

MONITORING PERMEABLE REACTIVE BARRIERS USING ELECTRICAL RESISTANCE TOMOGRAPHY

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ABSTRACT

An electrical resistivity tomography (ERT) method is being evaluated as a measurement tool to determine the integrity of permeable reactive barriers (PRBs) during and after construction of the barrier and as a monitoring tool to determine the long-term operational health of the barrier. The method is novel because it inserts the electrodes directly into the barrier itself. Numerical modeling calculations indicate that the ERT method can detect flaws (voids) in the barrier as small as 0.11 m^2 ($0.33 \text{ m} \times 0.33 \text{ m}$) when the aspect ratio of the electrodes are 2:1. Laboratory measurements indicate that the change in resistance over time of the iron-filling mixture used to create the PRB is sufficient for ERT to monitor the long-term health of the barrier. The use of this ERT method allows for the cost-effective installation of the barrier, especially when the vadose zone is large, because borehole installation methods, rather than trenching methods, can be used.

INTRODUCTION

Within the various DOE facilities there exists a variety of different groundwater plumes that require remediation prior to closing the site and transferring ownership. Several of these plumes are moving toward water sources that are used by major population centers. Pump and treat systems have historically been used both to treat as well as control the migration of such contaminant plumes. These systems are not very efficient and will typically require many years of operation to remediate these plumes [1]. Due to the long operational times, the systems are also costly to use, and in many cases, they will not remediate a plume in the desired time frame.

To address these concerns, several innovative remediation techniques have been developed. One such remediation system, which shows strong promise due to the low operational costs, is permeable reactive barriers (PRBs) [2]. An example of a PRB is illustrated in Fig. 1. In this flow-through barrier, a reactive material is placed in the subsurface in front of the flow path of a contaminant plume to react with the plume contaminant and cause it to change form into a non-harmful material or to be captured by the barrier and held in place. Reactive barriers are very attractive, because they operate passively without any energy input. As a consequence, they can operate for long periods of time as the groundwater slowly flows through the barrier.

A key aspect to the benefit of these barriers is the potential for monitoring the barrier such that if a breakthrough of the contaminant occurs or is likely to occur, there is time to react and make corrections prior to the plume front reaching the compliance boundary. One such monitoring approach is the use of Electrical Resistivity Tomography (ERT) to both detect the presence of flaws

(holes) in the barrier that may develop during construction of the barrier and to monitor the operational "health" of the barrier over time.

ERT has conventionally been used to image various subsurface features by surrounding the feature with electrodes [3-10]. However ERT has not been used with the electrodes placed directly within the structure that is being imaged. By placing the ERT electrodes in the barrier, changes in the barrier due to the reaction with the plume or other changes in the geochemistry of the barrier can be monitored. The ERT measurements may also be used to determine if the barrier is retarding the natural groundwater flow and creating a significantly higher hydraulic head on the upstream side of the barrier. This may indicate plugging of the reactive barrier that may cause future flows to go around the reactive materials. This long term monitoring will allow site managers to determine if the barrier needs to be refreshed in certain sections prior to having a breakthrough of the contaminant. To address this potential operational issue, the ERT method should have sufficient resolution to identify specific regions of the barrier where the modification may be needed.

This paper describes the results of some numerical calculations and simple laboratory tests to determine if small voids can be detected in a PRB using electrodes inserted directly into the barrier and to determine if the changes in resistivity of the PRB material over time are sufficient to be detected.

Installation of Permeable Reactive Barriers

One of the key aspects of reactive barriers is that when they are placed they must be continuous in nature. Otherwise, contaminated groundwater may pass around, under, or through holes in the barrier. The best method of placement to ensure that the barriers are continuous is using slurry trench technologies, where a trench is actually excavated from the ground surface and held open by a slurry of the reactive material. Although this installation technique assures continuity, it is very expensive, because the trench must be excavated from the surface down to the groundwater-confining layer and through the entire vadose zone, which may not be impacted by the plume. Since the leading front of a plume can range hundreds to thousands of feet in length, this installation technique is generally prohibitively expensive, especially for sites with moderate vadose zone depths.

