I/
5/01

MILWAUKEE SCHOOL OF ENGINEERING

COST ASSESSMENT FOR REMEDIATION/ REDEVELOPMENT OF A FORMER MANUFACTURED GAS PLANT SITE

By

Florence Budiarto

xc for Matt
Jeff G.

and letter w/
letter copy for
me (send it
to Art Harrington

A Report Submitted to the Faculty of the
Milwaukee School of Engineering
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science
in Environmental Engineering

Milwaukee, Wisconsin

May, 2001

Table of Contents

List of Figures

Lists of Tables

Executive Summary

A Phase I Environmental Assessment was conducted by the City of Milwaukee on the *Milwaukee Solvay Coke and Gas Company (Solvay Coke), a former manufactured* gas plant (MGP). The study concluded that the site is most likely contaminated, based on the past site uses as a coal storage facility, a coking plant, a coal gas production plant, and a steel company. The Wisconsin Department of Natural Resource (WDNR) has found relatively high pollutant levels at other former coal and foundry products storage facilities and coal gasification facilities in the Milwaukee area. A Phase II Environmental Assessment has yet to be completed.

Based on the historic site information gathered, a conceptual contaminants model was developed in order to design a remediation plan for the site. Likely contaminatns include PAHs, phenols, benzene, and cyanide. Further site assessment is required to understand the level of contaminants.

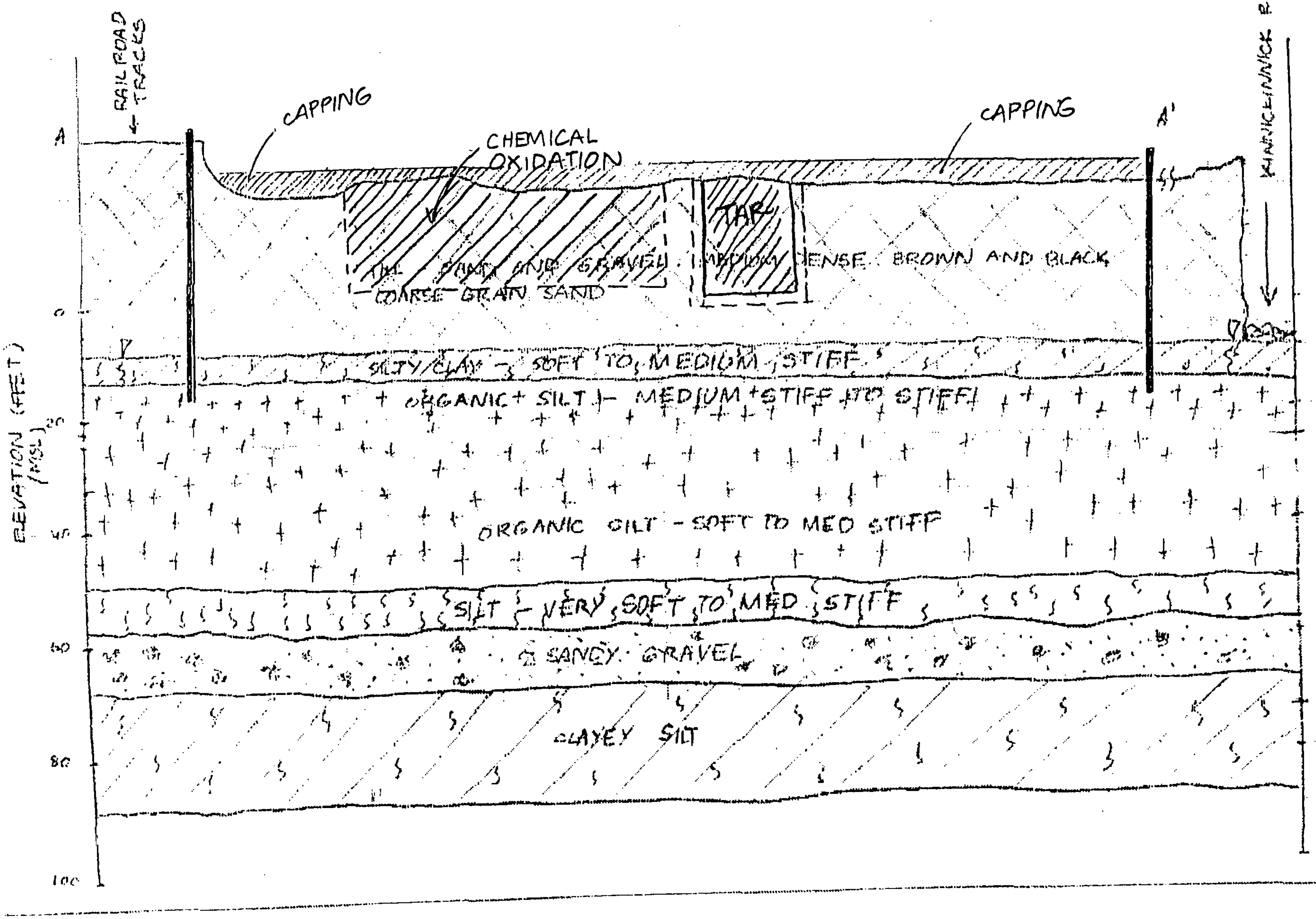
The goal of this project is to develop a conceptual remediation plan for the site. The remediation is geared toward reducing mass and mobility of the contaminants. This model includes selection of state-of-the-art technologies and cost estimation for remediating the site.

