Wireless Transmission of Monitoring Data out of an Underground Repository: Results of Field Demonstrations Performed at the HADES Underground Laboratory – 13589

T.J. Schröder, E. Rosca-Bocancea, and J. Hart
Nuclear Research and Consultancy Group (NRG), P.O. Box 25, NL-1755 ZG Petten, The Netherlands (schroder@nrg.eu)

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 large distances by low frequency magnetic fields in the framework of the geological disposal of radioactive waste. 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 of a repository. For that, measurements have been performed in the HADES Underground Research Laboratory (URL) located at Mol, Belgium, at 225 m depth. The experimental set-up utilizes a loop antenna for the transmitter that has been matched to the existing infrastructure of the HADES. Between 2010 and 2012 NRG carried out several experiments at the HADES URL in order to test the technical set-up and to characterize the propagation behavior of the geological medium and the local background noise pattern. Transmission channels have been identified and data transmission has been demonstrated at several frequencies, with data rates up to 10 bit/s and bit error rates <1%. A mathematical model description that includes the most relevant characteristics of the transmitter, transmission path, and receiver has been developed and applied to analyze possible options to optimize the set-up. With respect to the energy-efficiency, results so far have shown that data transmission over larger distances through the subsurface is a feasible option. To support the conclusions on the energy need per bit of transmitted data, additional experiments are foreseen.

INTRODUCTION

When the in-situ monitoring in a geological radioactive waste disposal facility is continued in the post-closure phase (i.e. after the repository and the access shafts have been closed and sealed), 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 deep geological repository sections or between the repository and the surface, the large attenuation of the signal by the presence of several hundred meters of 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 principal feasibility of long-term wireless data transmission from an underground repository through the enclosing host rock and the overlying geosphere to the surface.

DESIGN CONSIDERATIONS

Each of the applications summarized in the previous section uses different technical set-ups that are optimized for the particular purpose. In case of the transmission of monitoring data from a radioactive waste repository to the surface, a number of specific requirements and boundary conditions for the application of wireless technique can be defined:

- fixed antenna locations exist and the transmission path and distance are known
- the transmission properties of the host rock and overburden are invariable and known
- a large range of antenna geometries and sizes can be realized within a disposal concept when a horizontal loop-antenna set-up is selected
- localized sources of interferences, both underground and on the earth's surface, can be eliminated or reduced
- no specific timeframe for data transmission is necessary
- requirements on transmission speed are low
- an accurate transmission of data is essential
- the supply of energy in the disposal is limited

For the transmission of monitoring data out of a repository, a low energy need was assumed in this project as the most important design criterion in case of the long-term monitoring of a radioactive waste disposal in the post-closure phase. Irrespective of the energy supply provided by e.g. long-lasting batteries, techniques that convert thermal, chemical or radiation energy in the disposal facility, or wireless energy transmission from the surface, on the basis on the current state of technology it is reasonable to assume that the energy supply will be a limiting factor. The energy necessary to transmit monitoring data depends mainly on two factors:

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

The energy use per bit of data can be improved by analyzing the relevant components of the transmission chain and refining the transmission equipment and set up. The amount of data that will be sent can be decreased by careful consideration of the data need, e.g. the necessary interval of data transmission, the precision of the transmitted data, the coding of the data, and the kind of information that need to be transmitted in order to monitor the repository's evolution. Two example calculations may give a first impression of the order of magnitude of data that need to be transmitted:

- if readings of 100 sensors are transmitted every month for 30 years with a precision of 0.1% and 30% redundancy by error detection and correction codes, a total amount of about 60 kB of data will be transmitted

- if readings of 1000 sensors are transmitted every week for 100 years with a precision of 0.1% and 30% redundancy by error detection and correction codes, a total amount of about 8.5 MB of data will be transmitted

These examples can be used to define first rough criteria for the energy efficiency that has to be achieved: when powered e.g. by the energy equivalent of a conventional car battery (500 Wh), assuming 50% of the energy is actually used for transmission, in the first example an energy efficiency of 2 Ws/bit would be sufficient. In the second example, data need to be transmitted with less than 0.01 Ws/bit. When energy is supplied by other, potentially less powerful sources (e.g. nuclear batteries, Peltier elements), the necessary energy efficiency of the used technology can be specified accordingly.

