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The influence of cathode material on electrochemical degradation of trichloroethylene in aqueous solution

Ljiljana Rajic¹, Noushin Fallahpour¹, Elizabeth Podlaha², and Akram Alshawabkeh^{1,*}

¹Department of Civil and Environmental Engineering, Northeastern University, Boston, MA, 02115, USA

²Department of Chemical Engineering, Northeastern University, Boston, MA, 02115, USA

Abstract

In this study, different cathode materials were evaluated for electrochemical degradation of aqueous phase trichloroethylene (TCE). A cathode followed by an anode electrode sequence was used to support reduction of TCE at the cathode via hydrodechlorination (HDC). The performance of iron (Fe), copper (Cu), nickel (Ni), aluminum (Al) and carbon (C) foam cathodes was evaluated. We tested commercially available foam materials, which provide important electrode surface area and properties for field application of the technology. Ni foam cathode produced the highest TCE removal (68.4%) due to its high electrocatalytic activity for hydrogen generation and promotion of HDC. Different performances of the cathode materials originate from differences in the bond strength between atomic hydrogen and the material. With a higher electrocatalytic activity than Ni, Pd catalyst (used as cathode coating) increased TCE removal from 43.5% to 99.8% for Fe, from 56.2% to 79.6% for Cu, from 68.4% to 78.4% for Ni, from 42.0% to 63.6% for Al and from 64.9% to 86.2% for C cathodes. The performance of the palladized Fe foam cathode was tested for degradation of TCE in the presence of nitrates, as another commonly found groundwater species. TCE removal decreased from 99% to 41.2% in presence of 100 mg L⁻¹ of nitrates due to the competition with TCE for HDC at the cathode. The results indicate that the cathode material affects TCE removal rate while the Pd catalyst significantly enhances cathode activity to degrade TCE via HDC.

Graphical Abstract

*Corresponding author: Tel: 617-373-3994, aalsha@coe.neu.edu.

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Keywords

electrochemical; cathode; palladium; trichloroethylene; groundwater

1. Introduction

Trichloroethylene (TCE) has been widely used as an ingredient in industrial cleaning solutions and as a “universal” degreasing agent. Improper disposal of TCE coupled with its physical and chemical properties (low solubility and limited degradation) led to persistent TCE contamination at many hazardous waste sites (Moran et al., 2007). The USEPA has set Maximum Contaminant Levels (MCLs) for TCE in drinking water at very low concentrations of $5 \mu\text{g L}^{-1}$.

The presence of chlorine in the TCE structure contributes to its carcinogenic and mutagenic properties; thus, complete dechlorination is favorable for degradation of TCE dissolved in groundwater. So far, the efficient reductive dechlorination of chlorinated organic compounds (COCs) was achieved via zero-valent iron and palladium-based materials (Lowry and Reinhard, 2001; Lien and Zhang, 2005; Liu et al., 2006; Wu and Ritchie, 2006; Petersen et al., 2007a; Phillips et al., 2010; Ma et al., 2012; He et al., 2013).

Recently, electrochemically-induced reduction has gained interest for removal of COCs from groundwater (Li and Farrell, 2000; Petersen et al., 2007b; Mishra et al., 2008; Mao et al., 2011, 2012a, 2012b). Electrochemical reduction through hydrodechlorination (HDC) occurs at the cathode due to water electrolysis. The water electrolysis at the cathode leads to the hydrogen evolution via electrochemical hydrogen adsorption (Volmer reaction) where atomic hydrogen (H_a) is chemically adsorbed on active site of the electrode surface (M). The H_a further involves in electrochemical desorption (Heyrovsky reaction) or chemical desorption (Tafel reaction) to create hydrogen gas or interacts with the reducible chemicals like chlorinated substances, which leads to HDC. The dechlorination rate is affected by mass transfer, electron transfer and chemical reactions, as well as surface reactions, such as adsorption and desorption (Chaplin et al., 2012; He et al., 2013). Apart from electroreduction, electrochemically-induced oxidation of COCs can be achieved through reactions at the anode (Azzam et al., 2000) or via hydroxyl radicals generated in bulk solution (Martinez-Huitle and Ferro, 2006; Panizza and Cerisola, 2009; Yuan et al., 2012, 2013). The oxidation rate at the anode highly depends on the anode material; with active

