Wireless Transmission of Monitoring Data out of the HADES Underground Laboratory - 12450

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ABSTRACT

As part of the European 7th framework project *MoDeRn*, Nuclear Research and Consultancy Group (NRG) performed experiments in order to demonstrate the feasibility of wireless data transmission through the subsurface over larger distances by low frequency magnetic fields. The main objective of NRG's contribution is to characterize and optimize the energy use of this technique within the specific context of post-closure monitoring. For this, measurements have been performed in the *HADES* underground laboratory located at Mol, Belgium, at 225 m depth. The experimental set-up makes use of a loop antenna for the transmitter that has been matched into the existing infrastructure of the *HADES*. The experimental work of NRG is divided into several stages: in 2010, the necessary hardware has been designed and assembled and tested in the Netherlands. Site-specific magnetic background noise in Mol and frequency-dependent signal attenuation by the geologic medium has been measured. Signal transmission has been demonstrated and several transmission channels around 1 kHz have been identified. In 2011, additional measures and experiments have been performed in order to characterize and test relevant element of the transmission chain and to optimize the energy use of the set-up. A mathematical model description has been developed that includes the most relevant characteristics of the transmitter, receiver and transmission path and was used to analyse possible options to optimize the set-up. In 2012, experiments are planned in order to test several data transmission options. Results so far have shown that signal transmission over larger distances through the subsurface is feasible. However, to make quantitative conclusions on the energy need per bit of transmitted data, additional experiments planned in 2012 are necessary.

INTRODUCTION

When the in-situ monitoring in a geological radioactive waste disposal is continued after the post-closure phase (i.e. when the access shaft is closed), data acquired by the underground monitoring system need to be transmitted wirelessly to the surface. For the wireless transmission of data, high-frequency electromagnetic waves are used in many applications. Electromagnetic waves can be transmitted easily over larger distances in air, but the presence of solid objects is known to potentially impede the wave propagation. The application of high-frequency techniques in a geologic waste disposal is therefore limited to shorter distances (few meters to tens of meters). When it comes to the wireless transmission of data between different repository sections or between the repository and the surface, the large attenuation by the geologic medium makes the application of high-frequency waves unfeasible.

Within the European 7th framework project *MoDeRn*, *Monitoring Developments for safe Repository operation and staged closure,* NRG is conducting tests on the wireless transmission of monitoring data using low frequency magneto-induction techniques. These techniques are applied e.g. in mine communication and rescue ("trapped miner detection") [1, 2, 3] or military communication, both on medium distances [4] and globally [5]. For these applications, the used frequency ranges from a few tens of Hz to a few tens of kHz. The specific objective of NRG's contribution is to characterize and optimize the energy use of this technique within the specific context of post-closure monitoring. This should help to judge the general feasibility of long-term wireless data transmission from an underground repository through the enclosing host rock and the overlying geosphere to the surface.

Besides the decrease of the field strength by increasing distance that can be approximated by the law of Biot-Savart [6], interactions with the geologic medium will attenuate the field strength. The attenuation of the magnetic waves by interactions with the geologic medium can be characterized by the so-called skin depth (δ) [7]. A distinction can be made between a "good conductor" and a "poor conductor", with the skin depth for a "good conductor" expressed by

$$\delta[m] = \frac{1}{\sqrt{\pi \cdot \mu_o \cdot \mu_r \cdot \sigma \cdot f}} \qquad \text{Eq. 1}$$

with

- μ_o permeability constant ($1.257 \cdot 10^{-6}$ V·s/A·m)
- μ_r relative (magnetic) permeability [-]
- σ conductivity [S/m]

The conductivity σ of geological media can vary to a large extent, from µS/m to mS/m range for crystalline rock, and mS/m to S/m range for argillaceous rock. The water-filled porosity of the geological media has an important influence on the conductivity ($\sigma_{\text{ground water}} \approx 0.5$ S/m). For the Dutch generic disposal design [8] in argillaceous rock, the transmission path will behave over a large frequency range as a "good conductor" due to the high water content of the Boom Clay and the sandy aquifers situated above the host rock. As a result, the skin depth will decrease with the square-root of the used transmission frequency. In contrast, granite or salt rock will behave - dependent on the conductivity and the transmission frequency - as a "poor conductor", which make it possible to consider the use of higher frequencies than in case of "good conductors".

