ELECTROCHEMICAL REMEDIATION TECHNOLOGIES FOR METALS REMEDIATION IN SOIL, SEDIMENT AND GROUND WATER, PRESENTATION OF CASE HISTORIES[1]

William A. McIlvride[2], Falk Doering, Niels Doering, Donald G. Hill, and Joe L. Iovenitti

Abstract. ElectroChemical Remediation Technologies (ECRTs) utilize an AC/DC current passed between an electrode pair (one anode and one cathode) in soil, sediment, or ground water to either mineralize organic contaminants through the ElectroChemicalGeoOxidation (ECGO) process, or complex, mobilize, and remove metal contaminants through the Induced Complexation (IC) process, either *in-situ* or *ex-situ*. Field remediation data suggest that ECRTs-IC cause electrochemical reactions in soil, sediment, and ground water that generate metallic ion complexes from the target contaminant metals. These complexes, along with naturally occurring dissolved metals, migrate to the electrodes down the electrokinetic gradient and are either concentrated at the electrode (e.g., cesium, strontium) or deposited onto the electrodes (e.g., mercury, cadmium, lead). The metal contaminants concentrated at the electrodes can be pumped and treated, and the metals that deposit on the electrodes can be either disposed of or recycled. ECRTs-IC operates at electrical power levels below those of conventional electrokinetic methods. A unique feature of ECRTs-IC, in marked contrast to electrokinetics, is that metals generally migrate to both the anode and cathode. European field projects include remediation of (1) mercury in brackish water silty sediments, where 76 kg (168 lbs) of mostly mercury were deposited at both electrodes in 26 days of total remediation time; (2) parts per billion ground water contamination of a variety of metals beneath a steel mill waste lagoon, where metal concentration decreases up to 93% were achieved in 30 days of total remediation time; and (3) mercury in sewage sludge contaminated with dental amalgams, which showed an average decrease from 35 mg/kg to 0.185 mg/kg in seven days. A recently completed U.S. laboratory test for the U.S. Department of Energy under fresh water conditions corroborated the European field remediation results. Existing field and laboratory results indicate that ECRTs-IC is a rapid and effective remediation process.

Additional Key Words: innovative, *in-situ*, contaminant, mercury, lead, zinc, chromium, nickel, copper, heavy metal.

---

[1] Paper was presented at the 2003 National Meeting of the American Society of Mining and Reclamation and the 9th Billings Land Reclamation Symposium, Billings MT, June 3-6, 2003. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

[2] William A. McIlvride is a Senior Project Hydrogeologist with Weiss Associates, Emeryville, California, 94608. Dr. Falk R. Doering is Chief Executive Officer of electrochemical processes, llc (ecp), Stuttgart, Germany, and the developer of ECRTs. Niels Doering is Chief Technical Officer of ecp. Dr. Donald G. Hill is a Senior Associate Geophysicist/Petrophysicist with Weiss Associates. Joe L. Iovenitti is Vice President and Director of Innovative Technologies with Weiss Associates.

Proceedings America Society of Mining and Reclamation, 2003 pp 475-495
DOI: 10.21000/JASMR03010475

https://doi.org/10.21000/JASMR03010475

Introduction

ElectroChemical Remediation Technologies (ECRTs), developed by Dr. Doering of electrochemical processes, llc (ecp), are a field-developed, empirically-based suite of technologies. Over 50 sites and two million metric tons of soil have been remediated using ECRTs in Europe. ECRTs are geophysically based and use a proprietary AC/DC electrical signal and are related to colloidal and electrode electrochemistry. They belong to the class of Direct Current Technologies (DCTs) where predominantly DC electricity is passed between two electrodes. DCTs for environmental remediation consist of two types, ECRTs and electrokinetics (Probstein et al., 1991), Figure 1. The primary distinctions between these two electrical technologies are the (1) operative mechanisms, (2) energy input, (3) nature of the current applied, and (4) resulting outcome. ECRTs are comprised of two principal processes (1) ElectroChemicalGeoOxidation (ECGO), which mineralizes organics to their inorganic components, and (2) Induced Complexation (IC), which complexes metal contaminants via the ECRTs-ECGO process, and transports these metal complexes and naturally occurring metals via electrokinetics to the electrodes, where the metals are either concentrated and/or deposited onto the electrodes. To remediate dissolved phase contaminants in ground water a third complementary technology is employed, Carbon Dioxide Vacuum Stripping (CVS) wells.

Employing low-energy and proprietary AC/DC current, ECRTs appear to cause reduction-oxidation (redox) reactions and electrolysis at the pore scale. Figure 2 shows that ECRTs require less electrical energy input than electrokinetics and significantly less than in-situ vitrification.

The proprietary AC/DC signal used by ECRTs to introduce electrical energy into the soil/sediment (soil) is believed to polarize the soil by storing electrochemical energy at polarization sites located at soil grain surfaces and/or pore throats (c.f. Vacquier et al., 1957). Under these conditions, the soil acts much like a capacitor, charging and discharging stored electricity energy (Doering, 1997, 2001; Doering and Doering, 1998; Doering et al., 2002).

Figure 3 displays an example oscillogram pattern showing the measured voltage and current

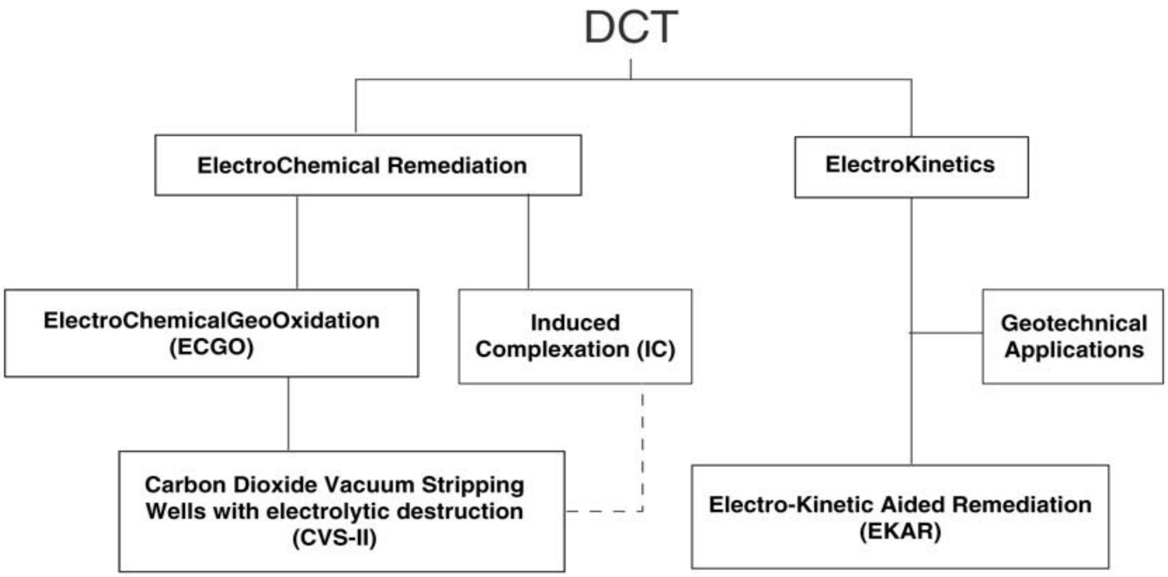


Figure 1. Types of direct current remediation technologies.

output from an ECRTs project. In this case, over two half-cycles, the voltage and amperage supplied to the soil by the AC/DC power converter are in phase (i.e., track each other), but when the soil is charging/discharging electricity, electrical spikes appear in the voltage curve. Between these spikes, a significant component of the current is out of phase with respect to the voltage. We believe that it is in the time interval between the electrical spikes that the redox reactions are occurring.