anodes the oxygen production is promoted over formation of hydroxyl radicals and COCs oxidation is limited while non-active anodes (e.g. boron doped diamond) provide complete COCs transformation to CO₂ through reaction with hydroxyl radicals (Scialdone et al., 2010a; Randazzo et al., 2011). In mixed electrolyte systems, which are easier to implement and maintain in practice, the electrochemical degradation can be achieved by: a) reduction (Mao et al., 2011, 2012a; 2012b), b) oxidation via Fenton reaction (Yuan et al., 2012, 2013) or b) simultaneous oxidation and reduction with the selection of appropriate electrode materials (Gilbert and Sale, 2005; Scialdone et al., 2010a). When using an active anode, the presence of oxygen competes with the target contaminant for the reaction sites at the cathode and limits HDC and it can involve in creation of hydrogen peroxide and promote Fenton reaction. A new system was designed to promote electrochemical reduction, which is the primary degradation mechanism of highly oxidized chemical compounds such as TCE. The design, introduced by our laboratory, adopts a flow-through cell with the cathode placed in front of the active anode with respect to the flow direction, to minimize the effect of oxygen on HDC of TCE (Rajic et al., 2014, 2015a, 2015b, 2015c).

The type of cathode material has a major effect on the HDC reaction. The good HDC catalyst should have strong bond with H_a to allow proton-electron transfer process but weak enough to ensure the bond breaking and the product release (Zheng et al., 2015). If the hydrogen-metal surface (H_a-M) binding energy is too high, adsorption is slow and limits the overall rate but if it is too low, desorption is slow. The standard free energy for H_a adsorption on solid electrode can be used to evaluate the adsorption of H_a and the product release. Good catalytic activity of noble metals (e.g., Ag, Pt and Pd) arises from the fact that the free energy of hydrogen adsorption is close to zero (Zheng et al., 2015). It has been demonstrated that noble metals can be effectively used for the reductive de-chlorination of chlorinated hydrocarbons when used as working electrodes, and as coatings on different electrode materials (Sonoyama and Sakata, 1999; Hoshi et al., 2004; Xu et al., 2007; Scialdone et al., 2008; Rondinini and Vertova, 2010; Scialdone et al., 2010b).

Specifically, palladized electrodes were widely investigated for removal of COCs (Li and Farrell, 2000; Roh et al., 2001; Jovanovic et al., 2005; Yang et al., 2006, 2007; He et al., 2013; Li et al., 2013). In this case, the deposition of small amounts of Pd catalyst on the cathode substrate enhances its ability to absorb hydrogen into the lattice and increases the rate of HDC. It was found that the hydrogen absorption is higher in thin Pd films than in the bulk metal; thin Pd films crystallites size is much smaller and more hydrogen may be located in the grain boundaries (Bucur and Bota, 1982; Stuhr et al., 1997; Gabrielli et al., 2004). Various permeable materials were used as cathode substrates for palladium coating, such as activated carbon fiber/cloth/felt, reticulated vitreous carbon, carbon nanotubes meshed Ti, Ti/TiO₂ nanotubes, silver, Ni foam, Fe foam and Ebonex® (Cheng et al., 1997, 2003; Yang et al., 2006, 2007; Durante et al., 2009; Scialdone et al., 2010b; Sun et al., 2010; Durante et al., 2013; Xie et al., 2013). Ni foam is known to be an ideal cathode substrate for hydrogenation catalyst; Cu is potentially a good catalyst for the hydrogenation for treatment of selected chlorinated aliphatic hydrocarbon (Zhu et al., 2010). However, slightly stronger adsorption of hydrogen by Cu and weaker adsorption by Ni and Fe leads to less electroactivity than noble metals (Zheng et al., 2015). It was found that in the bimetallic Pd/Ni foam system, the Pd particles at the cathode substrate influence on HDC rate by

increasing the surface area and allowing the diffusion of H_a among particle, which maintain and regenerate electrocatalytic activity (Yang et al., 2007).

