

## THE ADVANCED ELECTRIC REACTOR: A NEW TECHNOLOGY FOR HAZARDOUS WASTE DESTRUCTION

KENNETH W. LEE, FRANK P. WINGATE and JIMMY W. BOYD

*J.M. Huber Corporation, Borger, Texas (U.S.A.)*

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### Summary

The Advanced Electric Reactor (AER) is a new kind of device intended for the destruction of hazardous wastes. It is capable of a wide range of operating conditions for treatment of solid, liquid or gaseous feed materials. This paper describes the AER, and gives the results of a series of tests on PCBs and  $\text{CCl}_4$ , as well as of leaching tests on feed and treated materials. The advantages offered by the AER are discussed, and future applications are described.

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### Introduction

The Advanced Electric Reactor (AER) represents a new technology undergoing testing and commercial permitting for destroying hazardous wastes. It provides a wide range of operating conditions, including temperatures up to  $2760^\circ\text{C}$ , pressures from partial vacuum to moderate positive pressure, and oxidizing, neutral, and reducing atmospheres. Feed materials can be solids, liquids, or gases. The AER is being developed for commercialization by the Huber Technology Group, a high-technology group within the J.M. Huber Corporation. Two fully equipped AERs are maintained at Huber's AER facility in Borger, TX.

A significant feature of the reactor design is the porous, vertical reactor core made of graphite. The core radiates heat to the reactants, achieving heating rates in the range of  $50,000^\circ\text{C}$  to  $500,000^\circ\text{C}$  per second based on heat balance calculations on the differential shell of the particle exterior. The graphite combined with a gaseous fluid wall which isolates the reactants from the core allows the severe reactor conditions.

The AER is particularly well suited for the destruction of hazardous chemicals in soils and concentrated liquids. Organic materials are rapidly vaporized and decomposed to basic elemental forms, such as carbon, hydrogen, and chlorine. Gas-phase destruction efficiencies (DEs) greater than 99.9999% and destruction and removal efficiencies (DREs) of  $>99.9999\%$  have been demonstrated on selected organics. Comparable solid-phase DREs were also observed.

In September of 1983, a trial burn was conducted under EPA supervision and Toxic Substance Control Act (TSCA) regulations [1] using polychlorinated biphenyls (PCBs) on sand. As a result of the trial burn, EPA certification of the process for PCBs on soils was received in May of 1984. More recently, test series have been performed with carbon tetrachloride ( $CCl_4$ ) and leaching tests have been conducted on feed and treated materials.

A description of the AER, the results of the PCB,  $CCl_4$ , and leaching tests, and a discussion of the advantages offered by the AER and future plans are presented below.

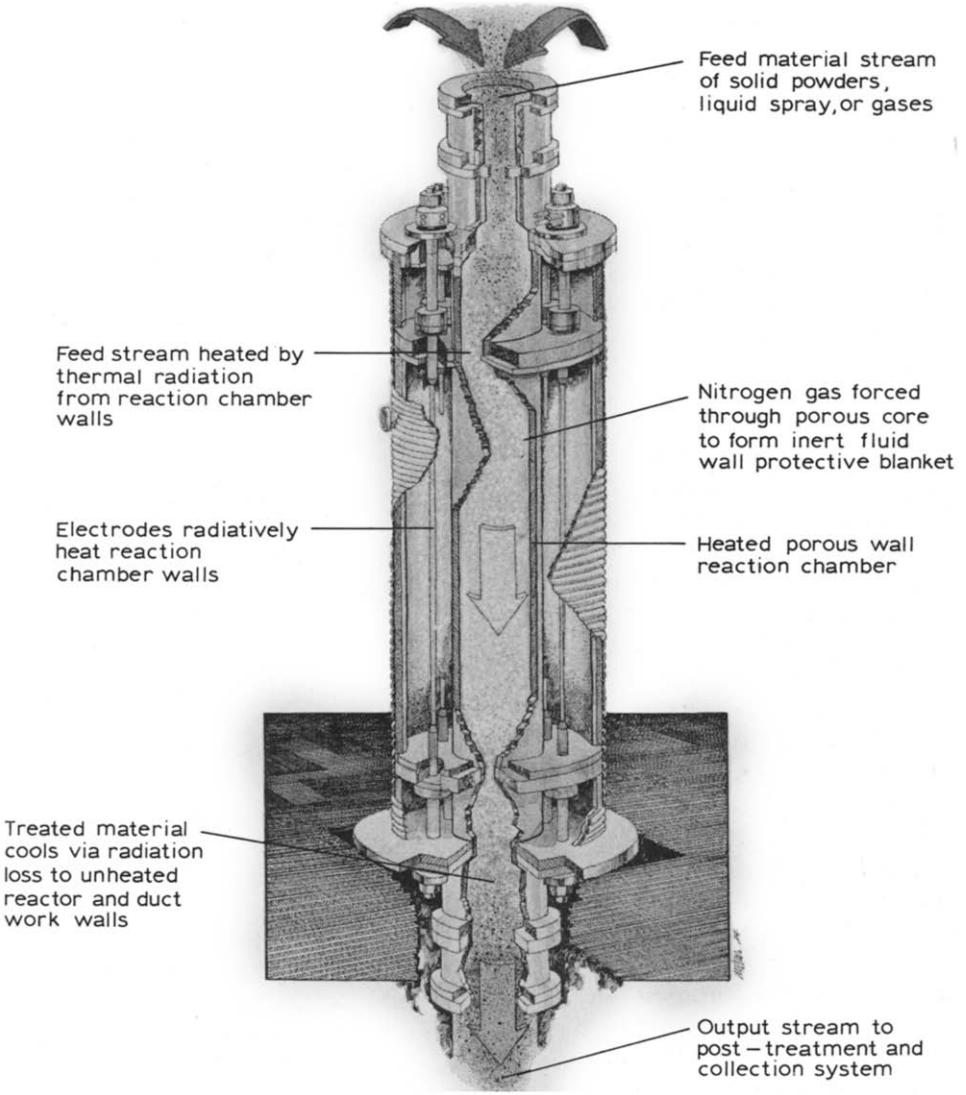


Fig. 1. Advanced Electric Reactor.