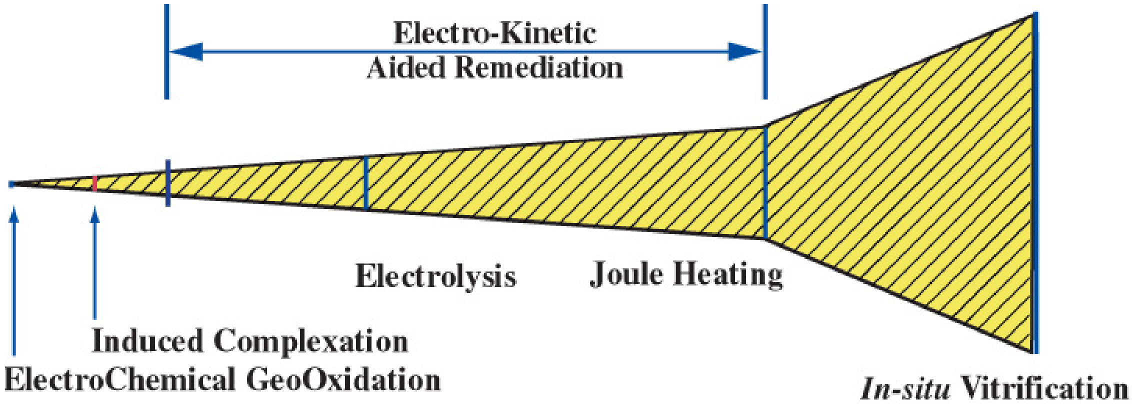


Figure 2. Relative electrical energy input for selected direct current technologies.

Repeated charging/discharging of the electrochemically-stored energy at a high frequency is thought to provide the electron flux to perform remediation by redox reactions. Electrolysis of water occurs throughout the process when conditions for breakdown of water, theoretically 1.23 V, are achieved. Field evidence also suggests that the reaction rates are inversely related to grain size, such that contaminants are remediated faster in clays and silts than in sands and gravels.

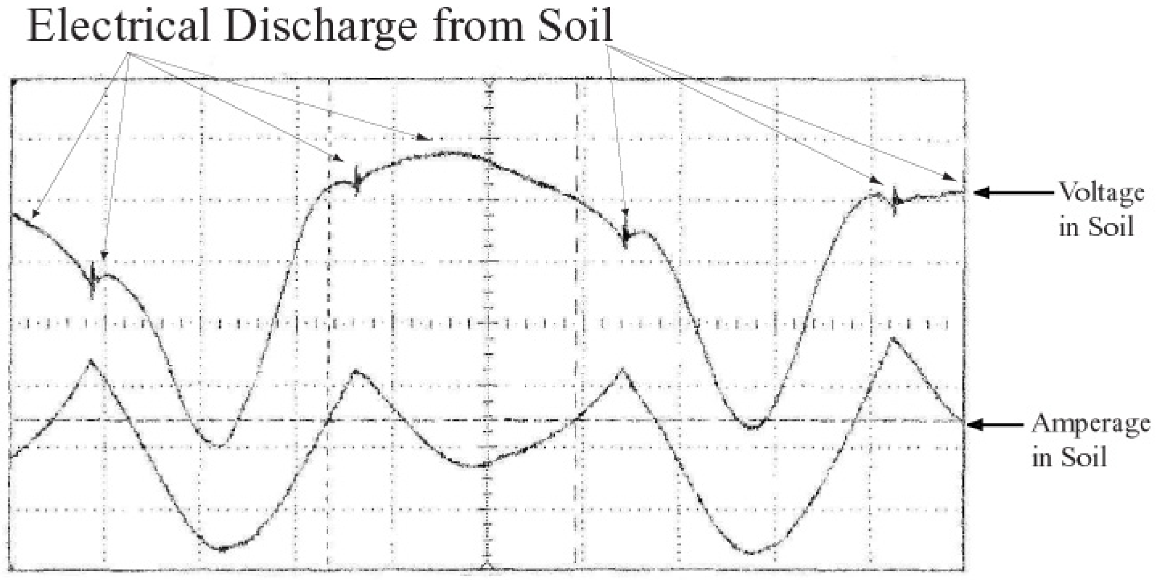


Figure 3. Example oscillogram for an ECRTs-ECGO project.

ECRTs induced reactions may occur at any and all interfaces in the electrode–soil–contaminant–ground water system. However, soil volumetrically dominates the system. Field soil pH values are found to generally stabilize in the range of 6.5 to 7.8 during ECRTs operation (Figure 4).

Typically, ECRTs are preferred to be implemented in-situ. As such, site activities are only minimally disturbed, in contrast to excavation and offsite disposal. ECRTs are powered by the existing site electrical grid or through a power generator.

