DEVELOPMENT OF WIRELESS MONITORING SYSTEMS FOR GEOLOGICAL DISPOSAL

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Abstract

In developing a monitoring program for geological disposal of radioactive waste, it is important that measuring instruments and cables do not affect the performance of the engineered barriers. Several studies have been conducted with underground wireless transmission systems, wireless transmission technology for data transmission, and wireless power transfer (WPT) technology for long-term power supply for monitoring systems. We have studied a wireless transmission technology with low frequency electromagnetic waves and its applicability to geological disposal monitoring systems. The applicability and the redundancy of the systems have been increased by reducing the size of both transmitter and receiver devices, and developing a multi-stage relay system and transmission route changing technologies, respectively. Meanwhile, underground monitoring systems have some challenges such as the limited capacity of the battery. In view of this, we have studied a wireless power transfer technology using a magnetic resonance coupling method. Through design and trial fabrication of transmitter and receiver coils, and experiments for power transfer efficiency and optimum frequency, the power transfer over buffer materials has been confirmed to be viable, demonstrating its applicability to geological disposal facilities. In this paper, we report on the latest development of the underground wireless transmission systems.

1. Introduction

In deep geological disposal, the isolation and containment of high-level radioactive wastes are required for long term safety after closure of the geological repository. The long-term safety will be ensured by a passive safety system composed of an engineered barrier system (EBS) and a natural barrier system (NBS) without relying on monitoring or institutional control [1]. From the technical viewpoint, whether monitoring is needed to understand the state of EBS has been discussed in recent years in an International Collaborative Research Project, MoDeRn project (Monitoring Developments for safe Repository operation and staged closure [2]) supported by co-funding from Euratom.

When implementing monitoring inside or around the repository, one of its purposes is to confirm that the EBS and NBS in the near-field will demonstrate the performance expected to secure long-term safety after closure. In implementing monitoring of the EBS and the near-field, one of the technical challenges is to prevent the formation of possible preferential pathways for flow induced by monitoring equipment installation with cables. The Radioactive Waste Management Funding and Research Center (hereinafter referred to as RWMC), under its basic concept of boundary condition in monitoring, that monitoring should not impair the function and performance of the barrier, has been studying a specific way of monitoring and consider its feasibility. We then focused on underground wireless transmission technology [3, 4] as an effective method to prevent the formation of possible preferential pathways for flow due to the installation of monitoring devices with cables.

Our underground wireless transmission technology uses low frequency electromagnetic waves with frequencies of several kHz or less to suppress attenuation in the ground and water, instead of those in the range of several MHz to GHz, which is used for general wireless transmission technology.

Relevant international organizations have been paying attention to underground wireless transmission technology. The MoDeRn has recognized the effectiveness of underground wireless technology. It is their policy to perform monitoring using underground wireless transmission in case studies on performance confirmation monitoring. Also, the French radioactive waste management agency (hereinafter referred to as ANDRA) has been studying the applicability of the technology on monitoring in their deep geological repository since 2004. From 2010 to 2014, they have carried out collaborative research with RWMC to enhance the efficiency of the R & D.

In underground wireless transmission technology, the power is supplied by a chemical battery, which limits the measurement period depending on its usage. Therefore, in long-term operation for about 100 years from the construction of the geological disposal site to its closure, continuous monitoring is difficult. In order to solve the limitation in the monitoring period, we have been carrying out R & D on the applicability of Wireless Power Transfer (WPT) technology to underground wireless transmission devices. This technology supplies energy by electromagnetic waves or electromagnetic fields without using cables.

This article outlines our latest development results on the underground wireless transmission system and the study on the applicability of the WPT technology.

2. Development of underground wireless transmission system

In order to enable monitoring in a limited space such as inside buffer materials or near-field environment, we set several important development goals in 2009 such as miniaturization of transmitters, improvement of pressure resistance, development of sensor adaptors, and development of a relay network, and then have developed them.