The technology selections were based on available and most applicable technologies for remediating MGP residues. The technologies recommended for remediating this site include in-situ chemical oxidation, thermal treatment, capping, natural attenuation, and a vertical barrier. These technologies have been proven to be successful in treating MGP residuals at other sites.

The conceptual remediation plan for the Solvay Coke site includes excavating the areas containing coal tar and sludge and treating the contaminated soil using onsite thermal treatment. The heavily contaminated soil will be treated using in-situ chemical oxidation, and the lightly contaminated soil will be covered by soil cap. Residual groundwater contamination will be treated by natural attenuation, after the source of contaminants has been successfully removed. A slurry wall will be placed to contain the groundwater if natural attenuation is not sufficient to address groundwater issues and to prevent offsite migration of the contaminants. Figure ES-1 presents a conceptual remediation plan for the site.

As the result of this study, cost estimation for remediating the site was developed. The cost for remediating the site is estimated to be $11 million. The cost includes the cost of demolition, site investigation, materials excavation and treatment, and indirect costs. The cost estimate also includes the cost for implementing slurry wall, which is estimated to be about $1.2 million. The cost estimate is considered very preliminary, and, as discussed, is based on the likely extent of contaminants as can be determined from available site records. Future environmental Assessments would be required to provide detailed information for the cost estimate.

ES-1. A CONCEPTUAL SITE GEOLOGY REMEDIATION PLAN



Section 1.

Introduction

From the early 1800s until the 1960s, gas fuel was produced in more than 5,000 manufactured gas plants (MGPs) throughout the United States. Town gas plants were established in most American cities to supply the necessary commodity for their town. These town gas plants were designed to generate gas from readily available coal, carbureted water or oil. By the late 1940s, natural gas was widely available in this country through pipelines. Failing to compete with natural gas, the manufactured gas industry declined after the 1950s. By the late 1970s, only a few MGPs remained active.

2.2m x 2.

It was estimated that from 1880 to 1950, gas plants produced approximately 15 trillion cubic feet of gas and approximately 11 billion gallons of tar as a by-product [1]. Although most of the MGPs, have closed and have been demolished, they typically have left behind environmental contamination. At many MGPs, underground storage tanks were constructed of wood or brick, with process piping and equipment, which frequently leaked. Releases– coal tars, oils, and condensates produced – are still beneath the surface or seeping into the groundwater. Typical contamination includes polycyclic aromatic hydrocarbons (PAHs), phenols, benzene, and cyanide [2].

A Phase I Environmental Assessment was conducted by the City of Milwaukee on the Milwaukee Solvay Coke and Gas Company (Solvay Coke), located at 311 East Greenfield Avenue [3]. This facility was an MGP site for most of the 1900's. The study concluded that the site is most likely contaminated, based on the past site uses as a coal storage facility, a coking plant, a coal gas production plant, and a steel company.

This project identifies state-of-the-art remediation technologies for contaminants generated during coking and gas manufacturing. Based on the information gathered, a conceptual contaminant model was developed in order to design a remediation plan for the site. Finally, a cost estimate for remediating the site was completed. Further environmental studies are required to determine the actual extent of soil and groundwater contamination and hence the actual cost of cleanup.

