

## Chapter 5

# Technologies for Source Material Treatment

## 5.1 Introduction

This chapter describes technologies for treating former MGP residues. These technologies have either been proven successful and cost effective or are new and promising for use at former MGP sites. The technologies described below destroy or encapsulate MGP residuals in the vadose zone, reducing or eliminating the threat that chemicals from these materials will reach groundwater or human populations and thus limiting or reducing the responsible party's liability. (This is in contrast to past methods of disposal that often involved sending wastes to landfills where the responsible parties continue to bear long-term responsibility for the waste's environmental and health effects.)

The technologies discussed in this chapter are summarized in the following table. Although each technology is discussed independently, multiple treatment technologies may be applied at a site to address the various chemical components. For example, soil vapor extraction (SVE) may be applied at a former MGP site to remediate the volatile components of the MGP residues concurrent with or prior to in situ stabilization (which will treat the heavier, less mobile chemical compounds). Multiple technologies applied concurrently or sequentially are often referred to as treatment trains, and are often formed to address an overall site remediation.

The costs provided in this section are based on limited data and are dynamic. Many variables will affect the cost of a remediation technology as applied to a specific site or set of sites. The cost information provided herein reflects an order-of-magnitude guide to cost, and is provided on an informational basis.

This document does not address the treatment of NAPLs or MGP contaminants in groundwater. These issues may be addressed in a future volume of this document. However, remediation at a site should address all the site's contaminants, including those present in both soil and groundwater.

## 5.2 Technologies for Source Material Treatment

The following sections contain specific information pertaining to each of the technologies for treating residuals and contaminated soil from former MGP sites.

<b>Source Material Treatment Technologies</b>				
<b>Name</b>	<b>Description</b>	<b>Benefits</b>	<b>Limitations</b>	<b>Approximate Cost *</b>
<b>Co-Burning</b>	Combustion of MGP residues with coal in utility boilers and cement kilns.	<ul style="list-style-type: none"> <li>Recycles wastes</li> <li>Destroys organic contaminants</li> <li>Cost effective</li> </ul>	<ul style="list-style-type: none"> <li>Long-term impacts on boiler efficiency, maintenance, and operation is unknown</li> </ul>	\$44-\$309/ton
<b>Thermal Treatment Processes</b>				
<b>Ex Situ Thermal Desorption</b>	Desorption and/or destruction of organic contaminants in excavated soil by heating.	<ul style="list-style-type: none"> <li>Demonstrated PAH and organic contaminant reduction</li> <li>Moveable units available for onsite treatment</li> </ul>	<ul style="list-style-type: none"> <li>Hazardous levels of contaminants may not be accepted at offsite facilities</li> <li>Wet or saturated media requires dewatering prior to treatment</li> <li>Soil with high organic content is unsuitable for treatment</li> <li>Air emissions control may be required</li> </ul>	\$100-\$200/ton
<b>In Situ Thermal Processes</b>				
<b>Dynamic Underground Stripping (DUS)</b>	Injection of steam into subsurface contaminants to volatilize and mobilize contaminants.	<ul style="list-style-type: none"> <li>Minimal disruption to site operations</li> <li>Removes contaminants under existing structures</li> <li>Works well under wide range of soil types</li> </ul>	<ul style="list-style-type: none"> <li>Utility costs may be high</li> <li>Sufficient contaminant mass may not be removed during treatment</li> </ul>	\$110/cy
<b>In Situ Thermal Desorption (ISTD)</b>	Soil heating via in-well heater or electrodes to vaporize/volatilize fluids and contaminants.	<ul style="list-style-type: none"> <li>Minimal disruption to site operations</li> <li>Removes contaminants under existing structures</li> <li>Works well under wide range of soil types</li> </ul>	<ul style="list-style-type: none"> <li>Utility costs may be high</li> <li>Works best in unsaturated conditions</li> </ul>	\$120-\$300/cy
<b>Contained Recovery of Oily Wastes (CROW)</b>	Hot water flushing/displacement and extraction of subsurface contaminants.	<ul style="list-style-type: none"> <li>Minimal disruption to site operations</li> <li>Removes contaminants under existing structures</li> <li>Works well under wide range of soil types</li> </ul>	<ul style="list-style-type: none"> <li>Utility costs may be high</li> <li>Sufficient contaminant mass may not be removed during treatment</li> </ul>	N/A

## Source Material Treatment Technologies, continued

Name	Description	Benefits	Limitations	Approximate Cost *
<b>Asphalt Batching</b>				
Cold-Mix Asphalt Batching	Encapsulation of contaminant by blending residues, wet aggregate and asphalt emulsion at ambient temperature.	<ul style="list-style-type: none"> <li>• Reuses materials</li> <li>• Immobilizes PAHs</li> <li>• Viable treatment technology for coal tars</li> </ul>	<ul style="list-style-type: none"> <li>• Curing times can be affected by temperature</li> <li>• Not viable for fine-grained materials (e.g., clays)</li> <li>• Physical properties of final product not always appropriate for traffic reuse</li> </ul>	\$40-\$70/ton
Hot-Mix Asphalt Batching	Encapsulation of contaminant by blending residues, wet aggregate and asphalt emulsion at high temperature.	<ul style="list-style-type: none"> <li>• Reuses materials</li> <li>• Immobilizes PAHs</li> <li>• Viable treatment technology for coal tars</li> </ul>	<ul style="list-style-type: none"> <li>• Curing times can be affected by temperature</li> <li>• Not viable for fine-grained materials (e.g., clays)</li> <li>• Physical properties of final product not always appropriate for traffic reuse</li> </ul>	\$40-\$70/ton
<b>Bioremediation/ Chemically Enhanced Bioremediation</b>				
<b>Ex Situ Bioremediation</b>				
Landfarming	Destruction of organic compounds in contaminated soil by microorganisms. Treatment occurs on lined beds during contaminated soil tilling and irrigation.	<ul style="list-style-type: none"> <li>• Shorter treatment periods than in situ bioremediation alternatives</li> <li>• Reduces contaminant concentrations</li> </ul>	<ul style="list-style-type: none"> <li>• Not effective for higher molecular-weight hydrocarbons</li> <li>• May be slower than alternative treatment technologies</li> </ul>	\$75/cy exclusive of lab and pilot studies
Biopiles	Destruction of organic compounds in contaminated soil by microorganisms. Treatment occurs through soil amendment and stockpiling.	<ul style="list-style-type: none"> <li>• Shorter treatment periods than in situ bioremediation alternatives</li> <li>• Reduces contaminant concentrations</li> </ul>	<ul style="list-style-type: none"> <li>• Not effective for higher molecular-weight hydrocarbons</li> <li>• May be slower than alternative treatment technologies</li> </ul>	\$100-\$200/cy exclusive of lab and pilot studies
Bioreactor	Destruction of organic compounds in contaminated soil by microorganisms. Treatment occurs in an enclosed reactor vessel.	<ul style="list-style-type: none"> <li>• Shorter treatment periods than in situ bioremediation alternatives</li> <li>• Reduces contaminant concentrations</li> </ul>	<ul style="list-style-type: none"> <li>• Not effective for higher molecular-weight hydrocarbons</li> <li>• May be slower than alternative treatment technologies</li> </ul>	\$216/cy exclusive of lab and pilot studies
In Situ Bioremediation/ Bioventing	Destruction of organic compounds in subsurface contaminated soil by microorganisms.	<ul style="list-style-type: none"> <li>• Generally inexpensive</li> <li>• Minimal disruption of existing operations</li> <li>• Removes contaminants from under existing structures</li> </ul>	<ul style="list-style-type: none"> <li>• Verification of destruction is sometimes difficult</li> <li>• Not effective for higher molecular-weight hydrocarbons</li> <li>• Treatment uniformity uncertain because of subsurface variables</li> </ul>	\$10-\$70/cy exclusive of lab and pilot studies

## Source Material Treatment Technologies, continued

Name	Description	Benefits	Limitations	Approximate Cost *
<b>Containment</b>	Containment or capping of contaminated soil to prevent or significantly reduce contaminant migration and to prevent human and animal exposure.	<ul style="list-style-type: none"> <li>• Quick installation</li> <li>• Does not require soil excavation</li> <li>• Prevents vertical infiltration of water</li> <li>• Prevents human and animal exposure</li> </ul>	<ul style="list-style-type: none"> <li>• Contains wastes; does not reduce contaminant concentration</li> <li>• Requires operation and maintenance program</li> <li>• Typically requires institutional controls (e.g., deed restriction)</li> </ul>	\$45,000- \$170,000/ac
<b>Stabilization/Solidification</b>				
In Situ S/S	Encapsulation of contaminant by in situ blending with chemical binders to immobilize contaminant of concern.	<ul style="list-style-type: none"> <li>• Immobilizes contaminants</li> <li>• Neutralizes soil</li> <li>• Improves bearing capacity or shear strength of treated area</li> </ul>	<ul style="list-style-type: none"> <li>• Possible leaching of volatile or mobile contaminants</li> <li>• Creation of concrete-like material in subsurface</li> <li>• Effective in situ mixing may be difficult</li> </ul>	\$40-\$60/cy in shallow applications, exclusive of lab and pilot studies
Ex Situ S/S	Encapsulation of contaminants in excavated soil by blending with chemical binders to immobilize contaminant of concern.	<ul style="list-style-type: none"> <li>• Immobilizes contaminants</li> </ul>	<ul style="list-style-type: none"> <li>• Performance dependent upon chemical composition of wastes</li> <li>• Long-term immobilization of contaminant may be affected by environmental conditions</li> </ul>	\$100/ton exclusive of lab and pilot studies
<b>Soil Washing</b>	Physical/chemical process for scrubbing soils ex situ to remove contaminants.	<ul style="list-style-type: none"> <li>• High degree of certainty regarding treatment performance</li> </ul>	<ul style="list-style-type: none"> <li>• Material handling possibly expensive</li> <li>• Effectiveness limited by complex waste mixtures and high humic content</li> </ul>	\$170/ton
<b>Soil Vapor Extraction</b>	Extraction of air from subsurface to remove volatile compounds from vadose zone soils.	<ul style="list-style-type: none"> <li>• Removes contaminant from under existing structures</li> <li>• Promotes in situ biodegradation</li> <li>• Well established treatment technology</li> <li>• Minimal disruption to site operations</li> </ul>	<ul style="list-style-type: none"> <li>• Not effective for low-volatility compounds</li> <li>• May not be effective in areas with water tables shallower than 5 to 10 feet bgs or in fine-grain soils</li> <li>• Limited effectiveness on pools of contaminants</li> </ul>	\$2-\$450/cy
* Approximate costs do not include cost of excavation, transportation, material handling, etc.				

### **5.2.1 Co-Burning**

#### **Technology Description**

Co-burning is the process by which MGP residues such as coal tar and tar-contaminated soils are combusted along with coal in utility boilers. Developed by the Edison Electric Institute's (EEI) subcommittee for MGP sites with technical support from the Electric Power Research Institute (EPRI), this technology blends remediation waste recovered during site excavation with coal so as to render it nonhazardous for co-burning in utility boilers. EPRI also developed a sampling approach that is consistent with EPA test methods for characterizing soils and wastes and for developing blending ratios for treating soils. This strategy is intended to ensure that only nonhazardous MGP wastes are co-burned in utility boilers, and allows utilities to burn this waste without entering the RCRA hazardous waste permit program or paying the high cost of commercial incineration (EPRI, 1995).

#### **Operational Considerations**

Utilities have co-burned MGP site wastes in a variety of utility boilers, including stokers, cyclones, and those fired by pulverized coal. Preparation consists of screening waste to remove oversized material and rendering the material nonhazardous under RCRA if necessary (GRI, 1996). MGP materials are typically blended with coal feedstock in the range of 5 to 10 percent coal or wastes. Co-burning increases the amount of ash requiring management. For example, a 10 percent co-burning mixture doubles the amount of ash generated by a boiler (GRI, 1996).

#### **Applications and Cost**

As of 1996, co-burning was used as part of full-scale remediation at five MGP sites; four other demonstration tests have been completed (GRI, 1996). Media that have been treated include coal tars, purifier box wastes, and contaminated soils. Co-burning is currently offered as a commercial service by one utility in the northeast United States. The cost of co-burning in a case study in Rochester, New York, ranged from \$44 to \$142 per ton for soil and from \$134 to \$309 per ton for tars.

The utility company currently offering co-burning charges a tipping fee of approximately \$90 per ton to incorporate the MGP site residuals into its boiler feed, but this cost does not include any preprocessing, transportation, or analytical work necessary for disposal (GRI, 1996).

#### **Benefits**

- Reuses/recycles waste into a usable product
- Has demonstrated technical feasibility to destroy organic contaminants
- Allows utilities to expedite flexible, cost-effective remediation at MGP sites

#### **Limitations**

- Long-term impact of co-burning on boiler efficiency, maintenance, and operation is unknown

## **Case Studies**

### ***Rochester, New York***

Rochester Gas and Electric (RG&E) with the assistance of EPRI, the Gas Research Institute (GRI) and the New York Gas Group evaluated co-burning for use at their plant. RG&E operates an 80-megawatt, tangentially fired, pulverized coal unit built in 1959 by Combustion Engineering. It is located on the same site as the former West Station MGP. Residues in the form of “neat” coal tar and soil with major amounts of rock, brick, coke, concrete, and other demolition debris remain at the West Station site. The soil contains from 40,000 to 70,000 ppm of PAHs. Although preprocessing was needed to remove large rocks and other debris, the tar and soil were easily blended with coal to make two distinct fuel products. One fuel product contained 4 percent tar, and the other contained 5 percent soil, with the balance in both cases made up of coal.

The test burn program contained a series of inspection and evaluation protocols directed at monitoring the effects of these mixed fuels on the boiler and ancillary systems. In a program that lasted approximately 12 weeks (4 weeks of which were dedicated to actual co-burning), the boiler performed without significant performance losses, PAH removal efficiency exceeded 99 percent, electrostatic precipitator performance was unchanged, and emissions appeared unaffected (air emissions were actually significantly reduced for certain parameters).

Two factors that arose in this demonstration could greatly affect the feasibility and cost of co-burning. The first factor is that the state environmental agency required ash leachate to meet drinking water standards before it would grant RG&E permission to reuse the ash. Because drinking water standards are set below the method detection limit for many parameters, the ash could not meet these standards, and the state denied permission to reuse it. If not resolved, this prohibition on reuse will add more than \$50 per ton to the cost of the residues to be treated. (One bottom ash sample also showed PAH concentrations of 800 ppb, attributed to spillover from the mill reject system.) The second factor that affects co-burning is the potential physical damage to a boiler using this technology. Mill abrasion was measured during the test and one measurement indicated a rate of wear about eight times that from processing ordinary coal. If this measurement and test are representative, maintenance costs of co-burning could increase proportionally.

### **Contact**

Kevin L. Hylton, Rochester Gas and Electric Corporation, (716) 546-2700

### ***Greenville, South Carolina***

Co-burning of MGP residues was demonstrated in a pulverized-coal, tangentially fired utility boiler at the Duke Power Company in South Carolina. The remediation site was the Broad Street MGP in Greenville, where a 1.2-acre, carbureted water gas plant operated from 1875 until 1951. The co-burn facility was Duke Power Company’s Lee Steam Station, located in Pelzer, South Carolina. The MGP residues were co-burned in unit No. 3, which has a capacity of 175 MW and was constructed in 1956.

The project's remediation goals were to prepare the site for future sale as an industrial/commercial property. A cleanup level of 200 ppm total PAHs was required. The matrix treated consisted of soil impacted with MGP residues. Prior to co-burning, soil was screened to ½ inch and then blended with coal at a maximum rate of 5 percent. Plant operations preferred a 2 percent blend.

This was a full-scale operation. The plant had a permit for 19,000 tons of soil per year, but the actual amount treated was estimated at 3,000 tons per year. Before treatment, total PAH concentrations in site soils ranged up to 1,600 ppm. After treatment, BTEX and PAH concentrations were below the detection limit in all bottom ash and fly ash samples. Stack gas concentrations were the same as when co-burning was not taking place. The project is now complete, with 3,000 tons of material treated and managed; a destruction and removal efficiency (DRE) of 100 percent was obtained. No additional co-burns of MGP residues are planned at this time.

**Contacts**

Ralph Roberts, Duke Power Company, (704) 875-5536, rrobert@duke-energy.com  
Lori Murtaugh, South Carolina Department of Health and Environmental Control, (803) 734-4668

***Illinois Power Company/Illinova Resource Recovery***

Illinois Power and Illinova Resource Recovery, Inc. operate a commercial waste management facility at Illinois Power's Baldwin Power Station. The program is designed to co-burn MGP remediation wastes from the utility industry. These wastes are blended with coal and burned in the Baldwin Power Station's two cyclone boilers.

**Power Station Description**

The Baldwin Power Station is located outside the village of Baldwin, Illinois, approximately one hour southeast of St. Louis, Missouri. The area is primarily rural agricultural property.

Two 600-megawatt cyclone boilers are utilized to co-burn remediation wastes. The cyclone units are especially suited to burning these wastes due to the fact that materials can be fed at up to a one-inch size, without the need of pulverization to 200 mesh as is required in some coal-fired power plants. In addition, 90 percent of the ash generated from cyclone boilers is in the form of a vitrified, inert slag material. All this slag is sold commercially as sandblast grit and roofing shingle aggregate. Both power station boilers are base-load units, meaning that they operate 24 hours per day, 7 days per week at full-load. This allows co-burning to be conducted on a steady basis and maximizes the capacity of the program. The Baldwin units are equipped with electrostatic precipitators and continuous emission monitors. The units are fueled with Illinois Basin coal.

**Waste Management Facility**

A dedicated waste management facility has been constructed at the Baldwin Power Station specifically designed to receive, store, and process remediation wastes. All waste storage and processing activities are conducted in a 30,000

square foot water-tight concrete and steel containment pad. The containment pad can store 8,000 cubic yards of contaminated soil. Baldwin is allowed to load waste at a rate of 5 percent of the coal loaded daily. This corresponds to approximately 450 tons per day capacity. Baldwin has demonstrated a 300-ton-per-day sustained rate capacity. The practical annual capacity is currently about 100,000 tons per year. The waste materials are delivered by dump trailer and off-loaded directly into the containment pad. The materials are then crushed, screened, and blended with coal to produce a final product that is homogenous, less than two inches in size, and free of metal, plastic and other unprocessable debris. Rock, gravel, and masonry are accepted and crushed with the other materials and burned in the boilers. The processed material is delivered to the power plant coal conveyors using an enclosed conveyor system.

### **Environmental Permits**

The Baldwin facility is fully permitted by the Illinois Environmental Protection Agency as a commercial waste treatment and storage facility. Solid waste permits limit types and quantities of acceptable waste, and define the management practices, documentation and inspection requirements, and quality control procedures. Water discharge permits require collection, treatment, and analysis of runoff water prior to discharge to the environment. Air permits limit the amount of dust generated and the emissions from the boiler stacks. The Illinois Environmental Protection Agency has been very supportive of the program as a safe and effective means of permanently eliminating the hazards and liabilities associated with these wastes, which previously were disposed of in landfills almost exclusively. Three USEPA Regions have approved the operation for receipt of coal tar and petroleum contaminated soil and debris for federal Superfund sites.

### **Operating History**

A test burn in March of 1994 convinced Illinois Power that the power plant systems could handle the contaminated soils effectively with acceptable impacts to boiler operations and efficiencies. The costs, however, indicated that the process would not be cost effective for only Illinois Power's quantities of waste. It was determined that a commercial operation could be supported by the quantities of waste market, thereby providing the economies of scale required to make the project feasible.

Since the initiation of operations in June of 1996, over 135,000 tons of waste have been accepted and treated at Baldwin. Materials have been received from as far as 1,200 miles away. Baldwin has been an integral contributor to the remediation of over 40 contaminated sites for more than 20 customers.