As to the development of the relay network, we have begun developing two different types of underground wireless relay systems. One is to transmit data for a long distance of about 500 m by a large relay device consuming a relatively large amount of electricity, and the other is to arrange multiple relay devices in multiple stages, each of which can transmit data for about 100 m. A schematic diagram of the transmitter and the relay systems is shown in Fig. 1.

In this section, we report on these development results.

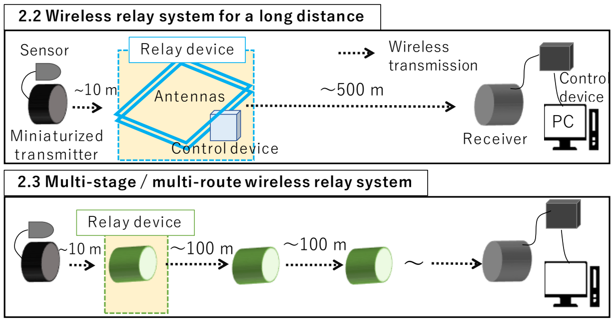

Fig. 1 Conceptual diagram of relay systems (upper: wireless relay system for a long distance, lower: multi-stage / multi-route wireless relay system).

2. 1 Development of miniaturized transmitters

We have developed a miniaturized transmitter with the pressure and heat resistance necessary for geological disposal application, while limiting some functions (see Table 1 and Fig. 2).

Table 1 Specifications for the recently developed miniaturized transmitter.

Transmission frequency	once a week
Transmission distance*	-- 12 m*
Durability	About 10 years
Size (diameter×length)	Φ60 mm×200 mm
Frequency	8.5 kHz
Pressure resistance	10 MPa
Operating temperature	0 -- 40 ℃

* Under the environmental noise of 10 mV rms.

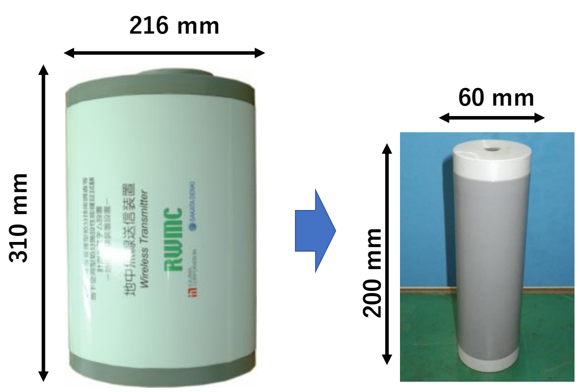

Fig. 2 Conventional transmitter (left) and miniaturized transmitter (right). Modified from RWMC (2010, 2012).

We have been conducting verification tests at the underground research laboratories in the Horonobe and the Mizunami Underground Research Laboratory (hereinafter referred to as Horonobe URL and Mizunami URL, respectively) of the Japan Atomic Energy Agency (hereinafter referred to as JAEA) using miniaturized transmitters. At the Horonobe URL, we installed the miniaturized transmitters in buffer materials (see Fig. 3) and tunnel backfill material and have been carrying out monitoring of soil pressure and pore water pressure in performance confirmation tests for the engineered barrier. Based on the analysis of wireless transmission data received from the installed miniaturized transmitters, it is confirmed that data are successfully transmitted and received at a fixed time and at a certain frequency (twice a day).

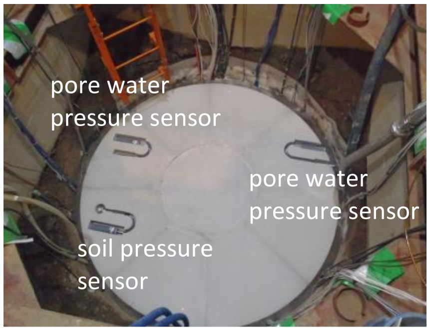

Fig. 3 Miniaturized wireless transmitters installed in buffer material blocks of a simulated disposal hole in performance confirmation tests of engineered barriers (Lower left: soil pressure sensor, upper left and right: pore water pressure sensor). Modified from RWMC (2015).