The influence of commonly found chemicals in groundwater, such as nitrates, is critically important to implement remediation technology. Nitrates are commonly found species in groundwater at high levels due to the intensive use of nitrogen fertilizers, industrial wastes, animal wastes and septic systems and present a significant environmental problem (Wakida and Lerner, 2005; Burkart and Stoner, 2007). Electrochemical reduction by palladized electrodes is found to be an efficient mechanism for the nitrates removal from water (de Voos et al., 2000; Peel et al., 2003; Wang and Qu, 2006; Abdallah et al., 2014). The nitrates reduction mechanism initially involves interaction with the atomic hydrogen (Reactions 1–2) and is a competing reaction with HDC.

The performance of different cathode materials for HDC was investigated using divided electrochemical cells. The main goal of this study is to evaluate the performance of different cathode materials for the electrochemical dechlorination of TCE in a mixed, undivided electrolyte system. The cathode followed by anode setup was used since it promotes HDC in the undivided, flow-through electrochemical cell. We tested the performance of Fe, Cu, Ni, Al and C foams and their palladized forms for degradation of TCE by a cathode upstream of an anode electrode sequence. These materials show good electrocatalytic properties towards dechlorination and are cost-effective and commercially available materials – important properties for possible field application of the technology. In addition, the influence of nitrates on electroreduction of TCE in aqueous solution was also investigated.

2. Materials and Methods

All chemicals used in this study were analytical grade. TCE (99.5%) was purchased from Sigma-Aldrich. Calcium sulfate was purchased from JT Baker, sodium chloride, sodium nitrate and sodium bicarbonate from Fisher Scientific and hydrocarbon gas standard (analytical standard, 1% (w/w) methane, ethene, acetylene in nitrogen) from Supelco. Deionized (DI) water (18.2 M Ω ·cm) obtained from a Millipore Milli-Q system was used in all the experiments.

Synthetic groundwater was prepared by dissolving 413 mg L⁻¹ sodium bicarbonate and 172 mg L⁻¹ calcium sulfate in deionized water. The sodium nitrate was also added to solution to achieve concentrations of 10 to 100 mg L⁻¹ of nitrates (2.25–22.5 mg L⁻¹ as N). The maximum contaminant level (MCL) of nitrates in groundwater is 44.2 mg L⁻¹ (10 mg L⁻¹ as N). The concentrations of bicarbonate ions and calcium ions are representative of groundwater from limestone aquifers, resulting in electrical conductivity of 800 to 920 μ S cm⁻¹. The initial TCE concentration in all experiments was 5.3 mg L⁻¹. The initial pH of the contaminated synthetic groundwater was 8.0 $\pm$ 0.3 and the initial oxidation-reduction

potential (ORP) value was 210 ± 5 mV. The temperature was kept constant at 20°C . Darcy's velocity was selected as 0.25 cm min^{-1} (3 mL min^{-1}) and was maintained by a peristaltic pump (Cole Parmer, Masterflex C/L). Constant currents during treatments were applied by an Agilent E3612A DC power supply.

TCE concentration was measured by a 1200 Infinity Series HPLC (Agilent) equipped with a 1260 DAD detector and a Thermo ODS Hypersil C18 column ($4.6\text{ mm} \times 50\text{ mm}$) as described in Mao et al. (2011). pH and ORP of the electrolyte were measured by pH meter and ORP meter with corresponding microprobes (Microelectro, USA). The microprobes allow measurement of these parameters using a small amount of liquid ($\approx 0.2\text{ mL}$). Analysis of chlorides and nitrates was performed by ion chromatography (IC) instrument (Dionex 5000) equipped with an AS20 analytical column. A KOH solution (35 mM) was used as a mobile phase at a flow rate of 1.0 mL min^{-1} .