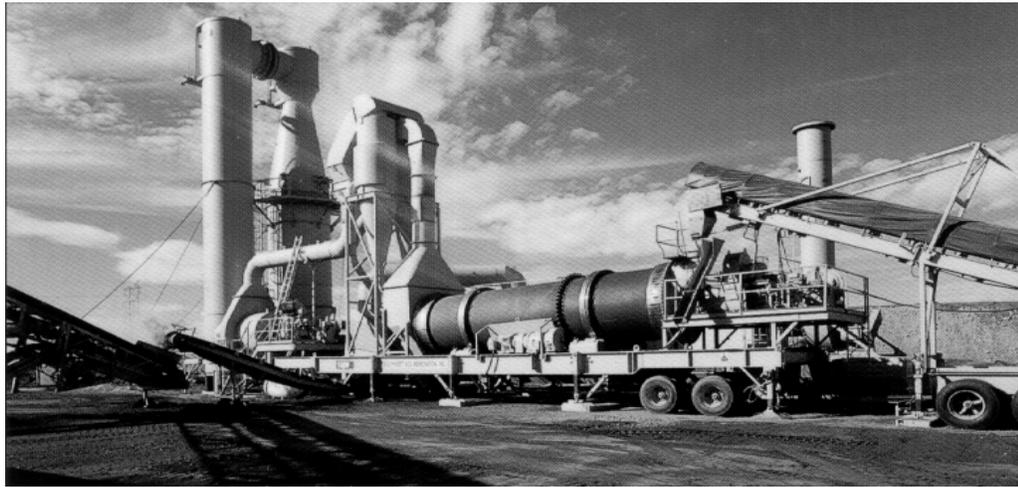
## **5.2.2 Thermal Treatment Processes**

Thermal desorption is a treatment technology in which organic chemical constituents contained within a contaminated soil matrix volatilize as a result of heating. The volatilized constituents are then extracted from nonvolatile materials, such as soil, and treated prior to release. Thermal desorption can be grouped into in situ and ex situ practices. Both technologies are described below.

### **5.2.2.1 Ex Situ Thermal Desorption**

#### **Technological Description**

Full-scale thermal desorption has been successfully used to remediate soils containing MGP wastes (e.g., lampblack, coal tar) since the early 1980s, achieving concentration reductions of more than 98 percent for TPHs, BTEX compounds, PAHs, and cyanide. Thermal desorption has been used in many non-MGP applications, and is a common remediation technology for MGP sites. The technology can be applied on site with a mobile unit or at an off-site facility. Below is a photograph of a thermal desorption unit.



Thermal desorption uses temperatures ranging from 400°F to 1,200°F to desorb chemicals from the soil. Soil is fed into a material dryer where heated air causes chemicals to volatilize. In general, temperatures between 200° F and 900°F are required to desorb VOCs and many PAH compounds. Higher temperatures (up to 1,200°F) are required to desorb high-molecular-weight PAHs (Barr, 1996). After chemicals in the offgas are treated, the cleaned air is vented to the atmosphere. The dry, hot soil is then discharged to a pug mixer where water is introduced to reduce dust and lower the soil temperature. The quenched soil is discharged and transported to a stockpile. Each day's production volume of soil is held separately while residual concentrations are determined. The treated soil is then returned to the excavation, transported to an off-site facility for disposal, or reused at a different location. A typical thermal desorption unit can treat approximately 8 to 45 tons per hour, depending on soil conditions (e.g., water content, waste concentrations, etc.) and the size of the dryer unit used.

#### **Operational Considerations**

The thermal desorber's operational characteristics depend on soil type and properties, contaminant type and concentrations, moisture content, organic material content, pH, compound volatility, and temperature and residence time during drying. This technology may require a pilot test demonstration. Blending is recommended to reduce variations in organic concentrations.

**Application and Cost**

Full-scale systems have achieved a DRE of 99 percent when treating contaminated soils from MGP sites at temperatures of 750°F to 850°F with residence times of approximately 10 minutes (GRI, 1996). A summary of costs from six remediation efforts conducted to date in California (see the table below) shows on-site treatment costs ranging from approximately \$110 to \$130 per ton for 16,000 and 9,000 tons of soil, respectively, and offsite treatment costs ranging from approximately \$100 to \$200 per ton for 11,000 and 1,000 tons of soil, respectively. All estimates include costs for general contracting, confirmation sampling, construction management, permits, and transportation for offsite treatment (GRI, 1996). Recent projects suggest the potential for even more favorable pricing.

<b>Summary of Total Project Costs for Thermal Desorption at six California Former MGP Sites</b>						
(Cost/Ton (\$))	Santa Barbara	Dinuba	Covina	Inglewood	Orange	Visalia
Thermal Treatment	\$52	\$49	\$45	\$38	\$44	\$32
Transportation	--	--	\$18	\$19	\$20	\$30
General Contractor	\$42	\$25	\$31	\$35	\$62	\$24
Confirmation Sampling	\$10	\$4	\$7	\$5	\$19	\$2
Construction Management	\$30	\$21	\$17	\$11	\$45	\$7
Miscellaneous Costs (Agency oversight, air permitting)	\$14	\$4	\$8	\$8	\$13	\$3
<b>Adjusted Total Cost</b>	<b>\$131</b>	<b>\$106</b>	<b>\$120</b>	<b>\$115</b>	<b>\$202</b>	<b>\$96</b>
<b>Total Cost</b>	<b>\$178</b>	<b>\$140</b>	<b>\$130</b>	<b>\$133</b>	<b>\$202</b>	<b>\$96</b>
<b>Total Project Costs</b>	<b>\$1,556,974</b>	<b>\$2,257,630</b>	<b>\$906,735</b>	<b>\$666,416</b>	<b>\$212,384</b>	<b>\$1,055,950</b>
<b>Tons Soil Excavated</b>	<b>8,745</b>	<b>16,120</b>	<b>7,000</b>	<b>5,024</b>	<b>1,050</b>	<b>10,775</b>
Source: Southern California Gas Company						

**Benefits**

- Demonstrated PAH reduction to less than 1 mg/kg under optimal conditions
- 80 to 99 percent removal of carcinogenic PAHs
- 90 to 99.7 percent removal of total PAHs (Barr Engineering, 1996)
- Production rates of 8 to 15 tons per hour for small units and 25 to 45 tons per hour for large units

**Limitations**

- Very wet or saturated media must be dewatered prior to treatment
- Soil with high organic content (peat) is unsuitable
- Air emissions of chlorinated compounds, sulfur, etc. may need to be abated

**Case Studies**

***Huron, South Dakota, Former MGP Site***

The Huron MGP site is a 3-acre parcel that once housed a process plant for the production of carburetor water gas. Site geology consists of a surficial fill unit underlain by a clayey lacustrine deposit and a glacial till unit. Depth to bedrock beneath the site is approximately 100 feet. The glacial till unit acts as a barrier to the vertical migration of MGP residuals.

The requirements under which the ex situ thermal desorption project was conducted were negotiated with the state regulatory agency. These included excavation criteria, a treatment performance criterion, and an operating permit for thermal treatment. Field demonstration activities consisted of excavating and staging soils containing MGP residuals, preparing the staged soils, treating the prepared soils, backfilling and compacting the treated soils, and managing wastewater.

The Huron MGP site used a low-temperature thermal desorption (LTTD) system, a two-stage counter-flow direct-fired rotary desorber capable of heating contaminated soils to 1,200 °F. The system is equipped with an oxidizer that can operate at 1,800 °F. Field demonstration costs included mobilization/demobilization, material excavation and handling, thermal treatment, soil and water analyses, utilities, backfilling and compaction, dewatering and wastewater management, and project oversight. The total cost of the project was \$3,819,000. Approximately 47,000 tons of soil containing total PAH concentrations ranging from 84 to 3,733 mg/kg were treated to below the treatment performance criterion of 43 mg/kg for the sum of cPAHs, at a cost of \$82 per ton.

Conclusions from the Huron MGP site field project are summarized as follows:

- The thermal desorption system achieved removal/destruction rates of greater than 79 percent to greater than 99 percent for cPAH compounds, and greater than 89 percent to 99.7 percent for total PAH compounds.
- The system showed good operating stability; critical operating parameters, shown below, were relatively constant:
  - Feed rate of 20 to 31 tons per hour with an average rate of 26 tons per hour
  - Desorber temperature of 1,050 °F to 1,200 °F with a residence time of 18 minutes
  - Oxidizer temperature of 1,741 °F to 1,773 °F with a residence time of 2 to 2.5 seconds

- Stack emissions, which were in compliance with the operating permit requirements, were as follows:

Opacity	<20 percent
Sulfur Dioxide	2.4 pounds per million Btu of heat input
Oxides of Nitrogen	10.7 pounds per hour
Total Hydrocarbons	0.07 pounds carbon per hour
Naphthalene	<926 micrograms per second

- Soil type and moisture content affected total cost. Had the clay and moisture content of the site soils been lower, soil preparation time would have been shorter, and unit treatment costs would have been lower.
- Inclement weather significantly affected project costs. Approximately 20 days out of a 6-month period were lost to rain delays. The rain delays increased soil preparation time and costs associated with dewatering, wastewater management, and project oversight.

### **Contact**

Ed Highland, Northwest Public Service Co., (605) 353-7510

### ***Waterloo, Iowa, Former MGP Site***

A two-stage thermal desorption unit was installed on the Waterloo, Iowa, former MGP site. The treatment used natural gas as a fuel. In the first stage of the two-stage desorber, the soil was mixed in a rotating drum and heated to approximately 300 °F to 500 °F by a 40-million-Btu-per-hour burner. In the second stage, the soil was further heated to between 1,100 °F and 1,200 °F by three additional 6-million-Btu-per-hour burners. The first stage was used to drive off moisture and the more volatile hydrocarbons; the second stage desorbed the contaminants from the soil.

All heating conducted by the two-stage desorber was direct fired and oriented counter to soil flow. The vapors from the desorption stage were passed through an oxidizer (secondary burner) and heated to between 1,750 °F and 1,800 °F to destroy hydrocarbon contaminants. The desorber unit used at the Waterloo site was specifically modified for treatment of coal tar compounds and operated at a higher temperature in the high-temperature stage of the two-stage desorber than some thermal desorption units. This was necessary to desorb higher-molecular-weight coal tar compounds. The desorber used at the Waterloo site was capable of thermally treating soil at a rate of 25 to 40 tons per hour, depending upon the concentration of contaminants, and soil type and moisture content. During the trial burn conducted at the site, soil was treated at a rate of 31.6 tons per hour.

The minimum space required for setup and operation of the Waterloo desorber unit was approximately 140 feet by 120 feet, not including space for storage of soils prior to and after treatment. The thermal desorption unit and all auxiliary equipment were transported to and from the temporary locations with 14 tractor

trailers. It took approximately 7 days to complete setup of the equipment and an additional 5 days for startup and fine tuning of the equipment in preparation for trial burn or routine treatment of soils. Natural gas (or propane), electricity, and water were required to operate the system. In addition, water was required for rehydration of the treated soil and other cooling operations.

The remediation goal for the project was to treat the soil to less than 5 mg/kg total PAHs. Routine sampling of treated soil showed concentrations well below 5 mg/kg. A total of 83 samples of treated soil (one sample for every 300 tons of soil) had an average concentration of 0.59 mg/kg total PAHs. The media treated included clay, sand, and silt.

A trial burn of coal tar materials was conducted to determine the DRE for the organic contaminants in the excavated coal tar materials. A grab sample of soil was collected for every 100 tons of treated soil, composited with two other 100-ton representative samples, and analyzed for PAHs. Routine thermal treatment of soil began as soon as the Iowa DNR and USEPA approved the results of the DRE testing. The treated soil could not be backfilled, however, until laboratory analysis was received and the results were shown to be below the treatment criterion of less than 5 mg/kg total PAHs.

The specific operating conditions observed during the trial burn were used as the operating criteria for the remainder of the soil to be treated. Continuous monitoring included waste feed rate, system treatment temperatures, carbon monoxide concentration in stack gas, and other parameters. Of the 83 samples of treated soil that were collected and analyzed throughout the project, three lots of 300 tons each did not pass. These values were not included in the average above because the soil was blended with other soil and retreated.

The following table shows the amount of soil excavated and treated for each of the four sites:

Site	Tons of Soil Treated
Hampton	3,651
Charles City	2,138
Independence	4,734
Waterloo	14,167
<b>Total</b>	<b>24,690</b>

Treated soils from all sites were used to backfill an earlier excavation on the Waterloo site. All contaminated oversized debris was crushed and thermally treated. Some exceptionally large debris, such as foundations, was decontaminated in place and left in the excavation. All scrap steel was cleaned and sent to a recycler. As a result, nearly all of the materials removed were thermally desorbed

or recycled. Very little material, primarily wood debris and tree roots, was taken to the local landfill. The total cost of the project was \$2 million. This cost includes preparing the thermal desorption site and installing utilities, excavating all the sites, hauling excavated material from Hampton, Charles City, and Independence to Waterloo, backfilling, and labor to place the fill; it also includes the thermal desorption services, with the cost of fuel. The average cost per ton of soil treated was calculated for the project and is shown in the table below.

<b>Item</b>	<b>Average Cost per Ton* (\$)</b>
Excavation	4.83
Thermal Treatment	47.87
Transportation	12.53
Backfill	4.83
Miscellaneous*	8.62
<b>Total</b>	<b>78.62</b>
*This includes the cost of analytical and engineering services, air monitoring, etc.	

**Contacts**

Sam Nelson, MidAmerican Energy Company, (712) 277-7851  
 Dan Klimek, MidAmerican Energy Company, (712) 277-7930  
 Johanshir Golchin , Iowa Department of Natural Resources, (515) 281-8925  
 Jim Colbert, USEPA Region VII, (913) 551-7489

***Mason City, Iowa, Former MGP Site***

Thermal desorption was used at a site in Mason City, Iowa, owned by Interstate Power Company. The property had been used for production of natural gas from coal in the late 1900s and had become contaminated with a variety of heavily weathered PAHs and cPAHs. From April to October 1996, approximately 22,000 tons of soil were thermally treated at temperatures of up to 1,200 °F. A process rate of 32 tons per hour was achieved.

The soil that was treated contained concentrations of PAHs in excess of 3,000 mg/kg, and in many areas, soft, agglomerated, heavy oil was present. Pretreatment of excavated soils included shredding, crushing, screening, and blending to avoid exceeding the process capacity of the thermal desorption system. Also, a significant amount of brick, concrete, wood, and steel pipe required specialized material handling and processing. The brick and concrete were crushed and blended with more heavily contaminated soil before thermal treatment; the steel and wood were separated and sent off for recycling.

Six test runs were performed during a comprehensive demonstration testing program. The average results of these test runs showed that concentrations of total and cPAHs in the treated soil were reduced from 804 mg/kg and 95 mg/kg, respectively, to less than 3.3 mg/kg and less than 1.22 mg/kg, respectively. A DRE of greater than 99.99 percent was demonstrated for all combined PAH compounds. Stack gas was sampled and analyzed for all combined PAH compounds. Sulfur dioxide, nitrogen oxide, carbon monoxide, and PAH emissions were in accordance with the USEPA and Iowa DNR protocol.

**Contacts**

Bruce Greer, Alliant Energy, (608) 252-3948

Johanshir Golchin, Iowa Department of Natural Resources, (515) 281-8925

Diane Engeman, USEPA Region VII, (913) 551-7746

**5.2.2.2 In Situ Thermal Processes**

In situ thermal processes are treatment processes designed to increase the mobilization of contaminants via volatilization and viscosity reduction. The addition of heat to the subsurface by radio frequency, electrical resistance, or steam increases the removal of organic compounds particularly in low permeability formations. Heat also increases volatility (and hence removal) of compounds that are not readily extractable using conventional SVE (e.g., heavy oils). Three in situ thermal processes are reviewed in this section: Dynamic Underground Stripping (DUS), In Situ Thermal Desorption (ISTD), and Contained Recovery of Oily Waste (CROW™).

**5.2.2.2.1 Dynamic Underground Stripping (DUS)**

**Technology Description**

Lawrence Livermore National Laboratory and the School of Engineering at the University of California, Berkeley (UC Berkeley), developed DUS in the early 1990s. The area to be cleaned using DUS is ringed with wells for injecting steam. Extraction wells in the central area are used to vacuum out vaporized contaminants. To ensure that thick layers of less permeable soils are heated sufficiently, electrode assemblies may be sunk into the ground and heated, which forces trapped liquids to vaporize and move to the steam zone for removal by vacuum extraction. These combined processes achieve a hot, dry, treatment zone surrounded by cool, damp, untreated areas. Steam injection and heating cycles are repeated as long as underground imaging shows that cool (untreated) areas remain (Newmark, 1998).

**Operational Considerations**

The capacity of DUS treatment systems is limited only by the size of the installation. DUS generally does not require material handling or pretreatment prior to application at a site. Electrical heating may be applied to less-permeable contaminated clay layers in situ to help release contaminants prior to steam injection. DUS requires both subsurface and aboveground equipment. Aboveground equipment includes a steam generation plant, electrical heating

equipment, and treatment systems for recovering free product and contaminants from the separate liquid and vapor streams collected from the extraction wells. Because the aqueous and gaseous streams are in intimate contact with the free product, they will typically be saturated with dissolved or vaporized free product components following their passage through the oil/gas/water separators.

The DUS treatment system consumes significant quantities of electricity, water, and, for some applications, natural gas. Operation difficulties that may be encountered during DUS include biofouling (especially from microorganisms destroyed by steaming), scaling and deposits on sensors, clogging from fines brought to the surface, and difficulties in maintaining the cycling, pressure-varying, and high-temperature technology. Further refinement is also required for system design and operating and monitoring techniques.

The DUS technology is labor intensive, requiring significant field expertise to implement. It is best applied to sites with contaminants above and below the water table and complex sites that are difficult to clean up.

#### **Applications and Cost**

Although the initial capital outlay for DUS is higher than for pump-and-treat systems, DUS could save money in the long run because it is completed much more quickly. Most of the equipment, such as boilers for generating steam, can be rented. Initial expenditures include installing the heating wells and operating the system intensively for a short period of time. Because the technology is short term, long-term operation and maintenance costs are reduced or eliminated. In a 1993 field trial of DUS at Lawrence Livermore National Laboratory, the technology cost about \$110 per cubic yard of soil treated (Newmark, 1998).

#### **Benefits**

- Will work in a wide range of soil types
- Works in both saturated and unsaturated conditions
- Treatment possible in areas where traditional excavation and removal are impossible
- Minimal disruption to nearby industrial operations or surrounding neighborhoods; no digging and hauling of contaminated materials eliminates exposure to toxic fumes and dust
- Will work close to or under existing structures, including buildings and roadways

#### **Limitations**

- Although DUS removes considerable mass and may improve groundwater quality, there is currently limited experience regarding the ability of DUS to achieve maximum contaminant levels (MCLs) and thus alleviate the need for pump-and-treat.

### **Case Study**

#### ***Visalia Poleyard, California***

The Southern California Edison Visalia Poleyard site was used for 80 years to treat utility poles with both creosote and pentachlorophenol (PCP). Creosote contains PAHs similar to those found in MGP wastes. This 4-acre site was one of the first to be listed on the National Priorities List. The sediments underlying the poleyard are alluvial fan deposits, and the site currently contains DNAPL contamination in three distinct water-bearing zones. There are several shallow aquifers from about 35 to 75 feet bgs, and an intermediate aquifer from about 75 to 100 feet bgs. The most sensitive groundwater resource is found in the deep aquifer below about 120 feet. The thermal remediation system was designed to remove contaminants from the intermediate and shallow aquifers without disturbing the deep aquifer.

DUS was selected for the Visalia poleyard. An array of 11 injection wells was installed encircling the contaminant source area. Although each injection point had two injection pipes, screened in either the shallow or the intermediate aquifer, only the 11 pipes completed in the lower unit were used for injection from 80 to 100 feet bgs. Three additional extraction wells were placed in the central area to supplement existing extraction wells. No supplemental electrical heating was performed; the entire site was heated using steam alone. Steam was generated utilizing commercially available oil field steam generators (Struthers type). Steam was injected at pressures up to 150 psi, routinely at pressures less than 100 psi. Vacuum pressures of approximately 0.5 atmospheres (atm) were applied in a steady mode.

Ancillary equipment included cooling equipment for the extracted water and vapor, two stages of free product separation (including dissolved air flotation), and final filtration of the pumped water by activated carbon. Approximately 16 percent of the contaminant was destroyed in place, yielding carbon dioxide. Both vapor and water streams were continuously monitored for hydrocarbon and carbon dioxide content.

In addition to thermocouples, an innovative geophysical technique was employed to monitor movement of steam and progress of heating. Electrical resistance tomography is an imaging method like CAT scanning that provides near-real-time images of underground processes between pairs of monitoring wells. Baseline measurements are used to characterize a site and predict steam pathways. Soil electric properties vary with temperature, soil type, and fluid saturation. During treatment at Visalia, daily resistivity readings provided a picture of the progress of the steam front and heated zones. Monitoring the progress of the heating fronts ensured that all soil was treated. Temperature measurements made in monitoring wells revealed details of the complex heating phenomena in individual soil layers.