## Process description

Figure 1 shows a cut-away of the Advanced Electric Reactor. The AER is an electrically heated, gravity-fed, fluid-wall reactor which destroys organics by rapidly heating feed materials to temperatures of 2200–2760°C using intense radiation in the near infrared. Reactants are isolated from the cylindrical reactor core by a gaseous blanket formed by flowing nitrogen radially inward through the proprietary porous core wall. Carbon electrodes, designed to operate reliably at extremely high temperatures, are located in the annulus between the core and the outer vessel. These electrodes are used to heat the core wall to incandescence. Heat transfer to the feed materials is accomplished predominantly by radiative coupling. Destruction of organics is accomplished by pyrolysis rather than oxidation.

Figure 2 shows a simplified process diagram of the 12-inch pilot unit used for the tests described in this paper. The solid feed is gravity fed from an airtight feed hopper into the top of the AER. Solids fall through the AER where waste vaporization and pyrolysis occur. For a given reactor length, solids residence time is determined by the balance between the highly viscous, hot nitrogen and gravitational forces. The product gas and waste solids then pass through two post-reactor treatment zones (PRTZs). The first PRTZ is an insulated vessel which provides approximately 5 seconds of additional gas-phase residence time at approximately 1370°C. The second PRTZ

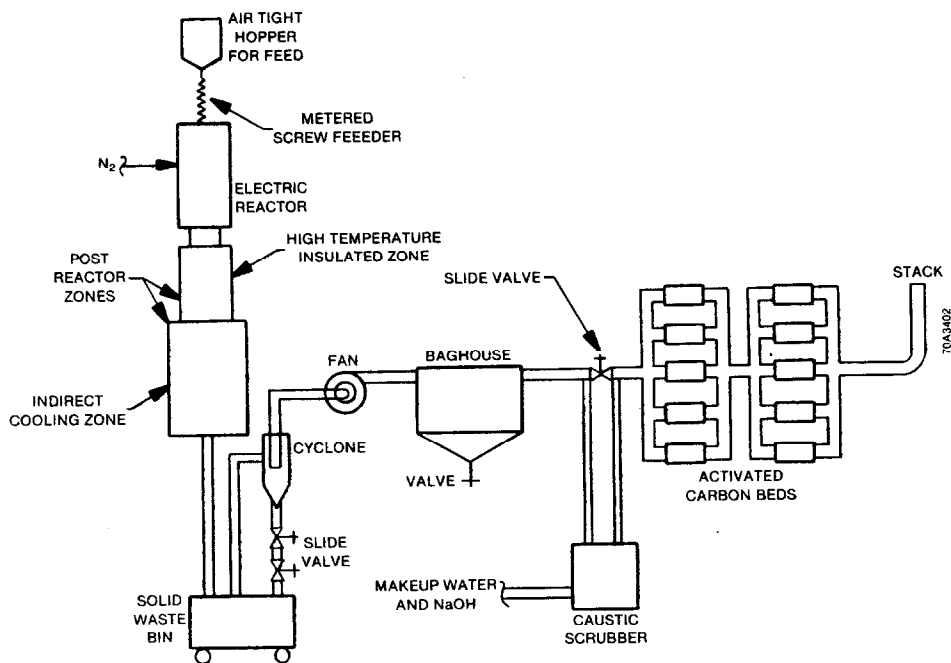


Fig. 2. Process configuration for the test series.

is water-cooled. It primarily cools the gas to less than 540°C, requiring a residence time of about 10 seconds. Solids exiting the second PRTZ are collected in a bin which is sealed to the atmosphere as a safety precaution. Any solids remaining in the product gas are removed by a cyclone followed by a baghouse for fine particle filtration. The product gas then enters an aqueous caustic scrubber for chlorine removal. Any residual organics and chlorine are removed by activated carbon beds just upstream of the process stack. The product gas, essentially nitrogen at about 50% relative humidity, is then emitted to the atmosphere.

### Test descriptions

This section describes tests performed on PCBs and CCl<sub>4</sub> and leaching tests performed on two solids before and after treatment (PCBs on sand and 35 mesh soil). The PCB test series consisted of four tests conducted on September 27–29, 1983. The CCl<sub>4</sub> test series was significantly more complex, consisting of 17 tests conducted on May 18 and 21–23, 1984. Sampling and analyses for the PCB test series, analyses of selected samples for the CCl<sub>4</sub> test series, and leaching tests and analyses were performed by Radian Corporation (Austin, TX).

TABLE 1

Range of operating parameters

Parameter	PCB tests	CCl <sub>4</sub> tests
Test duration (min)	220–271	5–10
Waste concentration — solid feed stock (%)	0.3	0.37–13.76
Waste concentration — liquid feed stock (%)	NA <sup>a</sup>	99
Solid feed rate (kg/min)	7.0–7.2	0.5–19
Liquid feed rate (kg/min)	NA	1.5
Reactor temperature (°C)	2260	2060–2440
Nitrogen feed rate (SCM/min) <sup>b</sup>	4.2	3.0–5.4

<sup>a</sup>NA = not applicable.