Ti/mixed metal oxide (MMO) mesh (3N International) was used as the anode in all experiments. The Ti/MMO electrode consists of IrO_2 and Ta_2O_5 coating on a titanium mesh with dimensions of 36 mm diameter by 1.8 mm thickness. Iron foam (45 pores per inch, PPI, 98% iron and 2% nickel) was purchased from Aibixi Ltd., China, and Ni foam (100 PPI, Purity > 99.99%) was purchased from MTI corporation. Cu foam (40 PPI, Purity > 99.99%), carbon (C) foam (45 PPI, Purity > 99.99%) and Al foam (40 PPI, Purity > 99.99%) were purchased from Duocel®. Holes (0.5 cm diameter) were drilled in the foam cathodes to prevent accumulation of the gas bubbles in the cathode vicinity. Ni foam was immersed in 80 g L^{-1} sulfuric acid for 5 min to remove the oxide layer and then washed thoroughly with water. Fe electrodes were immersed in 1M HCl to remove any foreign metals and surface oxide layers. Al foam was degreased and cleaned in acetone for 20 min under ultrasonic vibration.

The palladization procedures were performed under the conditions shown in Table 1. Pd load was 0.38 , 0.76 and 1.52 mg cm^{-2} of geometric electrode surface area. After palladization, cathodes were washed with DI water and dried at room temperature. The amount of deposited Pd was calculated from the concentrations of the PdCl_2 solution estimated spectrophotometrically at 480 nm , before and after electroless plating (except for the palladization of Al foam). Pd distribution on the Fe, Cu and Ni electrodes was tested by energy dispersive X-Ray Fluorescence (XRF), model Omicron by Kevex. The XRF analyses were performed at X-ray energy of 50 kV , current of 2 mA and acquisition time of 60 s . Composition results are accurate within 1% . Additionally, scanning electron microscope (Hitachi S-4800 FESEM) was used to analyze the Fe foam surface after palladization.

The electrochemical flow-through setup is shown in Fig. 1. A vertical acrylic column was used as electrochemical flow-through column reactor. The galvanostatic experiments were conducted with Fe, Cu, Ni, Al, and C foam, with (0.76 mgPd cm^{-2}) and without Pd under 60 mA current which enables hydrogen evolution on the cathodes (all cathodes worked at a hydrogen-releasing potential ensuring HDC to be the main TCE degradation mechanism.) The influence of Pd load (0.38 , 0.76 and 1.52 mg cm^{-2} of geometric electrode surface area) and current intensities (30 , 60 and 90 mA) were tested on the Fe foam cathode. The electrolytic cell potential during treatments was $25 \pm 1\text{ V}$.

The TCE concentration is determined at specified times during treatment (mg L^{-1}). Results are expressed as the means of the duplicate experiments, with their corresponding standard deviations (SDs).

It is assumed that the electrochemical reduction of TCE involves 8 electrons for production of ethane (Yuan et al., 2012). Current efficiencies (CE) were calculated according to Faraday's law. The cumulative energy consumption was calculated as:

$$Wh = \int UI dt \quad (1)$$

where U is electrolytic cell voltage (V), I is the electric current (A) and t is treatment time (h). The value is calculated for the amount of TCE (in kg) removed during the treatment.

3. Results and discussion

3.1 The performance of foam cathodes for TCE degradation

Fe, Cu, Ni, Al and C foams were evaluated as cathode materials for TCE degradation and their influence on TCE concentration decay during treatment is given in Fig. 2. A summary of relevant experimental results are presented in Table 2.

