields \cite{7, 26, 27}. But also relaxation exchange experiments can provide some information about molecular displacements \cite{28}--\cite{30}. Such experiments are simple to perform even with logging tools without particular demands on the magnetic field homogeneity, but the data are difficult to analyze quantitatively, as the evolution, mixing and detection times are all in the same range for fluids in porous media. Exchange rates can be quantified with the help of numerical simulations \cite{31}--\cite{33} from which distances between relaxation centers can be inferred given the diffusion coefficient of the fluid filling the pores. With the help of such experiments, the concept of describing porous media by a pore-size distribution can be extended to one that describes the pore space in terms of average pore geometry. The distances between relaxation centers identified by NMR can be used as constraints in setting up a model of the average pore. A direct correlation of distances traced by moving molecules with relaxation exchange can be achieved by more sophisticated, mixed Fourier–Laplace techniques with the pulsed gradient fields \cite{34, 35}.

As a proof of concept, first measurements of relaxation exchange were executed with an unshimmed 0.51 T Halbach magnet for different sand and soil samples and at different saturation levels (figure 3(a)) \cite{36}. The 1D $T_2$ distributions exhibit 2–5 relaxation peaks. Cross-peaks connecting diagonal peaks at full saturation provide distance constraints, while at partial saturation they help to identify paths of moisture transport. Multi-site relaxation exchange spectra show some peculiarities. They are often asymmetric when more than two sites exchange, diagonal peaks may vanish from relaxation while cross-peaks are still visible, and the peak positions may be shifted by noise and baseline offset \cite{33}.

The distance range accessible by molecular transport in relaxation exchange experiments is extended beyond that probed by molecular diffusion if the molecules flow in a pressure gradient (figure 3(c)). With the flow rate increasing from the equivalent of light to heavy rain, the signature of relaxation exchange from water-saturated sand maps varies dramatically, showing exchange cross-peaks at zero flow, tilting of the 1D distribution around a pivot point on the diagonal of the 2D map at slow flow, and a contraction of the signal to a single peak at the pivot point at faster flow. At slow flow, surface-bound water and the water in the flow channels appears to slowly exchange with the interstitial water, giving rise to an off-diagonal signal that is asymmetric most likely due to multi-site exchange and unidirectional flow. At rapid flow, the exchange between sites cannot be resolved, and only one relaxation peak is observed. Computer simulations are required for a more detailed analysis of these exchange maps.

1D and 2D relaxation-time distributions are fit for measuring in the inhomogeneous stray fields of logging sensors. First moisture measurements were performed with a 5 cm diameter slim-line logging tool in the soil of a field close to the surface (figure 4). The CPMG decays revealed broad mono-modal distributions at different depths while the moisture content varied. The main problem faced in the measurements was strong electromagnetic noise received by the tool. By shielding the guide pipe in the ground with copper foil for three quarters of its circumference and covering about 60 m$^2$ of the surface near the hole with electrically conducting parachute silk, the electromagnetic noise contamination could be attenuated sufficiently well to acquire useful signals in 4096 scans. Relaxation exchange maps measured with such a sensor in the field over extended periods in different seasons, weather and plant growth conditions are expected to provide detailed information about moisture supply, transport and dissipation at the pore level, which is inaccessible by other methods.
Figure 3. Relaxometry of water in soil samples. (a) Each soil type (FH31, Selhausen, Merzenhausen) exhibits a different signature in the 1D relaxation time distribution \([\frac{T_2}{\text{s}}]\). Cross-peaks in 2D exchange maps report diffusive distances between relaxation centers at full saturation \((S = 100\%)\) in the absence of flow. At lower saturation \(S\), peak positions and cross-peak intensities provide information about moisture transport pathways. (b) Setup for flow-relaxation exchange NMR of soil samples in a Halbach magnet (right). (c) The distance range probed by relaxation exchange NMR in soil and covered by diffusion is increased by directional flow. The signature of the relaxation exchange of sand maps varies dramatically as the flow rate increases from the equivalent of light rain to heavy rain.