As of August 1998, the DUS process recovered approximately 110,000 gallons of free product a rate of about 46,000 pounds per week. In addition, approximately 29,400 pounds of hydrocarbon were burned in the boilers; 17,500 pounds of dissolved hydrocarbon were collected in the activated carbon filtrator; and, based on removed carbon dioxide, an estimated 45,500 pounds were destroyed in situ.

Contaminant concentrations in recovered groundwater continue to decline. Southern California Edison will treat the liquid free product onsite and may use it as a lubricant. Current estimates are that the project will be completed in 1 to 2 years, with an additional 4 years of monitoring. This is in contrast to the 20 or more years expected for pump-and-treat remediation.

With DUS, contaminants are vaporized and recovered at the surface. Approximately 50 percent of the cost of cleanups is associated with treating recovered groundwater and disposing of contaminants. The addition of hydrous pyrolysis oxidation (HPO) to the basic DUS technology could save additional costs. HPO involves injection of steam and air to aerate a heated oxygenated zone. When injection is halted, the steam condenses and contaminated groundwater returns to the heated zone. The groundwater mixes with the condensed steam and oxygen, destroying dissolved contaminants. As noted above, HPO is estimated to be responsible for a portion of the contaminant treatment at the Visalia site. To evaluate the progress of in situ chemical destruction, field methods were developed to sample and analyze hot water for contaminants, oxygen, intermediate products, and reaction products.

Laboratory testing on the Visalia suite of contaminants showed that both PCP and the range of PAH compounds present are readily destroyed by HPO's in situ oxidation process. Isotopic testing during remediation showed that the carbon dioxide being recovered in the vapor stream was coming from oxidation of creosote. This process is expected to aid in bringing groundwater concentrations to regulatory standards.

**Contacts**

Roger D. Aines, Lawrence Livermore National Laboratory, (925) 423-7184

Robin Newmark, Lawrence Livermore National Laboratory, (925) 423-7184

Kent Udell, UC Berkeley, (510) 642-2928

Craig Eaker, Southern California Edison, (626) 302-8531

**5.2.2.2.2 In Situ Thermal Desorption (ISTD)**

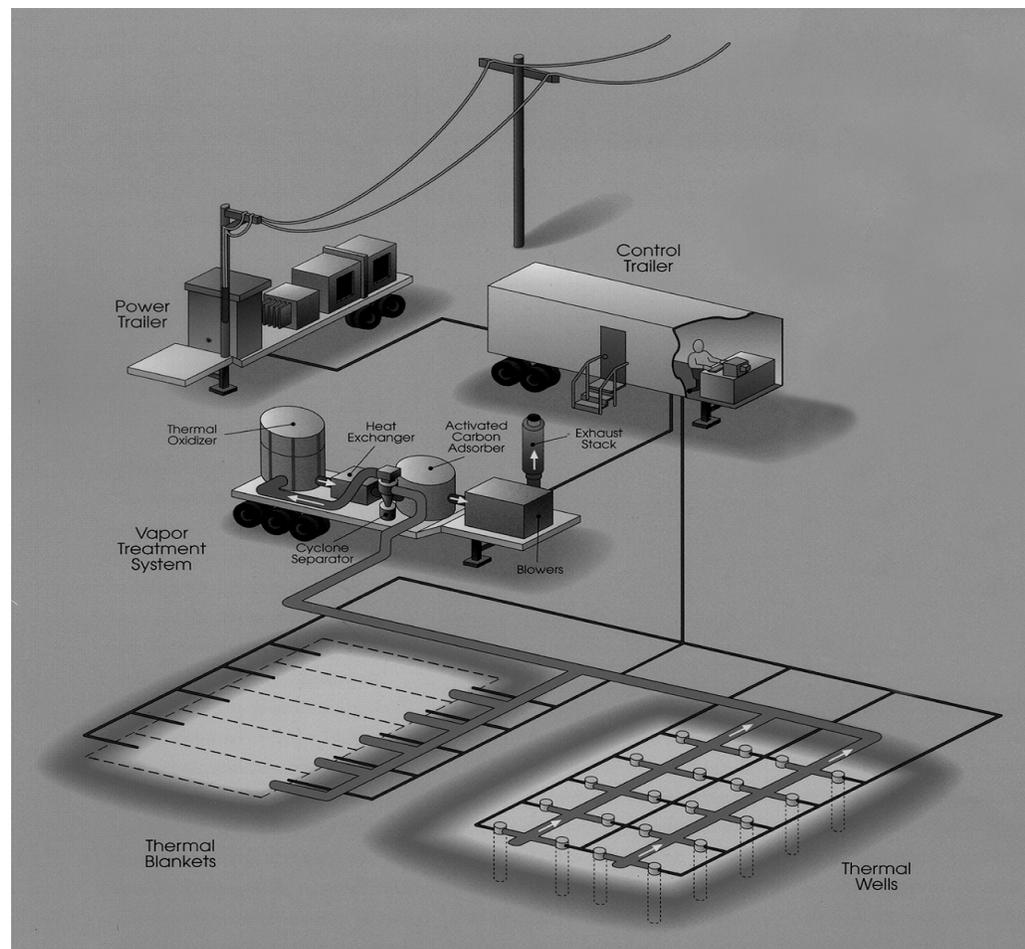
**Technology Description**

ISTD consists of a system or array of surface and/or in-well heaters or electrodes combined with vacuum wells to heat contaminated soils and extract the resulting vaporized/volatilized fluids and contaminants. Vapors produced through the soil heating process are treated in surface facilities to remove residual contaminants. According to the ISTD vendor, up to 99 percent of contaminants are destroyed.

ISTD involves the placement of Thermal Blankets (over areas of surface contamination to a depth of approximately 18 inches) or Thermal Wells (which can be drilled in areas of deep contamination) in the area to be treated. Both the blankets and the wells use electricity to heat soil to the boiling temperatures of contaminants. The contaminant vapors are then extracted and further processed through a flameless thermal oxidizer and activated charcoal filter. Water and carbon dioxide are released to the atmosphere during treatment.

### Operational Considerations

A staging area near the contaminated site and accessibility to a local power grid are required for the placement of ISTD process and control trailers. Limitations of the ISTD process are primarily related to the amount of moisture in the soil. Too much water (e.g., groundwater recharge) requires either dewatering or installing of a barrier to halt groundwater recharge as the soil is heated. There is minimal impact to surrounding neighborhoods during ISTD treatment because the process is confined to the site, and there is no direct handling of contaminated soils. Minimal dust and noise are generated during treatment. A schematic ISTD setup is shown below.



A limited number of applications have been conducted to date; therefore, other operational considerations that may affect the application of this technology at former MGP sites are not known. Additional unknown factors include how the technology will handle tarry waste material and underground subsurface structures (e.g., former gas holders) at former MGP sites, and the depth of soil to which this technology can practicably be applied.

### **Applications and Cost**

ISTD can be applied to shallow contamination (to a depth of 18 inches below grade) through the use of Thermal Blankets and to deeper contamination through the use of Thermal Wells. The technology is capable of treating a wide variety of volatile and semivolatile organic contaminants including PCBs, chlorinated solvents, pesticides, and petroleum wastes. The system is designed to control emissions through use of a flameless oxidizer and activated carbon absorber.

Soil treatment by TerraTherm Company's ISTD at the Missouri Electric Works (MEW) Superfund site in Cape Girardeau, Missouri, cost \$120 to \$200 per cubic yard of soil. Sites with special water-handling requirements, custom well or blanket configurations, or other size restrictions may cost up to \$300 per cubic yard.

### **Benefits**

- Will work in a wide range of soil types
- Treatment possible in areas where traditional excavation and removal are impossible
- Minimal disruption to nearby industrial operations or surrounding neighborhoods; no digging and hauling of contaminated materials eliminates exposure to toxic fumes and dust
- Will work close to or under existing structures, including buildings and roadways
- Demonstrated ability to recover PCBs with residual soil concentrations well below 2 ppm

### **Limitations**

- ISTD has not been applied in full-scale at an MGP site to date, nor has it been applied to MGP wastes (e.g., PAHs, tars)
- Unclear whether sufficient contaminant mass can be recovered to alter groundwater quality
- Utility costs associated with heating may be high

### **Case Studies**

#### ***Mare Island Naval Shipyard, California***

A demonstration of ISTD was performed at the Mare Island Naval Shipyard in California from October through November 1997. Soil samples at Mare Island's former electrical shop site were contaminated with PCB Aroclors 1254 and 1260, with average pretreatment concentrations of 54 ppm and maximum concentrations of 2,300 ppm. The most stringent USEPA requirement for residual PCB concentrations is 2 ppm following treatment.

The Mare Island demonstration was conducted as a collaboration between the U.S. Navy, the Bay Area Defense Conversion Action Team, TerraTherm (a subsidiary of Shell Technology Ventures, Inc.), and RT Environmental Services, who acted as

general contractor. Agencies participating included the USEPA, California EPA, and the Bay Area Air Quality Management District. A draft Toxic Substance Control Act (TSCA) permit was issued by USEPA. California EPA worked closely with TerraTherm to streamline the permit process and expedite approvals with the California DTSC and the Bay Area Air Quality Management District while still providing strong regulatory oversight.

The test site was chosen to demonstrate the effectiveness of ISTD near an existing large structure without damaging it. Both Thermal Blankets (two 8-foot by 20-foot units) and Thermal Wells (12 wells containing heating elements drilled to a depth of 14 feet) were used during the demonstration. The soil was heated to the boiling point of the PCBs (approximately 600 °F); heated vapors were extracted through a vacuum collection system utilizing a flameless ceramic oxidizer and an activated charcoal filter. Resulting vapor releases to the atmosphere contained primarily carbon dioxide and water. Both aspects of the demonstration were completed in a total of 44 days. All post-treatment samples exhibited nondetectable PCB concentrations (less than 0.033 ppm).

**Contact**

Rich G. Hansen, TerraTherm, (281) 544-2020

***Cape Girardeau, Missouri***

A field demonstration of ISTD was completed at the Missouri Electric Works Superfund site in Cape Girardeau, Missouri, from April 21 to June 1, 1997. This demonstration removed high-concentration PCB contamination from clay soils using 12 heater/vacuum wells installed in multiple triangular arrays with 5-foot well spacing to a depth of 12 feet. Surface heating pads were placed at the center of each triangle to assist in heating near-surface soils between the wells. A vacuum frame structure was constructed around the well area to insulate the surface and provide a seal. Steel sheets were fitted together and welded to the heater wells. A 16-inch-thick layer of vermiculite insulation was placed over the steel plates to reduce heat losses and insulate the surface-piping manifold embedded in the vermiculite (TerraTherm, 1997).

During remediation, electric resistance heating and vacuum were applied to the wells for 42 days. Approximately 500 watts per foot were initially injected into the clay soil at heater temperatures of 1,600 °F. Later in the process as the soil dried, about 350 watts per foot could be injected. The thermal wells were connected to a single manifold, which delivered the desorbed and partially treated vapors to a thermal oxidizer unit. Stack sampling was performed to monitor for by-products (e.g., hydrogen chloride) and to measure DRE of PCBs.

Soil temperatures were monitored throughout the experiment, and soil samples were taken with a split-spoon sampler fitted with 6-inch brass coring sleeves to verify the removal of contaminants. Temperatures above 1,000 °F were achieved in the interwell regions, and PCB concentrations in the treated area were reduced from a maximum of approximately 20,000 ppm to nondetect (< 33 ppb) after treatment by EPA Method 8080. The system DRE for PCBs was 99.98 percent (TerraTherm, 1997).

**Contacts**

Ms. Paulette France-Isetts, USEPA Region VII, 726 Minnesota Avenue, Kansas City, KS 66101, (913) 551-7701

Mr. Donald Van Dyke, Missouri Department of Natural Resources, P.O. Box 176, Jefferson City, MO 65102, (573) 751-3176

Mr. Rich G. Hansen, TerraTherm, (281) 544-2020

**5.2.2.2.3 Contained Recovery of Oily Waste (CROW™)**

**Technology Description**

The CROW™ process was developed by the Western Research Institute (WRI) in the 1970s as a hot-water flushing technology to aid in extraction of oil from sands and deep shale deposits. During the 1980s, the concept of hot water flushing was revisited as a remedial technology. Hot-water displacement is used to move accumulated oily wastes and water to production wells for aboveground treatment. Hot water is injected through wells and in groundwater to dislodge contaminants from the soil matrix. The mobilized wastes are then displaced toward pumping wells by the hot water.

With the CROW™ process, subsurface accumulations of oily wastes are reduced by reducing NAPL concentrations to residual saturation. Controlled heating of the subsurface reverses the downward penetration of NAPL. The buoyant oily wastes are displaced to production wells by sweeping the subsurface with hot water. NAPL flotation and vapor emissions are controlled by maintaining both temperature and concentration gradients in the injection water near the ground surface.

**Operational Considerations**

CROW™ requires both subsurface injection and extraction wells and an aboveground treatment train. No pretreatment of soils is required for CROW™ operation.

**Applications and Cost**

The CROW™ process has been demonstrated to treat PAHs, coal tars, pentachlorophenol, creosote, and petroleum by-products.

**Benefits**

- Will work in a wide range of soil types
- Applicable in both saturated and unsaturated conditions
- Treatment possible in areas where traditional excavation and removal are impossible
- Minimal disruption to nearby industrial operations or surrounding neighborhoods; no digging and hauling of contaminated materials eliminates exposure to toxic fumes and dust
- Will work close to or under existing structures, including buildings and roadways

**Limitations**

- Ability to control injected steam in the subsurface has been questioned
- Unclear whether sufficient contaminant mass can be recovered to alter groundwater quality

**Case Study**

**Stroudsburg, Pennsylvania**

The Brodhead Creek MGP Site is an NPL site located in Stroudsburg, Pennsylvania. The site occupies a flood plain area of approximately 12 acres at the confluence of Brodhead Creek and McMichael Creek. The enhanced recovery technology CROW™ was utilized to mobilize and extract free coal tar from the subsurface at the site. The ROD specified that 60 percent of the free coal tar be removed from the subsurface at the site. Because of sampling difficulties and the heterogeneity of the subsurface, the tar volume was not quantified although it was estimated to be several thousand gallons. Without a reliable starting figure, removal of 60 percent was impossible to document.

However, based on treatability results, the enhanced recovery process was expected to recover more than 80 percent of the free tar present. For this reason, EPA allowed a performance standard to be written that the enhanced recovery process would operate until the increase in cumulative recovery of coal tar dropped to 0.5 percent or less per pore volume of water flushed through the formation.

The affected soils at the site were 30 feet bgs, below the water table. The soils were a sand/gravel mixture residing above a silty sand confining layer. The sand and gravel soils did not allow for representative sampling of the subsurface to determine chemical characterization although free DNAPL was observed in wells in this portion of the site at depths from inches to several feet.

At the Brodhead Creek site, six injection wells were installed near the edges of the tar deposit. Two production wells were installed near the center of the tar deposit. Water and tar were pumped from the production wells at approximately 40 gallons per minute (gpm), which produced a drawdown within the wells and induced a gradient from the injection points to the production points. The induced gradient contained the heat within the target zone and prevented mobilized contaminants from being released into the surrounding aquifer. Once the tar/water mixture was pumped to the surface, tar and water were separated. The tar was then stored in the gravity settling tanks and an oil storage tank until being trucked off site for disposal. Approximately 33 gpm of separated water was recycled through the water heater and injected into the six injection wells. The remaining 7 gpm was pumped to a granular activated carbon fluidized bed reactor where the organic constituents were biologically degraded. The treated water was then pumped through four carbon adsorption units prior to discharge to Brodhead Creek.

Because of sampling difficulties in the gravelly matrix and because of heterogeneity of the subsurface soils, no pre- and post-remediation samples were obtained that were representative of the subsurface. CROW™ was operated at the

site for one year. During that time, the CROW™ process swept approximately 5,000 to 6,000 cubic yards of soil in the subsurface to recover more than 1,500 gallons of DNAPL. Remediation at the site has been completed, and the equipment has been dismantled and removed. The final Remedial Action Report has been accepted by USEPA Region III.

**Contacts**

Mr. James F. Villaume, Pennsylvania Power & Light Company, (610) 774-5094

Dr. Thomas D. Hayes, Gas Research Institute, (773) 399-8325

Mr. John Banks, USEPA Region III, (215) 566-3214

### **5.2.3 Asphalt Batching**

Asphalt batching is a widely demonstrated technology for reuse of petroleum-contaminated soils. During asphalt batching, contaminated soils are mixed with asphalt, aggregate, and other emulsions to create a product for use in paving and backfilling. Asphalt batching can be a cold-mix or hot-mix process; both are described below.

#### **5.2.3.1 Cold-Mix Asphalt Batching**

**Technology Description**

Cold-mix asphalt batching has been successfully used to immobilize and reuse MGP-contaminated soils and residues. Asphalt batching is essentially an ex situ stabilization process that binds contaminated soil and tarry residues into the matrix of an asphalt product. Residues are mixed with wet aggregate and asphalt emulsion at ambient temperature. The product is used as paving.

In the cold-mix asphalt batch process, wet aggregate material and an asphalt emulsion are mixed and left at ambient temperature. The cold-mix batch product is then cured or allowed to set undisturbed for a specific period that depends on its ingredients. This curing process can begin either before or after the pavement has been placed and compacted.

The asphalt batching process is generally performed in several steps:

- Excavation and stockpiling of materials
- Material preprocessing (typically screening and/or crushing material to the desired size)
- Stabilization with asphalt emulsion reagent
- Curing in a stockpile
- Using material for paving

The final product is a material that can be used as a sub-base for paving in areas of heavy vehicular traffic or possibly as surface paving in areas of light traffic. Additional grading and paving or excavation are often required around the treated material to accommodate its height.

Cold-mix asphalt batch products are typically produced either at a central plant location or are mixed in place. The choice between producing them at a central plant pavement or mixing in place must consider the intended use of the product and the logistics and economics of staging an onsite treatment versus transporting to an offsite facility (EPRI, 1997). A photograph of asphalt plant operations is shown below.



### **Operational Considerations**

This technology requires a treatability study to test leachability and engineering properties of the treated material. The mix design is dependent on the performance requirements of the finished product and the nature of the soil being treated. Clayey soils are generally not appropriate for cold-mix asphalt batching because a high clay content will reduce the strength of asphalt concrete. However, soils with high clay or loam content can be mixed with high-grade aggregate to produce a material used in lower-performance applications such as parking lots or driveways. Similarly, the percentage of fine grains in contaminated soil should be less than 20 percent passing the No. 200 sieve because excessively fine-grained particles could lead to both an increase in the required asphalt content and performance problems such as cracking and instability.

### **Applications and Cost**

Before processing soil for cold-mix asphalt batching, an asphalt batching contractor typically examines the physical and chemical characteristics of the soil to determine whether it can be incorporated into a usable-quality pavement. For offsite asphalt batching, the preacceptance criteria for using soil that contains tar are plant specific and designed to meet certain chemical and physical thresholds. None of the preacceptance criteria require that the chemistry of the MGP tar be examined to see how closely it resembles that of asphalt (EPRI, 1997). The

analytical requirements of the batch plant may include EPA-certified analyses for VOCs and SVOCs, petroleum hydrocarbons, pesticides, herbicides, and metals.

Because there have been few full-scale applications of cold-mix asphalt batching, cost information is limited. In California, vendor quotations range from \$40 to \$50 per ton for onsite cold asphalt batching and \$60 to \$70 per ton for offsite batching (transportation included).

**Benefits**

- Material reused rather than disposed of offsite
- Effective in immobilizing PAHs

**Limitations**

- Curing times can be long, particularly in cold weather
- Limits on acceptable percentage of fine-grained material
- Few examples of long-term durability of the product

**Case Studies**

***Monterey Former MGP Site***

From 1900 to 1947, an MGP in Monterey, California, provided gas to canneries in the immediate area. This former MGP site was subsequently sold to the City of Monterey, which planned construction of a gymnasium and pool complex. Site investigations indicated that MGP wastes were present in the form of an oxidized mixture of crude oil and bunker fuel to depths of 20 feet below grade. Soil at the site consisted of sandy silt to clay material with a moisture content ranging from 6 to 22 percent.

Contaminated soil excavated from the former MGP site was blended into an asphalt product at a rate of 300 tons per hour using onsite portable mixing equipment. The treated material was then trucked to a second location, also owned by the city of Monterey. The treated material was used in place of ¾-inch Class II aggregate base in a new construction project. A 2-inch lift of dense hot mix was applied as a wearing surface over the treated material.