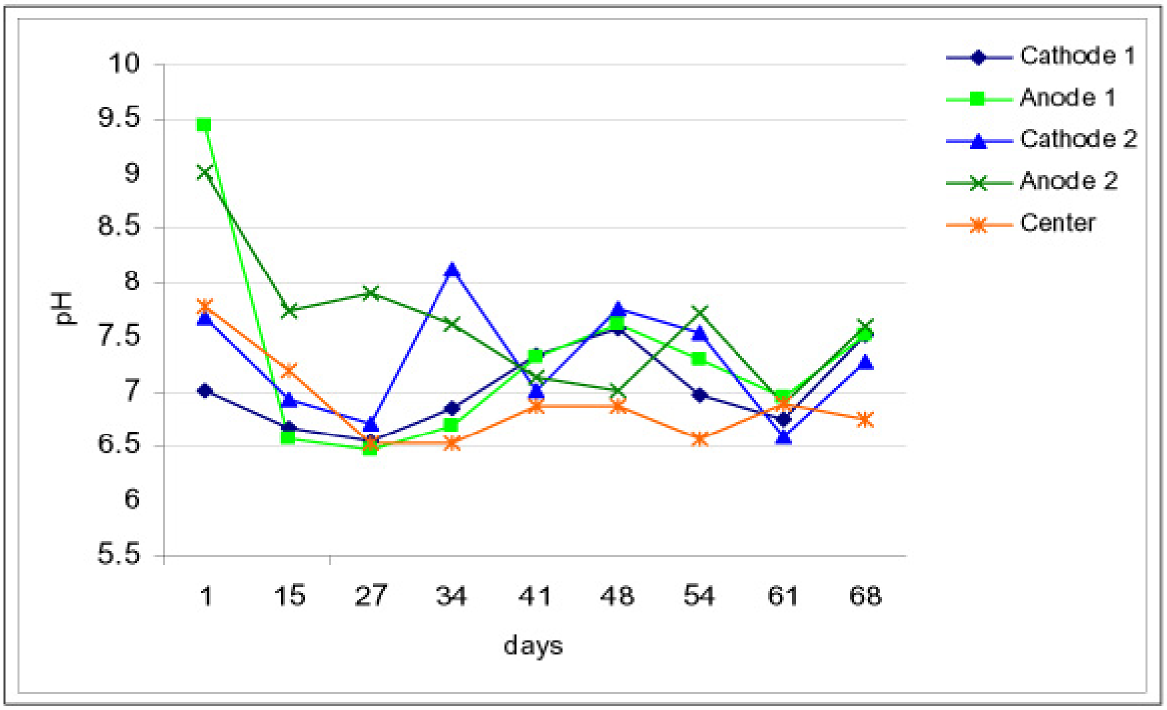


Figure 4. Stabilization of pH during an ECRTs-ECGO project in Deuben, Germany.

ECRTs, developed in Europe, are patented in both U.S. and Europe. A variety of metal contaminants such as mercury, copper, chromium, nickel, cadmium, zinc, and lead, as well as organics, have been remediated below the local regulatory levels. More than 50 projects have been completed to date in Europe, remediating over two million tons of soil. The use of ECRTs are documented, ISO 9001-certified and insurable. ECRTs work rapidly, on the order of months, at costs competitive with excavation and disposal. A number of demonstration and full-scale remediation projects using ECRTs-ECGO, ECRTs-IC, and combined applications for sites containing both metal and organic contaminants are ongoing in the U.S. Select ECRTs-IC European case histories and a recently completed U.S. project are described below.

ECRTs-IC Case Histories

Case History No. 1: *In-Situ* Mercury Remediation in Sediments, Union Canal Scotland

A mercury remediation demonstration project was conducted in 1997 at the Union Canal in Scotland. The canal contains brackish water (total dissolved solids content = 3,500 mg/L), and is 10 m wide x 1.1 m deep. The canal is almost completely filled with silt, which contains both elemental and organic mercury originating from an upstream detonator factory. The site ECRTs-

IC remediation layout in plan and cross-section view, and sediment sampling locations are shown in Figure 5.

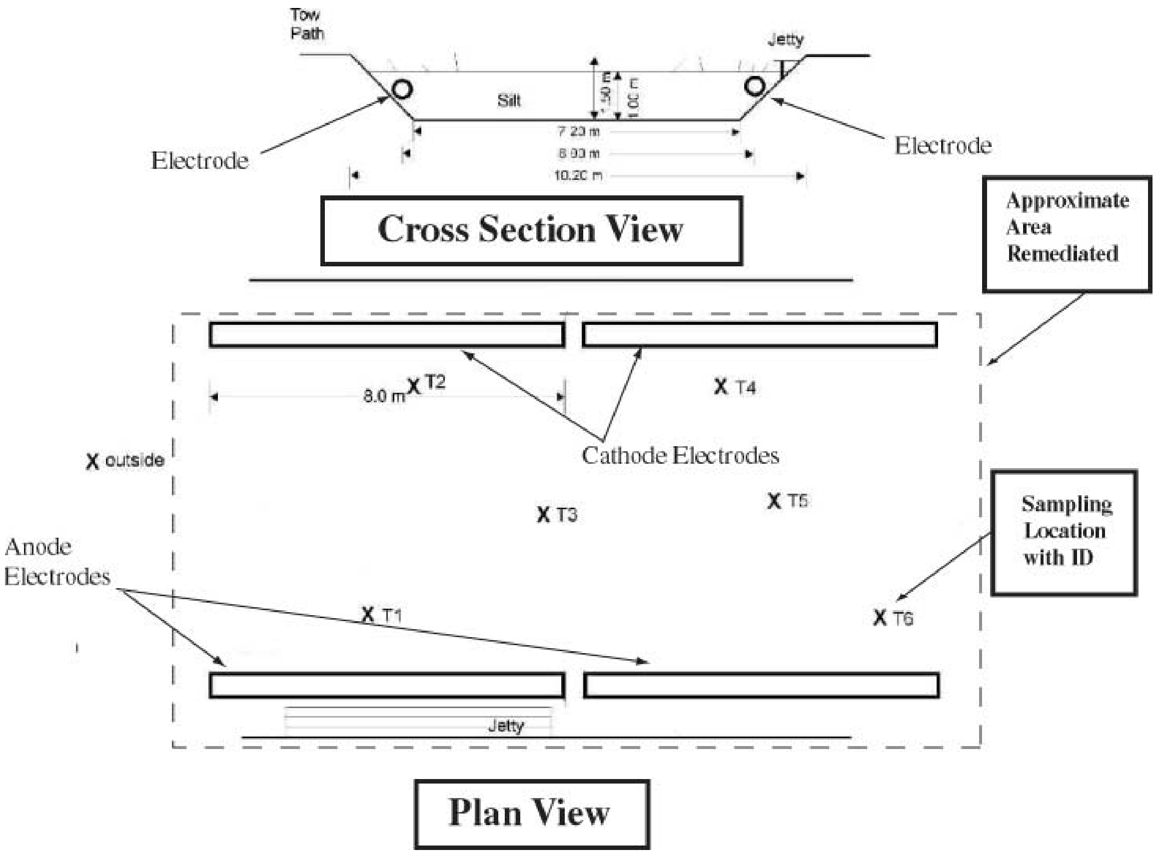


Figure 5. Cross-section and plan view of Union Canal ECRTs-IC site, Scotland (see text for an explanation).

The volume of sediments remediated in the Union Canal was 220 cubic meters (cu m), 20 m x 10 m x 1.1 m working depth (i.e., the depth interval over which the remediation occurred). Two electrode pairs were placed within the silt in the canal and parallel to the banks of the canal (Figure 5). Six sampling locations within the remediation cell and one outside the cell were established.