4. Moisture in concrete structures

NMR signals from gray concrete are hard to measure, due to extremely short relaxation times from paramagnetic impurities. Nevertheless, with an echo time of 60 \(\mu\)s, a few echoes can be measured from residual water in concrete and signal averaged over times of the order of a
Figure 4. Measurement of soil moisture by slim-line logging. (a) Setup at Selhausen. The instruments are located in the tent. The ground surrounding the hole is covered with electrically conducting parachute silk. (b) Logging hole with a preinstalled 5 cm pipe and the sensor (10 MHz NMR frequency). (c) CPMG decays and relaxation-time distributions at different depths (700 echoes, 0.06 ms echo time, 4096 scans, 0.5 s recycle delay). (d) Moisture profile in terms of the amplitude sums of the first few echoes in the CPMG train measured at each depth.

A few minutes to obtain CPMG signals of sufficient quality to determine the effective transverse relaxation time (figure 5(d)) and the signal amplitude extrapolated to time zero relative to that of pure water. This value can be rescaled with the density of concrete to yield the NMR moisture content in grams of water normalized to grams of concrete, so that depth profiles of moisture can be measured with the NMR-MOUSE® (figure 5(c)). Such depth profiles were measured in a tunnel near Stuttgart (figure 5(a)) and in a lock near Magdeburg (figure 5(b)). Reference moisture data were available from electrical resistance measurements performed with electrodes permanently installed at positions nearby those where the NMR measurements were performed and from drying studies of the gravel collected from drilling holes into the concrete wall.

The moisture values derived from NMR signal amplitudes showed appreciable deviations from the reference values, which may be attributed to several factors. Apparent shortcomings were that NMR measures proton content, electrical resistance measurements explore electron and ion mobility, and drying studies suffer from low depth resolution and moisture change in the time lag between sampling and analyzing the samples. Furthermore, concrete is a mixture of cement and stones, two materials with widely differing water uptake capacities. Since the diameter of some stones is not much smaller than the diameter of the sensitive plane of the profile NMR-MOUSE®, the signal amplitude is not a good parameter for measuring...
moisture content in concrete. In the follow-up measurements on reference concrete blocks of the particular formulations used for the investigated buildings, depth profiles of CPMG amplitude and corresponding relaxation time $T_{2,\text{eff}}$ were acquired during water uptake and drying. From these data, correlation maps of amplitude versus $T_{2,\text{eff}}$ were constructed (figures 5(e) and (f)). Both parameters correlate linearly [37]. While the amplitude is affected by the presence of stones in the concrete, $T_{2,\text{eff}}$ is not, so that the data points are grouped in the lower right triangle of the graph. The slope of the dividing line is different for both samples and depends on the type of concrete. To explain this observation, it is postulated, that the moisture collects at the small pores first upon wetting and that large pores empty first upon drying. The result is that the transverse NMR relaxation time is a better parameter to quantify moisture content in real concrete than the signal amplitude, as confirmed by independent moisture measurements.

**Figure 5.** Measurement of moisture in concrete with the 25 mm NMR-MOUSE®. (a) Setup in the Gäubahntunnel near Stuttgart. (b) Moisture profiles near the tunnel entrance (outside) and 120 m inside. The moisture values were derived from the echo-train amplitudes by extrapolation to zero echo time, renormalized to moisture content given the density of concrete, and a depth correction to account for the steel reinforcement of the wall. (c) Corresponding relaxation-time profiles. Due to the presence of stones in the concrete, the amplitudes are a poor representation of concrete moisture. (d) Setup while measuring moisture profiles in the walls of the lock Hohenwarthe near Magdeburg. The equipment is located on the boat. The sensor is bolted to the wall. (e) Amplitude versus relaxation-time correlation determined from depth profiles measured in the laboratory at different drying times on a concrete reference sample from Gäubahntunnel. (f) Same as (e) but for the lock Hohenwarthe.
5. Moisture in mortar layers

Mortar is similar to concrete but lacks large stones, so that the signal amplitude measured with the profile NMR-MOUSE® can be expected to indeed scale well with moisture content. To study the moisture distribution at different positions of Roman frescoes with different conservation histories was the original motivation to measure CPMG depth profiles in a number of buildings excavated in ancient Herculaneum [38]. The Greco-Roman beach town was heavily damaged in an earthquake in the year 62 AD. During reconstruction, the nearby volcano Vesuvius erupted and buried the city under its lava in the year 79 AD. For over 300 years, the ancient city has been excavated and various preservation efforts have been undertaken since, which are largely undocumented.