**Contact**

Robert Doss, Pacific Gas and Electric Company, (415) 973-7601

***Salt Lake City Former MGP Site***

From 1872 to 1908, the American Barrel NPL site in Salt Lake City, Utah, was used as a coal gas manufacturing plant with an oil gas plant for meeting peak demands. The plant had one holder, one tar well pump, six tar wells, and two coal tar stills. From approximately 1920 to 1950, creosote operations were conducted at the site. From 1955 to 1987, the site was leased to a barrel refurbisher, American Barrel, who stored approximately 50,000 barrels on the property. The surface soils contained high levels of PAHs, phenolic compounds, heavy metals and other organic residues associated with the barrel storage activities. Subsurface soils had high levels of PAHs and phenolic compounds.

USEPA and state agency regulatory managers felt that recycling the material was superior to landfilling or thermal desorption. Salt Lake City is a Clean Air Act nonattainment area; therefore at the time of the remediation, the air quality division of the state would not allow thermal desorption in the valley. Cold-mix asphalt batching was selected over hot-mix asphalt batching for the proposed remedial technology because the regulators felt that the hot mix was simply another form of thermal desorption. USEPA and the state required that the asphalt produced be used for roads and not for parks and schools.

Approximately 20,700 tons of soil and debris were removed from the site. About 12 tons of this material were determined to be hazardous (e.g., wood from the tar wells) and shipped to an incinerator. About 1,300 tons of the material were nonhazardous but were not acceptable for asphalt batching (e.g., contained metal and other debris). These were shipped to a landfill. The remaining 19,400 tons of material were incorporated into cold-mix asphalt, including bricks and concrete from the gas holder, tars from the holder and tar wells, and contaminated surface and subsurface soils. This produced 194,966 tons of cold-mix asphalt. The gravel pits in the Salt Lake City area are very low in fines, and the contaminated soil had a high percentage of fine-grained material, so the asphalt with the contaminated soil was of higher quality than could be produced with local gravel. The original estimates for blending the contaminated soil into asphalt were 10 percent contaminated soil, 7 percent oil, and 83 percent aggregate. The contaminated soil had enough tar and oils in it to replace 40 percent of the oil needed to produce the cold-mix product.

The first batch of asphalt produced with 7 percent oil was not of good quality and had to be removed and mixed with additional aggregate. The final batches of asphalt contained 4 percent oil, 10 percent contaminated soil, and 86 percent aggregate and were of very high quality. All the resulting asphalt product was donated to counties and cities. The county and city that ultimately used the product asked the contractor if the mix could be made as a regular product because of its superior performance in Utah's cycles of cold and hot weather.

**Contact**

Jeff Tucker, Pacific Corp, (801) 220-2989

**1993 Harbor Point Study, Utica, New York**

In August 1993, Niagara Mohawk Power Corporation (NMPC) and United Retek Corporation jointly performed a field demonstration of cold-mix asphalt batching of soils at the Harbor Point site located in Utica, New York. Four 100-ton pilot batches of soil were processed into pavements; three of the batches included MGP soils containing tar; the fourth was a control sample of aggregate that met the grading requirements of cold-batch pavements. The following evaluations were then conducted:

- Leachability and permeability testing to determine how well hazardous constituents were immobilized
- Marshall stability tests to determine the structural applicability of the finished product

- Road tests to evaluate how the fines content and constituents of the MGP soils affected the product's environmental acceptability
- Evaluation of the extent of contaminant migration from the installed product as measured by a stormwater runoff test
- Additional nondestructive deflection road tests to further evaluate structural performance

General conclusions of the testing indicated that the incorporation of MGP tar-containing soils in cold-batch asphalt pavements reduced the leachability of the tar constituents associated with these soils (EPRI, 1997). The data showed that the more water-soluble compounds, such as benzene and naphthalene, would continue to leach from these pavements after 21 days of curing. Further research to establish the curing time to decrease leaching needs to be conducted. During the study, unconsolidated material curing durations of the pavements was 2 weeks; however, depending on the site-specific tar composition, curing durations may need to be extended to ensure benzene and naphthalene concentrations in leachate are minimized.

MGP asphalt products appear to be slightly lower in strength than PCS asphalt while still meeting the minimum requirements specified by the Asphalt Institute. The durability of MGP asphalt was inferior to the control asphalt in the Harbor Point study, as evidenced by the development of some potholes in the test road sections (EPRI, 1997).

#### ***California Former MGP Site***

A cold-mix asphalt batching study was performed for a California utility to assess the potential for treating tar-containing soils from MGPs in standard cold-batch pavements. Chemical data consisting of total and extractable PAHs were evaluated to determine how successful the batching was in immobilizing contaminants. Several structural parameters were also evaluated to determine the engineering properties of the pavement created by the batching process.

The results of the study indicated that some lighter-weight PAH compounds leached from the pavement. However, the study also concluded that, had additional leaching tests been conducted on the asphalt products after longer curing periods, improvement in chemical immobilization might have been observed. Further investigation into the relationship between curing times and chemical immobilization was recommended (EPRI, 1997). Engineering data also indicated that as the MGP soil percentage was increased, engineering properties deteriorated, most notably for durability parameters such as moisture loss. Nonetheless, the pavements generated through the cold-mix asphalt batching process were strong enough for general use (all batches exceeded the minimum Marshall stability value of 2,200 Newtons) even though their moisture content was higher than is generally accepted for cold-batch pavements (EPRI, 1997).

**1995 to 1996 Harbor Point Study, Utica, New York**

Niagara Mohawk Power Company conducted a joint hot- and cold-mix asphalt batching study in 1995 and 1996 at its Harbor Point facility. As part of this study, tar-containing soils from MGP sites were thermally desorbed before cold-mix batching. The desorption step was necessary because of acceptance criteria established by New York State Department of Environmental Conservation (NYSDEC). Approximately 100 tons of previously excavated MGP soils were mixed and designated for use in the project; these consisted of 30 percent coal tar soils, 30 percent water gas tar soils, 30 percent processed construction spoils, and 10 percent tar emulsion soils (EPRI, 1997).

Following thermal desorption, two cold-mix designs were used. The first cold-mix design was for a bituminous stabilized base course; the second was a dense graded mix. Desorbed material was supplemented with clean aggregate: 56 percent desorbed soil for cold-mix No. 1 and 40 percent desorbed soil for cold-mix No. 2. The cold-mix products were prepared offsite by combining the desorbed material and clean aggregate in a pugmill with a predetermined addition of asphalt emulsion.

Two areas were selected for test panels using the cold-mix asphalt. Panel A consisted of a composite design of a 3-inch-thick layer of bituminous stabilized base course overlain with a 3-inch-thick layer of hot-mix top course. Panel B consisted of adjoining 3-inch-thick sections of the two cold-mix products. After the panels were placed, they were subjected to qualitative and quantitative evaluations. Visual inspections were made over six months. The cold-mix products improved over that period, consistent with previous observations that cold-mix asphalt batch products require longer curing times. A quantitative analysis which consisted of in-place density and deflection testing was also conducted. Based on the results of these tests, the study concluded that the test panels performed satisfactorily for a variety of applications, especially for roads subjected to light and moderate traffic.

**5.2.3.2 Hot-Mix Asphalt Batching**

**Technology Description**

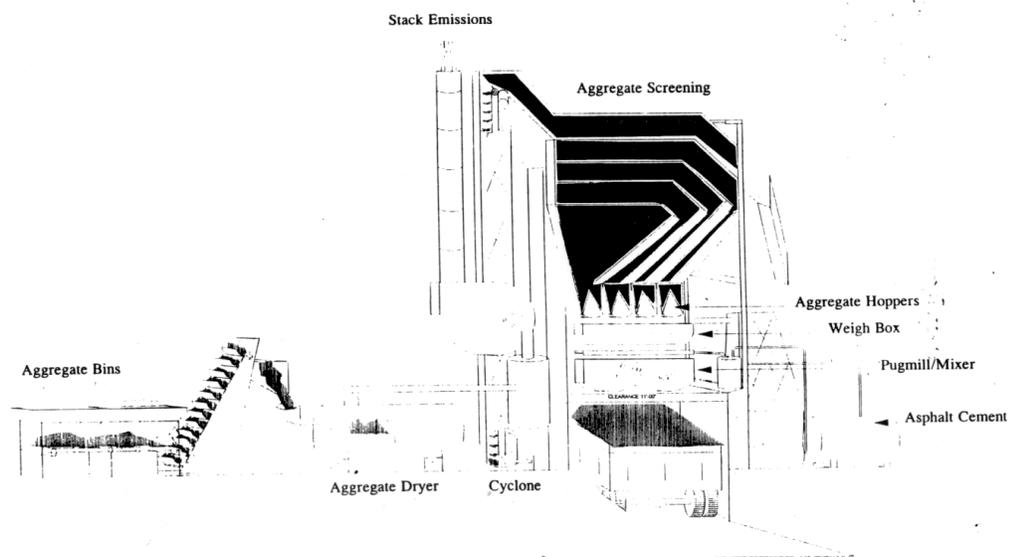
Pilot projects have used hot-mix asphalt batching to immobilize and reuse MGP-contaminated soils and residues. Hot-mix asphalt batching is an ex situ stabilization process that blends contaminated soil and tarry residues with aggregate and asphalt emulsion to create a hot asphalt product. The high processing temperatures of hot asphalt batching volatilize lighter weight compounds found in MGP wastes (e.g., benzene) and promote formation of a homogenous blend of aggregate and asphalt cement. Materials treated via hot-mix asphalt batch are used in paving surfaces.

The hot-mix asphalt batching process is generally performed onsite or offsite in several steps:

- Excavation and stockpiling of materials

- Material preprocessing (typically screening and/or crushing material to the desired size)
- Heating and drying aggregate material prior to mixing
- Stabilization of dried material with asphalt emulsion reagents
- Compacting the finished product at temperatures well above ambient
- Using treated material for paving

The final product is a material that can be used as a sub-base for paving in areas of heavy vehicular traffic.



### **Operational Considerations**

Hot-mix asphalt batching requires a treatability study to test leachability and engineering properties of the treated materials. The mix design is dependent on Marshall and Hveem testing of the performance requirements of the finished product and on the nature of the material being treated. Clayey soils are generally not appropriate because a high clay content will reduce the strength of asphalt concrete. However, soils with high clay or loam content can be mixed with high-grade aggregate to produce a material used in lower-performance applications such as parking lots or driveways. Similarly, the percentage of fine grains in the contaminated soil should be less than 20 percent passing the No. 200 sieve because excessively fine-grained particles could lead to both an increase in the required asphalt content and performance problems such as cracking and instability.

### **Applications and Cost**

Prior to processing soil for hot-mix asphalt batching, an asphalt batching contractor typically examines the soil's physical and chemical characteristics to

determine whether it can be incorporated into a pavement of usable quality. For offsite asphalt batching, different plants have different preacceptance criteria regarding use of soil that contains tar; these criteria establish certain chemical and physical thresholds. None of the preacceptance criteria require that the chemistry of the MGP tar be examined to see how closely it resembles that of asphalt (EPRI, 1997). The analytical requirements of a plant may include EPA-certified analyses for VOCs, SVOCs, petroleum hydrocarbons, pesticides, herbicides, and metals.

Because there have been few full-scale applications of this technology, cost information is limited. In California, vendor quotations have ranged from \$60 to \$70 per ton for offsite asphalt batching (transportation included).

**Benefits**

- Material reused rather than disposed of offsite
- Effective in immobilizing PAHs and volatilizing VOCs
- One of the few viable technologies available for MGP tars

**Limitations**

- Potential for leaching of contaminant from the asphalt product
- Potential for release of volatile contaminants
- Potential for objectionable odors
- Excavation treatment primarily limited to gravelly soils and sands
- For offsite asphalt batching, possible difficulty in identifying a local facility technically prepared and permitted to process MGP waste
- Few examples of long-term durability of the product

**Case Studies**

***Wisconsin Power & Light***

EPRI, in cooperation with Wisconsin Power & Light, performed a limited study on the chemical and physical properties of hot-batched asphalt pavements that incorporate tar-containing soils from MGPs. The aggregate blend produced for hot batching consisted of 25 percent tar-containing soils, 20 percent clean sand, 40 percent bottom ash with <sup>9</sup>/<sub>16</sub>-inch diameter, and 15 percent bottom ash with <sup>3</sup>/<sub>32</sub>-inch diameter. The tar-containing soils used in this study had total PAH concentrations as high as 690 mg/kg. The only TCLP metal detected in a pretreatment extract was barium. This constituent actually increased in extract concentration after treatment. The average reduction in contaminants was 88 percent. TCLP extract concentrations were reduced to below the practical quantitation limit (PQL) for all of the metals and all VOCs except benzene, toluene, and naphthalene, which were reduced but still detected in the low parts per billion range (EPRI, 1997).

***Harbor Point Study, Utica, New York***

Niagara Mohawk Power Company conducted a joint hot- and cold-mix asphalt batching study in 1995 and 1996 at its Harbor Point facility. In this study, tar-containing soils from an MGP were thermally desorbed prior to hot-mix batching. The desorption step was necessary because of the acceptance criteria set by the state regulatory agency. Approximately 100 tons of previously excavated MGP soils were mixed and designated for use in the project; these consisted of 30 percent coal tar soils, 30 percent water gas tar soils, 30 percent processed construction spoils, and 10 percent tar emulsion soils (EPRI, 1997).

Following thermal desorption, two hot-mix designs were used. The first hot-mix design was for a top course, and the second hot-mix design was for a modified bituminous plant mix. Desorbed material was supplemented with clean aggregate: 30 percent desorbed soil for hot-mix No. 1, and 40 percent desorbed soil for hot-mix No. 2. The hot-mix products were prepared at an offsite batch mix plant, with hot asphalt and the desorbed material-aggregate blended in a pugmill. These products were then conveyed to the site in trucks. Temperature loss during transport of the hot mix was approximately 25°F, which was within acceptable limits.

Three areas were selected for test panels using the hot-mix asphalt. Panel A consisted of a composite design of a 3-inch layer of bituminous stabilized base course overlain with a 3-inch thick layer of hot-mix top course (hot-mix design No. 1). Panel C consisted of adjoining 3-inch sections of the two hot-mix products. After the panels were placed, they were subjected to qualitative and quantitative evaluations. Visual inspections were made over 6 months. A quantitative analysis was also conducted which consisted of in-place density and deflection testing. Based on the results of these tests, the study concluded that the test panels performed satisfactorily for a variety of applications, especially for roads subjected to light and moderate traffic.

## **5.2.4 Bioremediation/Chemically Enhanced Bioremediation**

### **5.2.4.1 Ex Situ Bioremediation**

Bioremediation generally refers to the breakdown of organic compounds (contaminants) by microorganisms. This degradation can occur in the presence of oxygen (aerobic) or in the absence of oxygen (anaerobic). Bioremediation techniques create a favorable environment for microorganisms to use contaminants as a food and energy source. Ex situ bioremediation processes treat soil above grade using conventional soil management practices to enhance degradation of contaminant. Generally, some combination of oxygen, nutrients, and moisture are provided and pH is controlled. Bioaugmentation may be used, in which microorganisms adapted for degradation of specific contaminants are applied (USEPA, 1998).

Although not all organic compounds are amenable to biodegradation, bioremediation techniques have been successfully used to remediate soils and sludges contaminated by petroleum hydrocarbons, solvents, pesticides, wood

preservatives, and other organic chemicals. The rate and extent to which microorganisms degrade these contaminants is influenced by the specific contaminants present, soil type, oxygen supply, moisture content, nutrient supply, pH, and temperature. Other factors that influence the rate and extent of degradation include the availability of contaminant(s) to the microorganisms, the concentration of the contaminants (e.g., high concentrations may be toxic to the microorganisms), and the presence of other substances toxic to the microorganisms, (e.g., mercury), or inhibitors to the metabolism of the contaminant (USEPA, 1998).

For MGP applications, biological treatment is generally most effective on BTEX and 2- and 3-ring PAH compounds, with treatment efficiency declining for 4-, 5-, and 6-ring PAH compounds because of their reduced solubility and availability to microorganisms.

A common observation with bioremediation is that eventually the degradation rate reaches a plateau and it is difficult to reduce concentrations further in a practical manner. Residual PAHs after bioremediation, though detectable and often above regulatory standards, may have little or no significant effect on the environment. The leaching potential from residual PAHs in soils and direct contact toxicity from these residuals are the subject of ongoing research.

The most commonly used ex situ biological technologies include landfarming, biopiles (composting), and slurry phase biological treatment. Each of these is described below.

#### **5.2.4.1.1 Landfarming**

##### **Technology Description**

Landfarming (also called land treatment) involves placing contaminated soil in lined beds and periodically turning it over or tilling it to aerate the waste. The soil is irrigated, and nutrients are added as needed to optimize growing conditions. Land farming requires excavation and placement of contaminated soils onto prepared beds or liners to control leaching of contaminants. Contaminated soil is then treated in lifts that are up to 18 inches thick. After the desired treatment is achieved, the lift is removed and a new lift is constructed. It is advantageous to remove only the top of the remediated lift and then to construct the new lift by adding more contaminated media to the remaining material and mixing. This strategy inoculates the freshly added material with an actively degrading microbial culture and can reduce treatment times (USEPA, 1998).

##### **Operational Considerations**

Soil conditions are controlled for ex situ bioremediation to optimize the rate of contaminant degradation. Conditions normally controlled include:

- Moisture content (for biopiles and landfarming; solids content for slurry treatment)
- Aeration

- pH
- Nutrients
- Other amendments (e.g., bulking agents)

Although a contaminant might have been shown to be biodegradable in the laboratory or at another site, its rate and extent of degradation in each particular location and specific soil condition depend on many factors. To determine whether bioremediation is an appropriate and effective remedial treatment for the contaminated soil at a particular site, it is necessary to characterize the contamination, soil, and site, and to evaluate the biodegradation potential of the contaminants. A preliminary treatability study for all ex situ bioremediation methods should identify:

- Amendment mixtures that best promote microbial activity
- Percent reduction and lowest achievable concentration limit of contaminant
- Potential degradation rate

Landfarming requires a large amount of space and is dependent on environmental conditions affecting biological degradation of contaminants (e.g., temperature and rainfall). VOC emissions and dust control are also important considerations, especially during tilling and other material handling operations. Waste constituents may be subject to “land-ban” regulation and thus may not be eligible for treatment by landfarming.

#### **Applications and Cost**

Ex situ bioremediation methods have been used to treat petroleum hydrocarbons, VOCs, and PAHs. As a rule of thumb, the higher the molecular weight (and the more rings a PAH has), the slower the degradation rate. Landfarming is very simple from a technology point of view.

Costs for treatment include approximately \$75 per cubic yard for the prepared bed. Studies conducted prior to treatment can range from \$25,000 to \$50,000 for laboratory studies, and \$100,000 to \$500,000 for pilot tests or field demonstrations.

#### **Benefits**

- Ex situ’s main advantage is that it generally requires shorter time periods than in situ treatment, and there is more certainty about the uniformity of treatment because soil can be homogenized, screened, and continuously mixed
- Ex situ treatment is favored over in situ biological techniques for heterogeneous soils, low-permeability soils, areas where underlying groundwater would be difficult to capture, or when faster treatment times are required
- Bioremediation reduces the source of contamination

#### **Limitations**

- None of the ex situ biological treatment options can completely remove organic contaminants

- All ex situ treatment requires excavation of soils, with associated costs and engineering for equipment, permits, and material handling/worker exposure considerations

### **Case Study**

#### ***Vandalia Road MGP Site***

MidAmerican Energy has used the Institute of Gas Technologies (IGT) MGP-REM, a chemically enhanced bioremediation process, for a full-scale remediation of its MGP site near Des Moines, Iowa. This was the first full-scale use of the MGP-REM chemical/biological treatment process for coal-tar contaminated soils in a solid-phase application (landfarming). The process combines the two complementary remedial techniques of chemical oxidation and biological treatment. The MGP-REM process uses the addition of Fenton's reagent ( $\text{H}_2\text{O}_2$  plus  $\text{Fe}^{2+}$ ) to produce hydroxyl radicals that start a chain reaction with the organic contaminants. These contaminants, specifically PAHs, are transformed into products that are more readily degraded by microorganisms; the ultimate products of the process are carbon dioxide, water, and biomass (Srivastava, 1996).

The Vandalia Road site is a former landfill that contains residues from a former MGP related to the Capital Gas Light Company site located in Des Moines. This site operated from 1876 to 1957. The Vandalia Road MGP site was selected for a full-scale test of the MGP-REM technology because of a number of site attributes:

- The site is located on property that is currently owned by MidAmerican.
- The site is located in a rural area, even though it is within the city limits of the City of Pleasant Hill.
- The site is surrounded by company-owned farmland that could be used to construct an adjacent treatment facility (Kelley, 1997).