The accumulation of hydrogen gas bubbles at the vicinity of the Ni foam cathode was observed during the experiments and assumed that the relatively slow flow rate (3 mL min^{-1}) and dense foam structure inhibited the hydrogen gas bubble movement. Perforation (drilling 0.5 cm holes in the cathode) was used to minimize gas bubble accumulation. Perforation improved TCE removal by Ni foam cathode from 29.6% without perforation to 68.4% of TCE with perforation. This significant increase in TCE removal indicates that bubble accumulation at the cathode prevents interaction between TCE molecules and cathode surface (Wuthrich et al., 2005). All foam cathodes used in this study were perforated to prevent entrapment of hydrogen gas bubbles.

The order of electrodes performance for transformation of TCE was $\text{Fe} \sim \text{Al} < \text{Cu} < \text{C} < \text{Ni}$. As mentioned before, different cathode reactivity towards TCE HDC can be explained by different $\text{H}_a\text{-M}$ binding energies (Zheng et al., 2015). The slight differences between the $\text{H}_a\text{-M}$ binding energies of Ni, Fe and Cu cathodes contributed to the differences in their HDC activity. Weak bond strength between H_a and Al surface explains low removal rate achieved by using the Al cathode (Table 2). In addition, Al cathodes interact with hydroxyl ions during the process of water electrolysis, which causes corrosion and precipitation (Picard et al., 2000). In the bulk solution, cationic hydrolysis products of Al react with OH^- ions to finally transform into amorphous $\text{Al}(\text{OH})_{3(s)}$ according to complex precipitation kinetics (Mouedhen et al., 2008).

Concentration profiles of chloride ions measured after treatment correspond to the chloride released from TCE removal (Table 2). The absence of oxalates and acetates, which was proven while optimizing the cathode followed by anode sequence in our previous study (Rajic et al., 2015) indicate that the HDC is the main removal mechanism. Although, it was reported that MMO anode used in this study enables TCE oxidation (Lakshmipathiraj et al., 2012), oxygen evolution significantly competes with the TCE oxidation, especially under

the current levels applied in this study. The oxygen formed could induce generation of water or hydrogen peroxide; hydrogen peroxide could initiate Fenton reaction if conditions allow (e.g. Pd catalyst presence, pH, presence of Fe(II)) (Yuan et al., 2012). However, the anode is placed above the cathode (Fig. 1) so the oxygen flow is opposite from the cathode placement and minimizes its interaction with cathode. In addition, no chlorinated intermediate products such as cis-DCE and vinyl chloride were detected in the effluent.

3.2 Degradation of TCE by palladized cathodes

XRF mapping was used to confirm the presence of Pd on the foam surfaces (Fig. 3). The dispersion in the Pd content reflects the non-uniformity of deposition that is distributed through the materials surface. This is due to the small islands of Pd formed locally on the electrode surface. However, the duplicate experiments showed that differences in electrodes performance were less than 2% for each sampling time. Further analysis and characterization of palladized Al and C was not performed since certain characteristics are not suitable for real application: a) release of Al in the effluent is undesirable since there is an association with neuropathological diseases including pre-senile dementia and Alzheimer's disease (Srinivasan et al., 1999) and b) C foam is shown to be an efficient cathode for TCE removal, but due to its fragile nature, it is not proper electrode material for field application.

Cathode palladization was performed to enhance TCE reduction in a flow-through system with a cathode followed by an anode electrode sequence. The influence of Pd catalyst loading on Fe foam cathode was evaluated for TCE transformation (Fig. 4a). The final TCE removal without Pd, with 0.38 mgPd cm⁻², 0.76 mgPd cm⁻² and 1.52 mgPd cm⁻² were 43.5%, 62.2%, 99.8% and 58.3%, respectively. Results indicate that the TCE removal improves with increasing Pd content (linear correlation) but there is an optimum value beyond which the removal rate decreases. Lower Pd loading was not sufficient to bound highly reactive hydrogen on Pd surface. Higher catalyst loading (1.52 mgPd cm⁻²) favors proton reduction over TCE HDC, which lowers the removal. The results for the highest catalyst loading are not shown in the Fig. 4a. The materials with 0.76 mgPd cm⁻² were used in the experiments. CE increased by 90% with the use of Pd catalyst (0.76 mgPd cm⁻²) compared to the Pd absence.