SET-UP OF DEMONSTRATOR EXPERIMENT

Within the MoDeRn-project, wireless data transmission experiments of NRG have been performed at the HADES Underground Research Laboratory (URL) in Mol, Belgium [6], situated at 225 m depth in a 100 m thick layer of Boom Clay, with geological conditions quite comparable to the generic Dutch disposal facility in Boom Clay [7]. Because the generic depth for the Dutch disposal design is about twice as deep as the HADES URL (500 m), a proper characterization of the field propagation behavior is important in order to be able to extrapolate the experiments performed in Mol. Due to their high electrical conductivity, Boom Clay and the overlying aquifers will attenuate the magnetic fields stronger than other countries' repository host rocks [8]; experiments in other URL's (e.g. in granite, salt rock or Opalinus clay) will therefore not lead to representative results. With respect to the location specific boundary conditions, the experimental conditions at Mol are not optimal with respect to three features:

- the size of the transmitter antenna is limited by the diameter of the HADES URL (Fig. 1), leading to an antenna aperture far below optimum
- due to the presence of several on- and off-site power-lines, strong interferences exists on the surface above the HADES URL
- experimental work is performed at day time, leading to additional transient interferences (e.g. by passing cars, operation of the shaft lift)

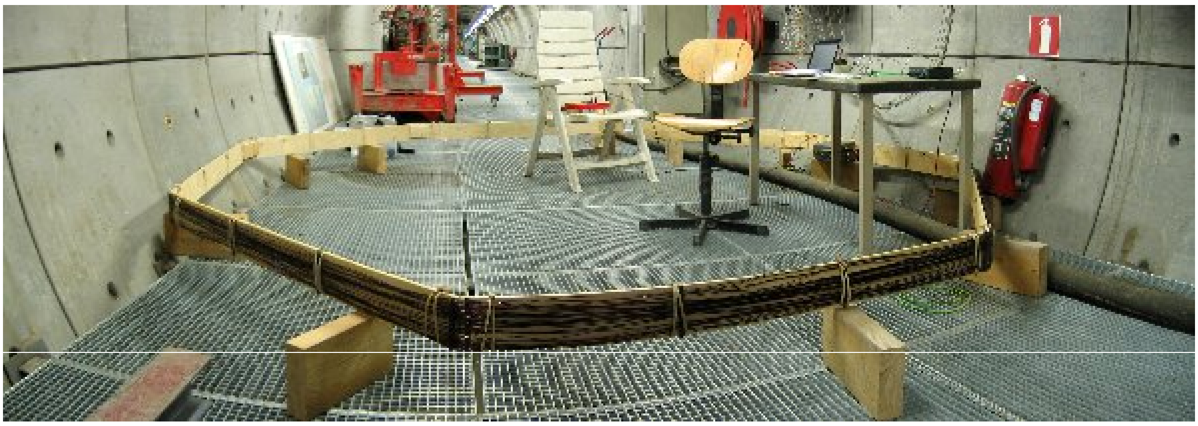

Fig. 1. Transmitter antenna ECN-1 in the *HADES* URL.

Before starting experimental work, all components of the transmission chain were analyzed with respect to energy efficiency of the design, and in several iterative steps, equipment and set-up were modified in several iterative steps in order to anticipate to the local circumstances in the HADES URL and at the surface. To overcome limitations imposed by strong interferences of the power network present at the Mol site, additional experiments were performed at a 'silent', recreational area, close to the NRG site in Petten, The Netherlands. Although these tests were limited to surface-surface transmissions, they provided valuable information by demonstrating the sensitivity of the receiver part.

Fig. 2. Receiving antenna NRG-4.

In 2010, the principal experimental set-up and experimental boundary conditions have been established: first, the necessary hardware was designed and assembled and a proof-of-principle experiment was executed 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. In a third step, the frequency-dependent signal attenuation by the geologic medium between the HADES URL and the surface was determined. Those experiments have delivered sufficient information to proceed to the last step: the selection of a suitable data transmission channel and the demonstration of data transmission from the HADES URL to the surface, including tests of different data modulation options and methods in order to optimize the energy efficiency.

