Applicability of Wireless Power Transfer for Monitoring Technology of Radioactive Waste Geological Disposal – 16156

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ABSTRACT

To assure the engineered barrier of a high-level radioactive waste repository functions correctly, long-term monitoring inside the backfilled deposition holes and tunnels is planned. Cables are used to power monitoring equipment and send signals however complete isolation will not be possible. Previously developed monitoring systems send information wirelessly and used batteries. Due to the limited battery life, these systems cannot be used for long-term monitoring. In this paper a wireless power transfer method based on magnetic resonant coupling is presented. The necessary transmitter and receiver coils have been developed. The performance of the individual coils has been tested. The performance of the system of transmitter and receiver with both air and bentonite as medium was tested. The results showed that the system with bentonite performed similarly well as the system with air. Wireless power transfer based on magnetic resonant coupling is therefore a feasible method for high-level radioactive waste repository monitoring applications which could in principle work for a period of 100 year or longer.

INTRODUCTION

Background

It is Japanese policy to reprocess used nuclear fuel. The Japanese waste classification distinguishes between high-level radioactive waste (HLW) and low-level radioactive waste (LLW) [1]. Fission products remaining after the recovery of uranium and plutonium are classified as HLW and everything else as LLW.
A LLW disposal site is currently in operation in Rokkasho-mura, Aomori prefecture. For HLW, as well as LLW classified as long lived, low heat generating radioactive wastes (also referred to as TRU wastes), deep geological disposal is planned to assure isolation from human activity for several tens of thousands of years. Internationally deep geological disposal for this type of wastes is currently carried out at the Waste Isolation Pilot Plant (WIPP) in the USA for the disposal of radioactive wastes generated by the research and development of nuclear weapons. In Finland a site for ~~a~~ final repository has been decided upon and a construction permit application has been submitted in December 2012. In Sweden a planned disposal site location has been identified as well, and a siting and construction permit application has been submitted in March 2011. In Japan the “Designated Radioactive Waste Final Disposal Act” has been established by the Diet in 2000. In this act the Nuclear Waste Management

Organization of Japan (NUMO) is designated as the implementation organization for planning the geological disposal of high-level radioactive wastes in Japan.
In planning for geological disposal, isolation of the radioactive waste from human activity after closure of the repository is of utmost importance. This isolation is to be provided by a multi-barrier system which comprises both a man-made engineered barrier and a natural barrier [2]. Demonstrating the integrity of the multi barrier system is essential.

Multi-Barrier System

Japanese law stipulates that radioactive waste is to be disposed underground at depths greater than 300m. The engineered barrier and the natural barrier together form the multi-barrier system that isolates the radioactive waste from human activity. The engineered barrier consists of the vitrified waste, which is packed in a canister, and emplaced in a bentonite buffer material. The natural barrier consists of a stable host rock which has been selected based on the requirement that groundwater flow in the rock is slow. The combination of engineered and natural barrier is to prevent migration of radionuclides by groundwater after closure of the repository.
To investigate and research the performance of such a multi-barrier system, analyses and fundamental laboratory studies have been carried out (e.g. [3], [4]). In recent years tests have been carried out above ground that simulate high-level radioactive waste disposal to investigate the monitoring of the engineered barrier performance. After construction of the underground facilities, the emplacement of the waste and backfilling of the tunnels, long-term monitoring might be conducted to observe the multiple barrier system. The various changes in behavior and characteristics after backfilling of the tunnels, such as heat generated by the waste, saturation and swelling of the buffer material, water pressure and deformation of the rock, are to be measured to confirm the engineered barrier behavior. A multitude of sensors, signal and power cables would have to be installed in the engineered barrier to carry out the various measurements. A monitoring system using cables is shown in Figure 1. The installation of cables would however significantly affect the performance of the engineered barrier, by creating artificial pathways for water and gas movement. To mitigate this problem, wireless methods to operate the monitoring devices in the engineered barrier are therefore required [5].