After laboratory treatability studies were completed at the IGT laboratory facilities in Des Plaines, Illinois, and the data indicated that the contaminated media at the Vandalia Road MGP site were amenable to the MGP-REM process, the full-scale treatment facility was constructed in the fall of 1996 and the spring of 1997. The soil treatment portion of the facility was 100 feet by 300 feet, bermed and lined with high-density polyethylene (HDPE). The two 12-inch lifts each had a capacity of 1,000 cubic yards. Overall capacity for a given treatment phase was 2,000 cubic yards. At the end of the first treatment phase, treated soil was removed from the facility and used for backfill in the former excavation. Adjacent facility structures included a water retention basin for runoff and runoff control, an automatic sprinkler system, a decontamination/soil processing pad and a field laboratory. The total cost of the treatment facility and associated structures was approximately \$360,000 (Kelley, 1997). Additional phases of treatment may be required to complete the site remediation.

In 1997, contaminated soil was excavated from the former landfill and placed in the treatment facility. All of the soil that was excavated from the former landfill was located below the groundwater level, so a dewatering area was constructed adjacent to the excavation to assist in reducing the water content of the excavated

media prior to loading into the land treatment unit (LTU). Once sufficiently dewatered to allow handling, the material was hauled to the adjacent treatment facility and placed in the LTU (Kelley, 1997). A small bulldozer was used to spread the materials across the facility to a consistent depth of 12 inches. Originally, excavated material was to be processed through a screening plant to remove oversize debris; however, the material, even after dewatering, was too wet to pass through the screening plant. Because the landfill appeared to consist of coal tar materials placed there in liquid form, the debris typically found at an MGP site (brick, concrete, timbers, etc.) was not present, which reduced the need for screening.

The routine operations for the biological portion of the process consisted of aeration of the soil, addition of nutrients, and maintenance of the proper moisture content. All of the equipment used for operation of the treatment facility was standard agricultural equipment, such as field cultivators, rototillers, subsoilers, and a two-bottom plow. The two-bottom plow was necessary to turn over the entire lift of soil placed in the facility, for proper aeration. The plow was necessary because the lower 4 to 6 inches of soil were so compacted by loading in the LTU that the soil could not be turned over using a tiller or field cultivator. A critical parameter for biological degradation is the moisture content of the media treated; moisture content needs to be between 40 and 80 percent of field-holding capacity. An irrigation system was installed to automate the soil moisture adjustments. During the first year of operation, too much water, in the form of heavy rain, affected the facility's operations. This made aeration difficult and may have caused a lack of oxygen, which may have inhibited biological degradation.

Chemical enhancement was also used in this bioremediation treatment process. IGT's MGP-REM chemical treatment process consisted of three steps. First, the soil pH was adjusted to approximately 5.0. Next, ferrous sulfate was added to the soil and mixed by rototilling. Third, hydrogen peroxide was added to the process resulting in a combination of direct oxidation and hydroxylation of the 4-, 5-, and 6-ring PAH compounds. Both of these chemical reactions (oxidation and hydroxylation) generally increase the solubility of the PAH compounds and, as a result, improve their biological availability to the bacteria (Kelley, 1997). The chemicals were added to the plot using commercially available agricultural equipment modified for this project.

During the first year of operation of the biological treatment phase, total PAH reduction was 51 percent. Chemical treatment reduced total PAHs by an additional 20 percent. In addition, the reduction of 4- to 6-ring compounds was increased twofold. Overall, the MGP-REM process used at the Vandalia Road MGP site reduced total PAHs by 70 percent. Based upon current cost estimates for continued operation of the facility, MidAmerican expects to save approximately \$1.2 million using this technology as compared to co-burning the soil in its power plant facility near Sioux City, Iowa (Kelley, 1997).

#### **5.2.4.1.2 Biopiles**

##### **Technology Description**

Biopile treatment is a variation of composting in which excavated soils are usually mixed with soil amendments and placed in piles on a treatment area. Biopiles often include leachate collection systems and some form of aeration. In most cases, indigenous microorganisms are used. Soil amendments may include nutrients, moisture, or bulking agents such as wood chips.

Moisture, heat, nutrients, oxygen, and pH can be controlled to enhance biodegradation. The treatment area will generally be contained with an impermeable liner to minimize the risk of contaminants leaching into uncontaminated soil. Biopiles often have a buried distribution system that passes air through the soil either by vacuum or by positive pressure. As an alternative to forced aeration, biopiles may also be turned regularly. Biopiles can be covered with plastic to control runoff, evaporation, and volatilization (USEPA, 1998). Heat can be generated in the piles, potentially providing for higher degradation rates and winter operation.

##### **Operational Considerations**

Soil conditions are controlled for ex situ bioremediation to optimize the rate of contaminant degradation. Conditions normally controlled include:

- Moisture content (for biopiles and landfarming; solids content for slurry treatment)
- Aeration
- pH
- Nutrients
- Other amendments (e.g., bulking agents)

Although a contaminant might have been shown to be biodegradable in the laboratory or at another site, its rate and extent of degradation in each particular location and under specific soil conditions depend on many factors. To determine whether bioremediation via biopiles is an appropriate and effective remedial treatment for contaminated soil at a particular site, it is necessary to characterize the contamination, soil, and site, and to evaluate the biodegradation potential of the contaminants. A preliminary treatability study for all ex situ bioremediation methods should identify:

- Amendment mixtures that best promote microbial activity
- Percent reduction and lowest achievable concentration limit of contaminant
- Potential degradation rate

For biopiles, batches of the same size may require longer retention times than in slurry-phase processes. Static treatment processes may result in less uniform treatment than processes that involve periodic mixing, which is difficult for biopiles. Windrow composting is an alternative that overcomes that problem.

### **Applications and Cost**

Ex situ bioremediation methods have been used to treat petroleum hydrocarbons, VOCs, and PAHs. As a rule of thumb, the higher the molecular weight (and the more rings a PAH has), the slower the degradation rate. Biopiles are a little more complex technologically than landfarming. The associated costs of this method reflect the increased complexity. Costs for biopiles may run \$100 to \$200 per cubic yard, exclusive of laboratory and pilot studies. Laboratory studies may cost between \$25,000 and \$50,000. Pilot tests or field demonstrations may cost \$100,000 to \$500,000.

### **Benefits**

- Ex situ treatment's main advantage is that it generally requires shorter time periods than in situ treatment, and there is more certainty about the uniformity of treatment because soil can be homogenized, screened, and continuously mixed
- Ex situ treatment is favored over in situ biological techniques for heterogeneous soils, low-permeability soils, areas where underlying groundwater would be difficult to capture, or when faster treatment times are required
- Bioremediation reduces the source of contamination

### **Limitations**

- None of the ex situ biological treatment options can completely remove organic contaminants
- All ex situ treatment requires excavation of soils, with associated costs and engineering for equipment, permits, and material handling/worker exposure considerations

### **Case Study**

#### ***Navy National Test Site***

A demonstration of biopile technology was performed to investigate and optimize methods of pretreatment, construction, operation, and performance monitoring. Soil contaminated with petroleum hydrocarbons was treated in 500-cubic-yard biopiles at Port Hueneme, California, following a treatability study that was conducted to predict biopile performance and to identify optimum nutrient rates. Two biopiles with the appropriate dimensions of 52 feet by 52 feet by 8 feet were constructed on a liner, with an aeration system consisting of slotted PVC piping and a positive displacement blower. An irrigation system was also included. The piles were covered with polyethylene, and a carbon emission control system was installed (Chaconas, 1997). The demonstration was conducted in two phases from 1994 to 1996. In the first phase, soils consisted of brown silty sand with a trace of clay (35 percent passing a No. 200 sieve), contaminated primarily with diesel fuel. The second phase of the test used soils that consisted of brown clayey silt (52 percent passing a No. 200 sieve), contaminated with a combination of diesel fuel and heavier fuel oils. In both phases, the petroleum hydrocarbons were found to be significantly weathered (degraded), as evidenced by the absence of normal

alkanes. In the second phase of the test, contaminated soils were pulverized with the hammer mill prior to placement in the biopile; in the first phase soils were directly placed in the pile.

Moisture and temperature probes, field respirometry testing, and innovative laboratory techniques to track degradation of various hydrocarbon classes were employed to monitor performance. Nondestructive field measurements of biological respirometry (oxygen uptake), moisture content, and temperature proved successful in monitoring the operation of the biopiles (Chaconas, 1997).

During the first phase, the technology removed 88 percent (reduction from an average of 1,990 mg/kg to 232 mg/kg) of petroleum hydrocarbons in the diesel range during 51 weeks. During 47 weeks of operation, the second phase achieved an 88 percent reduction in the diesel range, from an average of 4,769 mg/kg to 592 mg/kg, and a 71 percent reduction in the motor oil range, from an average concentration of 5,638 mg/kg to 1,617 mg/kg (Chaconas, 1997). In each phase, the largest reductions occurred during the first 4 weeks of biopile operations, and TEPH degradation rates slowed dramatically after 6 to 8 weeks of operation. This “plateauing” of concentrations is consistent with result of other studies in the literature for this technology. The hammer mill step in the second phase appears to have been successful because comparable results were obtained although the pulverized soil contained more clay. Degradation rates calculated from respirometry testing data correlated well with TEPH degradation observed in laboratory analyses.

#### **5.2.4.1.3 Bioreactors**

##### **Technology Description**

Slurry-phase biological treatment involves controlled treatment of excavated soil in a bioreactor. Excavated soil is first physically processed to separate gravel, sand, and debris, and the soil is then mixed with water to a predetermined concentration dependent upon the concentration of the contaminants, the rate of biodegradation, and the physical nature of the soils. Typically, a slurry contains from 10 to 50 percent solids by weight.

The solids are maintained in suspension in a reactor vessel and mixed with nutrients and oxygen. Microorganisms may be added if a suitable population is not present. When biodegradation is complete, the soil slurry is dewatered using clarifiers, pressure filters, vacuum filters, sand drying beds, centrifuges or other dewatering devices.

##### **Operational Considerations**

Soil conditions are controlled for ex situ bioremediation to optimize the rate of contaminant degradation. Conditions normally controlled include:

- Solids content (for slurry treatment, moisture content for biopiles and landfarming)
- Aeration

- pH
- Nutrients
- Other amendments (e.g., bulking agents)

Although a contaminant might have been shown to be biodegradable in the laboratory or at another site, its rate and extent of degradation in each particular location and under specific soil conditions depend on many factors. To determine whether bioremediation is an appropriate and effective remedial treatment for the contaminated soil at a particular site, it is necessary to characterize the contamination, soil, and site, and to evaluate the biodegradation potential of the contaminants. A preliminary treatability study for all ex situ bioremediation methods should identify:

- Amendment mixtures that best promote microbial activity
- Percent reduction and lowest achievable concentration limit of contaminant
- Potential degradation rate

For bioreactors, sizing of materials prior to putting them into the reactor can be difficult and expensive. Nonhomogeneous and clayey soils can create serious materials handling problems. Dewatering of treated soil fines can be expensive, and finding an acceptable method for disposing of nonrecycled wastewaters is required.

#### **Applications and Cost**

Ex situ bioremediation methods have been used to treat petroleum hydrocarbons, VOCs, and PAHs. As a rule of thumb, the higher the molecular weight (and the more rings a PAH has), the slower the degradation rate. Bioreactors are the most complex of the ex situ processes. The associated costs of this method reflect its complexity. However, bioreactors provide the highest level of treatment attainable for ex situ bioremediation of soils because they provide optimal conditions (e.g., mixing, temperature, pH). Costs for bioreactors run approximately \$216 per cubic yard, exclusive of laboratory and pilot studies. Laboratory studies may cost between \$25,000 and \$50,000. Pilot studies or field demonstrations may run between \$100,000 and \$500,000.

#### **Benefits**

- Ex situ treatment's main advantage is that it generally requires shorter time periods than in situ treatment, and there is more certainty about the uniformity of treatment because soil can be homogenized, screened, and continuously mixed
- Ex situ treatment is favored over in situ biological techniques for heterogeneous soils, low-permeability soils, areas where underlying groundwater would be difficult to capture, or when faster treatment times are required
- Bioremediation reduces the source of contamination

**Limitations**

- None of the ex situ biological treatment options can completely remove organic contaminants
- All ex situ treatment requires excavation of soils, with associated costs and engineering for equipment, permits, and material handling/worker exposure considerations

**Case Study**

***Niagara Mohawk Research***

A field-scale pilot test of bioslurry treatment was performed in 1995 at the Niagara Mohawk Power Corporation (NMPC) Remediation Research Facility in Utica, New York. Sediment was dredged from Utica Harbor and placed in two 10,000-gallon capacity slurry bioreactors where it was mixed by single top-mounted mixers, aerated by blowers, and treated for 68 days.

Grain size analysis of the sediments dredged from the harbor indicated that the material was approximately 34 percent sand, 52 percent silt, and 14 percent clay. The target slurry density for the pilot test was 20 percent by weight, and a working slurry volume of 7,300 gallons was used in each tank. Prior to treatment, the sediments exhibited a hydrocarbon odor and sheen. Initial concentrations of BTEX and PAHs were 86 and 651 mg/kg, respectively. Oil and grease analysis showed a concentration of 1.4 percent (dry weight), and total organic carbon was measured at 5.8 percent (dry weight).

Following bioslurry treatment, the sediments did not exhibit the hydrocarbon odor or sheen that had been observed when the material was dredged. No detectable BTEX was present in the sediments, and the total PAH concentration was measured at 203 mg/kg. The overall DRE for PAHs was 69 percent, ranging from a DRE of 89 percent for 3-ring PAHs to a DRE of 0 percent for 6-ring PAHs. The majority of PAH degradation was achieved within the first 21 to 35 days of treatment. The oil and grease concentration was measured following treatment at 0.31 percent, a reduction of 78 percent.

The sediments were tested before and after treatment using a 14-day earthworm test. Prior to treatment, only 24 percent of the test organisms survived using undiluted dewatered sediment; after treatment, 94 percent of the organisms survived. Decanted wastewater post treatment was found to be toxic to fish, in part because of residual nutrient concentrations from the treatment process. These results indicate that management of residual nutrients in the wastewater effluent will be required as part of full-scale bioslurry treatment.

The potential for leaching BTEX and PAHs before and after bioslurry treatment was measured using the EPA synthetic precipitation leaching procedure test (SPLP). Following treatment, no BTEX or PAHs were found in the SPLP extract above the detection limit.

This remedial technology demonstration confirmed that bioslurry treatment of aquatic sediments can be performed at a field scale. Although bioreactor treatment of the sediments did not achieve the removal efficiency typical of more aggressive

methods such as incineration or thermal desorption, this demonstration suggests that, after bioslurry treatment, sediments may be placed in aquatic or terrestrial environments. Using risk-based treatment criteria for such placement may be an environmentally acceptable option for biologically treated sediments.

**Contacts**

Jean-Pierre Moreau, Niagara Mohawk Power Corporation, 300 Erie Boulevard, West, Syracuse, NY 13322, (315) 428-6808

Dr. Thomas D. Hayes, Gas Research Institute, 8600 West Bryn Mawr Avenue, Chicago, IL 60631, (312) 399-8325

James B. Harrington, P.E., New York State Department of Environmental Conservation, 50 Wolf Road, Albany, NY, (518) 457-0337

**5.2.4.2 In Situ Bioremediation/Bioventing**

**Technology Description**

Bioremediation generally refers to the breakdown of organic compounds (contaminants) by microorganisms. This degradation can occur in the presence of oxygen (aerobic) or in the absence of oxygen (anaerobic). Bioremediation technologies stimulate the growth of microorganisms and their use of contaminants as a food and energy source. Biodegradation processes are enhanced by creating a favorable environment for microorganisms through the introduction of some combination of oxygen (aerobic), nutrients and moisture, and by controlling the temperature and pH of the soil or groundwater environment. Bioaugmentation is another bioremediation technology in which microorganisms adapted for the degradation of specific contaminants are added to enhance the biodegradation process (USEPA, 1998). Bioventing is a third bioremediation technology. It uses conventional soil vapor extraction (SVE) equipment to introduce oxygen to indigenous soil microorganisms.

Although not all organic compounds are amenable to biodegradation, bioremediation has been successfully used to clean up soils and sludges contaminated by petroleum hydrocarbons, solvents, pesticides, wood preservatives, and other organic chemicals. Aerobic biodegradation is the primary mechanism for in situ biotreatment of petroleum hydrocarbons and PAHs in soil. The rate at which microorganisms degrade contaminants is influenced by the concentrations of contaminants present, the degree of contact between the microorganisms and the contaminants, the oxygen supply, moisture, temperature, pH, and nutrient supply in the soil or water to be treated (USEPA, 1998). In situ biological treatment technologies are sensitive to certain soil parameters. For example, the presence of clay or humic materials in soil can cause variations in biological treatment process performance. For MGP sites, biological treatment of PAHs is generally most effective on BTEX and 2- and 3-ring PAH compounds; treatment efficiency declines for 4-, 5-, and 6-ring PAH compounds because of their reduced solubility and availability to microorganisms.

Of the available in situ biological treatment technologies, bioventing has been the most frequently demonstrated. As previously mentioned, this technology stimulates the in situ biodegradation of aerobically degradable compounds in soil

by providing oxygen to existing indigenous soil microorganisms. Bioventing uses conventional SVE equipment to stimulate biodegradation by providing oxygen to indigenous soil microorganisms. However, bioventing uses low air-flow rates to provide just enough oxygen to sustain microbial activity while minimizing contaminant volatilization (GRI, 1996), which is the opposite of the high air-flow rates used in treatment by SVE. Bioventing systems may either use a vacuum approach to draw air and oxygen into the contaminated subsurface area or a positive pressure system to inject air into the contaminated subsurface through wells. Extraction wells may be used at the perimeter of the treatment zone to control vapors. Bioventing is a medium- to long-term technology applicable only to soils in the vadose zone, and cleanup times range from a few months to several years (USEPA, 1998).

#### **Operational Considerations**

Soil characteristics that affect microbial activity (and therefore biodegradation rates) include pH, moisture, presence of nutrients, (e.g., nitrogen and phosphorus), and temperature. The optimal pH range is 6 to 8 for microbial activity although microbial respiration has been observed at sites that have soils outside this range. Optimum soil moisture is very soil-specific. For bioventing, too much moisture can reduce the air permeability of the soil and decrease its oxygen transfer capability. Too little moisture inhibits microbial activity. A sufficient population of microorganisms needs to be present to attain reasonable degradation rates.

#### **Applications and Cost**

In situ bioremediation is typically useful for treating the portion of MGP residues containing lower molecular-weight hydrocarbons (e.g., volatile and semi-volatile portions of coal tar.) Bioventing and in situ bioremediation techniques have been successfully used to treat soils contaminated by petroleum hydrocarbons, nonchlorinated solvents, pesticides, wood preservatives, and other organic chemicals. For example, the U.S. Air Force Bioventing Initiative is demonstrating that this technology is effective under widely varying site conditions. As of 1996, data have been collected from 125 sites (Leesch and Hinchee, 1996). Regulatory acceptance of bioventing has been obtained in 35 states and in all 10 USEPA Regions (Leesch and Hinchee, 1996).

The time required to remediate a site using bioventing or in situ bioremediation is highly dependent upon the specific soil and chemical properties of the contaminated media. Costs for operating a bioventing system typically are \$10 to \$70 per cubic meter of soil (\$10 to \$60 per cubic yard; AFCEE, 1994). Factors that affect the cost of bioventing include contaminant type and concentration, soil permeability, injection well spacing and number, pumping rate, and off-gas treatment. Bioremediation costs vary considerably depending on the volume of soil to be treated, specific soil and chemical properties of the contaminated media, and site-specific requirements for bioremediation enhancements or nutrients. The technology does not have high capital or operation and maintenance costs because it does not require expensive equipment and relatively few personnel are involved in the operation and periodic maintenance of the bioventing system.