A more economical installation technique is to use a line of boreholes or caissons, and either pressure grout in a sideways manner or use horizontal drilling between boreholes. This installation technique is more economical than trenching, because the reactive materials can be placed only in the zone where it will interact with the plume and not in the non-effective vadose zone. The primary concern for these pressurized injection type systems is the risk that the reactive materials are not continuous and that the pressure injection does not reach over and connect with the injection from the neighboring borehole. Therefore, to ensure the barrier continuity, techniques are needed that can efficiently image or measure the continuity of the barrier wall.

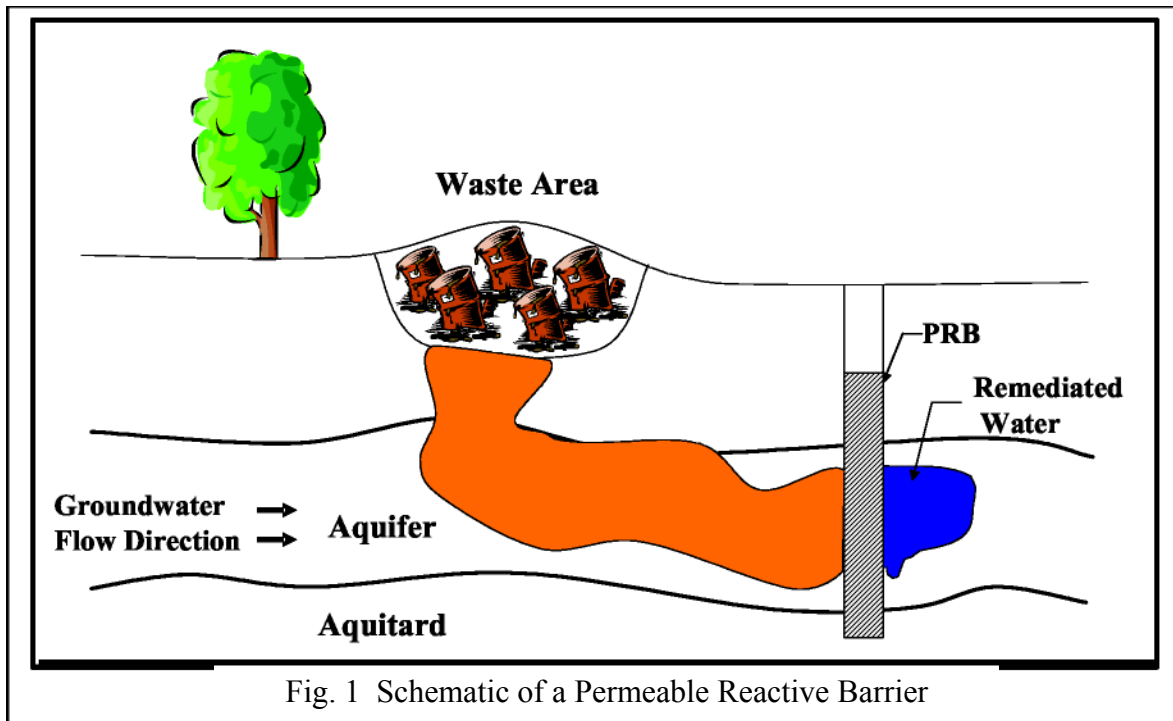


Fig. 1 Schematic of a Permeable Reactive Barrier

IMAGING BARRIER WALL INSTALLATIONS

ERT methods have the potential to assess the continuity of a PRB. Electrical resistivity has been studied for many years and has been used in a wide variety of practical applications. Such applications include, for example, imaging subsurface contamination plumes, detecting leaks from buried tanks, and locating buried metallic objects [4, 7, 9]. In the present application, electrical resistive methods can be used to address two important aspects relating to reactive barriers. First and foremost, electrical resistive techniques can be used to image the subsurface barrier that is created. This will allow examination of the barrier to verify that the barrier is continuous and extends over the depths and distances that it should. ERT methods can be used to determine the presence of any potential holes or places within the barrier where the pressure injections did not reach. The resistance measurements can be made over a time interval that is short enough to permit the installation to be modified to improve the creation of the barrier. The key technical issues, such as insufficient overlap between borings and insufficient depth penetration, can be addressed using this technique.