<sup>b</sup>Standard conditions = 21°C, 1 atm.

The process configuration for both sets of tests was the same as shown in Fig. 2. Process operating conditions for both sets of tests are summarized in Table 1. Operating conditions for the PCB test series were held essentially constant, while those for the CCl<sub>4</sub> series were varied to determine process performance over a wide range of conditions. The actual conditions for each CCl<sub>4</sub> test are given in Table 2.

### Polychlorinated biphenyls test series

Aroclor 1260 was mixed with sand to form a solid feed containing approximately 3000 µg/g PCB. Carbon black was added to the feedstock at

TABLE 2

CCl<sub>4</sub> test series operating parameters

Run No.	Test No.	Reactor temp. (°C)	N <sub>2</sub> flow (SCM/min)	Feedrate (kg/min)	Conc. (% CCl <sub>4</sub> )
1	1	2100	5.2	15	1.37
2	4	2260	5.4	10	1.37
3	5	2260	5.3	2.5	1.37
4	7	2100	3.0	2.5	1.37
5	6	2420	5.2	2.6	1.37
6	3	2090	5.2	3.0	1.37
7	2	2100	5.2	9.9	1.37
8	8	2080	5.4	19	0.37
9	15	2100	5.3	1.4	13.8
12	14	2090	5.4	0.5	13.8
10	11	2260	5.4	10	0.37
11	9	2060	5.4	9.8	0.37
13	12	2270	5.4	2.1	0.37
14	13	2440	5.4	2.3	0.37
15	10	2080	5.4	2.0	0.37
16	16	2090	5.4	1.5	99 <sup>a</sup>
17	17	2090	5.4	1.5	99 <sup>a</sup>

<sup>a</sup>99% as reported by Vulcan Chemical Company.

approximately a 6.25:1 ratio to the PCB oil to simulate the organic carbon content of soil and to inhibit feed coagulation. Solid feed rates were 7.03 to 7.17 kg/min with total feed masses ranging from 1600 to 1930 kg per test.

PCBs in the product gas were sampled at the cyclone outlet and the process stack. Sampling was performed over a period of about 4 hours to provide the large sample volumes and corresponding low detection limits necessary to allow calculation of DEs and DREs in the range of 99.9999% to 99.999999%. PCB concentrations were also measured for the solid feed and the solid and liquid waste streams. Concentrations of NO<sub>x</sub>, chloride, CO<sub>2</sub>, particles, volatile organics, and polychlorinated dibenzodioxins (PCDDs) and furans (PCDFs) were measured for the gaseous effluent. Samples for the PCB test series were taken by the methods listed in Table 3. PCBs, PCDDs, PCDFs, and volatile organics were analyzed using capillary gas chromatography—mass spectrometry (GC—MS) [2]. Extraction recovery efficiencies were verified using labeled surrogates.

#### *Carbon tetrachloride test series*

The primary feed material consisted of a screened, dried soil (less than 35 mesh) with activated carbon added at a 4:1 ratio (w/w) to CCl<sub>4</sub> to reduce the volatility of CCl<sub>4</sub> and prevent its loss before reaching the reactor. Tests were also conducted on CCl<sub>4</sub> and activated carbon without soil and on a commercially pure liquid. Soil with activated carbon was used in 13 tests, activated carbon alone in 2 tests, and pure liquid in 2 tests.

TABLE 3

## PCB test series sampling parameters and methodology

Parameter	Methodology
Mapping of velocity and sampling traverse points	EPA Method 1
Nitrogen flow rate	Process readings from calibrated orifice plates
CO <sub>2</sub> , O <sub>2</sub> , and N <sub>2</sub>	Fyrite (EPA Method 3 equivalent)
Organics and HCl at stack	EPA Method 5 <sup>a</sup>
Organics at the cyclone outlet	Modified EPA Method 5 <sup>b</sup>
Moisture and particulate loading at stack	EPA Method 5 <sup>a</sup>
Composited solids for HCB	Composite grab sampling
Halogenated organics at stack	Tenax/Spherocarb traps

<sup>a</sup>XAD-2 Resin and Florisil canisters added to trap organics.

<sup>b</sup>Glass fiber thimble used as filter due to high particulate loading. Hot box not used.

Sampling for gas-phase CCl<sub>4</sub> was performed using charcoal tubes according to NIOSH reference methods (P&CAM127 and S314) [3]. The feed material, treated solids and baghouse solids were also sampled for CCl<sub>4</sub>. Fixed gases were sampled in the gaseous process effluent. CCl<sub>4</sub> analyses were performed by GC according to the NIOSH methods except that benzene was used for extractions and an electron capture detector was used to improve sensitivity. Fixed gases were determined by GC with thermal conductivity detection.

### Leaching tests

Leaching tests were conducted using the RCRA Extraction Procedure (RCRA-EP) toxicity test [2] and a nine-step multiple extraction [4]. The EP toxicity test is a 24-hour extraction using 0.5 *N* acetic acid to leach solids at a pH of 5. The leached solids from the EP test were extracted in nine sequential 24-hour extractions using a synthetic acid rain solution (60/40 wt.% mixture of H<sub>2</sub>SO<sub>4</sub> and HNO<sub>3</sub> at pH of 3). The first and ninth extracts were analyzed. An acid digestion was performed on the total samples using HCl and H<sub>2</sub>O<sub>2</sub> [2].

Elemental analyses were performed by inductively coupled plasma emission spectrometry and atomic absorption spectrophotometry [2]. Chloride and sulfate were determined by ion chromatography [5]. Total dissolved solids were determined gravimetrically [6]. Radium was determined using a gas-proportional alpha counter [7].