**Benefits**

- Cost savings achieved by avoiding excavation and transportation of soil
- Generally inexpensive
- Contaminants partially destroyed
- “Low tech” and relatively easy to implement.
- Minimal disruption of current operations at sites
- Bioventing demonstrated highly effective for treating lighter-weight petroleum hydrocarbons (e.g., gasoline)

**Limitations**

- Generally more time required than for ex situ processes
- Verification that contaminants have been destroyed sometimes difficult
- Treatment uniformity uncertain because of variability in soil characteristics and contaminant distribution
- Not demonstrated effective for higher-molecular-weight petroleum hydrocarbons or PAHs
- Bioventing performance reduced by shallow groundwater table, saturated soil lenses, or low-permeability soils; low soil moisture content may limit bioventing effectiveness.
- Monitoring of offgases at soil surface possibly required for bioventing; possible vapors buildup in basements within the radius of influence of air injection wells can be alleviated by extracting air near any facility of concern

**Case Studies**

***Tar Site, St. Louis Park, Minnesota***

A demonstration of bioventing was conducted at the Reilly Tar and Chemical Corporation site in St. Louis Park, Minnesota. This site formerly housed a coal tar refinery and wood-preserving facility at which creosote in mineral oil served as the primary preservative. The facility operated from 1917 until 1979. A pilot-scale bioventing demonstration began in November 1992 to determine whether the technology was effective for PAHs.

The pilot-scale bioventing system consisted of a single-vent well with 12 tri-level soil-gas monitoring points. The vent well was screened from 5 to 15 feet below grade and was placed in the center of a 50-foot by 50-foot treatment area that was selected based on depressed oxygen concentrations measured during an initial soil gas survey (Alleman, 1995). The soil-gas monitoring points were placed radially outward at 10, 20, and 30 feet from the vent well in four directions towards the corners of the plot. The probes were set at 4, 6, and 8 feet below grade. A control area was established approximately 150 feet to the northwest of the treatment area.

Soil samples were collected from both the treatment and control areas to quantify PAH concentrations prior to bioventing. Respiration measurements were made to

estimate PAH biodegradation as a means of monitoring the progress of the bioventing. In situ respiration tests were conducted every 3 months to measure oxygen utilization rates and calculate biodegradation rates (Alleman, 1995).

Bioventing at the tar site achieved a greater than 10 percent reduction per year in total PAHs during the first two years of the study. Respiration measurements indicated that 13.4 percent and 17.3 percent degradation of total PAH content was possible during the first and second year, respectively. Although not all of the respiration can be attributed conclusively to PAH metabolism, strong correlations were found between the PAH concentration and biodegradation rates (Alleman, 1995).

#### ***Loring Air Force Base, Maine***

Bioventing was selected to treat petroleum-contaminated soils at Loring AFB in Maine. Sixteen bioventing systems were installed and all continue to operate. These systems cover approximately 17.6 acres and are treating a combined total of more than 500,000 cubic yards of fuel-contaminated soil. The major contaminants being treated by bioventing are TPHs, benzene, toluene, and xylene. The cleanup goal for TPHs is 870 mg/kg, based on risk to human health. Cleanup criteria for benzene, toluene, and xylene are based on soil leaching potential.

Operational difficulties have been encountered because of soil heterogeneity, high or perched groundwater, and inability to collect soil-gas samples. Oxygen utilization rates from more than 40 respiration tests range from 0.01 to 7.5 percent per hour, with the site median being 0.63 percent per hour (Underhill, 1997).

### **5.2.5 Containment**

#### **Technology Description**

Containment methods are used to prevent or significantly reduce migration of contaminants in soils or groundwater and to prevent human and animal exposure to contaminants. Containment is generally necessary whenever contaminated materials are to be buried or left in place at a site. In general, containment is chosen when extensive subsurface contamination at a site precludes excavation and removal of wastes because of potential health hazards, prohibitive costs, or lack of adequate treatment technologies (USEPA, 1998).

Containment or site capping can be implemented in various forms. The technology can be as simple as an asphalt or concrete cap or as elaborate as RCRA Subtitle C or Subtitle D engineered landfill cap. The goals of cap design are to prevent rainwater infiltration through impacted soils, prevent soil vapors from rising to the surface, and provide a barrier between animal and plant life and the underlying contaminated media. The final design of a cap depends on the structural and performance requirements of the particular area. The cap should be designed to facilitate water collection into drains and to minimize ponding. Cap maintenance consists of inspection for and repair of cracks.

Cap design is site-specific and depends on the intended or existing use of the former MGP site. The most effective single-layer caps are composed of concrete or bituminous asphalt. These materials are used to form a barrier between the waste and the surface environment. All covers should be designed to prevent the “bathtub” effect, which occurs when a more permeable cover is placed over a less permeable bottom liner or natural subsoil. When this occurs rainfall infiltrates the cover and ponds on the less permeable underlying material, thereby “filling up” the bathtub (USEPA, 1998).

Landfill caps are generally complex and can range from a one-layer system of vegetated soil to a complex multi-layer system of soils and geosynthetics. The most critical components of a landfill cap are the barrier layer and the drainage layer. The barrier layer can be low-permeability soil (clay) and/or geosynthetic clay liners (GCLs). The low-permeability material diverts water and prevents its passage into the underlying waste. The higher permeability materials placed atop the barrier layer carry away water to prevent percolation through the cap. Soils used as barrier materials are generally clays compacted to a hydraulic conductivity no greater than  $1 \times 10^{-6}$  cm/sec. Compacted soil barriers are generally installed in 6-inch minimum lifts to achieve a thickness of 2 feet or more (USEPA, 1998).

#### **Operational Considerations**

Aspects to be considered in cap design include the existing and future uses of the facility, the leaching potential of the waste materials, and the location of the waste relative to the groundwater table. Other considerations include the ease of relocating existing facility operations during construction activities.

Site capping mitigates migration, but does not lessen toxicity, mobility, or volume of hazardous wastes. Caps are most effective where most of the underlying waste is above the water table. A cap, by itself, can prevent only the vertical entry and migration of precipitation into and through waste, not the horizontal flow of groundwater through the waste. In many cases, caps are used in conjunction with vertical cutoff walls to minimize horizontal flow and migration. The effective life of the cap can be extended by long-term inspection and maintenance. Vegetation must be eliminated from the cap area because roots may penetrate deeply. Precautions must be taken to assure that the integrity of the cap is not compromised by surface activities.

Laboratory tests are needed to ensure that the materials being considered for cap components are suitable. Testing includes grain size analysis, Atterberg limits, and compaction characteristics (USEPA, 1998). The key engineering soil properties that must be defined are shear strength and hydraulic conductivity. Shear strength may be determined with the unconfined compression test, direct shear test, or triaxial compression test. Hydraulic conductivity of soils may be measured in the laboratory by the constant or falling head permeability test. Laboratory tests are also needed to ensure that geosynthetic materials will meet cap requirements (USEPA, 1998).

Quality assurance for cap construction is the most critical factor in containment; USEPA has generated a technical guidance document on this subject; this technical guidance should be consulted during design and construction.

### **Applications and Cost**

Containment approaches vary from repaving existing blacktop to installing a single- or double-layer concrete cap to installing a full-blown RCRA landfill cap. In between these extremes are double-layer concrete caps and non-RCRA Subtitle D landfill caps.

A RCRA Subtitle C multi-layered landfill cap is a baseline design that is suggested for RCRA hazardous waste applications. This cap generally consists of an upper vegetative (topsoil) layer, a drainage layer, and a low-permeability layer made of a synthetic liner over 2 feet of compacted clay. Compacted clay liners are effective if they retain a certain moisture content and are susceptible to cracking if the clay material dries out. Therefore, other cap designs are usually considered for arid environments.

RCRA Subtitle D requirements are for nonhazardous municipal solid waste landfills. The design of a landfill cover for a RCRA Subtitle D facility is generally a function of the bottom liner system or natural subsoils present. The cover must meet the following specifications (USEPA, 1998):

- The material must have a permeability no greater than  $1 \times 10^{-5}$  cm/s or equivalent permeability of any bottom liner or natural subsoils present, whichever is less.
- Generally the infiltration layer must contain at least 45 cm of earthen material.
- The erosion control layer must be at least 15 cm of earthen material capable of sustaining native plant growth.
- Concrete is somewhat less susceptible to cracking and is more durable than asphalt (engineered or standard) as a capping material.

The costs of single-layer concrete and asphalt caps are dependent upon the cost of the material and local labor costs. Approximate per-acre construction costs for concrete caps are \$140,000; for asphalt caps and multi-layer, \$170,000; for soil caps, \$45,000. Each type of cap involves some operations and maintenance costs. Costs per acre per year are estimated as follows: concrete caps, \$2,000; asphalt caps, \$4,000; multi-layer and soil caps, \$20. Additional cost information can be found in the Hazardous, Toxic, and Radioactive Wastes Historical Cost Analysis System developed by Environmental Historical Cost Committee of Interagency Cost Estimation Group.

### **Benefits**

- Requires only short installation times
- Unlike ex situ soil treatment, does not require excavation of soils and thus avoids some of the associated disadvantages (increased costs from engineering design of equipment, permits, waste handling)

- Generally less expensive than other technologies
- Minimizes potential worker exposure onsite at an operating facility
- Prevents vertical infiltration of water into wastes and subsequent vertical migration of contaminants
- Creates a land surface that can support vegetation and/or be used for other purposes

**Limitations**

- Generally contains wastes, does not address future liability at site
- Requires periodic inspections for settlement, ponding of liquids, erosion, and naturally occurring invasion by deep-rooted vegetation
- Usually requires groundwater monitoring for verification of containment
- Typically requires deed restrictions or other institutional controls
- Typically requires long-term operation and maintenance programs

**Case Study**

***Jackson MGP Site, Jackson, Michigan***

The Jackson, Michigan, site housed an MGP that operated from 1887 until 1947 and was demolished during the 1950s. The current land uses at the site include a residential apartment complex, city park, and elementary school playground. The remedy selected for a portion of the site was a cap consisting of an impermeable HDPE membrane covered with 3 feet of soil for frost protection. The cap was designed and constructed according to Michigan's requirements for an impermeable cap at a hazardous waste landfill.

The remedial goals for the cap were to: eliminate a potential direct human contact hazard posed by PAHs present in subsurface soils and fill materials at concentrations in excess of Michigan's residential criteria; and limit the leaching of PAHs to groundwater to less than Michigan's health-based drinking water criteria.

The matrix covered by the cap is a mixture of topsoil, sandy subsurface soils, and fill materials consisting of slag, wood, coal, and brick. A concrete slab foundation for a former gas holder is also present below ground. The area covered by the cap is approximately 2 acres. A cap was chosen because removal of the wastes would have resulted in greater human exposure.

Total PAH concentrations in the subsurface soils and fill materials range up to 9,000 mg/kg. The cap is not expected to affect the concentration of PAHs. However, the cap will control exposure by eliminating a direct human contact pathway at the site. The cap is also expected to serve as a source control by eliminating potential source of PAH loading to groundwater.

The volume of subsurface soils and fill materials impacted by PAHs and covered by the cap is estimated to be approximately 10,000 cubic yards. The Michigan Department of Environmental Quality approved the cap as an interim remedial

action (pending completion of the remedial investigation on other portions of the site) in May 1995. Construction of the cap was completed in August 1995.

**Contact**

G.L. Kelterborn, (517) 788-2484, fax (517) 788-1064

**5.2.6 Stabilization/Solidification (S/S)**

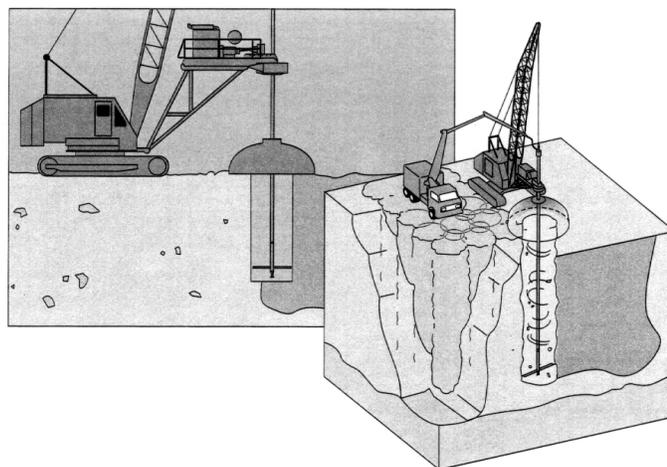
**5.2.6.1 In Situ Stabilization/Solidification**

**Technology Description**

In situ solidification/stabilization (S/S) is a remediation technology that can be used for MGP-related soil contamination. In-place cutoff walls are constructed, and soils and residues are treated in situ to depths of 30 feet or more. In situ S/S involves mixing soil with chemical binders such as cement, bentonite, additives, and proprietary chemicals that immobilize contaminants of concern (e.g., PAHs).

One method of in situ S/S uses a series of overlapping, large-diameter stabilized soil columns. A crane-mounted drill attachment turns a single-shaft, large-diameter auger head consisting of two or more cutting edges and mixing blades. As the auger head is advanced into the soil, grout is pumped through a hollow drill shaft and injected into the soil at the pilot bit. Cement, bentonite, additives, and proprietary chemicals may also be mixed into the grout. The cutting edges and mixing blades blend the soil and grout with a shearing motion. When the design depth is reached, the auger head is raised to expose the mixing blade at the surface and then advanced again to the bottom. Once the shaft is completed, another column is drilled using a specified pattern of overlapping columns; what is left behind is a series of interlinked columns.

The following is a schematic diagram showing the mixing augers.



A second method of in situ S/S requires the MGP wastes to be stabilized in shallow soil (approximately the upper 2 feet). In this scenario, admixtures containing Portland cement, bentonite, and other chemicals are placed directly on the ground surface. Tillers and sheepsfoot rollers are used to mix and compact the soil.

### **Operational Considerations**

The success of S/S methods depends on soil type and properties, contaminant type and concentrations, moisture content, organic content, density, permeability, unconfined compressive strength, leachability, pH, and particle size. A treatability study is recommended for this technology to create a mix that minimizes leaching and has appropriate strength characteristics. The creation of concrete-like material in the subsurface may severely limit access to utilities, which may need to be permanently rerouted. The machinery used for in situ S/S via mixing augers is approximately the same size as a large drilling rig; low overhead lines may limit the use of this technology.

### **Applications and Cost**

Inorganic constituents have traditionally been the target contaminant group for in situ S/S. The technology has limited effectiveness against SVOCs and no expected effectiveness against VOCs. It has been applied to MGP sites for PAH treatment. Costs for cement-based S/S techniques vary widely according to materials or reagents used and their availability, project size, and the chemical nature of the contaminants. In situ mixing/auger techniques average \$40 to \$60 per cubic yard in shallow applications.

### **Benefits**

- Immobilizes contaminants
- Neutralizes soil
- Improves bearing capacity or shear strength of treated area
- Leaves treated area, if reinforced, able to withstand differential soil and hydrostatic loading

### **Limitations**

- Possible leaching of volatile or mobile constituents
- Creation of concrete-like material in the subsurface (may severely limit access to utilities, which may need to be permanently rerouted)
- Possible significant increase in volume of mixture (up to double the original volume)
- Reagent delivery and effective mixing more difficult than in ex situ applications

### **Case Studies**

#### ***Columbus, Georgia, Former MGP Site***

A full-scale demonstration of in situ S/S for MGP contamination was performed in Columbus, Georgia, where an estimated 94,000 cubic yards of soil at a town gas

site were stabilized (Geo-Con, 1993). The 4-acre site is located in the central business district of Columbus and is bounded to the west by the Chattahoochee River. Contaminated soils extended over a 15-foot interval beneath 10 to 20 feet of miscellaneous fill. Depth to groundwater was approximately 20 feet bgs, and the 10-foot saturated zone was underlain by bedrock.

In situ treatment was accomplished by mixing/drilling a Type I Portland Cement slurry with the soil to an approximate depth of 35 feet using an 8-foot-diameter auger. A containment wall was installed adjacent to the river; the remainder of the site was stabilized by advancing augers at approximately 1,800 overlapping locations.

Prior to treatment, contamination of the MGP-affected soils was as high as 300 mg/kg of VOCs, 2,400 mg/kg of PAHs, and 5,500 mg/kg of petroleum hydrocarbons. The performance criteria for the concrete mixtures were:

- Ultimate Compressive Strength (UCS) of 60 psi within 28 days
- Permeability of no more than  $1 \times 10^{-6}$  cm/s for the containment wall and no more than  $1 \times 10^{-5}$  cm/s for the remainder of the site
- PAH concentration in TCLP leachate not to exceed 10 mg/L

UCS testing was conducted on all samples, and permeability and leach testing was performed on 10 percent of the samples obtained from approximately 300 randomly selected shafts of freshly stabilized soils. Any shafts that did not comply with the performance criteria had to be reprocessed. After the soils were stabilized, the area was covered with an HDPE liner and backfilled soil and then converted into a park and walkway.

#### **Contacts**

Darahyl Dennis, Georgia Power Company, Atlanta, GA 30302, (404) 526-7064  
Harold F. Reheis, Georgia Department of Natural Resources, Atlanta, GA 30334, (404) 656-4713

#### ***Manitowoc, Wisconsin, Former MGP Site***

The Wisconsin Fuel & Light site is a former MGP facility located along the Manitowoc River in Manitowoc, Wisconsin. The site had been filled with uncontrolled material, including debris and other material typically used behind sea walls. Portions of the foundations from the previous coal gasification structures also remained. The underlying soils at this site were contaminated with coal tars; these were stabilized using a reagent mixture of activated carbon, cement, fly ash, and organophilic clays.

The S/S treatment of impacted soil was accomplished by simultaneous injection and mixing of cement-based grout using 4- and 7-foot-diameter tools. This created a series of overlapping, vertically oriented columns of stabilized soil. The rotary and vertical movement of the boring/mixing tool was designed to assure effective mixing. In 1994 alone, a total volume of 6,859 cubic yards of soil was stabilized

with 209 soil columns. Overall, approximately 15,000 cubic yards of soil were treated during a 2-year period to an average depth of 32 feet.

A minimum UCS of 120 psi and a permeability of  $1.8 \times 10^{-7}$  cm/s were achieved through the stabilization process, and the stabilized material also passed ASTM D559 and D560 durability tests. Verification soil samples were extracted using a modified Static Leaching Method. Of 16 extracts, only one contained a PAH (naphthalene at a concentration of 16  $\mu\text{g/L}$ ), and no other SVOCs were detected above the Minimum Detection Limit. Four extracts contained a VOC, methylene chloride, but because this compound also showed up in an apparatus blank and is not a normal constituent of coal tar, it is thought that this was a laboratory contaminant.

**Contact**

Ted Vallis, Wisconsin Fuel & Light, Manitowoc, Wisconsin, (414) 683-2538

**5.2.6.2 Ex Situ Stabilization/Solidification (S/S)**

**Technology Description**

Stabilization/solidification (S/S) uses physical and chemical means to reduce the mobility of hazardous substances and contaminants. Unlike other remedial technologies, S/S seeks to trap or immobilize contaminants, instead of removing them. The term S/S has been used synonymously with other terms, including immobilization, encapsulation, and fixation (GRI, 1996). Specific definitions have been assigned to each of these terms by USEPA and others to differentiate among them. For the purposes of this document, all of these technologies will be referred to as S/S.

Ex situ S/S was originally developed for inorganic wastes. Although this technology has limited applicability to organics and cyanides, it may be useful at MGP sites for management of purifier box wastes, gas-holder tank sludge, and soils contaminated with organic compounds (GRI, 1996). Contaminants are physically bound or enclosed within a stabilized mass (solidification), or chemical reactions are introduced between the stabilizing agent and contaminants to reduce their mobility (stabilization).

Ex situ S/S is one method by which soil containing MGP wastes can be stabilized and replaced. The technology typically involves mixing the soil with chemical binders that solidify and/or immobilize the chemicals of concern. Pugmills are often used to perform mixing, although stockpiles may be mixed by mechanical means. Following S/S, treated materials may be replaced in their excavation, recompacted, and allowed to cure. Leachability testing is typically performed to verify contaminant immobilization.

There are many variations of the S/S technology using different processes and/or stabilizing agents such as Pozzolan/Portland cement, bitumen, and emulsified asphalt. The technology has been applied to soils, sludges, lagoons, and radioactive waste. The use of MGP soils in the production of asphalt is discussed

in Section 5.2.3. The discussion in this section will focus on the use of Pozzolan/Portland Cement with MGP soils.

Pozzolan/Portland cement consists primarily of silicates from Pozzolanic-based materials like fly ash, kiln dust, pumice, or blast furnace slag as well as cement-based materials. These materials react chemically with water to form a solid matrix that improves the strength of the matrix in which waste is found and minimizes the likelihood of contaminant leaching. They also raise the pH of the water, which may help precipitate and immobilize some heavy metals. Pozzolanic and cement-based binding agents are typically appropriate for inorganic contaminants. The effectiveness of this binding agent with organic contaminants varies (USEPA, 1998).