2. 2 Development of wireless relay system for a long distance

From FY2013, we set the development of the underground wireless relay system as a central objective. First, we developed a wireless relay device which includes a control device and a transmitter antenna and a receiver antenna for a long distance. This relay device makes it possible to transmit data to a location far away from the basic transmission distance by a miniaturized wireless transmitter alone. A large transmitter antenna with the size of 3 m by 3 m was designed to suppress the attenuation of the electromagnetic waves by bedrock, steel tunnel supports, and electromagnetic noise at its reception positions. The transmission frequency is set to be 8.5 kHz.

Using the developed relay device, we performed a transmission test at the Horonobe URL. A miniaturized wireless transmitter with a pore water pressure sensor and the wireless relay device were placed at the depth of 250 m, and a receiver was successively placed at the depths of 250 m, 140 m, and the surface to receive the signals from the relay device. Fig. 4 shows the received voltage plotted against the transmission distance. Though the received voltages at the depths of 140 m and 250 m are smaller than the theoretical attenuation line of the relay device, the signals received at all positions were confirmed to be transmitted by the relay device. This suggests that monitoring data from a miniaturized wireless transmitter can be relayed to a distance farther than tens of meters, which is the transmission distance by the transmitter itself.

The reason why the two plots at the depths of 140 m and 250 m are below the attenuation line is that the formation and the propagation of the electromagnetic waves at these two positions are likely influenced by steel tunnel supports. On the other hand, the value on the surface is plotted almost on the attenuation line even though it is received at the farthest position from the relay device. It may be because the attenuation decreased due to the bypass of a steel pipe or the shaft, but the details need to be investigated.

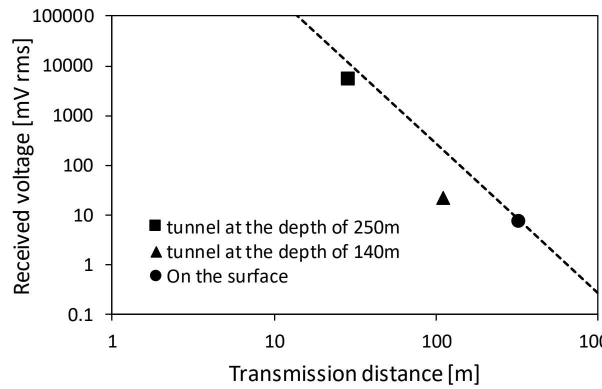

Fig. 4 Received voltage plotted against the transmission distance. The dashed line denotes the theoretical attenuation line of the relay device. Modified from RWMC (2014).

2. 3 Development of multi-stage / multi-route wireless relay system

A large internal power supply is necessary for long-distance transmission by underground wireless transmitters and relay devices, based on its conflicting relation between magnetic field intensity and transmission distance [4]. However, there is a limitation on the power supply. To address this issue, we have proposed a multi-stage relay system to shorten the transmission distance between devices and to reduce power consumption (see Fig. 5). By introducing this relay system, it is estimated that the power consumption can be reduced by 66% when one transmitter is controlled, compared to the case where only a transmitter is used to transmit data for the same distance at the same frequency [8]. Also, we have worked to improve redundancy by introducing a multi-route relay system to secure transmission routes in case of malfunction (see Fig. 5 right). The goal of the multi-stage / multi-route relay system is that more than two transmission routes are secured and that each relay device receives data from more than 10 transmitters at the same power consumption as is used by one of these transmitters.

In this section, we report on the development results of the multi-stage / multi-route relay system.