Section 2
Site Background

During the early 1900s, Milwaukee Solvay Coke and Gas Company was one of the largest gas manufacturers in Milwaukee. The coke produced was used in foundries and steel manufacturing operations in the Milwaukee area and Southeast Wisconsin. The 600 feet of dock frontage on the Kinnickinnick River and five miles of railroad track on the property provided access for the three locomotives lorries to carry the coal into the plant.

This section presents the background of the site, including the site location, history, and condition. The site location includes the geographic location of the site with respect to the city of Milwaukee. The site history portrays how the site has been used and how it is currently being used, which helps in understanding the source of contaminants. The site condition includes a discussion of the regional geology, area geology, and site specific geology.

2.1 Site Location

The Solvay Coke property is located within a triangle tract, lying between the Chicago and North Western and Chicago, Milwaukee & St. Paul Railways and the Kinnickinnick River, in the Menomonee River Valley (Figure 1). Figure 2 presents the Solvay Coke land use map. The site covers approximately 46 acres of water front land. The site itself is bordered by East Greenfield Avenue to the north, the Kinnickinnic River Basin to the south and east, and railroad tracks to the west. This site was originally marshland, but by reclamation was converted into one of the most valuable and advantageous industrial locations in Milwaukee [4]. Figure 3 shows the picture of Solvay Coke while it was on operating facility.

The Solvay Coke property is situated in a portion of the Northwest quarter and Southwest quarter sections of section 4, Township 6 North, Range 22 East and Southwest quarter section of section 33, Township 7 North, Range 22 East in Milwaukee County, Wisconsin.

2.2 Site History

Solvay Coke was established by Armin A. Schlesinger in 1902. In 1905, the company supplied gas under contract to the Milwaukee Gas Light Company. Through the early 1920s, the company was operated as a subsidiary of the Newport Company. In the mid 1920s, the Koppers Company, a Chicago based coke and manufactured gas conglomerate, acquired the company and changed its name to the Milwaukee Solvay Coke Company. In 1947, the Milwaukee Solvay Coke Company was purchased by the Milwaukee Gas Light Company. In 1949, the Milwaukee Gas Light Company switched to natural gas, even though Milwaukee Solvay continued to produce manufactured gas, as a backup for the natural gas supply [5].

In 1962, Milwaukee Solvay was acquired by Pickands, Mather and Company, who served as sales agents and shippers of Milwaukee Solvay product. In the late 1970s, Milwaukee Solvay was purchased by Wisconsin Gas Company. In the 1970s, some of their operations were shut down due to excessive dust emissions. The Milwaukee Solvay was identified by Wisconsin Department of Natural Resource (WDNR) as the largest source of dust emissions in Menomonee Valley [6]. Milwaukee Solvay was closed in 1983. In 1983, Wisconsin Wrecking Company (WWC), a concrete recycling company, entered into a lease/ purchase agreement with Cliffs Mining Co (f/k/a Pickands, Mather & Company). Today, WWC occupies the property and is still interested in buying it [7]. Figure 4 shows the 1986 Aerial photo of Solvay Coke.

At its peak, the plant operated 200 coke ovens, which produced up to 800 tons of coke per day. Over the past 80 years of operation, Milwaukee Solvay produced metallurgical coke for use in the production of steel. It also produced various byproducts from its coking production such as coal gas and coal tar [8].

The Sanborn maps were developed by Sanborn Company beginning in the late 1800s and used for fire insurance purposes. The Sanborn maps of the site were obtained from the American Geology Society Library of University of Wisconsin – Milwaukee and the Milwaukee Public Library. As shown on Figures 5 through 7, the Sanborn maps of the site document how the site was developed throughout the years of operation. The maps mainly show the process equipment, offices, laboratory, machine shop, gas tank, ammonia tank, coal pile, condensing houses, and brick coke ovens.

Throughout the years, there were changes inside the plant. For example, by the year 1931, Solvay Coke added coal tracks, which made coal unloading easier. Several conveyors were added to convey coal to the brick coke ovens that were located on the south and the north end of the site. Later on, Solvay Coke closed some of the railroad tracks inside the plant and built propane tanks. While the coke production increased, Solvay Coke added several ammonia tanks and gas holding tanks. However, due to incomplete information on the map date, it was difficult to establish exactly when the addition or removal of the structures took place. Currently, the remnant of the buildings can still be found on the site location. Figure 8 shows the present condition of the site.