#### **Operational Considerations**

A key design consideration is the identification of a stabilizing agent that is compatible with the waste at a site and that yields a treated product that contains no free liquids, meets a minimum compressive strength, and does not leach contaminants (GRI, 1996). Lab- and pilot-scale studies are required to identify the type and quantity of agent for each application. Physical and chemical characterization of the soil are also required to select suitable mixing materials.

The effectiveness of ex situ S/S depends primarily on effective mixing. If large materials (greater than 3/8 inch) are present, they must be excluded by screening. These materials can be used in the S/S process if they are crushed and screened. Mixing time should be sufficient to produce a homogeneous mix. This parameter has a great impact on project duration and treatment cost (GRI, 1996).

Soil parameters that must be determined for ex situ S/S include particle size, Atterberg limits, moisture content, metal concentrations, sulfate content, organic content, and density. Post-treatment parameters that require monitoring and testing include permeability, unconfined compressive strength, leachability, microstructure analysis, and physical and chemical durability (USEPA, 1998). Soil particle size is an important factor as fine particles may delay setting and curing times and can surround larger particles, causing weakened bonds in S/S processes (USEPA, 1998). Soil homogeneity and isotropy also affect S/S. Larger particles, such as coarse gravel or cobbles, may not be suitable for the S/S technology.

A consideration in the use of the technology at MGP sites is the presence of oil and grease. Oil and grease coat soil particles, which tends to weaken the bond between soil and cement in cement-based solidification (USEPA, 1998).

#### **Applications and Cost**

Ex situ S/S may be used to treat soils from MGP sites. It is a viable option when soil contaminants are primarily metals (as with purifier box wastes). Full-scale S/S of free-phase hydrocarbons and contaminated soils from MGP sites has been performed, but there is little documentation of the result of these demonstrations (GRI, 1996).

Cost of ex situ S/S depends on the costs of mobilization/demobilization of personnel and equipment, excavation, equipment, startup, supplies and

consumables, labor, utilities, and analytical requirements. Ex situ S/S processes are among the most accepted remediation technologies. Comparing representative overall costs from more than a dozen vendors gives an approximate cost of under \$110 per metric ton (\$100 per ton), including excavation (USEPA, 1998).

**Benefits**

- Has been widely used to immobilize inorganic chemicals; several vendors claim that their proprietary additives can make organics amenable to stabilization

**Limitations**

- Performance of S/S process is dependent upon the chemical composition of the wastes
- Long-term immobilization of contaminants possibly affected by environmental conditions
- Certain wastes incompatible with certain S/S processes; treatability studies generally required
- VOCs are generally not immobilized by the stabilization process
- Long-term effectiveness not demonstrated for many contaminant/process combinations
- Volumetric increase in amount of material

**Case Study**

***DuQuoin Former MGP Site***

Remedial activities were conducted under the Illinois Site Remediation Program at an 8-acre former MGP site owned by Ameren CIPS in DuQuoin, Illinois. The remedial work, funded jointly by Ameren CIPS, Commonwealth Edison, and Nicor Gas, was conducted during the first half of 1997.

Tar and purifier waste was excavated from a lagoon approximately 59,650 square feet in area. A total of 4,290 tons of tar and tar-contaminated soil was generated during the excavation of impacted material at the site. This material was manifested as a hazardous waste and transported to a RCRA Subtitle C landfill.

The area identified as the lagoon excavation was stabilized by incorporating calciment bottom ash at a ratio of 7 parts ash to 10 parts soil into the bottom two feet of impacted clay subgrade. The stabilized clay was then placed back in 6-inch lifts and compacted with a D-6 bulldozer and sheepsfoot roller.

Soils from other areas of the site, identified as posing a risk greater than  $10^{-6}$  to industrial workers (hot-spot soils), were excavated, stabilized with calciment bottom ash (at a one-to-ten ratio) and placed on top of the lagoon subgrade. The material was placed in 6-inch lifts and compacted with the use of the D-6 bulldozer and sheepsfoot roller. Approximately 4,611 cubic yards of stabilized material were used as backfill in the lagoon area. Confirmation sampling

performed in the area of excavation and stabilization activities indicated that the remediation activities were successful.

Backfill obtained from an offsite commercial source was used to cover the stabilized material in the lagoon area. The backfill was compacted in place, graded to promote drainage of precipitation, and seeded with prairie grass.

The site is zoned commercial/industrial and will be used for these purposes in the future. Because stabilized impacted soils are present beneath the 1-foot surface cover, certain procedures and precautions will be followed to maintain this layer.

**Contacts**

Don Richardson, Ameren CIPS, (314) 554-4867

Peter McCauley, Com Ed, (312) 394-4470

Stan Komperta, Illinois Environmental Protection Agency, (217) 782-5504

### **5.2.7 Soil Washing**

**Technology Description**

Soil washing is a physical/chemical process for scrubbing soils ex situ to remove contaminants.

The process removes contaminants from soils in one of two ways (USEPA, 1998): by dissolving or suspending them in the wash solution (which can be sustained by chemical manipulation of pH for a period of time); or by concentrating them into a smaller volume of soil through particle size separation, gravity separation, and attrition scrubbing (similar to techniques used in sand and gravel operations).

Soil washing is considered a media transfer technology because contamination is not destroyed but merely transferred from solid- to liquid-phase media. The contaminated water generated from soil washing is treated with the technologies suitable for the contaminants. Soil washing is potentially applicable to soils contaminated with a wide variety of heavy metals, radionuclides, and organic contaminants. Application of the process is not widespread in the United States. This technology has been more widely applied in Europe.

The concept of reducing soil contamination through the use of particle size separation is based on the finding that most organic and inorganic contaminants tend to bind, either chemically or physically, to clay, silt, and organic soil particles (USEPA, 1998). Silt and clay attach to sand and gravel particles by physical processes, primarily compaction and adhesion. Washing separates the fine (small) clay and silt particles from coarser sand and gravel soil particles thus concentrating contaminants into a smaller volume of soil that can then be managed (treated further or disposed of at a landfill). Gravity separation is effective for removing high- or low-specific-gravity particles such as heavy-metal-containing compounds. Attrition scrubbing removes adherent contaminant films from coarser particles. It can also increase the fines in soils. The clean soil can be returned to the site for reuse.

Complex mixtures of contaminants in soil (such as a mixture of metals, nonvolatile organics, and semivolatile organic compounds) and heterogeneous contaminant compositions throughout a soil mixture make it difficult to formulate a single washing solution that will consistently and reliably remove the different types of contaminants. Soil washing is typically not recommended for these types of sites.

#### **Operational Considerations**

Soil type is an important factor for soil washing. In general, coarse, unconsolidated materials, such as sands and fine gravels, are easiest to treat. Soil washing may not be effective where the soil is composed of large percentages of silt and clay because of the difficulty of separating the adsorbed contaminants from fine particles and from wash fluids (USEPA, 1998).

High soil moisture content may cause excavation, material handling, and material transport problems (USEPA, 1998).

The pH of the waste being treated may affect soil washing; high pH in soil normally lowers the mobility of inorganics in soil (USEPA, 1998).

High humic content will bind the soil, decreasing the mobility of organics and thus the threat to groundwater; however, high humic content can inhibit soil washing as a result of strong adsorption of the contaminant by the organic material (USEPA, 1998).

A complete bench-scale treatability study is typically required before using soil washing as a remedial solution. Like any ex situ soil treatment, this technology requires space for soil processing and materials handling.

#### **Applications and Cost**

This technology is suitable for treating soils and sediment contaminated with organics such as PCBs, creosote, fuel residues, and heavy petroleum; heavy metals such as cadmium, chromium, lead, arsenic, copper, cyanides, mercury, nickel, and zinc; and radionuclides. The technology can recover metals and can clean a wide range of organic and inorganic contaminants from coarse-grained soils.

At the present time, soil washing is used extensively in Europe but has had limited use in the United States. Between 1986 and 1989, the technology was one of the selected source control remedies at eight Superfund sites. The average cost for use of this technology, including excavation, is approximately \$170 per ton, depending on site-specific conditions and the target waste quantity and concentration.

#### **Benefits**

- Offered by multiple vendors
- High degree of certainty regarding treatment performance

#### **Limitations**

- Material handling possibly expensive and time consuming, especially for large amounts

- Applicability and effectiveness of the process limited by:
  - Complex waste mixtures (e.g., metals with organics) which make formulating washing fluid difficult
  - High humic content in soil, which may require pretreatment
- Washwater requiring treatment at demobilization
- Additional treatment steps that may be required to address hazardous levels of washing solvent remaining in the treated residuals
- Difficultly removing organics adsorbed onto clay-size particles

### **Case Studies**

#### ***Former Basford Gasworks, Nottingham, UK***

A large-scale UK soil washing project is being conducted at the former Basford gasworks site in Nottingham. The 7.8-hectare (ha) site is owned by BG plc, the UK gas supply infrastructure group. The cleanup is valued at \$7.5 million (Haznews, 1998).

Soil washing commenced in August 1997, and was scheduled to be completed in July 1998 after processing approximately 72,000 cubic meters of contaminated material. The soil washing was performed by Linatex/Heijmans, a joint-venture between UK and Dutch firms, using a plant with a nominal process rate of 50 tonnes per hour.

The Basford site is underlain by a drinking water aquifer, with no subsurface geological barrier to prevent off-site migration of contaminants. The soil conditions at the site made it a suitable candidate for evaluating the cost-effectiveness of soil washing; information which would be useful in evaluating this technology for other contaminated MGP sites. Basford began operating in 1854 and was the principal gas supply for the City of Nottingham. The site also provided by-products such as coke, sulphuric acid, and ammonium sulphate fertilizer until gas production stopped in 1972 (Haznews, 1998).

During the site characterization, 350 test pits were dug on a 10 meter grid, producing 2,500 samples for analytical testing. This detailed investigation allowed a more accurate identification of waste types, volume, and location. A model was subsequently developed to optimize the treatment technology and estimate the amount of materials that could be recycled. For example, 26,000 cubic meters of clean ash and clinker are being recovered for use in steel and building block production (Haznews, 1998).

Approximately 91,000 cubic meters of contaminated material was identified. Of this, about 15,000 cubic meters has been classified as untreatable (along with tar and asbestos wastes) and was sent to an off-site disposal location. The remainder of the wastes are being processed through the soil washing plant.

In the soil washing process, excavated material is crushed and screened to 100 mm and magnetically separated. The remaining material is wetted and then passed to

a 2-mm vibrating screen where it is disaggregated with high-pressure water. The > 2 mm gravel fraction goes to a counter-current washer and is eventually drained and discharged for reuse as onsite fill. The gravel washwater and a smaller slurry fraction is split between two hydrocyclones which separates the material into a 63 µm to 2 mm sand fraction and a < 63 µm slurry (Haznews, 1998). The sand is processed in a dense medium separator from which clean sand is dewatered and then discharged to a collection bay. The fines fraction slurry is treated in a thickener tank where flocculants may be added to improve the treatment process. This tank produces sludge with 20 to 40 percent dry matter which is pumped to a continuous filter press. The resulting contaminated filter cake is sent to a landfill for disposal.

Light materials, such as coke, wood fragments, and plastics, are separated out during the washing process and also sent to the landfill with the contaminated fines (Haznews, 1998).

According to BG's property division, the use of soil washing has resulted in a remediation period that is 60 to 70 percent longer than the conventional clean-up approach of excavation of contaminated material and landfill disposal. However the advantages of soil washing include the reduced need for imported clean fill, and a large reduction in transportation during the site work. Overall, the cost of the project is comparable to a "dig and haul" approach (Haznews, 1998).

***SITE Program Demonstration, Toronto, Ontario***

Soil washing was accepted into the Superfund Innovative Technology Evaluation (SITE) Demonstration Program in the winter of 1991. It was demonstrated in Toronto, Ontario, Canada, in April 1992 as part of the Toronto Harbour Commission soil recycling process.

The soil washing process begins when an attrition soil wash plant removes relatively uncontaminated coarse soil fractions using mineral processing equipment; contaminants are concentrated in a fine slurry that is routed for further treatment. The wash process includes a trommel washer to remove clean gravel, hydrocyclones to separate the contaminated fines, an attrition scrubber to free fines from sand particles, and a density separator to remove coal and peat from the sand fraction. If only inorganic contaminants are present, the slurry is treated in an inorganic chelator unit. This process uses an acid leach to free inorganic contaminant from the fine slurry and then removes the metal using solid chelating-agent pellets in a patented countercurrent contactor. The metals are recovered by electrowinning from the chelation agent regenerating liquid. Organic removal is accomplished by first chemically pretreating the slurry from the wash plant or metal removal process. Next, biological treatment is applied in upflow slurry reactors using bacteria that have developed naturally in the soils. The treated soil is dewatered using hydrocyclones and returned to the site from which it was excavated.

The technology is designed to reduce organic and inorganic contaminants in soils. The process train approach is most useful when sites have been contaminated as a

result of multiple uses over a period of time. Typical sites where the process train might be used include refinery and petroleum storage facilities, former metal processing and metal recycling sites, and manufactured gas and coal or coke processing and storage sites. The process is less suited to soils with high inorganic constituents that are inherent to the mineralogy.

Results of the demonstration described above have been published in the Demonstration Bulletin (EPA/520/MR-92/015), the Applications Analysis Report (EPA/540/AR-93/517), the Technology Evaluation Report (EPA/540/R-93/517), and the Technology Demonstration Summary (EPA/540/SR-93/517). These reports are available from USEPA.

The demonstration results showed that soil washing produced clean coarse soil fractions and concentrated the contaminants in the fine slurry. The chemical treatment process and biological slurry reactors, when operated on a batch basis with a nominal 35-day retention time, achieved at least a 90 percent reduction in simple PAH compounds such as naphthalene, but did not meet the approximately 75 percent reduction in benzo(a)pyrene required to achieve the cleanup criteria.

The biological process discharge did not meet the cleanup criteria for oil and grease; the washing process removed almost no oil and grease. The hydrocyclone dewatering device did not achieve significant dewatering. Final process slurries were returned to the excavation site in liquid form.

The metals removal process achieved a removal efficiency of approximately 70 percent for toxic heavy metals such as copper, lead, mercury, and nickel.

The metals removal process equipment and chelating agent were fouled by free oil and grease, forcing sampling to end prematurely. Biological treatment or physical separation of oil and grease will be required to avoid such fouling.

**Contact**

Teri Richardson, USEPA Project Manager, National Risk Management Research Laboratory, 26 West Martin Luther King Drive, Cincinnati, OH 45268, (513) 569-7949, fax (513) 569-7105

***SITE Program Demonstration, Saginaw, Michigan***

A field demonstration of Bergmann, Inc.'s soil washing technology was conducted in May 1992 at the Saginaw Bay Confined Disposal Facility in Saginaw, Michigan. The Applications Analysis Report (EPA/540/AR-92/075) and the Demonstration Bulletin (EPA/540/MR-92/075) are available from USEPA.

Demonstration results indicate that the soil- and sediment-washing system can effectively isolate and concentrate PCB contamination into organic fractions and fines. Levels of metals contamination were also beneficially altered. The effectiveness of soil and sediment washing on inorganic compounds equaled or exceeded its performance for PCB contamination.

During a 5-day test in May 1992, the Bergmann soil and sediment washing system experienced no downtime, operating for 8 hours per day to treat dredged sediments from the Saginaw River.

The demonstration provided the following results:

- Approximately 71 percent of the particles smaller than 45  $\mu\text{m}$  in the input sediment were apportioned to the enriched fines stream.
- Fewer than 20 percent of the particles smaller than 45  $\mu\text{m}$  in the input sediment were apportioned to the coarse clean fraction of soil.

The distributions of the concentrations of PCBs in the input and output streams were as follows:

- Input sediment = 1.6 mg/kg
- Output coarse clean fraction = 0.20 mg/kg
- Output humic materials = 11 mg/kg
- Output enriched fines = 4.4 mg/kg

Heavy metals were concentrated in the same manner as the PCBs. The coarse clean sand consisted of approximately 82 percent of the input sediment.

#### **Contacts**

Mr. Jack Hubbard, USEPA Project Manager, National Risk Management Research Laboratory, 26 West Martin Luther King Drive, Cincinnati, OH 45268, (513) 569-7507, fax (513) 569-7620

Mr. George Jones, Bergmann, A Division of Linatex, Inc., 1550 Airport Road, Gallatin, TN, 37066-3739, (615) 230-2217, fax (615) 452-5525

#### ***SITE Program Demonstration, New Brighton, Minnesota***

The BioTrol Soil Washing System is a patented, water-based volume reduction process used to treat excavated soil. The system may be applied to contaminants concentrated in the fine-sized soil fraction (silt, clay, and soil organic matter) or in the coarse soil fraction (sand and gravel).

In the first part of the process, debris is removed from the soil. The soil is then mixed with water and subjected to various unit operations common to the mineral processing industry. The equipment used in these operations can include mixing trommels, pugmills, vibrating screens, froth flotation cells, attrition scrubbing machines, hydrocyclones, screw classifiers, and various dewatering apparatus.

The core of the process is a multistage, countercurrent, intensive scrubbing circuit with interstage classification. The scrubbing action disintegrates soil aggregates, freeing contaminated fine particles from coarser material. In addition, surficial contamination is removed from the coarse fraction by the abrasive scouring action of the particles themselves. Contaminants may also be solubilized as dictated by solubility characteristics or partition coefficients.

Contaminated residual products can be treated by other methods. Process water is normally recycled after biological or physical treatment. Contaminated fines may be disposed of offsite, incinerated, stabilized, or biologically treated.

This system was developed initially to clean soils contaminated with wood preservative wastes, such as PAHs and PCP. The system may also apply to soils contaminated with petroleum hydrocarbons, pesticides, PCBs, various industrial chemicals, and metals.

The BioTrol Soil Washing System was accepted into the SITE Demonstration Program in 1989 and demonstrated between September and October 1989 at the MacGillis and Gibbs Superfund site in New Brighton, Minnesota. A pilot unit with a treatment capacity of 500 pounds per hour operated 24 hours per day during the demonstration. Feed for the first phase of the demonstration (2 days) consisted of soil contaminated with 130 ppm PCP and 247 ppm total PAHs; feed for the second phase (7 days) consisted of soil containing 680 ppm PCP and 404 ppm total PAHs. Contaminated process water was treated biologically in a fixed-film reactor and then recycled. A portion of the contaminated soil fines was treated biologically in a three-stage, pilot-scale EIMCO Biolift reactor system supplied by the EIMCO Process Equipment Company. The Applications Analysis Report (EPA/540/AR-91/003) and the Technology Evaluation Report Volume I (EPA/540/5-91/003a) and Volume II (EPA/540/5-91/003b and EPA/540/5-91/003c) are available from EPA.

Key findings from the BioTrol demonstration are summarized below:

- Feed soil (dry weight basis) was successfully separated into 83 percent washed soil, 10 percent woody residues, and 7 percent fines. The washed soil retained about 10 percent of the feed soil contamination; 90 percent of this contamination was contained in the woody residues, fines, and process wastes.
- The multistage scrubbing circuit removed up to 89 percent PCP and 88 percent total PAHs, based on the difference between concentration levels in the contaminated (wet) feed soil and the washed soil.
- The scrubbing circuit degraded up to 94 percent PCP in process water. PAH removal could not be determined because of low influent concentrations.

**Contact**

Dennis Chilcote, BioTrol, 10300 Valley View Road, Suite 107, Eden Prairie, MN 55344-3456, (612) 942-8032, fax (612) 942-8526

### **5.2.8 Soil Vapor Extraction (SVE)**

SVE is mechanically similar to bioventing (Section 5.2.4.2), but is operated at a higher flow rate to achieve volatile compound removal in addition to oxygen replenishment. SVE uses an electric- or gasoline-powered blower system connected to wells via manifolds. Air treatment, whether through a separate system (such as activated carbon or catalytic oxidation) or as part of a gasoline-

powered system, is usually the most expensive single component of an SVE project and may represent as much as 50 percent of the overall cost.

Performance of an SVE system is monitored using measurements at the blower system and at piezometers (small-diameter wells or soil gas sample points) installed in the zone being treated. Flow measurements at the blower or at individual wells can be used to help calculate removal rates. Vapor samples from piezometers, wells, or at the blower discharge can be analyzed in the field or by a laboratory, and the results can be used to estimate the rate of subsurface decontamination and the rate of volatile compound removal. Vapor samples from the discharge of the air treatment system are usually required to test system performance and to verify permit requirements. Final evaluation of SVE performance can be assessed by collecting soil vapor samples from piezometers and/or soil samples from the treated zone.