Table 1 presents the sediment sampling total mercury analytical results at remediation day 1 (baseline), day 12, and day 26. Pre-remediation average total mercury concentration based on the seven sampling locations was 243 mg/kg, with the total mercury concentration ranging from 33 mg/kg to 809 mg/kg. After 12 days of remediation, the concentration range dropped to

9mg/kg to 417 mg/kg (average 119 mg/kg). After 26 days, mercury concentrations decreased further to 0.7 mg/kg to 11 mg/kg, with an average value of 6.5 mg/kg.

Table 1. Sediment Total Mercury Concentrations (mg/kg), ECRTs-IC Demonstration, Union Canal, Scotland.

Sample Location	Remediation Time (*days*)		
	1	*12*	*26*
T1 (anode)	33	204	11
T6 (anode)	218	417	9
T3 (middle)	102	36	11
T5 (middle)	282	48	6
T2 (cathode)	98	45	4
T4 (cathode)	156	9	0.7
Outside	809	73	4
Average Concentration	**243**	**119**	**6.5**

A total of 76 kg (168 lbs) of mostly mercury was deposited on both the anode and cathode electrodes over the 26 days of remediation. Total mercury concentrations in the sediment decreased from an average of 243 mg/kg to 6.5 mg/kg. The cleanup objective was 20 mg/kg. A field mass balance was determined by taking the average concentration reduction of 236 mg/kg over the contaminated volume of about 220 cu m, and assuming a mass of 1,000 kg per cu m. The mass reduction is calculated as: 236 mg / 1,000,000 mg/kg x 1000 kg/cu m x 220 cu m = 52 kg of mercury removed. This calculated mass compares favorably to the field measurement of 76 kg of mostly mercury deposited on the electrodes, and the initial and post-remediation mercury volume in the sediments. The mobilization of elemental mercury (expected to occur via the formation of mercury complexes) and the deposition of mercury on both the anode and the cathode stands in sharp contrast to classical electrokinetic projects and provides evidence that ECRTs-IC creates both negative and positive mercury species in the formation, which migrate and deposit at both the anode and cathode electrodes.

Case History No. 2: *In-Situ* Heavy Metal Remediation at a Steel Rolling Mill Waste Water Lagoon, Berlin,Germany

For approximately 100 years, a rolling mill produced sheets, profiles, and tubes from steel, aluminum, copper and brass. The wastewater was and is discharged into flat lagoons in abandoned clay pits. Soil contaminant concentrations in the lagoons were highly heterogeneous with concentration variations up to 5,000% over short distances. The lagoons cover 0.41 hectare to 0.82 hectare, approximately 1.1 m deep, and are filled with extremely hydrophobic fine material (dust) comprised of blasting sands and metal particles, mainly iron and copper. The dust was dry and attempts to irrigate it caused dust clouds. Since the leachate from the lagoon adversely impacted the underlying ground water, the local regulatory agency required remediation of the lagoon.

ECRTs-IC was tested in this dried lagoon area for 30 days. Two square meter (sq m) sheet electrodes were placed in the dust about 8 m apart. A unique challenge in this project was developing a method to hydrate the hydrophobic dust, which exhibited an initial electrical system resistance of more than 320 ohms. By the end of the 30-day project, the system resistance of the dust had decreased to 19.6 ohms by using a proprietary fluid mixture injected at the anode and electrically driven to the cathode by electro-osmosis, an electrokinetic process.

Measurement of metals precipitated onto the electrodes was hampered by corrosion of the anode. Nevertheless, approximately 8.5 kg of heavy metals precipitated on both electrodes, with 38% of the metals at the anode and 62% of the metals at the cathode. These results exceeded initial expectations because the dust was hydrophobic and no removal of heavy metals was predicted during the 30-day test. As such, the remediation success criteria defined prior to project initiation were based on ground water remediation effects where clean up was found to be substantial. Table 2 presents the ground water remediation results after 30 days of operation for metal concentrations at the anode, cathode, and the center of the electrode array. All metals analyzed in each location were reduced from 59% to 93% (Table 2), except for the 23% lead reduction at the cathode, which most likely reflects a transient state as the lead is migrating to and depositing at the cathode.

Table 2. Heavy Metals Ground Water Concentrations (mg/L) During a Waste Water Lagoon ECRTs-IC Remediation Project.

	Anode			**Cathode**			**Center of Remediation Cell**	
	Baseline	**After 30 Days**		**Baseline**	**After 30 Days**		**Baseline**	**After 30 Days**
Pb	37	<15	Pb	31	24	Pb	65	< 15
Cd	< 1.8	< 1.8	Cd	< 1.8	< 1.8	Cd	< 1.8	< 1.8
Cr	<6.0	<6.0	Cr	< 6.0	< 6.0	Cr	6.6	< 6.0
Cu	48,000	3,500	Cu	2,400	670	Cu	49,000	4,200
Ni	530	170	Ni	290	120	Ni	340	110
Hg	< 0.1	< 0.1	Hg	< 0.1	< 0.1	Hg	< 0.1	< 0.1
Zn	4,600	700	Zn	4,900	1,200	Zn	3,100	840
As	< 10	< 10	As	< 10	< 10	As	< 10	< 10

Case History No. 3: Treatment of Mercury Compounds (Amalgams) in a Sewage Treatment Plant, Montluçon, France

ECRTs were employed to remove mercury from 350 metric tons of sewage sludge during reconstruction of a sewage treatment plant in Montluçon, France. The sewage sludge treated was obtained from three different operational basins: aeration and settlement, sludge dewatering and desiccation. Chemical analysis of these sludges detected mercury contamination, thought to originate from amalgams from dental offices. Given treatment plant operational schedules, remediation of the sewage sludge had to be performed within seven days. The clean-up level was defined at ≤ 5 mg/kg dry mass (d.m.), since at this mercury concentration sewage sludge was permitted for use locally as organic sludge. Other substances were of no interest and not analyzed. The sampling method consisted of collecting eight different sludge samples in the treatment basin, with analysis by atomic absorption spectroscopy for elemental mercury.

A plastic lined, wooden treatment basin was constructed to hold the mercury contaminated sewage sludge during the remediation process (Figure 6). Two electrodes, a cathode comprising a steel plate about 1 m x 2 m, and an anode comprising four non-ferrous rods about 30 cm diameter and 1 m long, were inserted on opposite sides of the basin. Electrical power of 2.3 kW was applied to the sludge for seven days.

Figure 6. Treatment basin containing 350 tons of sludge contaminated with mercury from dental amalgams, Montluçon, France.

The baseline concentrations of mercury in the sewage sludge in the aeration and settling basin, the dewatering basin, and desiccation basin were 54 mg/kg d.m., 15 mg/kg d.m, and 15 mg/kg d.m. respectively. The average concentration was determined to be 28 mg/kg d.m. After seven days of treatment by ECRTs-IC, a total of six samples were analyzed. The results ranged from 0.02 mg/kg d.m. to 0.35 mg/kg d.m., the average being 0.126 mg/kg d.m., and the remediation was accepted by the regulatory agency. As in the Union Canal project (Case Study #1), mercury was deposited at both the anode and cathode.