RESULTS

Fig. 3 shows the strong location-specific noise pattern at the surface in Mol as a result of strong harmonics of the 50 Hz power network. These interferences are visible over the whole range of frequencies that are envisaged for data transmission. The strong peaks limit also the maximum bandwidth that can be achieved for data transmission: under these conditions, data rates will be limited to less than 25 sym/s. Comparison with the noise pattern of a relatively 'silent' recreational area close to the NRG-site in Petten, The Netherlands, show that much lower background levels are achievable (Fig. 3). Fig. 3 also shows that by technical improvements of the receiver a higher sensitivity of the set-up could be realized during the project, allowing the detection of magnetic fields <100 fT. The increased receiver sensitivity will permit more efficient data transmission in an undisturbed environment, but are not of much advantage under the conditions present in Mol, because here the background noise is a limiting factor (Fig. 3).

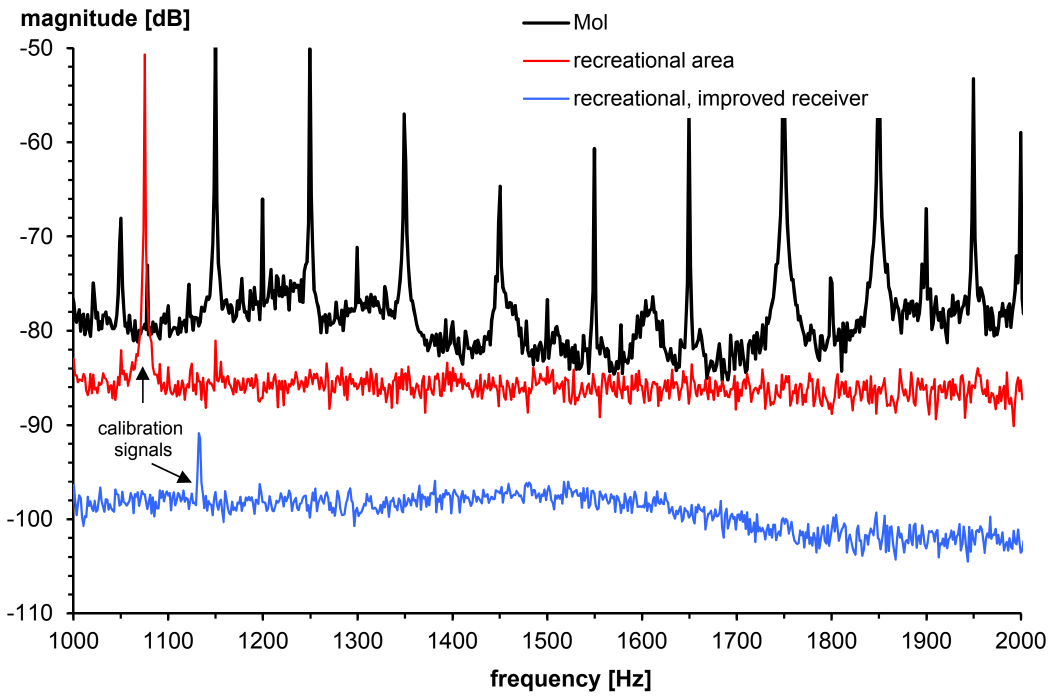

Fig. 3. Location specific noise pattern at Mol, and a recreational area.

Fig. 4 shows the reception of signals transmitted from the HADES URL to the surface. Signals up to 2.2 kHz can be received, with the most favorable signal-noise ratios (SNR) located between 1.0 and 1.7 kHz. It should be noted that without interference, optimum data transmission frequencies may be higher. Fitting of the electrical conductivity σ of the 225 m long transmission path (i.e. Boom Clay and overlying aquifers) resulted in a value of 35 mS/m, which is close to the values reported in [9].