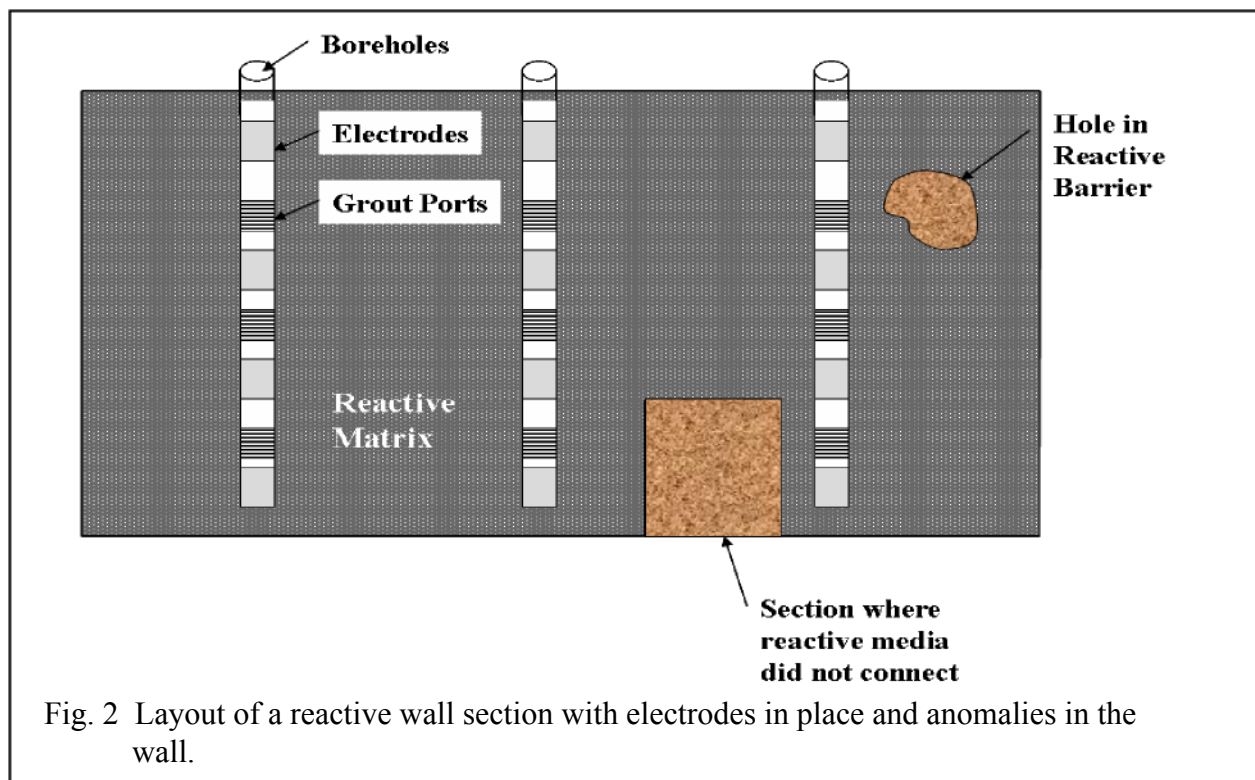
To analyze for potential holes or flaws in the barriers, ERT electrodes can be placed either outside or inside the barrier wall itself. Other investigators have considered the exterior application for imaging barrier for potential holes and flaws [8]. Our method uses the interior application. There are two electrode-installation methods. First, the electrodes can be installed in the boreholes used for the injection of the barrier materials into the subsurface materials, and second, the electrodes can be installed after the barrier has been created. The installation of electrodes after creation of the barrier is more expensive, but offers more flexibility in terms of electrode placement.