### Results

The results of the PCB and CCl<sub>4</sub> test series and the leaching studies are presented below. The primary parameters which were determined for both

test series were gas-phase DEs and DREs. These were calculated by comparing the organic species concentrations at the cyclone outlet and stack, respectively, with gas-phase feed concentrations which were calculated based on solid feed concentrations. Leaching tests were performed to determine the effects of treatment on the leaching characteristics of various metals and the suitability of the treated solids for landfill under Resource Conservation and Recovery Act (RCRA) guidelines [8].

### *Polychlorinated biphenyls test series results*

The PCB test series included the measurement of PCBs in the process streams to determine DEs and DREs and concentrations in process waste streams. Major gases, particulate loading, volatile organics, and chloride were measured at the stack. PCDDs, PCDFs and volatile organics were measured at the cyclone outlet.

#### *PCBs*

PCB concentrations in the process and emission streams are given in Table 4. Analyzed feed concentrations were in general agreement with the concen-

TABLE 4

PCB concentrations for process and emission streams by GC-MS

	Test 1 9-27-83	Test 2 9-28-83	Test 3 9-29-83	Test 4 9-29-83
<i>Gas streams (µg/SCM)</i>				
Stack	0.23	0.03	0.10	0.30
Cyclone outlet	4.1	4.1	21	2.4
<i>Liquid streams (µg/L)</i>				
Scrubber liquid	0.29	0.86	0.76	2.7
Pretest scrubber liquid	<0.14	NS	<0.14	<0.22
Scrubber feed water	<0.14	NS	NS	NS
<i>Solid streams (µg/g)</i>				
Feed	2530	3100	2710	2710
Treated feed	0.0005	<0.0005	0.0006	0.001
Baghouse filter catch <sup>b</sup>	0.024	0.29	NS	0.53 <sup>c</sup>
Charcoal bed	NS	NS	NS	0.001 <sup>d</sup>
Pretest charcoal	0.003	NS	NS	NS

Standard conditions = 21°C, 1 atm.

NS = not sampled.

Values are not blank subtracted.

<sup>a</sup>Single feed batch used for Tests 3 and 4.

<sup>b</sup>Baghouse catch was approximately 2% of the feed mass.

<sup>c</sup>Cumulative for Tests 3 and 4.

<sup>d</sup>Cumulative for Tests 1 and 4.

tration of 3000  $\mu\text{g/g}$  determined by weight during feed preparation. PCB concentrations ranged from 4.1 to 21  $\mu\text{g/SCM}$  at the cyclone outlet and from 0.03 to 0.30  $\mu\text{g/SCM}$  at the stack.

Results show that for PCBs, the treated feed, baghouse filter catch and scrubber liquid can be considered nonhazardous. Maximum PCB concentrations in the treated feed and baghouse filter catch were 0.001  $\mu\text{g/g}$  and 0.53  $\mu\text{g/g}$ , respectively. These values are well below the TSCA limit [1] of 50  $\mu\text{g/g}$  set for solids to be treated as hazardous wastes. Although results for the scrubber liquid were variable, ranging from 0.29 to 2.7  $\mu\text{g/L}$ , all were well below the TSCA limit of 50  $\text{mg/L}$  set for liquids to be treated as hazardous wastes. After the fourth test, the activated charcoal beds were sampled at the inlets to the first bank of five beds and composited. A pretest sample was also taken. Concentrations for both samples closely approached detection limits. However, surrogate recoveries are suspected to be high for the charcoal. Therefore, the charcoal data are inconclusive, since the recovery efficiency of PCBs may have been lower than indicated by the surrogate.

#### *PCB destruction and removal efficiencies*

DEs and DREs based on both weighed (process data) and analyzed feed concentrations are presented in Table 5. The minimum gas-phase DE was 99.9995% with results ranging from 99.9995% to 99.99995%. For Tests 1, 2, and 4, the DEs meet or exceed the TSCA DRE requirement of 99.9999% [1] for incinerators. In all cases, DREs exceeded 99.99999%, at least an order of magnitude greater than the TSCA requirement.

Monte Carlo simulations were performed to derive estimates of the uncertainty of the DEs and DREs. Measurement variables (i.e., gas-phase concentrations) were perturbed randomly to simulate the variation that would occur during actual testing. Variables were assumed to have a Gaussian distribution, except that efficiencies  $>100\%$  were not permitted. Means and standard deviations were based on actual test results for each variable. DEs and

TABLE 5

PCB gas-phase destruction efficiencies and destruction and removal efficiencies

Parameter	Test 1	Test 2	Test 3	Test 4
<i>Destruction efficiency</i>				
Process feed data <sup>a</sup>	99.99992	99.99992	99.99996	99.99995
Analytical feed data <sup>b</sup>	99.99990	99.99992	99.99995	99.99995
<i>Destruction and removal efficiency</i>				
Process feed data <sup>a</sup>	99.999995	99.9999994	99.999998	99.999994
Analytical feed data <sup>b</sup>	99.999995	99.9999995	99.999998	99.999993

<sup>a</sup>Based on weighed PCB feed concentrations from feed preparation.

<sup>b</sup>Based on analyzed PCB feed concentrations by GC-MS.



DREs were calculated for 400 trials and the results normalized to the average feed rate. Estimates were calculated which represent the limits which 95% of the results would fall in if actual efficiency tests were repeated indefinitely. From the results, it was concluded that the process, as configured, can routinely achieve DEs of at least 99.9995% and DREs of at least 99.99999%.