2.3 Physical Setting

The physical setting is describes the geology and hydrogeology. The regional geology provides an overview of geology in southeastern Wisconsin. The area geology section presents the geologic condition of the Menomonee Valley. Finally, the site-specific geology section provides information on the geology of the site itself, which includes topography, soils and bedrock structures of the site. Through this information, a conceptual cross section of the site was developed that serves as the basis for the contaminant distribution model.

2.3.1 Regional Geology

The southeastern Milwaukee area generally has low topographic relief that ranges from flat to gently undulating to hilly. The soil deposits overlying bedrock include soils formed as a result of continental glaciation and soils formed by recent fluvial and estuarine deposition. Estuarine deposits are usually found in shallow estuaries and marshy floodplains and range in color from green gray to dark brown. Grain size within these deposits ranges from organic clay to organic silts and silts without organics. They also exhibit low to very low permeability [9].

The glacial soils were deposited beneath a series of glaciers that advanced out of the Lake Michigan basin. According to data collected by the Wisconsin Geological and, Natural History Survey and the U.S. Geological Survey, the surficial geology of

Milwaukee consists of glacial deposits of Quarternary age. These deposits typically consists of till; unstratified clay, silt, sand, gravel, and boulders with thickness of up to 200 feet in portions of the regions.

A geologic cross section of the region is presented on Figure 9. Bedrock structure underlying the glacial deposits consists of undifferentiated Silurian and Ordovician age dolomites. Underlying these formations are the St. Peter Sandstone and undifferentiated sandstone [10].

2.3.2 Area Geology

The site in generally is located in the area of the Menomonee Valley. The geology of the Menomonee Valley is grouped into four geologically and hydrogeologically distinct units [11]:

The first unit is the shallowest unit and is comprised of fill material, which consists of reworked clay, silt, sand, and gravel with local inclusions of cinder, glass, wood, metal, rubble, brick, ash, and household type trash. The thickness of the material ranges from 2 to 22 feet and generally this unit would have the same composition of materials.

The second unit, which underlies the first unit, is a soft to stiff organic-rich silt, clayey silt, and/ or silty clay with local peat layers.

The third unit consists of the unconsolidated deposits of loose to dense sand, silt, and silty fine sand. Throughout the unit, a complex interbedding of silty fine sand and gravel with discontinuous laminae sequence of silt and clay are present. A relatively continuous silt/ clay rich zone is present at depth. The characteristic of this unit is the lack of organics, complex sequences of sand, silt, and clay. The thickness of this unit ranges from 35 to 200 feet [12].

The fourth unit consists of undifferentiated dolomite bedrock. Shale and sandstone were also observed below the dolomite in selected borings in the Menomonee Valley study area. The thickness of this unit in depth below the surface ranges from 25 to 250 feet. The Milwaukee Metropolitan Sewerage District studied the geology of this area as part of its deep tunnel system [13]. Figure 10 presents the area geology cross-section from this study.

2.3.3.Site Specific Topography and Geology

Based on the quarter section topographic map obtained from the SEWRPC (Figure 2), the surface topography of the vicinity is generally uniform and slightly elevated in some areas; ranging from 583.0 feet above the sea level to 597.7 feet above the sea level. The elevation of the property ranges from 584.8 feet above sea level to 593.8 feet above sea level.

Figure 11 presents a conceptual geologic cross section of the site. Coarse grained media, such as fill, sand, gravel, can be found with thickness ranging from 15 to 20 feet. Underlay the coarse grained media, silty clay and other fine grained medium can be found. The thickness of this zone is approximately 20 feet deep [14].

Section 3

Source of Contaminants

Throughout the process of producing coke and gas, by-products are produced that typically contaminate the soil and groundwater. This section provides information on the source of contaminants found at a typical MGP site. The discussion includes the process description and the typical byproducts from each process.

3.1 Typical Coal carbonization Process

There are primarily three processes for manufacturing gas:

1. Coal carbonization
2. Water gas and/ or carbureted water gas
3. Oil gasification

According to the Phase I Environmental Assessment Report, the process used at Solvay Coke was coal carbonization. The other two processes were commonly used in mid-1900s; however, they offered similar environmental problems as the coal carbonization process.

3.1.1 Coal

Coal derives from converted organic matter laid down in the swamps that covered large areas of the northern hemisphere during the Mississippian to Tertiary periods. Coal is composed of mostly organic matter and up to 50% inorganic matter [15]. The organic matter includes carbon, hydrogen, oxygen, nitrogen, and sulfur.