One of the major threats to the city is water that rises up the walls, carrying salts that damage the ornate wall paintings. Modern conservation efforts aim to manage moisture content and transport in walls and mortar layers by various means, such as impregnating the upper layer and diverting the moisture migration paths by maintaining high humidity locally. The profile NMR-MOUSE® is ideally suited to map moisture profile through mortar covered with wall paintings, as the wall need not be touched. Among other measurements, moisture profiles were acquired at selected positions in a recently excavated section of the Papyrus Villa (figure 6(a)) in Herculaneum and at a painted outside wall bordering a terrace above that room. The humidity inside the room was kept high to keep water from evaporating from the wall and to reverse the salt migration within the walls. The high moisture content gave a good NMR signal, so that depth profiles could be acquired across 16 mm in about 90 min. The moisture profiles revealed that the mortar bed for the paintings was prepared from many layers, as described by Vitruvius [39]. The layers differ in their moisture uptake, as reported by the amplitude profiles (figure 6(b)), as well as in their material properties, as reported by the relaxation time profiles (figure 6(c)). It is hoped that a detailed data analysis in combination with studies on layered mortar models will contribute to reconstruct the highly refined Roman technology of preparing walls for fresco paintings. From the measured profiles, it is clear at this time that two technologies can be discriminated by the number of layers and their depth ranges. The walls prepared before the earthquake show thicker mortar layers than the wall rebuilt after the earthquake and an outside wall. Surprisingly, the NMR signal amplitude of the mortar layer outside is higher at greater depth than that on the newer wall inside. This may be due to elevated salt content and thus higher moisture in the outside mortar layer due to moisture entering the walls in the room underneath as a result of the elevated air-moisture content.

The structure in the amplitude profiles is lost at low moisture content, as demonstrated by profiles measured through the mortar bed of the frescoes in the House with the Black Room (figure 6(d) and (e)). A dry wall (wall A) yielded an amplitude profile with little signal variation. But another wall (wall B) of the same room suffered from elevated moisture content and gave a better signal. As these profiles were measured prior to the ones in the Papyrus Villa and with the profile NMR-MOUSE® adjusted to a lower depth range, the fabrication technology of the mortar bed cannot be compared to the two technologies identified in the Papyrus Villa, but the prominent first peak in the profiles from the Papyrus Villa appears as well in the more moist wall and at about the same depth of 2 mm.

Different mortar layers have also been found in a very first study of wall paintings in the state room of Villa Palagione in Volterra, which dates from 1598 (figure 6(f)) [40]. There the interface between two mortar layers was found in an overnight measurement of a depth profile.
Figure 6. Moisture profiles through mortar layers. (a) Untreated and moist Roman frescoes at Herculaneum that have recently been excavated. (b) Moisture profiles through two positions dating from before the earthquake in 62 AD, at one position dating after the earthquake and at an exterior wall. (c) Corresponding relaxation time profiles. (d) Setup of the 25 mm profile NMR-MOUSE® at wall A in the black room at Herculaneum. (e) Moisture profiles through two walls in the black room at Herculaneum. Wall B suffers from high moisture infiltration. (f) Section of a painted wall in the state room of Villa Palagione in Volterra, which dates from 1598. There are two distinct mortar layers. (g) Depth profile of the wall shown in g measured after spraying it with water and before opening up the mortar layer.

after the wall had been sprayed with water to enhance the signal. The position of the interface was subsequently confirmed by destructive inspection of this and another painted wall. These first studies revealed that the mortar bed of all of these painted walls has been prepared from layers applied with high precision and reproducibility, and that different preparation techniques can be distinguished by noninvasive inspection with portable NMR.