#### *PCDDs and PCDFs*

In all cases, results for PCDDs and PCDFs at the cyclone outlet were below analytical detection limits based on the recovery of the  $^{13}\text{C}$ -TCDD surrogate. These detection limits equal gas-phase concentrations of  $<0.03$  to  $<0.06 \mu\text{g}/\text{SCM}$ . Because concentrations were below detection limits, analyses of the stack samples were not performed.

#### *Volatile organic species*

Volatile organics were sampled at the cyclone outlet and the stack to document the potential for production of low molecular weight halogenated species. These compounds are analogous to products of incomplete combustion. Major nonhalogenated species were also identified and quantitated.

Chloroethane, benzene, toluene, and naphthalene were detected in two of three samples taken at the cyclone outlet at concentrations of less than or equal to 200, 340, 60, and  $26 \mu\text{g}/\text{SCM}$ , respectively. Typically, benzene and toluene are found in ambient air at or slightly below these concentrations. Unknown hydrocarbons, with a profile suggesting a light oil contaminant, were measured in two of these samples at 2000 ppm or less.

Hexane was detected in 7 of 10 samples taken at the stack with an average concentration of  $200 \mu\text{g}/\text{SCM}$  versus an average of  $62 \mu\text{g}/\text{SCM}$  in 2 blanks. Toluene and unidentified hydrocarbons were observed in 3 of 10 samples at less than or equal to 180 and  $50 \mu\text{g}/\text{SCM}$ , respectively. Again, the concentrations are in the range of typical ambient levels.

#### *Major gases, $\text{NO}_x$ , particulate loading and chloride*

The results for major gases,  $\text{NO}_x$ , particulate loading, and chloride in the stack gas are presented in Table 6. Nitrogen accounted for virtually 100% of the gas composition in three of the four tests. During Test 1, 3.2% oxygen was observed. An inward leak in the baghouse was suspected, causing oxygen from air to appear. The maximum average concentration for  $\text{NO}_x$  was  $16 \text{ mg}/\text{SCM}$ . Data scatter for  $\text{NO}_x$  caused relatively large standard deviations, which included zero for two of the three data sets. The maximum particulate loading was  $<7.1 \text{ mg}/\text{SCM}$ . All loading values were well below  $180 \text{ mg}/\text{SCM}$ , the standard for incinerators [9]. Chloride for all tests was below detection limits. The maximum detection limit was  $<0.016 \text{ mg}/\text{SCM}$ , which would result in an emission rate of  $<4 \times 10^{-6} \text{ kg}/\text{h}$  compared to the limit of  $1.82 \text{ kg}/\text{h}$  for hazardous waste incinerators [10].

TABLE 6

PCB test series major gases, NO<sub>x</sub> concentrations and particulate loading in the stack gases

Parameter	Test 1 stack (9-27-83)	Test 2 stack (9-28-83)	Test 3 stack (9-29-83)	Test 4 stack (9-29-83)
Major gases <sup>a</sup>				
N <sub>2</sub> (%)	96.8	99.5	100	99.9
O <sub>2</sub> (%)	3.2	0.5	< 0.2	0.1
CO <sub>2</sub> (%)	<0.2	<0.2	< 0.2	<0.2
NO <sub>x</sub> (mg/SCM) <sup>b</sup>	16 ± 26	6.2 ± 4.8	NS <sup>c</sup>	8.0 ± 8.6
NO <sub>x</sub> blank (mg/SCM)	<1.3	NS	NS	NS
Particle loading (mg/SCM)	<4.5	<7.1	< 5.5	<5.8
Chloride (mg/SCM)	<0.01	<0.016	< 0.012	<0.012

Standard conditions = 21° C, 1 atm.

<sup>a</sup> Average values for 2 to 3 determinations.<sup>b</sup> Represents mean for 3 values (Test 1) or 4 values (Tests 2-4) ± 1 standard deviation.<sup>c</sup> NS = not sampled.

TABLE 7

CCl<sub>4</sub> concentrations for process and emission streams

Test No.	Feed (μg/g)	Treated material (μg/g)	Baghouse filter catch (μg/g)	Cyclone outlet		Gyclone stack	Stack
				Huber (μg/SCM)	Radian (μg/SCM)	Huber (μg/SCM)	Radian (μg/SCM)
1	1.2 × 10 <sup>4</sup>	0.69	NS <sup>a</sup>	0.03	0.02	0.002	0.0007
2	1.1 × 10 <sup>4</sup>	0.47	NS	0.008	NS	0.002	NS
3	1.3 × 10 <sup>4</sup>	NS	NS	0.006	NS	<sup>b</sup>	NS
4	1.8 × 10 <sup>4</sup>	0.47	NS	0.15	0.12	0.007	0.0004
5	NS	NS	NS	0.05	NS	<0.0002	NS
6	NS	NS	NS	0.01	NS	0.0007	NS
7	NS	0.07	24.10	0.06	NS	0.0004	NS
8	2.8 × 10 <sup>3</sup>	0.14	4.20	0.008	0.008	0.002	0.001
9	4.6 × 10 <sup>3</sup>	NS	NS	0.004	0.004	<0.0009	<0.0007
10	NS	0.56	1.33	0.0008	NS	<0.0004	0.0007
11	NS	NS	NS	0.003	NS	<0.0004	NS
12	NS	NS	NS	0.02	NS	<0.0004	NS
13	NS	NS	NS	<0.002	NS	<0.0004	<0.0004
14	NS	NS	NS	0.002	NS	<0.0008	NS
15	1.4 × 10 <sup>5</sup>	0.18	NS	0.02	NS	<0.0008	NS
16	NS	NS	NS	3300	NS	0.005	NS
17	NS	NS	NS	5700	NS	0.003	NS

<sup>a</sup> NS = not sampled.<sup>b</sup> The sampling pump failed while taking this sample.