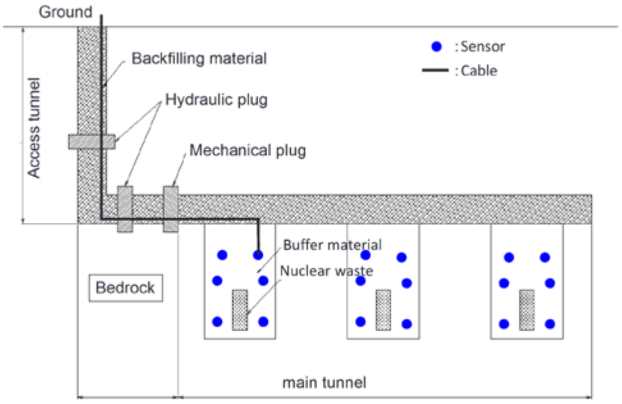


Fig. 1. Monitoring system of geological disposal using cables

Application of Wireless Power Transfer in Monitoring

Previous studies have been conducted that have investigated wireless transfer of sensor data ([6], [7], [8] and [9]). The wireless set-up used in these studies, is shown in Figure 2. In these studies, batteries have been used to power the sensors. Since in a real geological disposal site the batteries cannot be replaced, such a set-up is therefore not suitable for long-term monitoring.

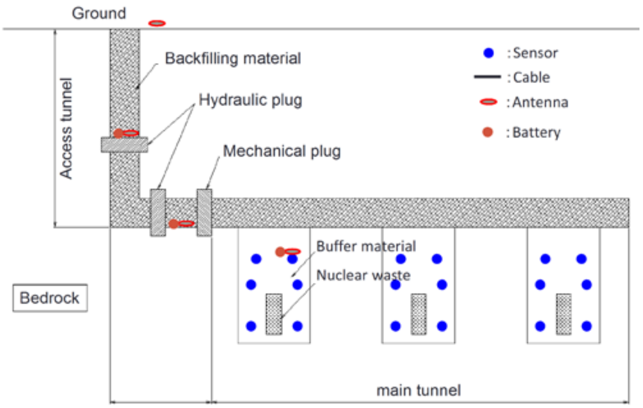


Fig. 2. Monitoring using wireless data transfer and batteries

In this paper we propose to use wireless power transfer based on magnetic resonant coupling in addition to the wireless data transfer for use in monitoring applications for geological disposal. With this method it is in principle possible to monitor the engineered barrier for very long time spans in excess of 100 years. Figure 3 shows the monitoring set-up including wireless power transfer. In this paper we summarize the results of developing and testing wireless power transfer as previously reported in [10], [11] and [12].

