Wireless Monitoring Study in the Meuse / Haute-Marne Underground Research Laboratory, France – 12046

SUZUKI Kei*, ETO Jiro*, TANABE Hiromi*, MAYER Stefan ** TAKAMURA Hisashi***, SUYAMA Yasuhiro***, BERTRAND Johan**
*Radioactive Waste Management Funding and Research Center (RWMC), Japan
**National Radioactive Waste Management Agency (ANDRA), France
***Kajima Corporation, Japan

ABSTRACT
Two types of wireless transmission systems using ultra low frequency (8.5 kHz) were developed and used in the Callovo-Oxfordian argillites layer in the Meuse / Haute-Marne Underground Research Laboratory (CMHM URL) in France. Short-range and mid-range transmission antennas received data transmitted from 25 m to 50 m away.

INTRODUCTION

In order to confirm the safety [1] and retrievability [2] of geological disposal, wireless data transmission using electromagnetic waves is a promising technique for monitoring geological HLW repositories. It should allow the transmission of essential data without requiring that wires cross the several layers of seals, such as disposal cell seals, gallery seals, and shaft seals.

Therefore, monitoring without any cable, so called “Wireless Transmission Monitoring” is addressed as a preferable solution to realize monitoring inside the bentonite seals of the geological repository [3]. The merits of using a wireless transmission system are summarized below:

- Monitoring without compromising the safety barriers
- Improved data reliability
- Improved workability and economy

Background of wireless transmission

Very low frequency wave

Wireless communication applications such as radio and television broadcasting and cellular phone communication ordinarily use high-frequency electromagnetic waves from several kHz to GHz. However, in media with electromagnetic conductivity, such as rock masses and bentonite, high-frequency electromagnetic waves are excessively attenuated. Consequently, the authors have been developing a wireless data transmission system that can be used in media such as rock or bentonite by using a very low frequency (VLF, approximately 1kHz to 10 kHz) electromagnetic wave as the data carrier. The lower the frequency, the smaller the attenuation of the host rock, bentonite or other medium becomes. The frequencies used in this system are around 1 kHz and 10 kHz. A key point in designing the transmission antenna is selecting the output power of the transmitter.

Principle of wireless transmission

Figure 1 shows the relationship between the intensity of the electromagnetic field and the transmission distance on a log-log graph. The intensity of the electromagnetic field decreases with increasing transmission distance, as described by Maxwell's equations (Eq.1 and Eq.2). The intensity of axial transmission *Hr*, where transmitter and receiver face each other directly, is twice as large as that of vertical or transversal transmission H_θ, where they are arranged in vertical direction or transversal transmission against the axial direction. Another factor is the ambient electromagnetic noise. When the intensity of the electromagnetic field from the transmitter that arrives at the reception point (= targeted distance) is larger than the noise level at that point, the transmission can be successful, so the transmission antenna is designed to meet this requirement.

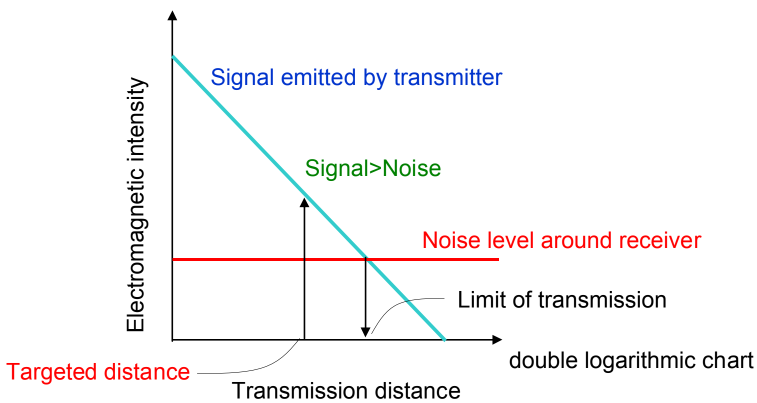

Fig1. Intensity of the electromagnetic field and the transmission distance

$$H_r = \frac{(SI)}{2\pi r^3}\cos\theta e^{-\gamma r} \qquad \text{(Eq. 1)}$$

$$H_\theta = \frac{(SI)}{4\pi r^3}\sin\theta e^{-\gamma r} \qquad \text{(Eq. 2)}$$

$$\gamma = \sqrt{j\omega\mu^*\sigma}$$

Where
H_r and H_θ[mV],: Magnetic field strength, S [m^2] : Area of coil antenna,
ω [Hz]: Angular velocity, [A]: Electric current, μ^* [H/m]: Magnetic permeability
($\mu^*=\mu\times\mu_0$(μ : relative magnetic permeability, μ_0 : magnetic permeability of vacuum))
σ [S/m]: Electrical conductivity

Attenuation effect

In the previous study, no effect on the wireless transmission was detected from the host rock, wire mesh inside the shot-crete, or the invert concrete [4]. However, when the axis of the transmission coil antenna and the axis of the receiving coil antenna were perpendicular to the drift axis, the steel supports caused a decrease to around 20% in the intensity of the electromagnetic field. Therefore, 80% attenuation was assumed in designing the transmission antenna.