### *Carbon tetrachloride test series results*

CCl<sub>4</sub> was chosen as a waste surrogate based on its availability and because it is difficult to destroy by thermal means (position No. 4 on EPA's hierarchy of incinerability [11]). Concentration data are presented in Table 7. Tests 16 and 17 were conducted with CCl<sub>4</sub> as a pure liquid. These tests resulted in relatively high quantities of CCl<sub>4</sub> at the cyclone outlet. However, CCl<sub>4</sub> levels for the liquid feed at the stack inlet are almost indistinguishable from those of soil-based tests. This clearly demonstrates the AER's ability to handle process upsets resulting in incomplete destruction, if they should occur.

DEs and DREs for CCl<sub>4</sub> are given in Table 8. DEs were 99.9999% or greater in most cases and 99.999% or greater in all cases except Tests 12, 16 and 17. The DRE results clearly demonstrate the treatment capabilities of the process. No test yielded results below 99.9999%. This is at least two orders of magnitude better than RCRA requirements for hazardous waste incinerators [7]. These results are supported by the Radian data.

Fixed gas data from 5 tests indicated greater than 98.9% N<sub>2</sub> in all cases, with O<sub>2</sub> ranging from 0.3% to 0.8% and CO<sub>2</sub> from not detected to 0.6%.

TABLE 8

CCl<sub>4</sub> destruction efficiencies and destruction removal efficiencies

Test No.	DE	DRE
1	99.999920	99.999992
2	99.999956	99.999990
3	99.999908	<sup>a</sup>
4	99.999240	99.999963
5	99.999018	> 99.999996
6	99.999749	99.999987
7	99.999296	99.999996
8	99.999914	99.999981
9	99.999922	> 99.999983
10	> 99.999924	> 99.999961
11	99.999952	> 99.999992
12	99.998355	> 99.999961
13	> 99.999873	> 99.999965
14	99.999978	> 99.999991
15	99.999916	> 99.999997
16	98.3	99.999997
17	97.1	99.999999

<sup>a</sup> Sampling pump failed.

### *Leaching tests on AER-treated sand and soil*

The end product from any treatment technology must be disposed of in an environmentally acceptable manner. The chemical nature of this material must be determined to evaluate the effectiveness of a treatment. This sec-

tion describes the results of a study to estimate the effect of the AER on the leaching potential of inorganic constituents. Pre- and post-treatment samples of two feed materials (PCBs on sand and a typical soil, dried and screened to 35 mesh) were evaluated.

Results for the RCRA-EP analyses are given in Table 9. Concentrations of

TABLE 9

RCRA extraction procedure toxicity analyses of solid samples (all concentrations in mg/L except where noted)

	Feed soil	Treated soil	Feed sand	Treated sand
<i>Primary drinking water parameters</i>				
Arsenic (5.0) <sup>a</sup>	0.99	<0.002	<0.002	<0.002
Barium (100)	0.17	<0.001	<0.001	<0.001
Cadmium (1.0)	<0.002	0.012	<0.002	0.006
Chromium (5.0)	0.004	0.010	<0.001	0.003
Cyanide	<0.02	<0.02	<0.02	<0.02
Fluoride	<0.02	<0.02	<0.02	<0.02
Lead (5.0)	<0.02	<0.02	<0.02	<0.02
Mercury (0.2)	<0.0002	<0.0002	<0.0002	<0.0002
Nitrate (as N)	<0.02	<0.02	<0.02	<0.02
Selenium (1.0)	0.003	<0.002	<0.002	<0.002
Silver (5.0)	<0.002	<0.002	<0.002	<0.002
Radium-226 (pCi/L)	0.34	0.14	<0.09	0.19
Radium-228 (pCi/L)	4.7	1.6	<2.5	<1.4
<i>Secondary drinking water parameters</i>				
Chloride	b	b	b	b
Copper	0.010	0.028	<0.001	0.019
Iron	0.009	0.12	0.027	0.096
Manganese	0.62	0.013	0.11	<0.029
pH	5.0	4.6	4.6	3.8
Sulfate	2	<2	<2	<2
TDS	NA <sup>c</sup>	NA	NA	NA
Zinc	0.011	0.011	0.007	0.023
<i>Irrigation use parameters</i>				
Aluminum	<0.050	<0.050	<0.050	<0.050
Beryllium	<0.0005	0.001	<0.0005	0.002
Boron	0.14	0.40	0.022	0.19
Cobalt	<0.006	0.018	<0.006	0.012
Lithium	0.020	0.027	0.005	0.017
Molybdenum	<0.002	0.023	0.002	0.010
Nickel	<0.003	<0.003	<0.003	0.006
Vanadium	0.007	0.086	<0.003	0.041

<sup>a</sup> Values in parentheses are RCRA limits.

<sup>b</sup> Chloride concentration not available by IC because of acetate interference.

<sup>c</sup> NA = not analyzed.

the eight RCRA trace elements (both treated and untreated samples) are well below minimum levels for hazardous classification under current RCRA regulations [7]. For the RCRA elements, only arsenic and barium in the feed soil were elevated in comparison to the other three samples. The concentration of both elements fell below detection limits after treatment. No other significant differences were noted in the EP extracts for the RCRA elements.