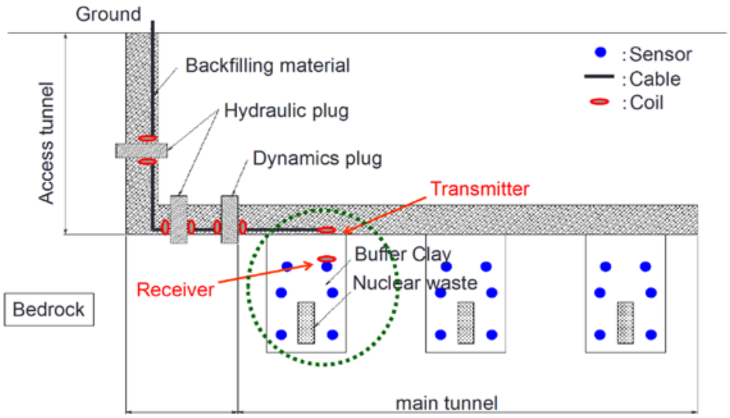


Fig. 3. Monitoring using wireless data and power transfer

DESCRIPTION AND DISCUSSION OF RESULTS

Fabrication and Evaluation of Transmitter and Receiver Coils

Different methods for wireless power transfer exist. For using power transfer underground through solid materials that include water, using the magnetic field was identified as the best methodology. To transfer power a transmitter and a receiver coil are necessary. The target of this study was to develop a system for monitoring a backfilled deposition hole. The dimensions of the coils are based on the reference repository design from the H12 report [13] as shown in Figure 4. The dimensions of the transmitter coil, with a radius 2.2m and a height of 0.4m, is based on the diameter of the deposition hole in the reference design. Due to limitations of space, the receivers should be as small as possible. The dimension of the receiver coils, with a diameter of 6cm and length of 37cm, is based on the dimensions of the wireless monitoring devices developed previously by Radioactive Waste Management Funding and Research Center (RWMC) [9]. It should be noted that the receiver coil developed by RWMC was developed for transmitting data and has so far not been used for the purpose of wireless power transfer.

Since the diameter of the transmitter coil with a diameter of 2.2m was impractical for laboratory testing, it was decided to scale both the transmitter and receiver coils down to one third the size. The dimensions of the transmitter and receiver coils are summarized in Table I.

A single transmitter coil and four different receiver coils have been made using different wires and different number of turns (Polyester cable 0.56mm, KIV0.5sq, KIV2.9sq, KIV3.5sq). This has been done to investigate the effect of the number of turns and wire thickness on the performance of the coils. Figures 5 to 9 show the manufactured coils as well as their properties.

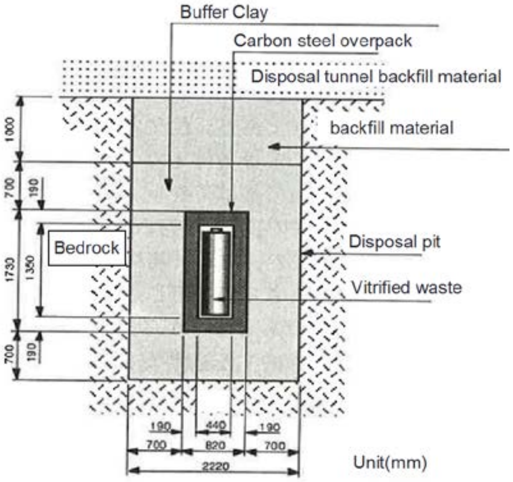
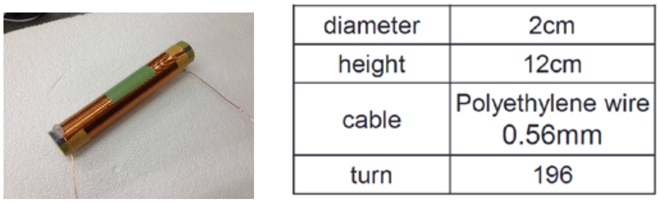


Fig. 4. H12 reference disposal pit design

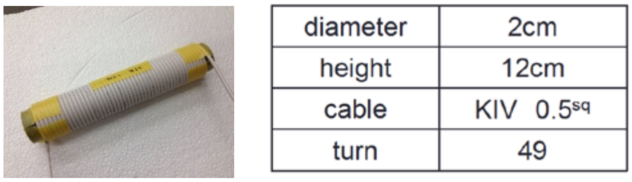
TABLE I. Dimensions of transmitter and receiver coils used.

Scale	Component	Diameter [m]	Length [m]
Site scale	Transmitter	2.2	0.4
	Receiver	0.06	0.37
1/3 scale	Transmitter	0.73	0.13
	Receiver	0.02	0.12



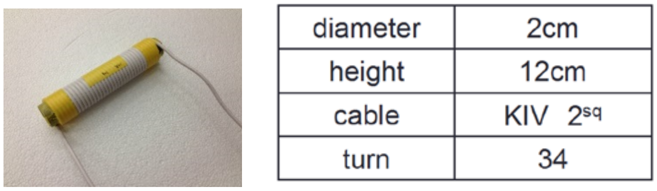
diameter	2cm
height	12cm
cable	Polyethylene wire 0.56mm
turn	196