The electrodes can easily be installed at the boring locations that are used for the pressure grouting or horizontal drilling. Ideally, three to five discrete electrodes would be placed in each borehole as the boring casing is installed. As illustrated in Fig. 2, each electrode would consist of discrete metal sections separated by nonconductive, plastic sections. Each electrode would have a wire, which

would be connected to traditional electrical resistive geophysical equipment. By exciting pairs of electrodes and measuring the potential on other pairs of electrodes, images can be generated of the electrical conductivity properties of the wall. If the wall is continuous, then these electrical resistance measurements would all be the same. However, if there is a hole in the wall, then the measurements would be different, because the native soil materials will be electrically different than the reactive barrier materials. Using these images of the possible breaks in the barrier, additional borings can be installed to correct a discontinuity of the wall.

Numerical Modeling of Electrode Spacing for Barrier Images.

A numerical modeling study was conducted to evaluate the capability of ERT to detect flaws in a passive reactive barrier (PRB) using the numerical code from LLNL. The model barrier is based on a real barrier described by Slater and Binley [8]. It consists of highly conducting, granular iron emplaced within a trench. It was assumed that the barrier was filled with a mixture of iron and sand and that vertical electrode arrays were embedded within the barrier.



The study considered varying PRB hole sizes (flaws in the barrier) and locations. For any given model, a hole was located right next to and near the center of an electrode array (maximum sensitivity and resolution), at the center between two electrode arrays (moderate sensitivity and resolution), or near the bottom centered between the two arrays (minimum sensitivity and resolution). We also considered various hole sizes. The thickness of the hole was always equal to the thickness of the barrier (0.66m). The smallest hole considered had a height and a width of 0.33 m (0.11 m^2), or 1/2 of the electrode spacing within an array. The largest hole had a height and a width of 1.22 m (1.74 m^2). We also modeled a medium sized hole with a height and a width of

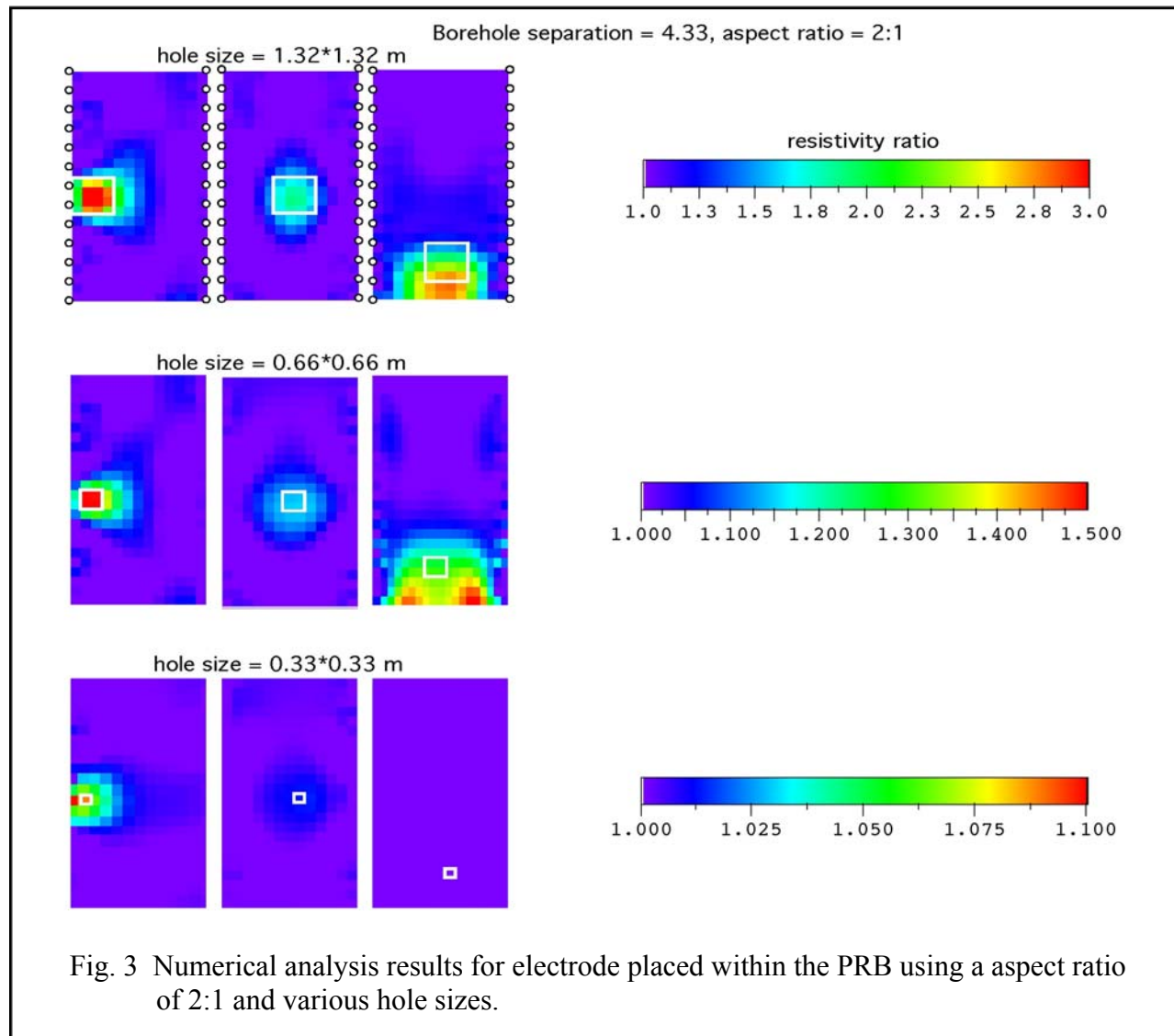
0.66 m (0.44 m²). It was assumed that the PRB material (a sand/iron mix) had an electrical resistivity of 0.3 ohm-m, which was based upon laboratory measurements, and the hole's resistivity was 3.0 ohm-m, which is typical of a saturated sand.