The project was done under locally determined regulations, with cleanup goals set by the responsible party and the regulators. While mercury was deposited on the electrodes, a mass balance was not calculated for the project and the amounts of deposited mercury were not quantified.

Case History No. 4: Container Test of Steel Mill Waste, Luebeck-Herrenwyk, Germany

A 240-acre site, occupied by a now-bankrupt steel mill, is contaminated to a depth of 20 m with heavy metals, PAH, BTEX, phenols, cyanides, TPH, and other pollutants. To identify a low-cost remediation alternative, ecp was requested to demonstrate the viability of removing heavy metals in a short container test. Given the test conditions, it is not known whether ECRTs-IC or electrokinetics alone was the operating mechanism.

Eleven tons of dark brown, loamy soils were placed into a steel container. The container served as the cathode; a steel plate 1 m x 2 m installed vertically into the soil mass in the center of the container served as the anode. The test was operated at 3.9 kW for 10 days. The results of composite soil sampling by the oversight consulting firm before and after the test are shown in Table 3. It is not known how many subsamples comprise the composite sample analyzed.

Table 3. Metals concentrations in contaminated steel mill soil before and after electrokinetic container scale testing.

Metal	Concentration Before Testing (mg/kg)	Concentration After 14 Days of Testing (mg/kg)	Percent Change
Arsenic	34	28	-18
Lead	400	210	-48
Cadmium	2.3	2.9	+26
Copper	330	150	-55
Zinc	1200	640	-47
Mercury	1.1	1.1	0

ECRTs-IC Case History No. 5: Bench Scale Heavy Metals Removal from Harbor Sludge, Port of Hamburg, Germany

The Port of Hamburg faces serious problems disposing of sludge dredged from the harbor bed, and ecp was asked to provide a method of sludge detoxification. The Port provided 100 L of the sludge to ecp for bench-scale testing of ECRTs to remove heavy metals from the sludge.

The 100 L of sludge were placed in a glass container measuring 100 cm x 40 cm x 40 cm. The sludge was about 78% gray-green, highly turbid water and had a strong hydrocarbon odor. Within the glass container, two plate electrodes were installed at a separation of 50 cm. The plate electrodes were made of carbon steel, and each had a surface area of 400 square centimeters. A total of 168 watts of power was applied for 14 days. Samples were collected before and at the end of the test, and analyzed at an accredited and independent laboratory using x-ray fluorescence analysis.

After 60 minutes of power application, the sludge settled on the bottom of the class container, forming a layer of 5 cm thickness. After 14 days of treatment, the water was clear, without color and without odor. The cathode was covered by a thin, blackish layer about 0.012 mm thick. The anode was covered by a thin blackish layer (thickness not measurable) and affected by pit corrosion. Table 4 presents the results of the bench-scale test.

Table 4. Metals concentrations in Hamburg Harbor sludge before and after ECRTs bench-scale testing.

Metal	Clean up Level (mg/kg)	Concentration Before Testing (mg/kg)	Concentration After 14 Days of Testing (mg/kg)	Percent Decrease
Arsenic	20	13	2.3	82
Lead	100	173	38	78
Cadmium	Not Available	10	2	80
Total Chromium	50	72	16	78
Copper	50	143	12	92
Nickel	40	56	5	91
Mercury	0.5	0.5	<0.1	>80
Zinc	150	901	54	94

Case History No.5: Laboratory Tank-Scale Mercury Treatment Test for Soil from the U.S. Department of Energy Y-12 Plant, Oak Ridge, Tennessee

A laboratory tank-scale ECRTs-IC test was recently completed, under contract to the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) for the Oak Ridge National Laboratory (ORNL) Y-12 National Security Complex (Y-12), on mercury contaminated soil from the Y-12 Plant. This work was conducted in cooperation with DOE Oak Ridge Operations Office, Bechtel Jacobs, LLC, the DOE Oak Ridge environmental site contractor, and ORNL.

The test was principally conducted to provide laboratory verification of the ECRTs-IC field remediation results (e.g., mercury being deposited on the anode and cathode) and qualify ECRTs-IC for a pilot scale field demonstration at ORNL. ECRTs performance cannot typically be demonstrated at the laboratory-scale, for reasons that are beyond the scope of this paper. However, a "hybridized" method was developed to address DOE's requirement for laboratory testing. Note that an inorganic chemical analysis of the Y-12 soil provided for testing contained 12,000 ppm of iron, making this soil highly electrically conductive. This allowed the tank-scale test to somewhat approximate field-scale conditions.

Project success criteria established with the NETL and Y-12 stakeholders prior to project initiation were:

- mercury is mobilized to both anode and cathode;
- mercury is deposited on one or both power electrodes;
- post-test mercury TCLP leachate concentration is at or below 225 µg/L; and
- mercury mobilization rate meets or exceeds that for the control cell, which is using electrokinetics to mobilize the mercury (traditional approach).

Test results met all four of the aforementioned objectives, as detailed in the following sections.

Test Setup. Approximately 150 L of contaminated soil was placed into a 90 cm x 50 cm x 45 cm test cell with an 800 mm x 320 mm x 1 mm cathode and an 800 mm x 320 mm x 9 mm anode separated by approximately 25 cm (Figure 7). The dry contaminated soil was homogenized and then mixed with local tap water during the tank filling operation. The test program was conducted under saturated conditions. Saturated soil samples were collected at five locations within the tank, at the (1) Anode Face, (2) Quarter Point, (3) Mid-Point, (4) Three Quarter Point, and (5) Cathode Face.

Figure 7. Test array and sampling during ECRTs tank-scale testing of soil from U.S. Department of Energy Oak Ridge Y-12 plant.

Mercury Mobilization and Migration. Figure 8 presents the total mercury concentration, as determined by AquaRegia Leach Test (USEPA Method 7471b), for the pre-test condition (baseline), and at 81 hours (hrs), 450 hrs, and 741 hrs from test start-up at the five sampling locations between the anode and cathode electrodes. The total mercury concentration in percent change relative to the baseline condition is shown in Figure 9. The average, pre-test total mercury concentration was 252 mg/kg. At 81 hrs from test start-up, migration of total mercury to the anode from the cathode portion of the test cell was suggested by the depletion of total mercury in the cathode area of the test cell relative to the pre-test mercury concentration and a complementary increase in total mercury concentration at the quarter point in the anode half of the test cell. Note that the depletion of total mercury relative to the baseline value probably reflects total mercury migration from the anode face. At 450 hrs after test start-up, total mercury concentration near the anode face increased to 317 mg/kg (Figure 8), or greater than 120% of the initial pre-test value (Figure 9). Note that there was also a decrease in total mercury concentration at the cathode face. At 741 hrs, the total mercury concentration in the cathode half of the test cell decreased further, and the concentration around the anode face increased significantly to greater than 100% of the initial pre-test (baseline) value (Figures 8 and 9).