Fig. 5. Receiver coil ① (Polyester wire 0.56mm)



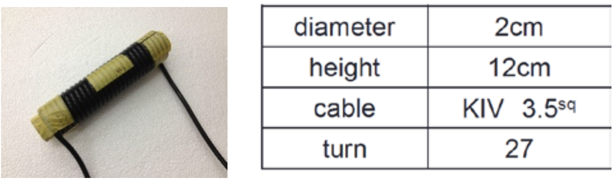
diameter	2cm
height	12cm
cable	KIV 0.5^{sq}
turn	49

Fig. 6. Receiver coil ② (KIV0.5^{sq})



diameter	2cm
height	12cm
cable	KIV 2^{sq}
turn	34

Fig. 7. Receiver coil ③ (KIV2.0^{sq})



diameter	2cm
height	12cm
cable	KIV 3.5^{sq}
turn	27

Fig. 8. receiver coil ④ (KIV3.5^{sq})

diameter	73cm
height	13cm
cable	KIV 0.5^{sq}
turn	50

Fig. 9. Transmitter coil

Equation 1 shows the maximum power transfer efficiency for magnetic resonant coupling using the SS configuration shown in Figure 10 [14].

$$\eta_{\max SS} = \frac{1}{1+\frac{2}{k\sqrt{Q_1 Q_2}}} \qquad \text{(Eq. 1)}$$

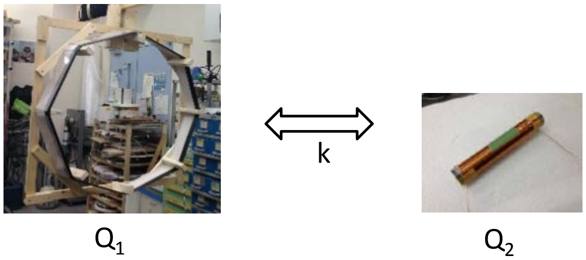


Fig. 10. Schematic diagram of magnetic field resonance coupling (SS configuration)

In this equation η_{maxSS} is the maximum transfer efficiency, *k* the coupling coefficient and Q_1 *and* Q_2 the quality factors of the transmitter and receiver coils. The coupling efficiency *k* is a number between 0 and 1 and is a function of the geometry of the system such as distance between coils, diameters, orientation. The quality factor Q relates to the quality of the coil used and is affected by the number of turns, the resistance of the wire, the magnetic permeability of the core but also the frequency of the signal used. Equation 1 shows that the efficiency can be increase by increasing coupling coefficient *k* or increasing the *Q* of the transmitter and receiver coils. Using a vector network analyzer (keysight E5061) the *Q* of the transmitter coil and the four receiver coils was measured. The measured *Q* of the receiver coils is shown in Figure 11. The measured *Q* of the transmitter coil is shown in Figure 12.

Figure 11 shows that *Q* increases when the frequency increases for all four receiver coils. Furthermore, *Q* increases most when increasing the frequency for the coil number 1 which has the most turns. The results suggest that when the volume of coil is constant, more turns results in better efficiency than using thicker wires. Figure 12 shows an optimal *Q* in the frequency range from 100 to 120 kHz for the power transmission coil. At a frequency of 350 kHz and beyond destructive interference occurs due to stray capacitance. The transmitter coil should therefore be used at frequencies lower than 350 kHz. Figures 11 and 12 show, that for the coils investigated, the best power transfer efficiency will be obtained using a frequency between 100 and 120 kHz.