There are many different types and grades of coal. The products of any given coal in any given reaction (combustion, pyrolysis, gasification, liquefaction, etc) may differ from those of another coal under identical process.

3.1.2 Coking Process

Coke making is a process where coal is treated in a reducing atmosphere with steam, carbon monoxide, hydrogen, or mixture of these gases to yield a combustible product, coke. Figure 12 shows the coke making process flow diagram.

3.1.3 Coal Carbonization Process Description

Coal carbonization is the high temperature destructive distillation process of coal in the absence of oxygen. In this process, approximately 30% of the coal weight is released as gas and residuals [16].

According to Phase I Environmental Assessment Report, on average, carbonization of a ton of coal produces of about [17]:

- 0.7 ton of coke, which is approximately 11,500 ft^3
- 345 m^3 of gas
- 12 gallons (45.6 liters) of tar
- 27 pounds (12 kg) of ammonium sulfate
- 50 gallons (190 liters) of benzol
- 0.9 gallon (3.4 liters) of toluene and naptha
- 0.5 pound (0.2 kg) of naphthalene

First, bituminous coal was added to a closed retort or coke oven and was heated at 2,000°F to burn off part of the carbon. Figure 13 shows a picture of a typical retort used in MGP site. Bituminous coal was used because it produced reliable fuel, which consisted of fixed carbon with less than 10% ash. When coal burns, it gives off sulfur dioxide, nitrogen dioxide and carbon dioxide, among other gases. Pyrolysis, incomplete combustion process, drives off the volatile gases without combusting them. The gaseous product was immediately quenched to cool and condensed to remove heavier compounds, such as naphthalene and other Polynuclear Aromatic Hydrocarbons (PAHs).

Following the condenser and before it entered the distribution system, the raw coal gas was purified to remove ammonia, cyanide, hydrogen sulfide gas, and benzol. The sulfur particulates, released by the condensing process, were partly removed with scrubbers or filters. Scrubbers used a wet limestone slurry to absorb sulfur as it passed through and could reduce sulfur emissions by up to 90 percent [18]. Small particulates were less likely to be absorbed by the limestone and could pass out the smokestack into the air.

In addition to coal gas, the most significant byproducts were coke, coal tar, and purifier box wastes. The remnants of coal were removed from the oven as coke, which was typically 80 to 90% carbon [19]. The typical manufactured gas process is shown in Figure 14.

3.2 The Solvay Coke Operation

Coal was supplied to Solvay Coke from mines in West Virginia and Kentucky. The coal was transported via boats through the Kinnickinnick River. From the dock, the coal was conveyed by a system of belt conveyors, to a large storage field, covering eight acres and capable of storing 450,000 tons [20]. Figures 15 and 16 show the coal pile and the cranes used to unload the coal from ships.

Coal reclaimed from storage was screened to 2 ½ " or smaller size, passed over magnetic separators which separated the tramp iron from the coal, and then conveyed into measuring machines which proportioned the high and the low volatile coals for the production of the best grade of coke [21].

Following the coal crushing and pulverizing process, the coal mixture was conveyed by a 2,000 foot system of conveyors to the oven storage bins, from which it was drawn and distributed to the ovens by three electric lorries, having a capacity of 2,800 tons each 24 hours. Figures 17 and 18 show the coal being loaded into lorries.

The next process was the coke oven. The coal was heated in an air-tight ovens for a period of 12 to 18 hours and then discharged by large electrically operated pushers into steel quenching cars, which carried the glowing coke to the spray area for quenching. After leaving the quenching shed, cars passed to the sorting station, where a foundry run of oven coke was loaded into boxcars by a car tipple, or was crushed and screened for furnace coke [22].

For the liquids, the condensation process was used to facilitate separation of the condensed water vapor with coal tar. Separated coal tar was stored in tar holding tanks and the water was typically discharged or re-used on site. The coal gas was first treated to remove liquids and then treated with purifiers to remove cyanide, ammonia, and sulfide. The gas product was stored in gas holding tank, which rose as the gas was injected and fell as it was withdrawn and transported through pipelines to local customers.

3.3 Coal Carbonization Wastes Products

The amount and character of coal tar produced by coal carbonization process varies with temperature. The carbonization temperature typically ranged from about 850 to 900°C and the horizontal retorts operated at higher temperature of 1,000 to 1,100°C [23]. As the carbonization temperature was increased, the amount of gas produced increased due to more of the tars being converted to coke and gas. The volume of the tar produced decreased as the temperature increased due to high heat and the by-product started to volatilize.