The wireless data transmission experiments of NRG are being performed at the HADES Underground Research Laboratory (URL) in Mol, Belgium, situated at 225 m depth in a 100 m thick layer of Boom Clay. Because the Boom Clay and the overlying aquifers is expected to attenuate the magnetic fields more strongly than other host rocks, it is assumed that transmission experiments performed in the HADES give a more realistic picture on field propagation than experiments performed e.g. in granite, salt rock or

Opalinus clay. Although the generic depth for the Dutch disposal design is 500 m [8], the experiments performed HADES URL are expected to give sufficient representative results to judge the feasibility of the technology for a future disposal situation.

RESEARCH SET-UP

When considering data transmission linking, three general elements can be distinguished (Figure 1):

- the transmitter, that transforms digitally coded data into a magnetic field
- the transmission path through which the magnetic field propagates
- the receiver, that transforms the magnetic field back into data

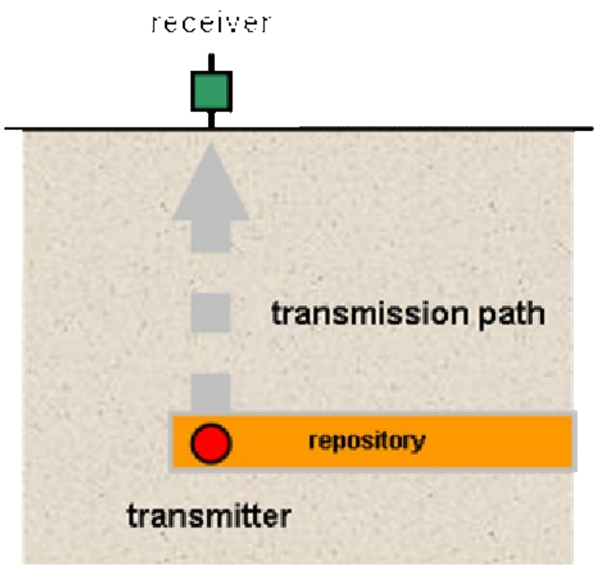

Fig. 1 Main elements of a wireless transmission chain.

In case of the transmission of monitoring data from an underground radioactive waste repository to the surface, a number of specific boundary conditions can be identified that should be considered when employing current knowledge for this particular application:

- fixed antenna locations exists and the transmission path and distance is known
- the transmission properties of the host rock and overburden are invariable and known
- there are only minor restrictions for the antenna geometry and size in case of a horizontal loop-antenna
- localized sources of interference, both underground and on the earth's surface, can be avoided, eliminated or reduced
- no specific timeframe for data transmission is needed
- transmission bandwidth is not a limiting factor
- a reliable transmission of data is essential
- energy use is a relevant topic

For the transmission of monitoring data out of a repository, the energy efficiency can be assumed as the most important design criteria in case of the long-term monitoring of a radioactive waste disposal in the post-closure phase. Although some potential techniques may exists either to convert heat or radiation into electrical energy within the disposal facility or to transmit energy by wireless techniques into the facility, on basis on the current state of technology it is reasonable to assume that the energy use of the monitoring system is an essential limitation and should therefore be minimized.

The energy-efficiency of a data transmission system depends mainly on two factors:

- the energy need per bit of transmitted data
- the amount of data that need to be transmitted

The amount of data that need to be sent can be optimized by a precise analysis of the data need, e.g. the necessary frequency of data transmission, the precision of the transmitted data or the kind of information that need to be transmitted. Moreover, the set-up of a bidirectional link may give additional options to decrease the amount of data to be sent.

The energy content per bit can be improved by proper engineering of the transmission equipment and set-up. In order to optimize the energy efficiency of the transmission links, all three elements depicted in Figure 1 has to be considered and characterized. In order to do so, NRG set out a 3-year working plan, as will be described below.