TCE decay by different palladized cathodes is shown in Fig. 4b. The results indicate varying influence of Pd catalyst on the performance of the different cathode materials. The removal rates significantly increased in the presence of 0.76 mgPd cm⁻² for all materials tested (Table 2). Palladization improved TCE degradation by 120% for Fe cathode, 41% for Cu, 14% for Ni, 29% for Al and 34% for C cathode. The materials performance for TCE removal in the presence of Pd catalyst was in the following order: Ni < Al < C < Cu < Fe. Although, palladized Ni foam showed high removal rate for the most of contaminants tested (Yang et al., 2006), Pd presence slightly influenced Ni foam performance compared to other materials under the conditions of this study. As with higher catalyst loadings, the current density for proton reduction was high for palladized Ni. This resulted in competition with TCE for cathodic reduction, where an excessive hydrogen gas evolution interfered with transfer of TCE molecules to the reactive cathode surface.

The decay of normalized TCE aqueous concentration by palladized Fe foam cathode under different currents is shown in Fig. 5. TCE removal rates were 59.5%, 99.8% and 87.5% under 30 mA, 60 mA and 90 mA, respectively. The pseudo-first-order reaction rate coefficients were $1.4 \times 10^{-3} \text{ min}^{-1}$ under 30 mA, $7.5 \times 10^{-3} \text{ min}^{-1}$ under 60 mA and $5.2 \times 10^{-3} \text{ min}^{-1}$ under 90 mA. Current increase from 30 mA to 60 mA significantly improved TCE removal but CE value decreased by 32%. TCE removal rate was high ($3.8 \times 10^{-2} \text{ min}^{-1}$) during the first 40 min of treatment under 90 mA. However, both removal and CE value (by 62%) decreased during further treatment. The increased bubbles growth density at 90 mA led to the electrode surface coverage. The hydrogen bubbles slowly detach from the electrode surface because of the capillarity forces; gas coverage lowers the active electrode surface area thus disabling TCE molecules degradation (Wuthrich et al., 2005). The energy consumption was 1.7 kWh per kg of TCE removed for the optimized treatment with palladized Fe foam cathode under 60 mA. The values are much less compared with energy consumption reported by other studies (Bejankiwar et al., 2005; Moon et al., 2005).

3.3 The influence of nitrates on performance of palladized Fe foam cathode

The performance of palladized Fe foam was tested in the presence of nitrates as commonly found species in groundwater at high levels. The influence of nitrate ions on TCE electrochemical reduction was evaluated together with the feasibility of the treatment to simultaneously remove TCE and nitrates. Nitrate presence in the concentration range evaluated in this study influence TCE removal. Compared to 99% TCE removal in the absence of nitrates, 85% of TCE was removed with 5 mg L^{-1} nitrates, 74.6% with 40 mg L^{-1} nitrates and 41.2% with 100 mg L^{-1} nitrates. The nitrates content slightly changes in the effluent (up to 20%) most likely as a consequence of the anodic oxidation of the reduction products in the cathode followed by the anode arrangement. The results imply that the electrochemical setup used in this study should be further optimized for the treatment of groundwater loaded with nitrates.

4. Conclusions

The use of different cathode materials was evaluated in a mixed electrolyte flow-through electrochemical reactor to degrade trichloroethylene (TCE) in aqueous solution. A cathode followed by an anode sequence was used to induce the reduction mechanism for TCE transformation. The order of electrodes performance for transformation of TCE was $\text{Fe} \sim \text{Al} < \text{Cu} < \text{C} < \text{Ni}$, which is consistent with their electrocatalytic activity. The use of foam electrodes may cause bubble accumulation, which limits the electrode efficiency. Electrode perforation improved performance: TCE removal with Ni foam cathode increased from 29.6% without perforation to 68.4% with electrode perforation. Presence of Pd enhanced TCE degradation by 120% for palladized Fe cathode, 41% for palladized Cu, 14% for palladized Ni, 29% for palladized Al and 34% for palladized C cathodes. Increasing the current from 30 mA to 60 mA enhanced TCE removal from 59.5%, to 99.8%. TCE removal is impacted by presence of nitrate competing species; TCE transformation decreased from 99% to 41.2% in presence of 100 mg L^{-1} of nitrates due to the competition with TCE HDC at the cathode.