The study also considered various array aspect ratios, because it is well known that aspect ratio controls sensitivity and resolution when line arrays of electrodes are used [11]. Aspect ratio is defined as the distance between the top and bottom electrodes in an array divided by the distance between adjacent arrays. Previous work suggests that an aspect ratio of 2:1 is a good compromise, because this aspect ratio offers good sensitivity/resolution while minimizing the need for closely spaced boreholes. In this study, we have considered aspect ratios of 2:1 (best resolution, closest borehole spacing), 1.5:1, and 1:1 (worst resolution, longest borehole spacing).

Figure 3 shows the results obtained for a monitoring scenario. Various hole sizes and positions are shown (the hole position is indicated by the white square superimposed on the images). The black and white circles on the sides of the images represent the electrodes. The hole-size in the model decreases along a given column of images from top to bottom. Each row of images is rendered using a different color bar. The aspect ratio is 2:1, which should offer the best resolution and sensitivity of the three investigated.

The study suggests that when an aspect ratio of 2:1 is used, flaws as small as 0.11m² (0.33 m on a side) can be detected for most locations in the barrier. When the aspect ratio changes to 1.3:1, the smallest flaw detectable at all flaw positions is 1.74 m² (1.32 m on a side). A 1:1 aspect ratio yields fairly poor results, only resolving flaws that are very close to an electrode array.

These results indicate that the approach of placing electrodes within the wall itself can provide an effective barrier characterization images that can be used to ensure that no hole of sufficient size exists within the barrier. The technique also permits the location of any flaw in the barrier to be determined, such that additional boreholes can be installed to correct these flaws.



LONG-TERM MONITORING OF PRB ELECTRICAL CHARACTERISTICS

One of the unique aspects of placing electrodes within the wall is that the electrodes can also be used for long term monitoring of the barrier. Although previous efforts utilized electrodes outside the wall [6, 8], so they could look back on the wall, this approach only permits images of the wall to be created, but does not permit long term monitoring of the barrier. Using electrodes within the wall offers the advantage of being able to monitor temporally the electrical characteristics of the barrier itself.

Since the majority of the PRB's installed to date have used zero-valent iron as the reactive material [2], most soil materials will be less conductive than the reactive materials, and therefore, will show an electrical contrast when compared to native soils. Likewise, as the zero-valent iron is reduced during the process of remediating the groundwater that flows through the barrier, its conductivity should decrease over time.

The conductivity changes as oxides (rust) forms within the barrier as part of the reduction reaction. The formation of this layer always occurs on the upstream side of the barrier, and if left unattended, tends to plug the barrier and reduce the permeability.