Antenna core

Another key point in designing the transmission antenna is the structure of the antenna, especially whether a “core” is used inside the coil or not. Such a core is made of an amorphous material with high magnetic permeability. The function of the core is to concentrate the magnetic flux and thus enable the miniaturization of the antenna, so a core is useful when the transmitter must be installed in a confined space. However, the self-attenuation of a core also shortens battery life.

A transmitter without a core is larger than one with a core, and battery life is longer. When space is not a significant constraint for the transmitter in the HLW disposal gallery, a mid-range transmission antenna with no core is preferable and used in the HLW disposal gallery. The benefits and inconveniences of antennas with and without cores are summarized in Table I.

Table I. Comparison of Antennas with and without cores

	Antenna with core	Antenna without core
Benefit	Smaller transmitter	Longer battery life of the transmitter
Inconvenience	Self attenuation of core	Antenna size is large

APPLICATIPN OF WIRELESS TRANSMISSION SYSTEM

From 2010 to 2011, Andra and RWMC have engaged in joint research on wireless monitoring in the CMHM URL in France. Two series of transmission tests were conducted. One series involved mid-range transmission tests where the distance is less than 100 m, between two different levels of the URL, and the other was for short-range transmission tests at distances less than 30 m using a small transmitter (Fig.2) [5].

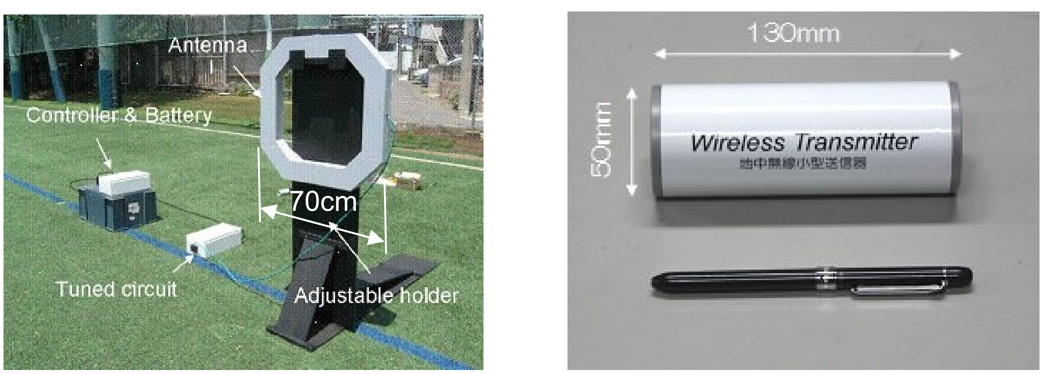

Fig 2. Mid-range transmitter (left) and short-range transmitter (right)

The purpose of the mid-range test was to confirm the feasibility and the performance of wireless transmission technology through a mid-range barrier of undisturbed host rock, without the assistance of wave guides in the rock. Case 1 shows mid-range transmission between open galleries, NCH and GT5 at a distance of 45m (Figure 3 left). The purpose of the short-range test is to confirm the transmission performance of a miniaturized transmission antenna in a borehole of a gallery. Case 2 shows wireless transmission between the galleries, GEX and GMR. Case 3 shows the buffer and an open gallery over a relatively short range (Figure 3 right).