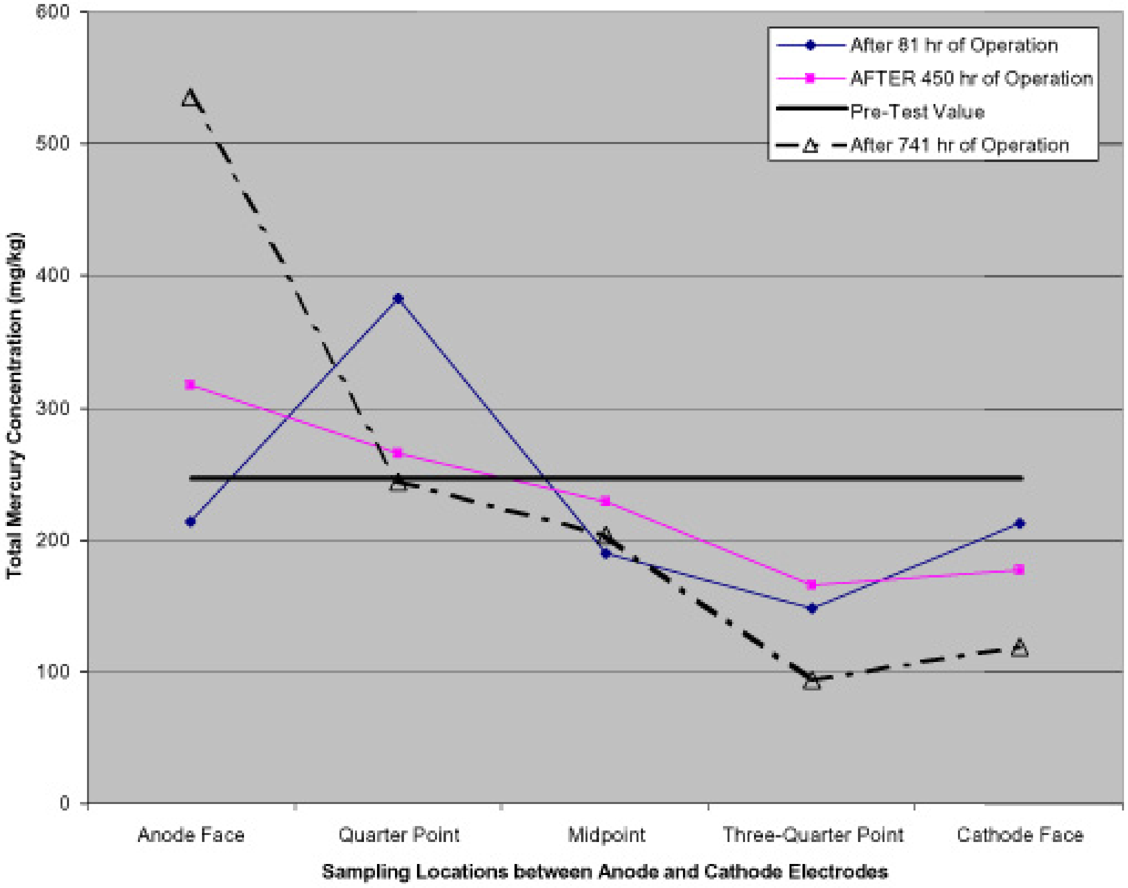


Figure 8. Total mercury concentration distribution during tank-scale testing of soil from U.S. Department of Energy Oak Ridge Y-12 plant.

<u>Deposition at Electrodes.</u> ECRTs-IC removed mercury from the area adjacent to the cathode and concentrated mercury in the area of the anode. The latter can only be accomplished through the formation of negative mercury complex ions. However, mercury was deposited at both electrodes, as shown by examining the presence and amount of mercury on the respective

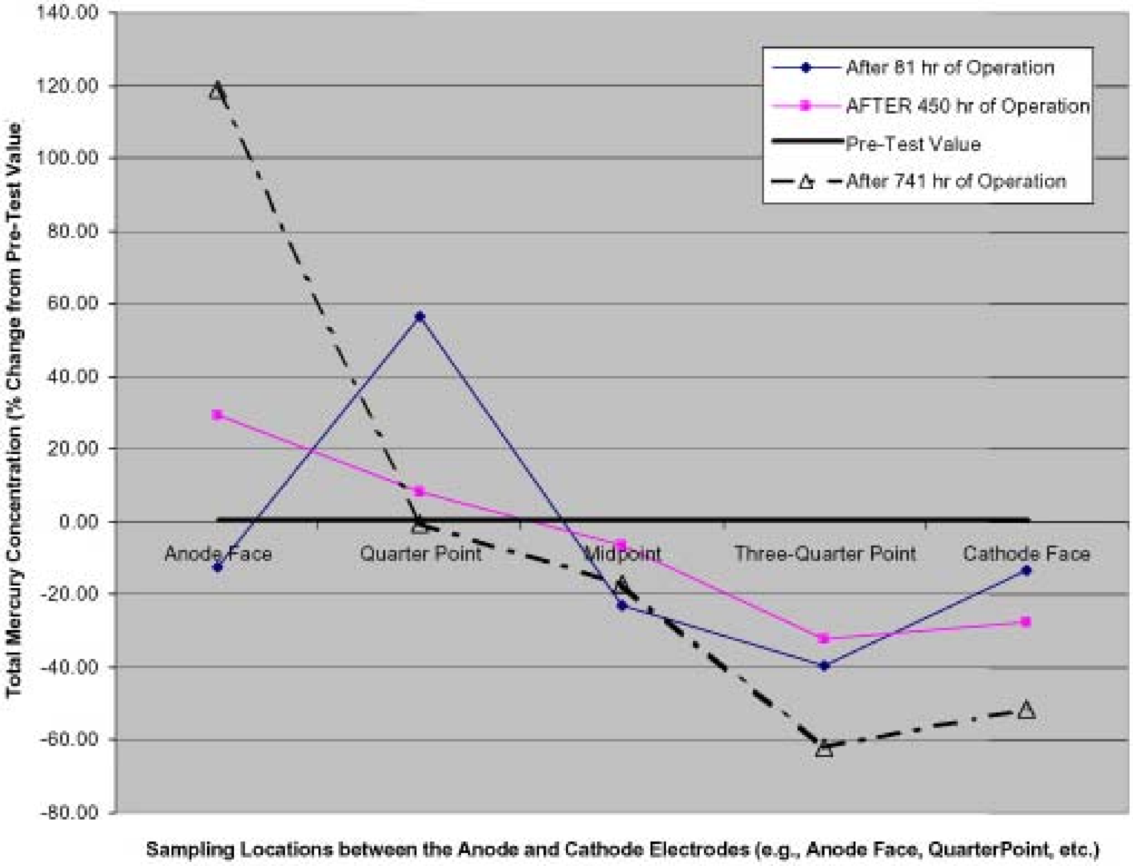
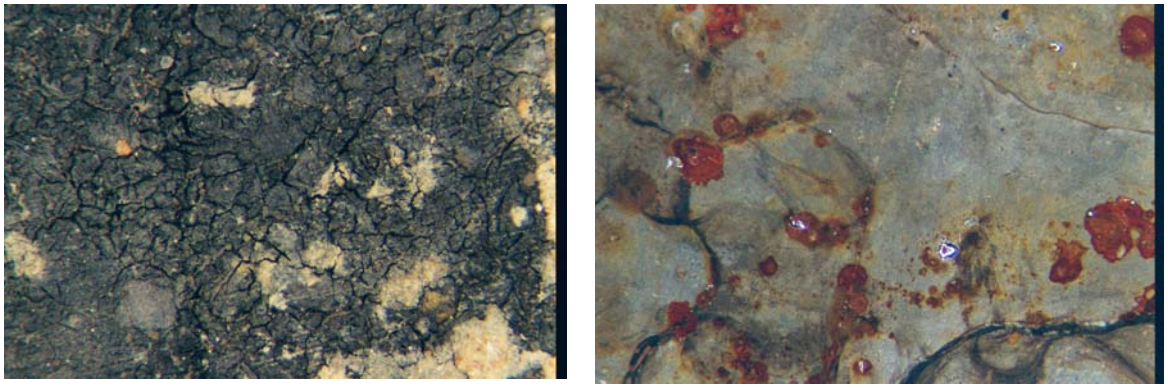