By monitoring the changes in the conductivity relative to a fixed reference point outside the wall, the overall "health" of that section of the barrier can be assessed. By using the various individual electrodes within the wall, specific areas or portions of the wall can be evaluated. This provides a very cost effective method for determining how fast the barrier is being used up and when additional reactive materials may be needed to prolong the life of the PRB. It also allows specific sections and not the whole wall to be replaced when there are indications of problems with the reactive barrier. When combined with downstream sampling, this information will provide the regulatory community the confirmatory feedback that the PRB is operating properly. The advantage of using electrical measurements is that measurements can be made on a much higher frequency, due to the lower costs, than traditional groundwater sampling.

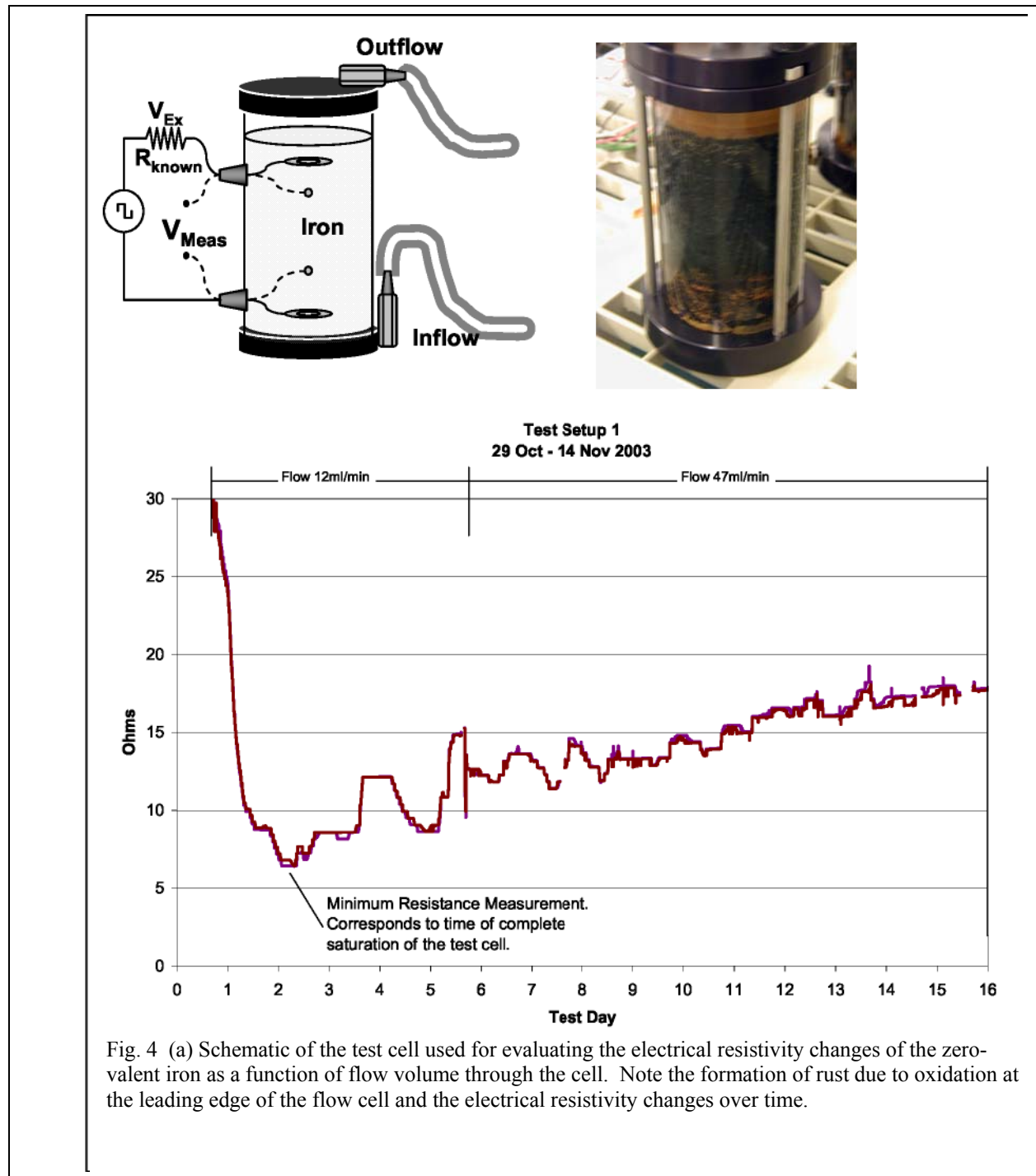
Laboratory Evaluation of Electrical Resistivity Changes

