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EXPERIMENT OVERVIEW

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IN SITU RF/MICROWAVE REMEDIATION OF SOIL EXPERIMENT OVERVIEW¹

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Abstract

Contaminant plumes are significant waste problems that require remediation in both the government and private sectors. We are developing an in situ process that uses RF/microwave stimulation to remove pollutants from contaminated soils. This process is more efficient than existing technologies, creates less secondary pollution, and is applicable to situations that are not amenable to treatment by existing technologies. Currently the most commonly used process is soil vapor extraction. However, even when it is successful, this technology is energy inefficient [1,2]. Our objective is to combine RF/microwave energy application with soil vapor extraction to help mobilize and efficiently remove the soil contaminants, specifically demonstrating the viability of RF/microwave induced, in situ, soil remediation of "light and dense non-aqueous phase liquids" (LNAPL, DNAPL) contaminants. This is conceptually depicted in Fig. 1.

INTRODUCTION

We have conducted a number of benchtop experiments involving RF/microwave energy deposition and vapor extraction on controlled contaminated soil samples with successful removal of the contaminants. This paper will describe the methods for characterizing the soil (dielectric property measurements), the experimental hardware utilized, the experiments performed thus far, the chemical analysis performed pre- and post- energy application, and results.

In order to determine the necessary RF/microwave frequency and the size of the source, preliminary characterization of the soil is requisite. A number of preliminary experiments were performed to establish some of these properties. The dielectric properties were measured for several different soil types. Two types of soil were selected to be used as baseline soils for the later experiments due to their availability and interest to potential sponsors. One type was excavated from LANL property and the other was provided from an environmental remediation firm responsible for cleanup of a number of US Department of Defense sites. The soil from this possible industrial partner came from an Air Force base in need of soil remediation. Since permittivity varies unpredictably with moisture content in soil, the soil was initially uncontaminated and slowly dried in an oven at 80°C in order to establish clear baseline measurements. Coaxial transmission line measurement methods are the basis of the soil dielectric properties determination.

The experimental setup used to measure the permittivity of the soil sample is given in Fig. 2. The dried soil was carefully packed into a coaxial cavity and held in place with Teflon retaining washers on either end. The washers were connected to a Hewlett Packard Network Analyzer and the transmission scattering parameters versus frequency of the soil were measured. The soil sample is located between planes A' and B' and the retaining washers are found between A and A' and between B and B'. Using ideal transmission line theory, the effect of the retaining washers was analytically removed and the measured scattering parameters were translated from the entire apparatus to just the material in question. A FORTRAN program was used to calculate the complex soil permittivity, ϵ_r , from the s-parameters in accordance with the following equation (assuming non-magnetic material) [3]:

$$\epsilon_r = \left(\frac{1 - \Gamma}{1 + \Gamma} \right)^2 \quad (1)$$

where Γ is the lowest magnitude solution of the following

¹ Work Supported by the US Department of Energy.

$$\Gamma = \frac{1 + (S_{11})^2 - (S_{21})^2}{2S_{11}} + \sqrt{\left(\frac{1 + (S_{11})^2 - (S_{21})^2}{2S_{11}}\right)^2 - 1} \quad (2)$$

In addition, the loss tangent of the material is calculated from

$$\tan \delta = \frac{\text{Im}(\epsilon_r)}{\text{Re}(\epsilon_r)} \quad (3)$$

The calculated loss tangent for the two baseline soils are plotted in Fig. 3. We are currently working to update this calculation to include non-unity permeability because many soils are magnetic.

The second set of experiments consisted of applying energy to a coaxial cavity packed with soil contaminated with a controlled amount of DNAPL. For these laboratory experiments, carbon tetrachloride (CCl₄) and trichloroethane (TCE) were the contaminants utilized. The RF source was a 425 MHz, 200 W, continuous wave amplifier, connected to a short-circuited coaxial transmission line. A portion of the coaxial line was isolated using gas barriers and filled with contaminated soil. A double stub tuner was used to minimize the reflected power. Air inlet and outlet ports on the gas barriers allowed for controlled stripping air flow. Rate-monitored inlet air flowed through the contaminated soil and exited through the outlet port to various collection apparatus. Collection equipment included a graduated cylinder in a chilled deionized water bath, an impinger cooled with dry ice/acetone, and a water trap for the air to bubble through. A thermocouple at the outer surface of the test sample monitored the soil temperature. By monitoring the soil temperature we were able to maintain a RF power level adequate to heat the soil near the DNAPL's boiling point, but less than the boiling point of water.

Mass balance calculations were performed in order to determine the amount of contaminant recovered post-RF energy application. The soil was examined by gas chromatography/mass spectroscopy (GC/MS) for the volatile in question to determine if we were only remediating the original contaminant, or if we were also producing other contaminants through the heating process. The results of these tests indicated that we were only collecting the original contaminant. Baseline measurements were performed with contaminated soil and air stripping without applying RF energy. The removal of contaminant due to air mobilization yielded 17% recovery. However, once RF energy was applied to the same setup, we were able to routinely achieve greater than 97% contaminant recovery. The relationship between RF power delivered, chamber temperature measured, and amount of contaminant recovered relative to the amount of time of RF exposure for the indigenous soil contaminated with CCl₄ is given in Fig. 4.

CONCLUSION

This paper has described an on-going soil remediation project being performed at Los Alamos National Laboratory. We are able to characterize a variety of soils using basic RF test equipment and theory. We have successfully extracted greater than 97% of contaminant from a controlled soil/contaminant mixture. Further work includes introduction of water to the soil to mimic realistic subsurface contaminated areas. The next phase of this project will entail designing a larger experimental chamber (2.5 gallons) and include an antenna to introduce the RF/microwave energy to the chamber. This setup will more closely represent the envisioned application of RF/microwaves in conjunction with vapor extraction. This phase should lead directly to a field demonstration.

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FIGURES

Fig. 1. RF energy enhanced vapor extraction.

Fig. 2. Experimental setup for permittivity measurements.

Fig. 3. Loss tangent as a function of frequency for two baseline soils.

Fig. 4. Plot of RF power delivered, chamber temperature measured, and amount of contaminant recovered (% fluid in place) relative to the amount of time of RF exposure for indigenous soil contaminated with CCl_4 .