Figure 9. Percent change from initial mercury concentration during tank-scale testing of soil from U.S. Department of Energy Oak Ridge Y-12 plant.

electrodes at the conclusion of the test. The electrode surfaces were photographed (Figure 10) and the amount of mercury deposited on them analyzed. The post-test electrode observations are presented in Table 5. These results satisfy the first two criteria for success of the tank-scale test. It was determined that the mercury deposited at the anode consisted primarily of non-volatile mercury species whereas the mercury deposited at the cathode consisted primarily of volatile species. It is not known, however, if the volatility of the mercury species is an artifact of the laboratory test conditions or a direct result of the technology application. Previous field remediation projects did not identify the occurrence of any volatile mercury species being deposited onto the electrodes.

Table 5. Post-test electrode observations.

Observation	Graphite Anode	Carbon Steel Cathode
Gross Appearance	Yellow-White Deposits	Pitting and Corrosion
Microscopic Appearance	Deterioration and Yellow-White Deposits	Mercury Metal Droplets
Mercury Vapor	0.002 mg/cu m	0.075 mg/cu m
Mercury Analyses	17.9-44.3 mg/kg	4.2-11.6 mg/kg



Anode Photomicrograph, ~30x

Cathode Photomicrograph, ~30x

Figure 10. Anode face shows deterioration of graphite and precipitation of yellow-white deposits; cathode face shows precipitation of droplets of metallic mercury.

Mercury Level Below TCLP Goal. Figure 11 shows the TCLP-derived mercury distribution at the beginning and end of the ECRTs-IC test. The TCLP values of the two sampling points closest to the cathode are well below the NETL defined clean-up goal of 225 ppb mercury in the TCLP leachate. This satisfies the third success criterion for the tank-scale test. The test cell mid-point sample TCLP value is above the clean-up goal, but well below the pre-test TCLP value of 940 ppb. The TCLP values for the two sampling points closest to the test cell anode are well above the pre-test TCLP value.

The post-test TCLP value pattern is also taken as evidence that the ECRTs-IC operation was mobilizing mercury towards the test cell anode. The laboratory test was not run to completion due to time and budget constraints. We expect that if more time were available for the test, all the soil within the test cell would have attained TCLP values below the 225 ppb value defined by NETL, as indicated by the two sampling points on the cathode side of the test cell.

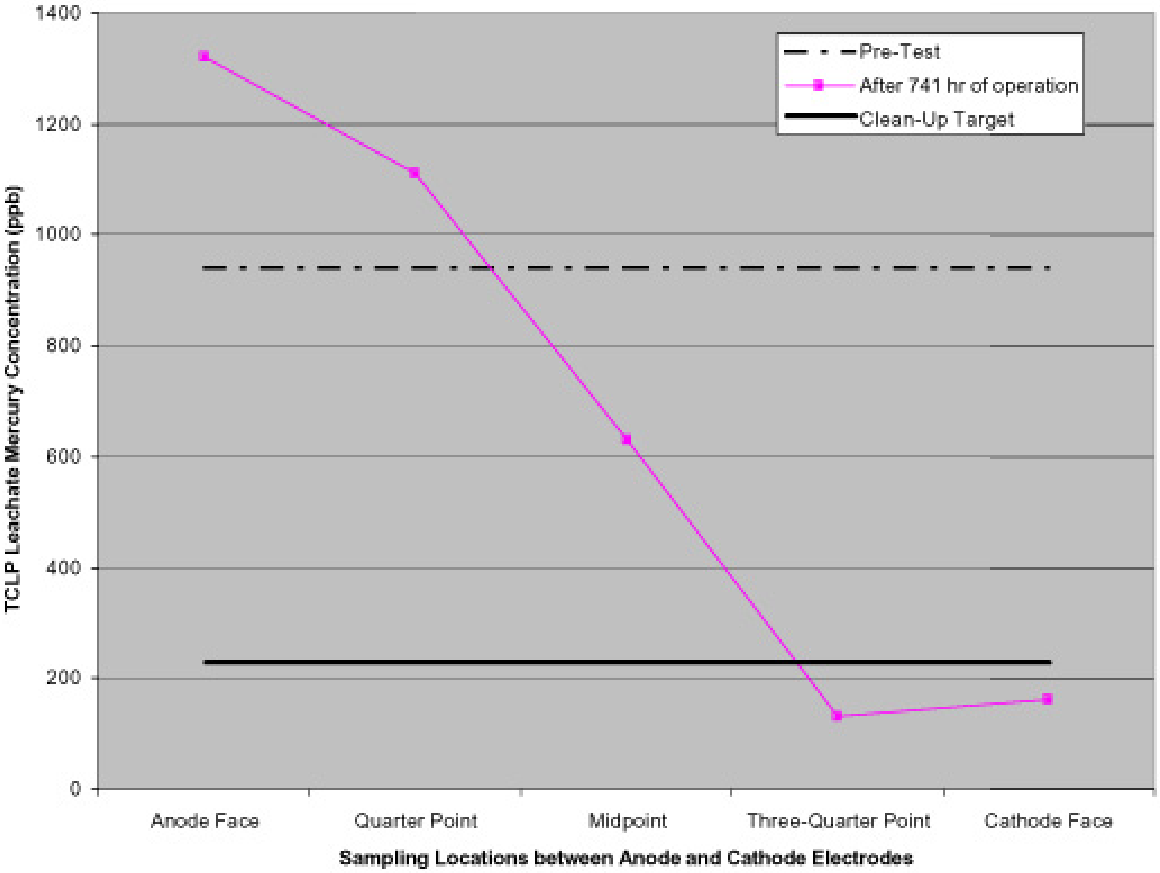


Figure 11. TCLP total mercury profiles from tank-scale testing of soil from U.S. Department of Energy Oak Ridge Y-12 plant.