Laboratory tests were conducted to investigate the electrical changes that occur as the zero-valent iron undergoes the reduction reaction. A special test cell was constructed to measure changes in electrical resistance of an iron sample under an induced flow of potable water. Four electrodes were embedded within the zero-valent iron filings in the permeameter cell to measure the electrical resistance of the sample. The test cell is shown below in Fig. 4. The outer two electrodes, spaced 13.0 cm apart, were used to apply a current to the sample. Two inner electrodes, spaced 7.6 cm apart, were used to measure the induced potential. A current was applied in iron filings by applying an 8 Vdc square wave across the outer electrodes. During each flat portion of the square wave, a voltage measurement was taken across the two inner electrodes. When no measurement was being taken, the excitation was removed to prevent polarization of the sample. A flow rate of 12 ml/min was used for the first 5 days of the test. After 5 days, a flow of 47 ml/min was maintained continually through the cell for the remainder of the test.

A resistance value was obtained from the voltage measurement across the inner electrodes by measuring the current applied to the sample. To measure the current, the voltage across a known resistor in the circuit is measured. The resistance within the sample is calculated using the equations:

$$I = \frac{V_{Ex}}{R_{Known}} \quad (\text{Eq. 1})$$

$$R_{Sample} = \left(\frac{V_{Meas}}{I} \right) = \left(\frac{V_{Meas}}{V_{Ex}} \right) (R_{Known}) \quad (\text{Eq. 2})$$



Initial resistance measurements prior to saturating the sample were about 86 ohms. The resistance quickly dropped to close to 40 ohms during the initial fill of the cell. A minimum resistance of 8.5 ohms was reached on day 2. This minimum resistance corresponds with complete saturation of the sample and removal of the trapped air pockets.

Within 4 hours of initiating the flow through the cell, the bottom 2 cm of the sample began to show discoloration. The normally dark gray or black color of the iron filings was showing

patches of orange oxidation. As shown in Fig. 4, over the course of the test, the oxidation (rust) slowly crept up the sample. The outflow had a light orange color continually throughout the test produced by particulates in the waste water.

A graph of the first 16 days of testing is shown in Fig. 4. Throughout the course of the test the resistance slowly increased. There are small fluctuations on the resistance measurements, but a definite increase is seen (over 10 ohms in 14 days).

Based upon the laboratory measurements there exists sufficient electrical resistivity change that the ERT method can be used to monitor the "health" of the barrier. Initially, the resistance values of the barrier will be very low, and then begin increasing over time as the rust begins to develop. Additional tests are being conducted with closer electrode spacing to better pinpoint the difference in the electrical resistivity of the rust zone as compared to an aggregate resistivity of a large section of the material in which the oxidation region is a just a fraction. A final test will be conducted using a contaminant that will likely increase the rate at which the oxidation is formed in the barrier. These results will be published in a subsequent paper.

CONCLUSION

A novel method of determining the integrity and long-term operational health of a permeable reactive barrier was described. An electrical resistivity tomography (ERT) method, where the electrodes are inserted directly into the barrier itself, is being evaluated. The initial numerical modeling calculations indicate that an ERT method can detect flaws (voids) in the barrier as small as 0.11 m^2 ($0.33 \text{ m} \times 0.33 \text{ m}$) when the aspect ratio of the electrodes are 2:1. Laboratory measurements indicate that the change in resistance over time of the iron-filling mixture used to create the PRB is sufficient for ERT to monitor the long-term health of the barrier. The use of this ERT method allows for the cost-effective installation of the barrier, especially when the vadose zone is large, because borehole installation methods, rather than trenching methods, can be used.

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