Treatment of the samples appeared to have an impact on several elemental concentrations. This is most apparent in the acid digestion results given in Table 10. In both sand and soil, aluminum and iron decreased significantly in

TABLE 10

Acid digestion analyses of soil samples (all concentrations in  $\mu\text{g/g}$  except where noted)

	Feed soil	Treated soil	Feed sand	Treated sand
<i>Primary drinking water parameters</i>				
Arsenic	16	2.6	1.9	1.2
Barium	74	<0.036	5.5	1.4
Cadmium	0.23	0.75	0.98	<0.12
Chromium	6.3	11	<0.083	<0.061
Cyanide	<0.02	<0.02	<0.02	<0.02
Fluoride	28	<0.02	<0.02	<0.02
Lead	<0.02	<0.02	<0.02	<0.02
Mercury	<0.0002	<0.0002	<0.0002	<0.0002
Nitrate (as N)	<1	<1	<1	<1
Selenium	<0.002	<0.002	<0.002	<0.002
Silver	<0.16	<0.15	<0.15	<0.12
Radium-226 (pCi/g)	0.83	1.2	<0.20	0.14
Radium-228 (pCi/g)	2.7	5.7	<1.9	<1.4
<i>Secondary drinking water parameters</i>				
Chloride	26	14	50	43
Copper	<0.078	<0.062	<0.083	<0.061
Iron	8,400	250	130	27
Manganese	300	3.1	4.1	1.4
pH	5.60	5.70	5.63	4.85
Sulfate	150	170	190	160
TDS	NA <sup>a</sup>	NA	NA	NA
Zinc	22	2.2	0.25	<0.18
<i>Irrigation use parameters</i>				
Aluminum	5,800	120	68	<3.0
Beryllium	<0.037	<0.030	<0.040	<0.029
Boron	<0.70	3.8	<0.75	<0.55
Cobalt	4.0	0.42	0.51	<0.36
Lithium	21	6.4	6.4	0.43
Molybdenum	<0.16	<0.13	<0.17	<0.12
Nickel	5.3	7.0	<0.25	25
Vanadium	12	0.90	1.7	<0.18

<sup>a</sup>NA = not analyzed.

the treated samples. Barium, lithium, manganese, and vanadium followed the same trend to a lesser degree. Only nickel increased for both treated samples, while boron, cadmium, and chromium also had slight increases in the treated soil. Most other elements were at or below detection limits.

The results for the first and ninth leachates in the multiple leaching procedure used to simulate acid-rain weathering for 1000 years are given in Tables 11 and 12. Increases from the first to the ninth extract in six elemental con-

TABLE 11

Multiple extraction analysis of soil samples (all concentrations in mg/L except where noted)

	Feed soil		Treated soil	
	ME No. 1	ME No. 9	ME No. 1	ME No. 9
<i>Primary drinking water parameters</i>				
Arsenic	<0.002	<0.002	<0.002	<0.02
Barium	0.019	0.035	0.017	0.007
Cadmium	<0.002	<0.002	<0.002	<0.002
Chromium	0.003	0.003	<0.001	<0.001
Cyanide	<0.02	<0.02	<0.02	<0.02
Fluoride	0.17	<0.02	<0.02	<0.02
Lead	<0.002	<0.002	<0.002	<0.002
Mercury	<0.0002	<0.0002	<0.0002	<0.0002
Nitrate (as N)	1.1	0.87	1.3	0.69
Selenium	<0.002	<0.002	<0.002	<0.002
Silver	<0.002	<0.002	<0.002	<0.002
Radium-226 (pCi/L)	<0.14	<0.13	0.27	<0.13
Radium-228 (pCi/L)	<1.0	<1.6	<0.91	2.6
<i>Secondary drinking water parameters</i>				
Chloride	<0.1	<0.1	0.3	<0.1
Copper	0.019	0.013	0.010	<0.001
Iron	0.033	0.045	0.64	0.098
Manganese	0.072	0.22	0.13	0.002
pH	5.0	3.7	3.3	3.0
Sulfate <sup>a</sup>	14	10	15	8.5
TDS	40	60	20	60
Zinc	<0.003	<0.003	0.024	<0.003
<i>Irrigation use parameters</i>				
Aluminum	<0.050	0.12	0.51	0.17
Beryllium	0.001	0.001	<0.0005	<0.0005
Boron	0.12	0.18	0.052	<0.009
Cobalt	0.014	0.015	<0.006	<0.006
Lithium	0.012	0.005	<0.0005	<0.0005
Molybdenum	0.016	0.014	<0.002	<0.002
Nickel	<0.003	<0.003	<0.003	<0.003
Vanadium	0.060	0.057	<0.003	<0.003

<sup>a</sup>Sulfate is present from sulfuric acid added to the leaching solution.

TABLE 12

Multiple extraction analysis of sand samples (all concentrations in mg/L except where noted)

	Feed sand		Treated sand	
	ME No. 1	ME No. 9	ME No. 1	ME No. 9
<i>Primary drinking water parameters</i>				
Arsenic	< 0.002	< 0.002	< 0.002	< 0.002
Barium	0.023	0.011	0.009	0.012
Cadmium	< 0.002	< 0.002	< 0.002	< 0.002
Chromium	0.003	0.004	< 0.001	0.003
Cyanide	< 0.02	< 0.02	< 0.02	< 0.02
Fluoride	< 0.02	< 0.02	< 0.02	< 0.02
Lead	< 0.002	< 0.002	< 0.002	< 0.002
Mercury	< 0.0002	< 0.0002	< 0.0002	< 0.0002
Nitrate (as N)	1.2	0.87	1.1	0.89
Selenium	< 0.002	< 0.002	< 0.002	< 0.002
Silver	< 0.002	< 0.002	< 0.002	< 0.002
Radium-226 (pCi/L)	0.24	< 0.14	< 0.15	< 0.14
Radium-228 (pCi/L)	1.6	< 1.5	< 0.98	2.6
<i>Secondary drinking water parameters</i>				
Chloride	0.2	< 0.1	< 0.1	< 0.1
Copper	0.005	0.027	0.027	0.013
Iron	0.30	0.13	0.13	0.082
Manganese	0.051	0.004	0.004	0.006
pH	3.2	3.3	3.3	3.2
Sulfate <sup>a</sup>	14	12	12	10
TDS	40	40	40	40
Zinc	0.022	0.007	0.007	< 0.003
<i>Irrigation use parameters</i>				
Aluminum	0.57	0.11	0.11	0.075
Beryllium	< 0.0005	< 0.0005	< 0.0005	0.001
Boron	0.060	0.022	0.022	0.21
Cobalt	< 0.006	< 0.006	< 0.006	0.014
Lithium	< 0.0005	< 0.0005	< 0.0005	0.002
Molybdenum	< 0.002	< 0.002	< 0.002	0.013
Nickel	< 0.003	< 0.003	< 0.003	< 0.003
Vanadium	< 0.003	< 0.003	< 0.003	0.055