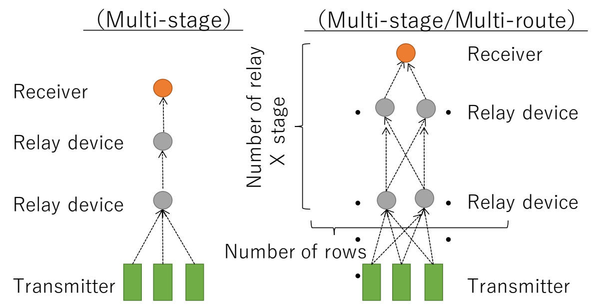

Fig. 5 Conceptual diagram of multi-hopping data relay (The figure on the right side shows reroute in malfunction of the relay device.). Modified from RWMC (2015).

2. 3. 1 Power saving by introducing multi-stage wireless relay system

The relay system described above can reduce the power consumption when managing one transmitter. However, the power consumption increases when the relay device manages several transmitters due to the increase of the time for reception standby. We analyzed the power consumption status for each function of the relay device, and found out that the power consumption for reception standby function consumes the most significantly (about 70 % of the total). To reduce the power consumption of this function, we introduced a low consumption activation code (GOLAY code; [9]) that optimizes the receiving circuit usage state. We developed the program and successfully reduced the power consumption of this function from the conventional 123 mA to 4.0 mA, allowing the relay system to be connected to the intended number of transmitters while saving the power.

We then designed and manufactured antennas, power supplies, and a container to contain the whole relay device. The specifications are summarized in Table 2.

Table 2 Specifications of the relay device.

Transmission frequency	Once a week
Transmission distance	--100 m
Durability	About 10 years
Number of transmitters managed	10

* Pressure resistance was designed to be 5 MPa, assuming the hydrostatic pressure at the depth of 500 m.

After storing the antenna, the power supply, and the board into the container, operation confirmation tests for the transmission distance of 15 m, 20 m, and 25 m were carried out at the surface, and the received voltages were measured (see Fig. 6). All plots were in the transmission available range, as well as the received voltage on the theoretical attenuation line at the distance of 100 m, which is the target performance of the device, confirming that the stable transmission was secured [10].

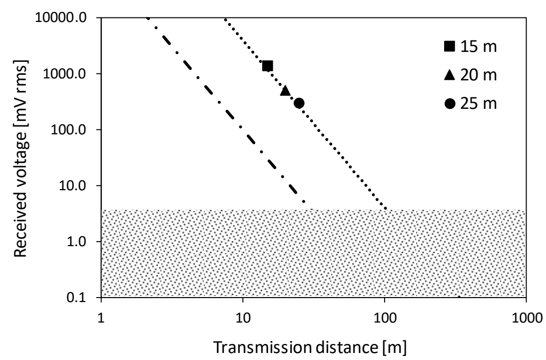

Fig. 6 Received voltage from the relay device plotted against the transmission distance. The dotted line and the dotted chain line denote the theoretical attenuation line of the relay device and the transmitter, respectively. The shaded portion denotes the area where transmission is disabled due to the noise level of 1 mV, which was learned from past experiments. Modified from RWMC (2017).

2. 3. 2 Securing redundancy by introducing multi-route wireless relay system

Furthermore, with the aim of securing the redundancy of the relay system in the case of malfunction, we carried out data rerouting tests using three relay devices by the following steps (see Fig. 7).

- Step 1: Transmitter 1, 2 → relay device 1 → relay device2 → receiver
- Step 2: Malfunction of relay device 2
- Step 3: Instruction signal from receiver manually sent to relay device 3 to transmit data to the receiver
- Step 4: Transmitter 1, 2 → relay device 1 → relay device 3 → receiver

As a result, data from the transmitter were successfully sent to the receiver even when the route was switched from the relay device 2 to 3.