<u>Performance Comparison of ECRTs-IC and EKAR.</u> The fourth success criterion of the NETL tank-scale test was to show that ECRTs-IC met or exceeded EKAR performance in mobilizing mercury. Table 6 compares the performance of the ECRTs-IC and EKAR test cells, using several performance measures. In all three cases, ECRTs-IC outperforms EKAR. The ECRTs-IC recovery rate is 1.6 times that of EKAR, satisfying the forth success criterion of the tank-scale test.

Table 6. Post-test electrode observations.

Measure	ECRTs-IC Test Cell	EKAR Test Cell
Mercury Recovery	54.62	54.55
Mercury Recovery Rate	0.038 g/hr	0.028 g/hr
Mercury Recovery Efficiency	0.2401 g/kW-hr	0.1159 g/kW-hr

Mass Balance. From an initial total of 52 g of mercury, 28.4 g, or 54.62 %, was removed by ECRTs-IC operation during the 741 hrs of operation (Table 7). Post-test analyses indicated that 22.7 g of mercury remained in the cell. The total post-test analyses accounted for 98.27% of the initial mercury content of the test cell indicating that volatility was not a factor in this test. The details of this mass balance show that the great majority of mercury in the vicinity of each electrode was in the soil, at the face of the electrode, rather than deposited onto the electrode. This is in contrast to field remediation experience, where the mercury was precipitated onto the power electrodes. The result is similar to that of other short-term laboratory tests conducted by the ECRTs developer. It is suspected that the accumulation of mercury in the soil adjacent to the electrodes is either a time-transient phenomena that would minimize to non-existent if the test would run for long times, or an artifact of laboratory testing.

Table 7. Test cell mercury mass balance.

Item	ECRTs-IC Test Cell Results
Initial Mercury in Test Cell (g)	52
Total Mercury at Cathode (g)	5.4
Total Mercury at Anode (g)	23
Total Recovered Mercury (g)	28.4
Mercury Recovery (%)	54.62
Total Mercury Still in Test Cell (g)	22.7
Accounted for Mercury (%)	**98.27**

Efficiency Comparison–Tank Scale and Field Scale ECRTs-IC Projects. The efficiency of mercury removal in the NETL test was compared with that of the Union Canal and Montluçon field remediation projects (Table 8). A total of 28.4 g, or 54.62 % of the pre-test contamination, was removed in 741 hr of tank-scale ECRTs-IC operation. The recovery rate was 0.038 g/hr. The mercury recovery efficiency was 0.24 g/kW-hr. Field projects have shown much higher (up to 26.6 g/kW-hr) mercury recovery efficiencies. This illustrates the inherent limitations of testing ECRTs-IC in the laboratory. Laboratory testing may provide proof of concept: (i.e., does it work), but it cannot provide scalable information on deployment costs and/or deployment efficiency.

Table 8. Comparison of mercury removal efficiency between tank-scale ECRTs testing and field-scale ECRTs projects.

Measure	NETL Tank-Scale Test	Union Canal Field Project	Montluçon Field Project
Mercury Recovery (% pre-test)	54.6	97.5	99.6
Mercury Recovery Rate (gm/hr)	0.038	143.77	58.33
Mercury Recovery Power Cost Rate ($/gm)	$0.42	$0.0039	$0.0039

Conclusions

ECRTs have remediated over 50 sites in Europe. The technologies are being used or demonstrated at a number of sites in the U.S. ECRTs-IC metal remediation case histories from Europe include (1) removal of 76 kg (168 lbs) of mostly mercury and deposition on both electrodes in 26 days of remediation of brackish water sediments; (2) up to a 93% metal concentration decrease in ground water beneath a waste water lagoon in 30 days with pre-remediation metal concentrations on the order of parts per billion; and (3) mercury concentration reduction in sewage sludge from an average of 28 mg/kg to 0.126 mg/kg in seven days, with deposition of mercury on both electrodes. A recently completed U.S. tank-scale laboratory test of mercury contaminated soil from the DOE Y-12 Plant in Oak Ridge, Tennessee, under saturated (fresh water) conditions, showed dramatic decreases in total mercury concentration in the vicinity of the cathode with complementary increases in total mercury concentration in the vicinity of the anode after about 740 hrs of testing. The results showed that mercury was mobilized to and deposited on both anode and cathode electrodes, that the defined cleanup objectives for the test were met, and that ECRTs-IC outperformed EKAR in mobilizing and removing mercury from the contaminated soil.

Acknowledgements

We wish to thank the United States Department of Energy National Environmental Technology Laboratory for funding the laboratory testing of mercury-contaminated soil from Oak Ridge National Laboratory, Y-12 Plant, under contract No. DE-AC26-01NT41346.

Literature Cited

Doering, F., 1997, “Method and Device for the Elimination of Toxic Materials from, in Particular, the Topsoil” United States Patent No. 5,595,644.

Doering, F., and Doering, N., 1998, “Method Related to the Sterilization of Microorganisms and/or to the Mineralization of Organic Substances Including Microbic Metabolites in a Ground Region and in the Groundwater by means of Electric Current”, United States Patent No. 5,738,778.

Doering, F., 2001, “Electrolytic Method for Sterilization of Microorganisms and/or Mineralization of Organic and/or Inorganic Substances in Ground Soil”, United States Patent No. 6,280,601.

Doering, F., Doering, N., Hill, D. G., McIlvride, W. A., Iovenitti, J. L., and Wittle, J. K., “Electrochemical Remediation Technologies for metals remediation in soil, sediment and ground water,” presented at the Battelle “Remediation of Chlorinated and Recalcitrant Compounds” Conference in Monterey, Calif., May 20-23, 2002.

Probstein, R. F., Renaud, P. C., and Shapiro, A. P., 1991, “Electroosmosis Techniques for Removing Materials from Soil”, U.S. Patent No. 5,074,986.

Vacquier, V., C.R. Holmes, P.R. Kintzinger, and M. Lavergene. 1957, Prospecting for Ground Water b y Induced Electrical Polarization”, Geophysics. v. 22, No. 3 (July). pp. 660–687. http://dx.doi.org/10.1190/1.1438402