<sup>a</sup>Sulfate is present from sulfuric acid added to the leaching solution.

centrations (aluminum, barium, boron, cobalt, iron, and manganese) were observed for the feed soil. The leachability of these elements may be influenced by pH, which decreased from 5.0 in the first extract to 3.7 in the ninth. Extracts of the treated soil did not follow the same general trends. None of the elements increased in concentration. The final pH was only slightly lower than the initial pH (3.3 vs. 3.0) for the treated soil.

Analyses of the feed sand and treated sand extracts showed several elements (beryllium, boron, chromium, cobalt, lithium, molybdenum, and vanadium) increasing in concentration. In general, concentrations for the sand samples for all parameters were very similar as were the initial and final pHs.

From the limited data for both organics and inorganics, the treated material appears to be suitable for backfilling into the hazardous waste site being decontaminated. However, as with other on-site treatment technologies, each waste site will require tests for delisting and on-site disposal.

### **Advantages and future plans**

The technology has five major advantages over competing technologies for the treatment and destruction of extremely hazardous chemicals in soils. These advantages and future plans for the AER are discussed below.

#### *Advantages over competing technologies*

1. The AER is capable of extremely high operating temperatures and rapid heating rates resulting in high destruction efficiencies. Normal operating temperatures are in the range of 2200–2760°C compared with approximately 1650°C for rotary kiln incinerators. Although there is little information in the literature for reactions at these temperatures, there is impressive empirical evidence that most organic compounds completely dissociate into their elemental states. Data from extensive testing also show that intermediate compounds from partial reactions of feed materials are not formed. Since these compounds can add to downstream clean-up requirements, their elimination assures reduced costs for gas cleaning equipment.

2. The ability to use very low gas flow rates provides relatively long residence times and permits the use of smaller, less costly, off-the-shelf downstream gas cleaning equipment. The destruction capability of the AER combined with high-efficiency gas cleaning equipment allows the achievement of DREs as close to 100% as a given application requires. The ability to use activated carbon beds also provides safety backup for removing hazardous organics from the process gas if an equipment malfunction should occur.

3. Because it is electrically heated, the AER can operate under a wide range of conditions including: chemical (oxidizing, reducing, or neutral), temperature (anything up to 2760°C), and pressure (partial vacuum to low positive). Under reducing conditions oxygen-containing byproducts such as PCDDs and PCDFs are not formed. Tests have verified this important characteristic. There are no significant concentrations of products such as organics, CO<sub>2</sub> and NO<sub>x</sub>. This is an advantage in air quality control regions where these pollutants are a problem. The ability to operate under partial vacuum prevents leakage and greatly increases the safety of the process.

4. The AER has the ability to treat a wide range of hazardous materials without contamination or corrosion of the reactor internals. In the case of



soils, the melted particles never touch the reactor core walls because of the fluid-wall feature. After treatment, soil particles are cooled below their melting point before collection and removal. The treated waste is a free-flowing, nonhazardous, granular material ideal for landfill. While soils can be treated in rotary kiln incinerators, it has been found in practice that molten soils can foul and plug the kilns and attack the ceramic linings.

5. The AER's compact, modular design allows the production of transportable units. This offers two major advantages: on-site treatment avoids costs associated with shipment to a nontransportable facility; and treated waste, after fulfillment of delisting requirements, can be backfilled into the site, avoiding costs associated with disposal of the treated material.

### *Future plans*

During the past five years, major technical improvements have been made in the areas of process design and construction. Future plans include a serious corporate commitment to refine and broaden the technology for environmental applications involving hazardous chemicals. Recently, J.M. Huber has announced a commitment to invest at least \$10 million plus justified capital costs to develop commercial applications. The AER has achieved commercial status by receiving certification to destroy PCBs on soils under TSCA. More extensive permits under RCRA are currently pending. The AER has also been recommended for evaluation to detoxify 500,000 tons of dioxin-contaminated soil in Missouri by the Office of Technology Assessment.

Test sites are actively being sought for the destruction of hazardous organics in soils and for inprocess destruction of potentially hazardous intermediates. A suitable waste site should include the need for on-site treatment, a large volume of soil to be treated (>20,000 tons), and the need for high destruction efficiency. Inprocess applications offer the advantage of bypassing the production of hazardous wastes and the associated regulatory requirements. A generic example would be the placement of an AER within a process making a chlorinated organic. As byproducts are separated from the desired product, they would be sent through the AER to form carbon, chlorine, and hydrogen. The carbon would be filtered out, the chlorine condensed and recycled, and the hydrogen burned or stored as a product. Several commercial applications of this nature are currently under investigation.

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