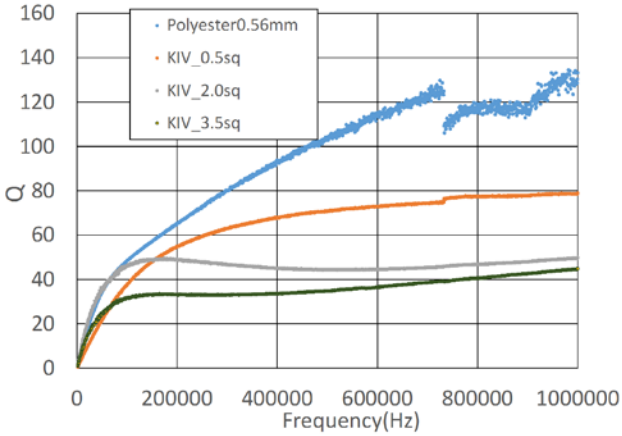


Fig. 11. Q of the receiver coils ① through ④

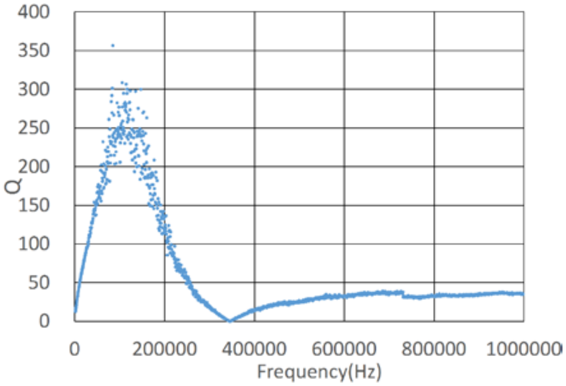
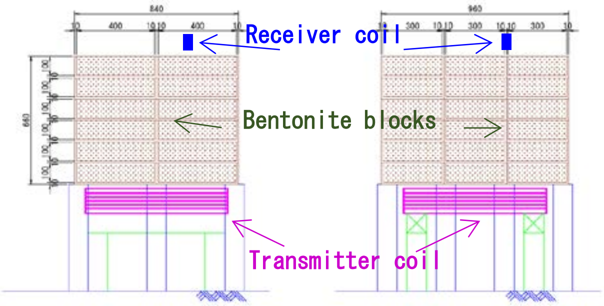


Fig. 12. Q of the transmitter coil

Effect of Bentonite Placed Between Transmitter and Receiver Coil

To investigate the impact of bentonite when placed between the fabricated transmitter and receiver coils on the power transfer efficiency, several experiments were conducted. Bentonite blocks with a thickness of 10cm each were progressively stacked between the coils as shown in Figure 13.



Front view Side view

Fig. 13. Experimental test lay-out with stacked bentonite blocks

Bentonite Blocks

For the construction of the bentonite blocks, acrylic molds with inner dimensions 300mmx400mmx100mm were made. The bentonite blocks were fabricated by compacting bentonite into the molds. Figure 14 shows the manufacturing process of the bentonite blocks. An acrylic mold and a finished bentonite block are shown in Figures 15 and 16 respectively. The bentonite blocks were stacked while placed in the acrylic molds to prevent the bentonite blocks from disintegrating during handling and testing.

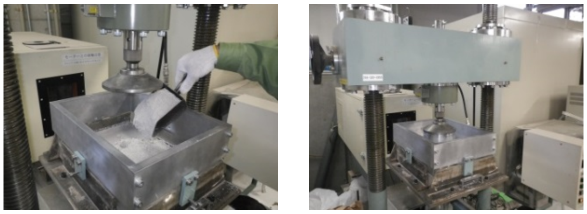


Fig. 14. Bentonite compaction

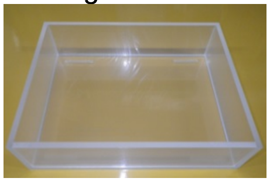


Fig. 15. Acrylic mold

Fig. 16. Bentonite block

Power Transfer Experiment

Using the transmitter coil and receiver coil 1, power transfer tests were carried out using the bentonite blocks described in the previous section. Figure 17 shows a diagram of all components of the experimental set-up. Table II shows the test parameters where 1W of power was transmitted. The left picture of Figure 18 shows the experimental set-up with air between the coils. The right picture shows the experimental set-up with bentonite blocks between the coils.