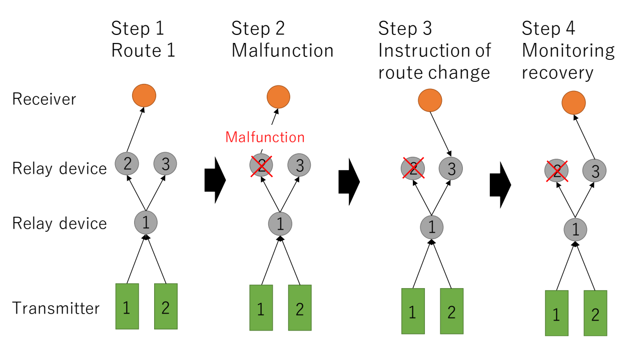

Fig. 7 Conceptual diagram of route change in the case of device malfunction. Modified from RWMC (2015).

3. Development of wireless power transfer system

The underground wireless transmission technology can reduce the adverse effects on the barriers function. It presents, however, a few challenges such as limited battery capacity. To address these issues, we have undertaken R & D that aims to apply the WPT technology to the underground wireless transmission system in order to extend the possible time period for monitoring [7]. Fig. 8 is a conceptual diagram in which the WPT technology is applied to the monitoring of an engineered barrier (buffer materials), showing a situation where power is wirelessly supplied to wireless monitoring devices with sensors integrated so that monitoring can be carried out without batteries. To do so, we have selected a magnetic resonance coupling method [11] (see Fig. 9) from a few WPT methods. This method enables transferring power for a few meters and is resistant to misalignment. Also, the power transfer efficiency through a medium such as buffer materials is least influenced.

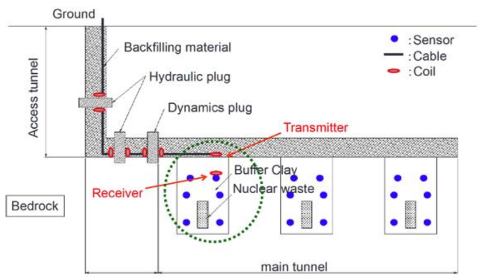

Fig. 8 Applicability of WPT technology for monitoring technology of radioactive waste geological disposal. Modified from RWMC (2015).

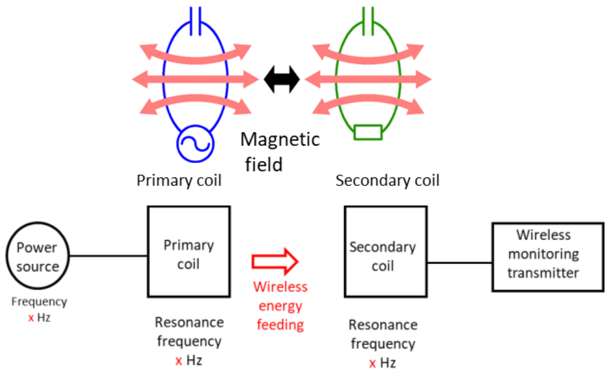

Fig. 9 Conceptual diagram of resonance frequency coupling method. Modified from RWMC (2015).

3. 1 Experiments of WPT

We performed an application test at a laboratory to understand the influence on the WPT efficiency of buffer materials, cementitious structures, and reinforcement steel.

In the past experiments, a proportional relation between distance of coils over the diameter and the efficiency was confirmed [12]. Then, we manufactured a transmitter and a receiver coil with a smaller scale of diameter; 730 mm and 20 mm, respectively (the diameter of a disposal hole is assumed to be about 2220 mm). The power transfer test for buffer material was carried out using the transmitter and the receiver coil. This test simulated a case where the power to run the underground wireless transmission devices installed in buffer materials is sent from the disposal tunnel just above the disposal hole. A bentonite block simulating buffer material was installed between the transmitter and the receiver coil, and the WPT efficiency was measured with both air and bentonite between these coils. The frequency of the power supply was adjusted to match the resonance frequency of the transmitter coil and the receiver coil (see Fig. 9) and was optimized to about 120 kHz. As a result, the WPT efficiency with air and bentonite were almost the same (see Fig. 10). Also, it was significantly improved by using ferrite for the receiver coil.