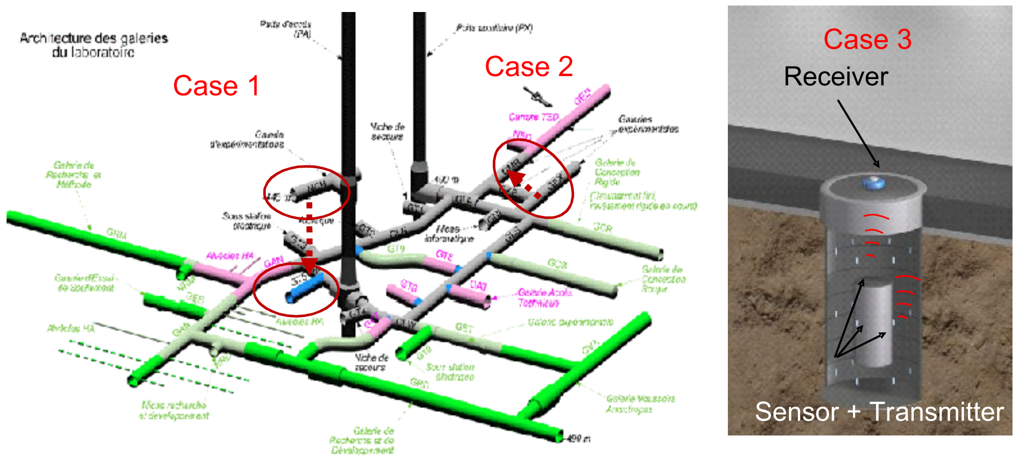

Fig 3. Mid-range (NCH-GT5), Short-range (GEX-GMR) and borehole transmission

DEVELOPMENT OF TRANSMISSION SYSTEM

Development of transmission antenna

Noise level test

Electromagnetic noise level measurements were made around 1 kHz and 10 kHz in the CMHM URL before the transmission test in the URL, to determine the preferable frequency and the best available conditions for the placement of the receiver. In these measurements, noise levels were classified as high (over 100 mV), middle (10 mV~100 mV) and low (under 10 mV). Because of the presence of power machinery, power supply devices, etc., the noise levels of GAN, GRM, and GLW are relatively larger. As the noise level at 10 kHz was lower than that at 1 kHz, 10 kHz was considered the preferred frequency for the transmitter carrier wave.

Design of mid-range transmission antenna

The design chart is shown in Figure 4. The mid-range transmitter was designed so as to create an electromagnetic intensity (= received voltage) that yields 25 mV at 100 m from the transmitter. The targeted 25 mV takes into account the attenuation by steel supports (= 80 %: estimated from the attenuation and the S/N ratio (= 2) for the noise level in NCH (= around 2.5 mV).

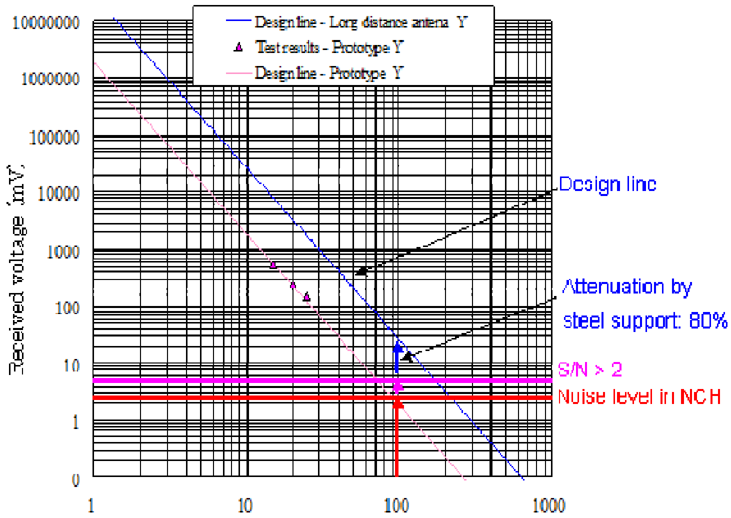

Fig 4. Design chart for electromagnetic intensity and transmission distance

The specifications of the mid-range transmitter are as follows. The benchmark of "Antenna gain" is not applicable for this antenna because the wavelength is too long. The antenna pattern is a figure-eight. Major and side lobes are 0 because the magnetic flux is parallel to the receiver's face at the side position. Front-to back ratio is equivalence.

- Antenna type: Loop (coil) antenna without core
- Carrier frequency: 1 and 8.5 kHz (8.5 kHz was used in the test).
- Antenna gain: - NA (Wavelength: 250 km (1kHz), 30 km(8.5kHz))
- Antenna pattern: Figure-eight
- Beam width: ± 45 °
- Major and Side (Minor) lobes: 0
- Front-to-Back ratio: equivalence
- Aperture: 70 cm outer diameter, 60 cm inner diamter
  Area of coil is proportional to the power.
  Prototype: Mid-range antenna = 1:19 (>15) = 16 cm: 70 cm outer diameter
- Battery: Lithium battery
- Sensors: maximum 10 sensors can be attached outside, but dummy data were transmitted from transmitter to receiver in this transmission test.

MID-RANGE TRANSMISSION ANTENNA TESTS

Surface test

A transmission test on the surface was carried out in Japan and in the countryside near the CMHM URL. The test conditions in the countryside were optimal due to the very low noise level. Transmission was successful up to 240 m. The received voltage at 240 m was 3.5 mV, which met the design criteria.

Transmission test between two galleries, NCH and GT5, a distance of 45 m

A transmission test was conducted between the NCH and GT5 galleries, a distance of 45 m. The NCH gallery is situated at -445 m and the GT5 gallery at -490 m. The measuring point was situated in the same vertical plane. The transmitter was placed in the NCH gallery and transmitted data in three directions, vertically (Z), axially (Y) and parallel to the axis of the NCH gallery, and along direction X, which is at right angles to the axis of the NCH gallery. The receiver was set in the GT5 gallery suitably for each transmission direction. Table II shows the received and design voltages and the attenuation.