### **Operational Considerations**

The suitability of SVE for MGP sites will depend on the site-specific requirements for volatile compound removal or prevention of volatile compound migration as a remediation objective. The site also needs to have a water table depth at least 10 feet and a subsurface profile that allows air to flow through the zone to be treated. This profile criterion is met if the soil is coarse- or fine-grained but not saturated and if the organic compound mass is infiltrated into the soil, rather than collected in a subsurface pool (which would be impermeable to air flow).

The design feasibility of SVE is typically proven through a field pilot test. The test typically consists of pumping a single well that is screened in the center of the zone to be treated. Piezometers are placed throughout and near the margins of the zone to be treated. The purposes of this test are to:

- Size the blower by assessing how much air can be pumped from a well.
- Size the air treatment system by determining what initial concentrations might be expected.
- Observe the subsurface flow pattern throughout the zone of treatment.

If the piezometers indicate the pilot test well did not produce an adequate subsurface flow pattern, the full-scale design could call for additional wells, a new well with a deeper screened interval, or sealing to eliminate surface leakage. Shallow sites may be more effectively treated using horizontal wells in trenches.

Most SVE systems operate for 1 to 3 years. During this time, the air treatment system requires periodic maintenance or changeout, a condensate tank requires emptying (especially in cold weather), and samples and measurements need to be collected and reported. At the site, the aboveground portion of the system usually takes up one or two parking spaces and almost always requires 115V or 220V electrical power. Natural gas is sometimes required (if catalytic oxidation is selected as the air treatment option). The blower itself may be a source of excessive noise if silencers (upstream and downstream) or soundproof containment are not provided or if the blower is undersized and working near its maximum output. The underground portion of the system is typically accessed through well vaults,

and the manifold lines connecting the wells to the blower system are often buried in frequently accessed areas.

Sites with relatively shallow water tables or with wells screened near the water table can experience excessive water accumulation and blockage of air flow if too much vacuum is applied to the system. Most systems can be operated safely under these conditions by managing the applied vacuum (in feet of water column) to be less than one half the distance from the water table to the top of the well screen.

Granular activated carbon is often selected as the air treatment alternative because of its minimal power requirements, its availability, and its acceptability to regulators. It is often the least expensive, on a unit basis, for sites with relatively low vapor concentrations. Carbon operates at highest efficiency when temperatures are lower than 120°F; however, most SVE design manuals fail to provide guidance on temperature management of the blower discharge to the carbon vessels. Excessive heat may be a concern at sites with high ambient temperature, such as in the south or southwestern United States, and/or where relatively high vacuums are required because of fine-grained soil conditions. In these situations, carbon may still be cost effective if used in conjunction with a condenser or a heat exchanger.

#### **Applications and Cost**

SVE has been used as a remediation process of choice at thousands of underground storage tank leak sites. Applications at MGP sites are not as widespread; however, SVE can be used to treat soils at sites contaminated with some SVOCs (such as naphthalene).

SVE can be applied with little disturbance to existing facilities and operations. The technology can be used at sites where areas of contamination are large and deep or when the contamination is present beneath a building. The system may be modified depending on additional analytical and subsurface characterization data and/or changing site conditions (RIMS, 1998).

The components of SVE systems are commonly available off the shelf, and the necessary wells can be installed by any qualified local engineering firm. Aboveground installations typically include:

- Vacuum pumps and/or blowers and associated controls
- Pressure gauges and flow meters at wellheads and pumps
- Control valves to adjust air flow
- An air-liquid separator (for removing moisture from the extracted gases)
- Vapor treatment unit(s)

More complex SVE systems may incorporate trenches, horizontal wells, forced air injection wells, passive air inlet wells, low permeability or impermeable surface seals, or multiple level vapor extraction wells in single boreholes. In addition, sophisticated systems are available to monitor moisture, contaminant levels, and temperature (RIMS, 1998).

The efficiency of SVE can be enhanced through the use of formation fracturing, pulsed pumping, or horizontal extraction wells. These enhancements can increase the soil permeability or the efficiency of mass removal or allow access to previously inaccessible areas of contaminated soil (e.g., below the water table, in less permeable formations) (RIMS, 1998).

Treatment costs for sites using SVE depend on various conditions such as site size, extent of contamination, regulatory requirements for permits, other site-specific and chemical-specific conditions, and site cleanup criteria. Therefore, cost can only be estimated on a case-by-case basis. To provide an indication of the range in SVE project costs, the treatment of 185,000 cubic yards of soil at one site cost \$2 per cubic yard while, at another site where 650 cubic yards required treatment, the cost was \$450 per cubic yard. These values represent treating the soil rather than cost per pound of contaminant treated. The major part of the total process cost associated with SVE is usually the operating expenses for labor, maintenance, and monitoring (RIMS, 1998).

#### **Benefits**

- Treats in situ, volatile compounds in soil, including areas beneath structures, at lower cost than excavation
- Accomplishes both volatile compound removal and oxygen replenishment, and promotes in situ biodegradation for compounds that may not be removed
- Can be implemented with relatively little disruption to ongoing operations
- Focuses on volatile compounds, including benzene and naphthalene; therefore treats the most mobile of the organic compounds beneath an MGP site, which makes it an effective risk-reduction approach
- Has well-established design and feasibility evaluations

#### **Limitations**

- Not effective at sites where remediation goals include concentration reduction of low-volatility compounds (which are frequently important for MGP site restoration)
- Difficult to successfully implement where the water table is shallower than 5 to 10 feet below grade, or where the soil is fine-grained (clayey) and nearly saturated
- Limited effectiveness on volatile compounds trapped in a liquid mass or pool of subsurface organic compounds (air will not flow through liquids; volatile compounds trapped in liquids will only be removed through diffusion, which is too slow to be cost effective)

#### **Case Study**

##### ***Beale AFB, Marysville California***

Numerous SVE systems were installed using granular activated carbon with no air temperature management. Upon start up, breakthrough of the carbon occurred within three days. Systems were retrofitted with a converted truck radiator

installed downstream of the blower. Air was produced at ten degrees above ambient for carbon treatment; and carbon efficiency increased three-fold (CH2M HILL, 1998; Nelline Scheuer).

**Contacts**

Ms. Carol Goudette, 9 CES/CEVR, 6601 "B" Street, Beale AFB, CA 95903

Ms. Cori Condon, RWGCB, Assistant Engineering Geologist, 3443 Routies Road, Sacramento, CA 95827

**Chapter 5**  
**Technologies for Source Material Treatment**

## Chapter 6

### References

AFCEE, 1994. Bioventing Performance and Cost Summary, Draft. Brooks AFB, TX.

ASTM, 1995. Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites. Designation E-1739-95.

ASTM, 1996. Provisional Standard Guide for Accelerated Site Characterization for Confirmed or Suspected Petroleum Releases. Designation PS 3-95.

Alleman et al., 1995. "Bioventing PAH Contamination at the Reilly Tar Site." In Situ Aeration: Air Sparging, Bioventing and Related Remediation Processes. Battelle Conference Proceeding.

Backhus, Debra A., Joseph N. Ryan, Daniel M. Groher, John K. MacFarlane, and Philip M. Gschwerd, 1993. "Sampling Colloids and Colloid-Associated Contaminants in Ground Water." *Ground Water*, May-June, Vol. 31, No. 3, pp. 466-479.

Barnett Alexander, Catherine, 1977. MGP Site Planning: New Community Development Opportunities. *American Gas*, November.

Barr Engineering Company, 1996. "Field Demonstrations of Thermal Desorption of Manufactured Gas Plant Soils." EPRI TR-105927. Electric Power Research Institute. Minneapolis, Minnesota. September.

Bay Area Air Quality Management District, 1996. BAAQMD CEQA Guidelines, Assessing the Air Quality Impacts of Projects and Plans. p. 66. April.

Biotreatment News, 1996. "BAC Meets." p. 10. November.

Bradley, L.J.N., B.H. Magee, and S.L. Allen, 1994. "Background Levels of Polycyclic Aromatic Hydrocarbons (PAH) and Selected Metals in New England Urban Soils." *Journal of Soil Contamination*. CRC Press, Inc.

Bevolo, A.J., B.H. Kjartanson, and J.P. Wonder, 1996. "Ames Expedited Site Characterization Demonstration at the Former Manufactured Gas Plant Site, Marshalltown, Iowa." Ames Laboratory. March.

Brown, S.M., D.R. Lincoln, and W.A. Wallace, 1988. "Application of Observational Method to Hazardous Waste Engineering." ASCE. *Journal of Management Engineering*, Vol. 6, No. 4, pp. 479-500.

Burton, Jacqueline C., 1994. "Expedited Site Characterization for Remedial Investigations at Federal Facilities." Argonne National Laboratory, FER III and WM II Conference & Exhibition. April 27-29.

- Cambridge, Megan and Adam Palmer, 1998. "Expedited Remedial Action Program, Alhambra Manufactured Gas Plant Site." Department of Toxic Substances Control, California Environmental Protection Agency. April.
- Chaconas, J. et al., 1997. "Bioremediation of Diesel-Contaminated Soils at Navy National Test Site." *In-Situ and Onsite Bioremediation, Volume 1*. Battelle Press, p. 497.
- Commonwealth of Pennsylvania, Department of Environmental Protection, 1996a. Multi-Site Remediation Agreements.
- Commonwealth of Pennsylvania, Department of Environmental Protection, 1996b. "News Release: DEP Signs Innovative Environmental Agreement with Utility Companies."
- Covello, Vincent T. and Miley W. Merkhofer, 1993. *Risk Assessment Methods: Approaches for Assessing Health and Environmental Risks*. Plenum Press, New York, NY.
- D'Appolonia, E, 1990. "Monitored Decisions." *Journal of Geotechnical Engineering*, 116:4-34.
- Daddario, David J, 1997. "Revitalizing Real Estate Having Contamination Constraints." Proceedings from Conference on Risk-Based Decision-Making Influencing Financial Transactions and Brownfields Redevelopments, RTM Communications, Inc., San Francisco, CA. November.
- Department of Energy, Grand Junction Projects Office. Grand Junction, CO.
- DíAngelo, Wm. Chip, and Anthony Chiesa, 1998. "Take it to the MART." *Soil & Groundwater Cleanup*, June.
- DMLS™. <http://www.margan.com>.
- Edwards, Nelson, T, 1983. "Polycyclic Aromatic Hydrocarbons (PAHs) in the Terrestrial Environment – A Review." *Journal of Environmental Quality*, Vol. 12, No. 4, p. 427. October-December.
- Elsevier Sciences Inc, 1997. "Three Innovative Soil Gas Monitoring Technologies Evaluated." *The Hazardous Waste Consultant*. Vol. 15, Issue 6, p. 1.8-1.10. (no author credited).
- EPRI. Undated. *Report Summary – Microscale Solvent Extraction Methods for the Analysis of Solids and Liquids, Vol. 1 and 2*. TR105317.
- EPRI Journal, 1995. "In the Field." May/June.

EPRI, 1997. *Cold-Patch Asphalt*. Report No. TR-108597.

EPRI, 1997. *Review: Asphalt Batching of MGP Tar-Containing Soil*. Report No. TR-108597. December.

Finley, et al., 1994. "Recommended Distribution For Exposure Factors Frequently Used in Health Risk Assessment." *Risk Analysis*, Vol. 14, No. 4.

Gas Research Institute (GRI), 1996. *Management of Manufactured Gas Plant Sites, Volume 2*.

Geo-Con, Inc, 1993. *SSM Soil Stabilization, Case Study No. 2, Shallow Soil Mixing from Geo-Con, Inc.*. C-SSM-02-93.

Haimann, Richard, Kathleen Schoen, Houshang Nezafati, and Jim Hartley, 1996. "An Observational Approach to Removing LNAPL." Non-Aqueous Phase Liquids (NAPLs) in Subsurface Environment. Proceedings of the Conference of American Society of Civil Engineers. November 12-14.

Hasbrouck, J.C., O.A. Dickenson, T.T. Boyd, and W.P. Hasbrouck, 1996. *Baseline Seismic Technology Report, 3D/3C Seismic for Site Characterization*. U.S. Department of Energy. Grand Junction, CO. April.

Haznews, 1998. "Gasworks Clean-Up First Large-Scale Soil Washing in U.K." *Haznews*, No. 122, p. 1. May.

*Human and Ecological Risk Assessment*, Vol. 4, No. 2, 1998. Special Issue: Probabilistic Methods in Risk Assessment. CRC Press. April.

Kelley, R.L., K. Kayser, V.J. Srivastava, et al, 1997. "MGP-REM Process in Full-Scale Landfarming Application: Integrating Low-Cost, Innovative Technology with Risk-Based Cleanup." Presented at the IGT Gas, Oil and Environmental Biotechnology and Site Remediation Technologies, Orlando, Florida. December 8-10.

Leeson, A. and R.E. Hinchee, 1996. Battelle Memorial Institute. Principles and Practices of Bioventing. Volume 1: Bioventing Principles.

Nelson, G.L., Steven Shipley, Johanshir Golchin, Robert K. Kelly, Kevin Kayser, Vipul Srivastava and Don Richard. "Risk-Based Remediation of MGP Wastes Using an Innovative Process."

Newmark, Robin L., and Roger D. Aines, 1998. "They All Like It Hot: Faster Cleanup of Contaminated Soil and Groundwater." *Science & Technology Review*. May.

New York State Department of Environmental Conservation, 1992. "News Release: For Release: Immediate, Tuesday, December 8, 1992, Niagra Mohawk to Act on 22 Former Coal Gas Plants Statewide."

- Nielsen, P.H., T. Christensen, H. Albrechsten, and R. Gillham, 1996. "Performance of the In-Situ Microcosm Technique for Measuring the Degradation of Organic Chemicals in Aquifers." *Ground Water Monitoring Review*, Winter: 130-140.
- NJDEP/PSE&G, 1996. *Manufactured Gas Plant Site Remediation Streamlining Report*. January.
- North American Realty, 1997. *CASE STUDY: Adaptive Reuse of Manufactured Gas Plant Site to Mixed-Use Redevelopment*. Racine, WI.
- Onsite Environmental Laboratories Inc, 1998. (510) 490-8571/(617) 472-8022. <http://www.onsitelabs.com>.
- Peck, R. B, 1969. "Advantages and Limitations of the Observational Method in Applied Soil Mechanics." *Geotechnique*, Vol. 19, pp. 171-187.
- PP&L, Resources, Inc, 1996. "News Release: PP&L to do Cleanup Work as Part of Lycoming College Redevelopment Project."
- PSE&G, 1997. Generic Remedial Investigation Work Plan. November.
- Precision Sampling, Inc, 1998. Technical literature from company.
- Rader, Kermit L., and Martin H. Sakolow, Jr, 1997. "Multi-Site Remediation Agreements." *Environmental Law, A Supplement to the Legal Intelligencer, PA Law Weekly*. April.
- RIMS, 1998. Online Remediation Technology Library. <http://remedial.com>.
- Risk Analysis*, Volume 14, Number 4, 1994. *Special Issue: Uncertainty Analysis*. Plenum Publishing Company. August.
- Saar, R.A, 1997. "Filtration of Ground Water Samples: A Review of Industry Practice." *Ground Water Monitoring and Remediation*, Winter, Vol. XVII, No. 1, pp. 56-62.
- Solinst Canada Ltd, 1998. Technical literature from company. 1-800-661-2023. <http://www.solinst.com>
- Srivastava, Vipul J, 1996. "MGP Site Remediation Strategies and a Review of Available Technologies" and "IGT's Innovative Approaches" from Proceedings from the Ninth International IGT Symposium on Gas, Oil, and Environmental Biotechnology. December 9-11.
- TerraTherm, 1997. Cost and Performance Report. Provided to USEPA Technology Innovation Office & Tetra Tech EM, Inc. October 7.
- The Annals of the American Academy of Political and Social Science*, Vol. 545, 1996. Challenges in Risk Assessment and Risk Management. May.
- Underhill, 1997. Battelle Bioremediation Conference Proceedings.
- USACE, 1995. *Engineering and Design Manual—Soil Vapor Extraction and Bioventing*. Publication No. EM 1110-1-4001. November.

- USACE, 1998. *Engineering and Design Manual—Soil Vapor Extraction and Bioventing*. Publication No. 1110-1-4001. November 30.
- USEPA, 1989. *Risk Assessment Guidance for Superfund, Volume 1, Human Health Evaluation Manual (Part A)*.
- USEPA, 1991. *Applications Analysis Report*. EPA/540/AR-91/003.
- USEPA, 1991. *Technology Evaluation Report. Volume 1*. EPA/540/5-91/003a.
- USEPA, 1991. *Technology Evaluation Report, Volume 2*. EPA/540/5-91/003b and EPA/540/5-91/003c.
- USEPA, 1992. *Applications Analysis Report*. EPA/540/AR-92/075.
- USEPA, 1992. *Demonstration Bulletin*. EPA/520/MR-92/015.
- USEPA, 1993. *Applications Analysis Report*. EPA/540/AR-93/517.
- USEPA, 1993. *Technology Demonstration Summary*. EPA/540/SR-93/517.
- USEPA, 1993. *Technology Evaluation Report*. EPA/540/AR-93/517.
- USEPA, 1997. *Analysis of Selected Enhancements for Soil Vapor Extraction*. EPA/542/R-97/007. September.
- USEPA, 1997. *Guiding Principles for Monte Carlo Analysis*. Office of Research and Development, NCEA. EPA/630/R-97/001.  
<http://www.epa.gov/ncea/monteabs.htm>.
- USEPA, 1997. "Policy for Use of Probabilistic Analysis in Risk Assessment at the U.S. Environmental Protection Agency." Office of the Administrator. Available at <http://www.epa.gov/ORD/spc/probcovr.htm> and <http://www.epa.gov/ORD/spc/probpol.htm>.
- USEPA, 1998a. *Bangor Gas Works, Bangor, Maine. A Superfund Redevelopment Success*. Office of Emergency and Remedial Response. EPA/540/F-98/008. June.
- USEPA, 1998. Region 9 Preliminary Remediation Goals (PRGs). May.
- USEPA, 1998. *Remediation Technologies Screening Matrix and Reference Guide*. Downloaded from USEPA's Technology Innovation Office homepage @ <http://clu-in.com>.
- Voorhees, John, Isaacson, Rosenbaum, Woods and Levy, 1997. "Managing Brownfields Risks Using the Systems Approach." Adapted from the *International Environmental Risk Management: ISO 14000 and the Systems Approach*.
- Wilson, John T., Jong S. Cho, and Frank P. Beck, 1997. "Field Estimation of Hydraulic Conductivity for Assessments of Natural Attenuation." *In Situ and On-Site Bioremediation: Volume 2*. Presented in New Orleans, April 28 - May 1 and reprinted by Batelle Press.
- Wilson, L.G., Larne G. Everett, and Stephen J. Cullen, 1995. *Handbook of Vadose Zone Characterization and Monitoring*." p. 569.

Winsor, Eleanor W, 1996. "Multi-Site Agreements: A Smart Strategy."  
*Pennsylvania's Environment*. June.

Work Systems Associates, Inc, 1995. "The Chartering Process to Create High  
Performance Work Teams."

## Chapter 7

# **Additional Sources of Information**

American Gas Association. MGP Management Symposium Conference Proceedings.

Electronic Power Research Institute. 1991. Selected Technologies for MGP Site Remediation GS-7554. October.

Institute of Gas Technology. Gas, Oil and Environmental BIOTECHNOLOGY IX Conference Proceedings.

Edison Electric Institute. 1984. Handbook on Manufactured Gas Plant Sites. September.

Historical Overview of Manufactured Gas Processes Used in the United States. Remediation Technologies, Inc. as presented at the International Symposium and Trade Fair on the Clean-up of Manufactured Gas Plants. September. 1995.

Institute of Gas Technology, Environmental Biotechnologies and Site Remediation Technologies Conference Proceedings.

Institute of Gas Technology, Hazardous Waste and Environmental Management in Gas Industry Conference Proceedings.

Electric Power Research Institute and Gas Research Institute, Management of Manufactured Gas Plant Sites, Technology Transfer Seminar Conference Proceedings.

Management of Manufactured Gas Plant Sites, a Two-Volume Practical Reference Guide from Gas Research Institute. 1996.

Manufactured Gas Plant Overview. Arizona Public Service Company, October. 1992.

Recovery of MGP Cleanup Costs Conference Proceedings.

U.S. Production of Manufactured Gases: Assessment of Past Disposal Practices. U.S. Environmental Protection Agency, October. 1987.

Summary Report of the Town Gas Site Workgroup. California Environmental Protection Agency, Department of Toxic Substances Control, Site Mitigation Branch. August. 1991.