By-products of the coal carbonization process that could not be recycled, sold, or given away were considered waste products. Often times, when the MGP site was abandoned, process byproducts remained in the structures, including the tar separator, tar wells, and gasholders. Typically, a gas holder has a diameter of 80 feet and a depth of over 20 feet below the ground surface. Gas holders, which were made of brick and concrete, may or may not contain the contaminated water and coal tars. Tar wells typically have smaller diameters than gasholders, however, their depth could extend to over 20 feet below ground surface [24]. Tar wells were also made of brick and concrete and have the potential to be contaminated by coal tars. Some MGP sites would also have tar pits, which were unlined, 3 feet deep and approximately 50 by 50 feet square [25].

These structures are the most targeted source for remedial action. The reason is because over the years, the coal tar, which is a dense non-aqueous phase liquid (DNAPL) can migrate from its original location to deeper and more widespread areas of contamination.

3.3.1 Chemical Characteristic of Process Residuals

The primary sources of residual at an MGP site are coke, coal tar, and purifier box wastes. However, the relative amount of each residual is influenced by the process characteristic. Coal tar itself is a black, tarry, resinous, odorous substances comprised mainly of PAHs (including naphthalene), tar acids (phenols) and "light oils" (benzene, toluene, ethylbenzene, and xylene – BTEX) [26]. In the subsurface, coal tar residues may exist in four phases, i.e.:

- As a free-phased NAPL
- Physically adsorbed to soil particles
- As a vapor in the interstitial space between soil particles; and
- Dissolved in water trapped in the pore spaces between soil particles.

Coal tar itself is not designated as hazardous wastes, but the chemicals contained in coal tars are either regulated by the Resource Conservation and Recovery Act (RCRA), the Toxic Substance Control Act (TSCA) and the Clean Water Act (CWA) [27].

A complete summary of the chemicals and wastes at a typical MGP site is given in Table 1 [28]. However, the contaminants of concern at MGP sites can be divided into organics and inorganics. Organics include tar/ oils, PAHs, VOCs, and phenolics. Inorganics include metals, cyanide, and sulfide. The following paragraph discuss each wastes in more detail.

Organic Residuals:

Tars and Oils

Tar is classified as a free-phase hydrocarbon, which also categorized as a dense non-aqueous phase liquid (DNAPLs) because it has specific gravity greater than 1 g/cm^3. [29]. The free phase DNAPL is an immiscible liquid that is capable of migrating vertically or laterally through a geologic zone.

The coal tar, being denser than water, moves vertically downward below the water table [30]. If vertically migrating DNAPL encounters a geologic formation of relatively low permeability; an accumulation or "pool" may form. The composition of the DNAPL residue that is immiscible liquid is held within the soil or rock by capillary forces. This DNAPL is generally not capable of migrating or being displaced by normal groundwater flow. Both free-phase and residual DNAPL can slowly dissolve in groundwater and produce "plumes" of aqueous contamination or volatilize to yield contaminated subsurface vapors [31].

The problem with coal tar is that coal tar consists of a complex mixture of thousands of organic compounds, each of which has its own physical, chemical, and microbial transformation products. Furthermore, over time the bulk of the tarry material often moves sufficiently far below the water table that the concentrations of volatile components at the air/ water interface are low, thereby reducing the likelihood that such compounds would be detected in the unsaturated zone [32].

The presence of oils, which are light non-aqueous phase liquids (LNAPLs), and tars, which are DNAPLs, creates a dual concern, which is the possibility of having a floating product on the water table and a sinking product that can penetrate the entire depth of an aquifer.

Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are found in coal tar, left over from the gasification process. PAHs are the most common organic chemicals of concern and are found at higher concentrations than any other organics. Among all of the PAHs identified, naphthalene has the highest concentration of about 4.7% [33]. Potentially carcinogenic PAHs represented approximately 40% of the total PAHs identified. In soil, concentration of individual PAH compounds are consistent within 1 to 1.5 order of magnitudes. The PAHs containing soils represent the largest waste type at most MGP sites. PAHs typically are not biodegradable and exhibit a long life. Even though, these chemicals are found in most MGP sites, a site-specific review is required to determine the more specific chemicals required to be addressed. However, the PAH concentrations in groundwater vary over a much greater range than in soil.