Table II. Test results of receiving voltage between two galleries at a distance of 45 m

Transmission direction	Received Voltage (mV)	Design Voltage (mV)	Attenuation (%)
Z	4.6	290	98
Y	8.9	145	94
X	4.6	145	97

This results shows that the attenuation is larger than the estimated 80%. The large attenuation was caused by the arrangement of reinforcing bars in the side walls and concrete floor of the GT5 gallery.

Numerical analyses of the two galleries

Numerical analyses were carried out by using software for three-dimensional electromagnetic field analysis called JMAG (v 10.0). To analyze the electromagnetic phenomena that occurred in the gallery required precise modeling of the electromagnetic field and of the several local materials that could affect electromagnetic flux. In this situation, JMAG software has the advantage of high capacity for analysis and efficiency of modeling. The analysis model needed to represent only half of the physical region under consideration, or 150 m × 150 m × 75 m, instead of 150 m × 150 m × 150 m. Components with little effect on electromagnetic propagation are:

- Host rock
- Rock bolts
- Invert concrete with no reinforcement
- Wire mesh

When long steel pipes and high magnetic permeability substances such as cables were arranged along the gallery, it was found that depending on the layout of the transmission unit and the receiving unit, and their relative angles, certain effects were observed on electromagnetic wave propagation. In a transmission test between the NCH and GT5 galleries in the Z direction, the magnetic flux flowed outside the sidewalls and the density of the magnetic flux inside was notably weak. The effects of steel supports and reinforcement arranged in sidewalls and floor were relatively large, causing the large attenuation that occurred.

MINIATURIZED TRANSMITTER TESTS

Surface test

The miniaturized transmitter was tested on the surface in Japan in 2009 for the following purposes:

- To confirm the wireless transmission characteristics of the design.
- To obtain benchmarks for comparison with an underground experiment

The test location was a quiet place in the western part of Tokyo. The test results were as follows: In the Y-direction test, with the transmitter and receiver directly facing each other, the received voltage was 7 mV at a distance of 25 m. In the X-direction test, with the transmitter and receiver arranged in vertical direction, the received voltage was 3.5 mV at a distance of 25 m.

Transmission test between two galleries, GEX and GMR at a distance of 25m

A transmission test was conducted between the GEX gallery and the GMR gallery at a distance of 25 m. The two galleries are situated on the same level at -490 m. The miniaturized transmitter was set in a vertical borehole of the GEX gallery, hung from a polyvinyl chloride pipe from floor level, with its position adjustable in every direction and depth up to -6 m. The transmitter was placed at levels of 0 m and -4 m in a vertical borehole in the GEX gallery and transmitted data to the receiver in the GMR gallery. The transmitter and receiver faced each other. Table III shows the received voltage, design voltage and the amplification.

Table III. Received voltage between two galleries at a distance 25 m.

Level of Transmitter	Transmission direction	Received Voltage (mV)	Design Voltage (mV)	Amplification (%)
0 m	Y	17.4	7.8	223
-4 m	Y	13.8	7.4	186

The results show that the received voltages were amplified to about double the design value. The large amplification was caused by the steel pipes arranged parallel to each other behind the receiver in the GMX gallery.

Numerical analyses of the two galleries

As in the analyses of mid-range transmission tests, a precise model of the electromagnetic field and all the materials that might affect the electromagnetic flux was made. When long steel pipes were arranged concentrically behind the receiver, the magnetic flux was concentrated in the region of the pipes, and the flux density became thicker at the receiver location, accounting for the large amplification.

Discussion

From the results of two series of tests, it is clear that transmission is practical when the received voltage is larger than the received noise. However, it is also clear that wireless transmission in the CMHM URL gallery is affected by the electromagnetic noise level and steel components, and the maximum transmission distance depends on the S/N ratio. The mid-range transmission antenna achieved a transmission distance of 240 m in the surface test, where the electromagnetic noise level was small and there was no environmental attenuation. The short-range transmission antenna achieved a transmission distance of 25 m in the surface test and in the CMHM URL gallery.

As the clay layer of the CMHM URL had little effect on the attenuation of the electromagnetic field, transmission over 200 m might be possible in the CMHM URL when the electromagnetic noise level is small enough and there are no significant factors enhancing attenuation. But in reality, the possible transmission distance was around 50 m.

In order to show the transmitter's ability, it is preferable to keep some distance between steel components and the transmitter. The most effective way to use this transmitter is to put it in a borehole drilled from a gallery to outside of a gallery around 10 m length. In this way, it might be possible to avoid almost of all the influence of steel components.

For the position of receiver, the recommendation is the same as for the transmitter. That is, place the receiver where the incoming signal from the transmitter suffers little attenuation from steel components. Therefore, the option of implementing a receiving antenna in a borehole is required.

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