6. Pore structure of a diesel particulate filter

Diesel particulate filters (figure 7(a)) are used in scrubber systems of diesel engines in the automotive industry to reduce air pollution in compliance with the European emission standards. The main body of such a filter consists of a large number of parallel channels with square cross-sections, which are separated by the porous ceramic walls. Their pore-size distribution is one of the most important factors for controlling the filtering mechanism. Mercury intrusion
Figure 7. Porosity study of a diesel particle filter. (a) Photo of the filter block. (b) Section of the block. For the NMR measurement it was saturated with water. (c) Moisture amplitude profiles at different spatial resolution showing the pores and the walls as well as variations in the porosity across the wall due to the manufacturing process. (d) Relaxation-time distribution from NMR and differential volume curve from mercury intrusion porosimetry. Both are monomodal.

Porosimetry (MIP) is the predominant method for determining pore-size distributions, but the procedure is destructive, expensive and toxic. In the near future, its use will be prohibited, so it needs to be replaced by another method. This is why the use of the profile NMR-MOUSE® was investigated for characterizing diesel particulate filters.

A section of a filter was prepared for an exploratory study and carefully saturated with water (figure 7(b)). The depth profile of the CPMG amplitude through this water-filled array of porous walls and channels maps the porosity and images the periodic structure of the filter with high accuracy. A symmetric variation of the CPMG amplitude across the filter walls between the channels is clearly resolved (figure 7(c)). The signal amplitude is lower near the wall and higher in the center, indicating higher porosity in the center. This is likely to result from the particular extrusion process of the green ceramic before sintering. The average porosity determined by NMR (49.4%) agrees well with the one determined by MIP (49.2%).

The relaxation-time distribution derived by inverse Laplace transformation of CPMG decay from a pore wall provides the pore-size distribution (figure 7(d)). It can differ somewhat from the distribution derive by MIP, as MIP cannot resolve different distributions across such a thin
and because the distributions from MIP are more sensitive to the pore-throat size than the pore size. It is concluded that NMR constitutes a valid alternative to MIP in characterizing diesel particulate filters, as NMR not only provides porosity and pore-size distribution, but also their spatial variation across filter walls in a nondestructive way.

7. Summary

The state of the art of portable NMR instrumentation has been reviewed. Halbach magnets and stray-field sensors, such as the profile NMR-MOUSE\textsuperscript{®}, find many applications in porous-media studies. 2D relaxation exchange NMR of fully fluid-saturated porous media has the potential to provide distance constraints for simulation of average pore geometry to characterize the porous media in a way complementary to the pore-size distribution. To this end, it is necessary to numerically invert experimental 2D maps, a demanding challenge if more than two exchanging sites or a continuum of sites is involved. Under partial saturation relaxation exchange, NMR can provide insight into the pathways of water migration. As the experiment does not demand high-field homogeneity, it may be performed with logging tools in the field to study the moisture transport in the vadose zone. Although the use of NMR-logging tools in the partially water-saturated upper meters of the earth’s surface is complicated by the strong rf noise, the first experimental data from field measurements with a 5 cm diameter slim-line logging tool could be reported.

Logging tools are stray-field NMR instruments such as the NMR-MOUSE\textsuperscript{®}. The use of the profile NMR-MOUSE\textsuperscript{®} with 25 mm depth access has been demonstrated with different practical examples. One concerned moisture measurements in the walls from of a tunnel and a lock from gray concrete. As the material contains stones of various sizes, the CPMG amplitude is poorly suited to measuring moisture profiles. On the other hand, the CPMG amplitude and transverse relaxation time were found in laboratory studies to correlate linearly with slopes that are characteristic of the type of concrete, so that relaxation measurements appear to be the better way to quantify moisture content in gray concrete.

Mortar is much easier to measure. It often contains less paramagnetic impurities, so that the CPMG trains are much longer than in gray concrete. Also, it does not contain stones but only sand, so that the CPMG amplitude from the sensitive slice of the profile NMR-MOUSE\textsuperscript{®} is a good measure of moisture content and the relaxation time distribution characterizes the type of mortar. Moisture profiles were measured through the mortar bases of wall paintings in Herculaneum and at Villa Palagione in Volterra. If not too dry, different mortar layers can be identified from the depth profiles and studied in view of fabrication techniques and conservation measures. The same experimental procedure was followed in studying diesel particulate filters built from an array of porous ceramic walls. At full water saturation, the porosity and the pore-size distribution, as well as their spatial variations, can be determined as a nondestructive alternative to mercury intrusion porosimetry.

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