Figure 19 shows the results of the power transfer experiment. Hardly any difference between the power transfer efficiency through bentonite and through air can be observed.

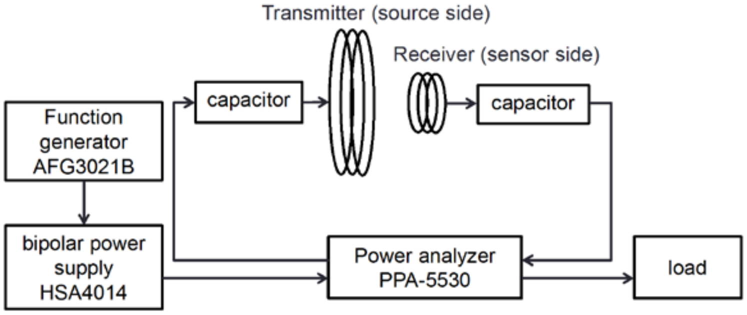


Fig. 17. Power transfer experiment lay-out diagram

TABLE II. Power transfer experiment parameters

Transmitter	
Inductance (uH)	3080.50
Capacitor (pF)	691.60
Resonant frequency (kHz)	109.04
Transmitter	
Inductance (uH)	140.99
Capacitor (pF)	15.19
Resonant frequency (kHz)	108.77
Power frequency	106.70

Fig. 18. Power transfer experiment (left: air as medium between coils, right: bentonite as medium between coils)

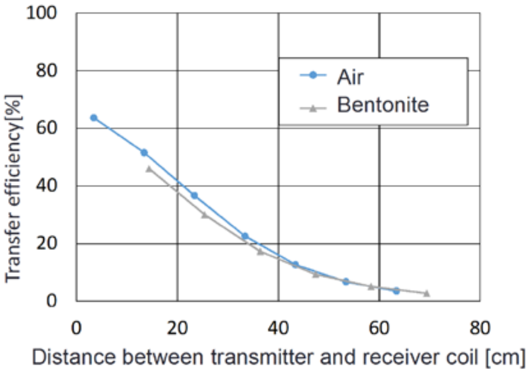


Fig. 19. Result of the power transfer experiment

The results in Figure 19 shows that wireless power transfer between transmitter and receiver coils through a bentonite engineered barrier as proposed in the reference design is possible. With bentonite as a medium between the transmitter and receiver coils yielded almost the same efficiencies as through air. These results show that wireless power transfer based on the principle of magnetic resonant coupling is feasible for radioactive waste disposal monitoring applications.

CONCLUSIONS

Transmitter and receiver coils have been fabricated and evaluated for the purpose of wireless power transfer in a reference design as described in the H12 report [13]. Experiments were conducted with air and bentonite as medium between the transmitter and receiver coils. The results of the experiments showed that the power transfer efficiency with air and bentonite as medium were similar and that wireless power transfer is therefore possible. Wireless power transfer using magnetic resonant coupling is suitable for the purpose of radioactive waste monitoring in a reference repository design layout.

Future Work

A number of issues remain that require further research. Power that is not transmitted to the receiver coil is lost mainly as heat in the transmitter coil which could further reduce the efficiency of the system. Further investigation and the development of mitigating strategies are required.
The tests in this study have been carried out using a smaller scale model and the results need to be translated to the full scale model wireless power transfer system. We plan to develop a numerical representation of the small scale model and use the measurement data to calibrate the model. Once a good model has been developed the performance of the full system can be evaluated numerically.
The real full scale model has some other challenges that need to be investigated. Since more than one receiver coil will be installed, a multi receiver system should be developed. Furthermore, metals used in the engineered barrier system such as the canister and the reinforcement in concrete, as well as some geological materials, may influence the performance of the wireless power transfer system and needs further study.

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