Volatile Aromatics

The primary volatile aromatics anticipated at MGP sites are benzene, toluene, xylene, and ethylbenzene (BTEX). These materials originate from the volatile fraction of the raw coal and the aromatic nature of the feedstock and carburetion oils.

The low levels of volatiles in the process residuals indicate that these chemicals would not be expected to be present in large quantities at MGP sites. However, at coal carbonization facilities which recovered the light oils or benzene as by products, high level of these contaminants were found. It is also noted that the concentration of chlorinated and nitrogenated derivatives are insignificant, unless there are other operations other than the manufactured gas occurred on the site.

Phenolic

Phenolics are part of the tar acids of coal tars and may include other compounds such as cresols and higher molecular weight tar acids. The most commonly found compounds in MGP sites are phenols, methyl phenols (i.e., croesols) and dimethylphenols (i.e., tar acids).

Inorganic Residuals

The largest volume of inorganic residuals and by-products are the solids, i.e., coke or ash, and the spent materials used for gas cleanup such as purifier wastes or various liquid scrubber blowdowns. The purifier wastes contain many of the trace metals originating in the feed coal or oil while the blowdowns contain most of the feed coal/ oil sulfur and nitrogen in the form of sulfates, sulfides, and cyanides.

Trace of metals

The ash from coal carbonization generally contains an array of trace metals. The Edison Electric Institute showed a list of trace of metals found at MGP sites, which are:

Aluminum
Antimony
Arsenic
Boron
Cadmium
Cobalt
Copper
Iron
Lead
Manganese
Nickel
Vanadium
Zinc

The actual presence and distribution of trace metals is depend upon the MGP feedstock and specific operation.

Cyanide and sulfide

Cyanide is usually found in the cyanide salts left in the iron oxide waste produced when the gas was purified.

Spent oxide and/ or spent lime were used to remove sulfur from the manufactured gas and generally contained significant amounts of sulfur and sulfur related compounds. In general, the coal carbonization plants produced larger quantities of this material due to the higher sulfur content in coal versus other operations.

The forms of cyanide and sulfur are critical to their treatment and is greatly affected not only by the original chemical form in the gas but also by the subsequent reaction of these chemicals with the oxide/ lime reactants.

Purifier box wastes are one of the residues concern at MGP sites and contain materials that are highly contaminated by cyanide. The purifier box can contain a variety of materials including iron impregnated wood chips or spent lime. Most of the chips were transported off site, spread around the site for dust control, or dumped in mixed wastes area. Those remaining on the site may have decomposed and thus lost their characteristic form. The waste residual, however, is easily recognized because of the blue staining imparted by ferrocyanide (e.g., Prussian blue). Another concern of these wood chips containing cyanide is, when cyanide pH is changed, it can turn into cyanide gas, which creates death threat for people.

3.3.2 Physical Characteristic of Process Residuals

For environmental remediation purposes, it is useful to separate contaminated media into the following:

- Free phase coal tar
- Sludge (a mixture of coal tar and soils or other solids)
- Heavily to lightly contaminated soils
- Contaminated groundwater
- Contaminated sediment

The free phase coal tars can be found in different areas throughout the site but primarily in and around the tar pits. During the tar separation process, the tar typically would sink to the bottom of the tar separators, with the water forming a separate layer above it. Depending on the geologic conditions, free tars may occur as accumulations.

Sludge, a mixture of coal tar and soil or demolition debris, is often found in areas where some of the process equipment has been removed. For example, tar/ water separator tanks which can be present at depths of up to 30 feet. This sludge may pose a direct contact risk, either by dermal or ingestion, with the soil or by inhalation of vapors that are released by volatilization of coal tar constituents.

Heavily contaminated soil is often associated with tar ponds, holder bottoms, spills and leaks, and stratigraphic traps. Volumes of pond and holder bottoms can be estimated fairly well if accurate site records are available. The volume of soil contaminated, spills, and traps is difficult to estimate without site-specific data.

Contaminated groundwater is commonly encountered at MGP sites. According to studies conducted to MGP sites, the contamination level in groundwater is very consistent with the contamination level in soil [34]. The degree that contaminants partition into the groundwater is determined by their physical/ chemical properties or notably the Henry's constant and the solubility [35]. BTEX and PAHs are typically found in the groundwater at MGP sites.