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Highlights

- The cathode material influences hydrodechlorination (HDC) rate of trichloroethylene.
- The effect of Pd coating is different for cathode materials tested.
- The Pd coating on the cathodes significantly enhances HDC of trichloroethylene.
- The presence of nitrates adversely influences the HDC of trichloroethylene.

Figure 1.
Electrochemical flow-through reactor

Figure 2.
The influence of different foam cathode materials on TCE removal (current: 60 mA, flow rate: 3 mL min⁻¹, TCE concentration: 5.3 mg L⁻¹)

Figure 3.
Pd distribution across foam material surfaces measured by XRF

Figure 4.

(a) The influence of Pd catalyst on TCE removal (current: 60 mA, flow rate: 3 mL min⁻¹, TCE concentration: 5.3 mg L⁻¹, Fe foam cathode) and (b) TCE concentration decay during treatment using different cathodes with and without Pd (current: 60 mA, flow rate: 3 mL min⁻¹, TCE concentration: 5.3 mg L⁻¹, 0.76 mg cm⁻² Pd load)

Figure 5.

The influence of current on palladized Fe foam performance on TCE removal (flow rate: 3 mL min⁻¹, TCE concentration: 5.3 mg L⁻¹, 0.76 mg cm⁻² Pd load)

Table 1

A summary of the palladization procedures

Electrode material	Conditions	Deposition type	Reference
Fe and Cu	5 mg Pd, 10 mg Pd and 20 mg Pd (as PdCl ₂); 50 mL 0.1 M HCl; 5 min	Electroless	(Jovanovic et al., 2005)
Ni	10 mg Pd (as PdCl ₂); 50 mL 30 mM NaCl; 5 min	Electroless	(Yang, Yu, & Shuai, 2007)
Al	10 mg Pd (as PdCl ₂); 50 mL 25% NH ₄ OH; 5 min	Electroless	(Pournaghi-Azar & Dastangoo, 2004)
C	200 mL solution of PdCl ₂ (10 mg Pd) in sodium acetate-acetic acid buffer (pH 5.0); 40 mA; Pt mesh anodes; 20 min	Electrodeposition	(I. F. Cheng et al., 1997)

Table 2

TCE removal rates and pseudo-first order coefficients

Cathode material	Removal (%)	Pseudo-first-order rate, k (min ⁻¹)	Correlation factor (R ²)	Chloride (mg L ⁻¹)	Chloride recovery* (%)
Fe	43.5	5.8 x 10 ⁻³	0.91	1.63	89.7
Cu	56.2	9.6 x 10 ⁻³	0.93	1.98	86.4
Ni	68.4	6.0 x 10 ⁻³	0.98	2.92	95.2
Al	42.0	3.4 x 10 ⁻³	0.91	1.69	96.4
C	64.9	5.5 x 10 ⁻³	0.97	2.35	98.2
Fe_Pd	99.8	3.8 x 10 ⁻²	0.97	3.92	95.7
Cu_Pd	79.6	2.2 x 10 ⁻²	0.99	2.97	91.3
Ni_Pd	78.4	9.5 x 10 ⁻¹	0.95	3.38	92.1
Al_Pd	63.6	1.3 x 10 ⁻²	0.91	2.41	94.3
C_Pd	86.2	1.0 x 10 ⁻²	0.97	3.41	93.5

* chloride recovery was calculated as the percentage of chlorides measured in the solution compared to theoretically calculated to be expected from degraded TCE.