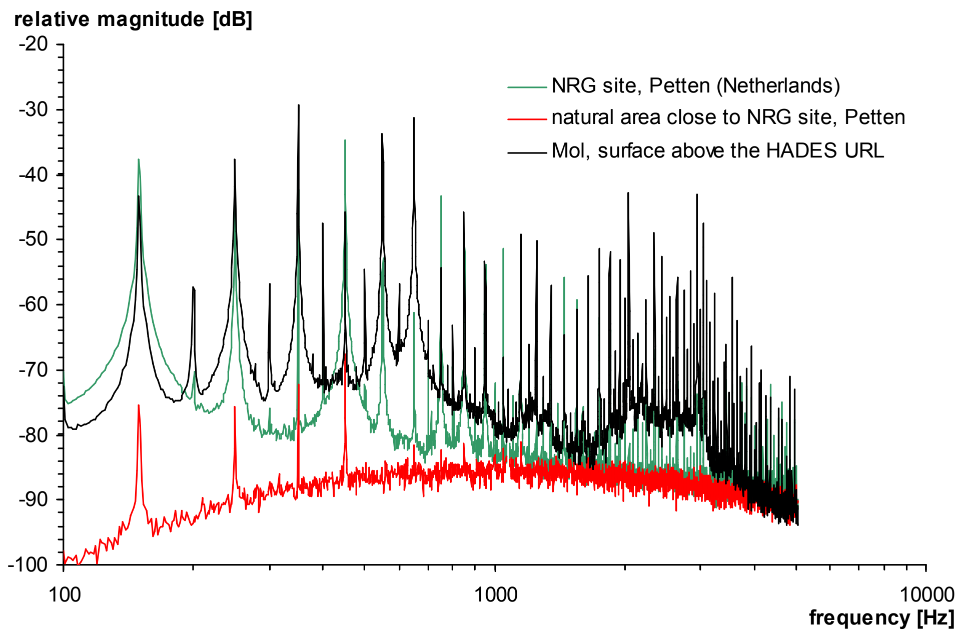

Fig. 2 Location specific noise pattern at Mol, the NRG site in Petten (Netherlands) and a natural area close to Petten.

In 2010, the principal experimental set-up and experimental boundary conditions have been established: first, the necessary hardware was designed and assembled and a first proof-of-principle was performed in the Netherlands to demonstrate that the transmitter-receiver set-up was performing as expected. In a second step, the site-specific magnetic background noise pattern at the surface in Mol was recorded and analyzed as a function of time and frequency. The results show a strong interference pattern due to the 50 Hz electricity network (Figure 2). Additional measurements were performed at NRG's site in Petten (The Netherlands) and in an natural area close to the Petten site (Figure 2), leading to the conclusion that for a future disposal situation, much smaller interferences must be achievable, leading to a higher sensitivity of the used method.

In a third step, the frequency-dependent signal attenuation by the geologic medium between the HADES URL and the surface was determined. During the experiments, signal transmission from the HADES to the surface was demonstrated for a range of frequencies. As expected, due to the high electrical conductivity of the subsurface, a strong attenuation of higher frequencies occurred; which limited the available bandwidth for data transmission to less than 2 kHz. Based on the data on the location specific background noise gained in the previous step, several potential frequency channels for the signal transmission at Mol have been derived that are assumed to be most promising with respect to the necessary transmission energy. These channels are located between 800 Hz and 1.4 kHz, due to the high interferences below 800 Hz and the high signal attenuation above 1.4 kHz (Figure 2).

In 2011, additional measures and experiments have been performed in order to characterize and test relevant element of the transmission chain and to optimize the energy use of the set-up. A mathematical model description has been developed that includes the most relevant characteristics of the transmitter, receiver and transmission path. The model description is used to analyse possible options to optimize the set-up and to estimate minimum energy demand for signal transmission. E.g., upscaling and an improved antenna design (Figure 3) and an advanced preamplifier design lead to an increase of the sensitivity of the receiver part.

However, for the transmission experiments in the HADES URL, the strong background noise (Figure 2) present at the Mol site was identified as a serious limitation to the possibilities of testing and demonstrating signal transmission using lower signal strength. Therefore additional experiments were performed in the Netherlands to demonstrate the principal capabilities of the technique at very low signal strength. The capability to detect magnetic fields below 0.1 pT at 1 kHz with the designed equipment was demonstrated.

Fig. 3 Receiving antenna NRG-4.

As final part of the programme, the bidirectional transmission of data may be demonstrated. This activity is optional and depends on the results obtained and if time and budget permit. A bidirectional data transmission system may be tested that enables interactive communication with the underground monitoring infrastructure ("talking with the repository"). Such a bidirectional link may facilitate a more efficient use of energy by reducing the amount of transmitted data. Besides, it may give the option to use and maintain the monitoring infrastructure more flexibly.

CONCLUSION

The experimental and theoretical results gained by NRG, as part of the European 7th framework project *MoDeRn*, so far demonstrated that signal transmission through 225 m of a geological medium is feasible, even in case of a "good conductor" as present in Mol. At this particular site the transmission distance through the different layers of clay and sandy aquifers is larger than the skin depth and clearly extends the near-field. The step from signal to data transmission will be made in 2012 and is essential to be able to make quantitative statements of the energy use per transmitted data bit.

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