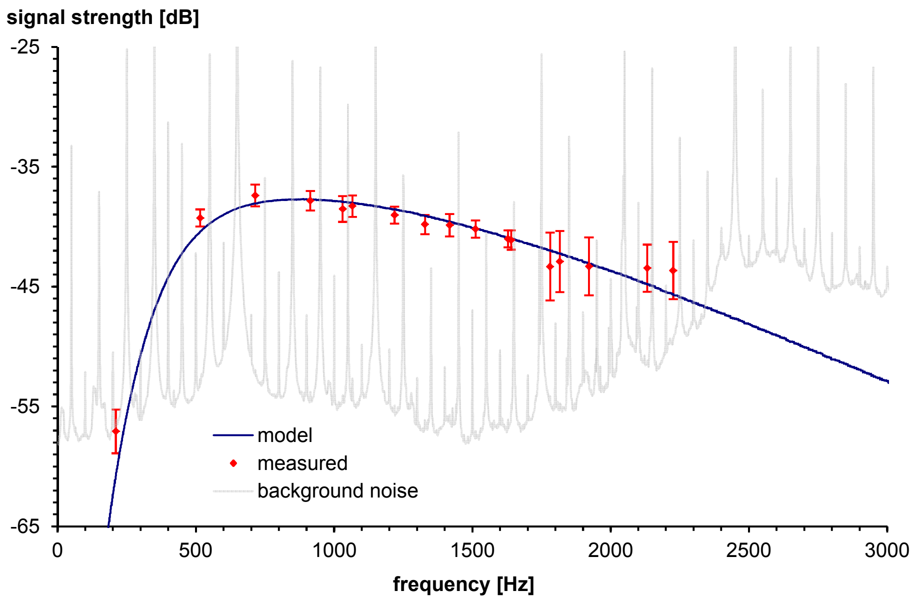

Fig. 4. Background noise pattern, measured and calculated signal strength at the surface in Mol. Assumed conductivity of the geosphere σ = 35 mS/m.

After having acquired data on the propagation behavior of the underground and the local noise pattern, data transmission experiments were carried out. First experiments demonstrated the ability to transmit data from the HADES URL to the surface at two frequencies with data rates up to 10 bit/s and bit error rates (BER) below 1%. Table I summarized a first set of indicative results. It should be note that the length of the experiments was too short to obtain meaningful statistical conclusions.

TABLE I: Bit Error Rates (BER) measured in the first data transmission experiments.

	Frequency	
Data Rate	**1031.3 Hz**	**1066.4 Hz**
3 bit/s	0 dB : 0.4% - 6 dB : 0.9% -12 dB : >1%	0.0%
5 bit/s	0.4%	0.1%
10 bit/s	>1%	0.7%

DISCUSSION

The experiments summarized in the previous section clearly demonstrated the ability to transmit data through approximately 225 m of highly conductive geological medium, even under unfavorable experimental conditions as present in Mol (limited space for transmission antenna and large local interferences).

The next step was to analyze the energy need for a generic disposal concept and to identify potential options to increase the energy-efficiency. A mathematical model has been developed that describes the expected signal strength on the surface on basis of the most relevant characteristics of transmitter, receiver and transmission path. The model is used to analyze the complex interactions of different parameters, and is used to design an optimized set up for data transmission and to estimate minimum energy demand for signal transmission.

Several calculations have been performed in order to design the most energy-efficient set-up for different situations. A preliminary rough estimation of the energy need, based on the results obtained so far, is summarized in Table II.

TABLE II: Estimated energy need for data transmission for different situations.

Set-up	**Transmitter Power**	**Achievable Data Rate**	**Energy per Bit of Data**
HADES URL small antenna (r = 1.85 m)	12 W	20 bit/s	0.6 Ws/bit
HADES URL assuming no interference from power network	0.8 W	50 bit/s	0.02 Ws/bit
HADES URL large transmitter antenna (r = 75 m)	<10 mW	20 bit/s	<0.5 mWs/bit
Dutch generic reference concept at 500 m, large transmitter antenna (r = 100 m)	<20 mW	50 bit/s	<0.4 mWs/bit

In order to substantiate the estimations in Table II, two additional measurements are planned:

- a data transmission experiment at the HADES URL will be performed with an improved set-up in order to support the estimated energy use as quoted in the first row of Table II
- an additional surface-surface measurement will be performed in order to demonstrate the sensitivity of the set-up, allowing to support the estimated energy need in the second row of Table II

The results of these tests will be available in the near future and will be elucidated in the oral presentation.

CONCLUSIONS

The experimental and theoretical results gained by NRG, as part of the European 7th framework project MoDeRn, demonstrated that data transmission through 225 m of a geological medium is feasible, even in case of a “good conductor” as present in Mol. The amount of energy necessary

to transmit data to the surface is within expectation, although due to the local conditions in Mol (limited space in the underground facility, strong interference aboveground) the capability to demonstrate the expected efficiency of the technique was limited.
Estimation of the energy need shows that transmission of monitoring data from a geological disposal facility to the surface may be realized with about 20 mW of energy per bit of transmitted data, but additional measurements are required in order to support the model calculations. Extrapolation of these results to more favorable conditions will be supported and verified by additional field experiments close to the NRG-site in Petten.

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