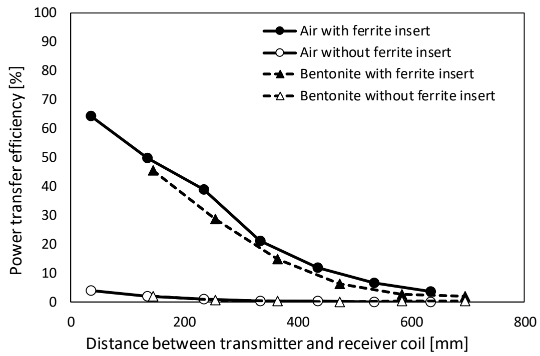

Fig. 10 Power transfer efficiency against the distance between a transmitter and a receiver coil. Modified from RWMC (2015).

Also, we manufactured a transmitter and a receiver coil with a diameter of 370 mm and conducted indoor application tests to evaluate the influence of cementitious structures and reinforcement steel on the power transfer efficiency. They are used as plug materials.

In the test on cementitious structures, a concrete block without steel was placed between the transmitter and the receiver coil, and the WPT efficiency was measured as the distance between these coils was changed in the range of 100 to 600 mm. The test result shows that the WPT efficiency at 300 mm, which corresponds to the thickness of a plug in the scale of 1/11, is only about 3% lower than in the air (see Fig. 11).

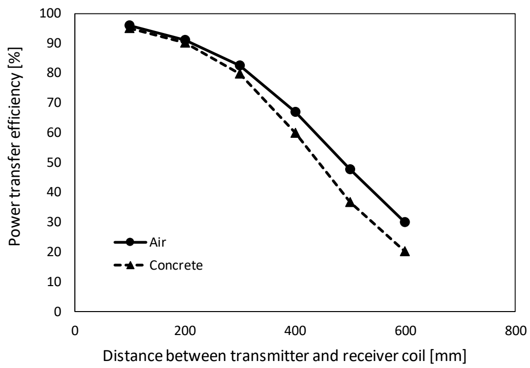

Fig. 11 Power transfer efficiency against the distance between a transmitter and a receiver coil. Modified from RWMC (2017).

In the test through reinforcement steel, the distance of these coils is fixed at 300 mm, and the steel was placed in the middle. As a result, the efficiency with the reinforcement steel between these coils greatly decreased from 82.6% to 16.6%. The efficiency reduction can be improved by about 18% (16.6% to 34.1%) by adjusting the resonance frequency and the optimum load resistance. For further improvement of the efficiency, we are considering applying materials with less magnetic loss to reinforcement steel, and to change the shape and the position of coils for the magnetic fluxes to bypass plugs and to go through the bedrock.

4. Conclusions

We reported the latest development results of the underground wireless transmission system and the study on the applicability of WPT technology.

In order to enable monitoring in a limited space such as buffer materials, we have developed miniaturized transmitters. Currently, demonstration tests for monitoring using these transmitters are under way at the Horonobe URL and the Mizunami URL. We have also developed two different types of underground wireless relay systems (relay system for a long distance and multi-stage / multi-route relay system). These systems enable relay of data sent from miniaturized wireless transmitters to the surface. Furthermore, in the latter method, redundancy as a relay system was improved by introducing a function to change the transmission route even when some of the devices fail.

In order to enable long term monitoring independent of internal batteries, applicability of WPT technology to underground wireless transmission devices was studied. Based on the results of laboratory tests which showed that the influence on the power transfer efficiency by buffer materials is insignificant, we concluded that the application of this technology to geological disposal is viable. In the future, it is necessary to confirm the influence based on the underground environment such as salt water and to conduct underground tests.

With all these developments described above, fundamental technologies that enable continuous monitoring while avoiding the introduction of piping to the barrier and near-field have progressed. It is important to improve the practicality of underground wireless transmission systems through more practical experiments using underground facilities, etc.

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