Coal tar contamination along riverbanks and in the shallow sediments is often found at MGP sites due to the tendency of the coal tar to be discharged into the adjacent water bodies through the site sewer or ditches. Much of the tar that escaped the plants in this manner did so as the incidental carryover of the hydrocarbon – water emulsion from the tar separators. Migration from tar wells and subgrade gasholder tanks also may have contaminated some streams within the site vicinity [36].

Section 4.

Evaluation of Potential Remediation Technologies

4.1 Introduction

The goal of this section is to identify the technologies which would most likely be applied to the Solvay Coke site based on currently available information. The technology selection was also based on successful remediation at other MGP sites. The technologies considered most applicable and cost effective for the Solvay Coke site are then described in ore detail in section 4.3.

4.2 Technology Screening

Abroad range of potential remediation technologies was considered for the Solvay Coke site. These technologies have proven successful and cost effective for use at former MGP sites. Table 2 presents a summary of the technologies considered applicable for remediting coal tar, sludges, heavily contaminated soil, lightly contaminated soil, and groundwater, which are expected to be the major problems at Solvay Coke. The table provides a brief description of each technology, its limitations, typical remediation times, and estimated remediation costs. The cost information provided reflects an order-of-magnitude level of accuracy and depends on the actual site conditions.

As the result of evaluating all the technologies listed on Table 2, four treatment technologies were selected to form the basis of the conceptual remediation plan, which is presented in Section 5. The following are the selected technologies:

- Thermal Treatment for the coal tar and sludges
- Chemical Oxidation for the heavily contaminated soil
- Capping for the lightly contaminated soil
- Natural Attenuation for groundwater

Recently, thermal treatment and capping have been used in remediating a former MGP site in Milwaukee. In-situ chemical oxidation is being used at another site in Southeastern Wisconsin.

Another remediation option, slurry walls, is presented in section 4.3. Slurry walls would be considered in the event that the performance of natural attenuation is not satisfactory.

4.3 Description of Selected Technologies

This section provides a detailed discussion of the selected technologies for remediating contaminated materials on the Solvay Coke site. These technologies were selected based on their capability and performance in treating sources of contaminants.

4.3.1 Thermal Treatment

4.3.1.1 Introduction

Thermal treatment is an ex-situ physical separation technique that transfers contaminants from soil and water to the gas phase. The process uses heat to volatilize and separate organic contaminants from the contaminated soil. Thermal treatment is used to treat contaminants in the vadose zone and this treatment includes incineration and thermal desorption. These processes focus primarily on the treatment of organic contaminants. Both technologies have the same remedial concept, i.e., excavated contaminated soil is heated to a temperature at which the water and the organic contaminants are volatilized. However, incineration is found to be more viable to remediate MGP contaminants. A brief description of incineration process follows.

Incineration Process Description:

Incineration uses controlled flame combustion to volatilize and destroy organic contaminants. A typical incineration system consists of two distinct units: (1) the kiln or primary combustion chamber into which waste is fed and in which initial volatilization and destruction of contaminants takes place; (2) a secondary combustion chamber, which is designed to increase the efficiency of the destruction of products of incomplete combustion or to incinerate a liquid feed system. Residual bottom ash produced during the incineration process typically exits the kiln through a gravity drop and is then cooled before subsequent management.

From the secondary combustion chamber, the off-gas is routed through an air pollution control system, which may include variety of units, depending on the types of contaminants being treated. The air pollution control system cools the gas and removes particulates or acid gases produced during the incineration process. Gases are drawn through the incineration system by an induced-draft fan, which maintains a negative pressure within the system. The negative pressure reduces the potential of fugitive emissions being produced and draws gases through the system at a specified flow rate to promote efficient destruction and removal of contaminants.

The efficiency of the combustion depends on three main factors of the combustion chamber: temperature, residence time of the waste material in the combustion chamber, and turbulent mixing of the waste material. The majority of organic compounds volatilize at temperatures between 1,100°F and 1,200°F. The majority of hazardous waste incinerators are operated at temperatures that range from 1,200°F to 3,000°F in the burning zone [37]. Therefore, any organic compounds heated up by the incinerator will be destroyed and will leave clean material, that can be disposed back onsite.

To achieve thermal destruction, residence time typically ranges from 30 to 90 minutes for solid waste and 0.5 to 2.0 seconds for liquid waste [38]. Turbulent mixing is important because the waste and fuel must contact the combustion gases if complete combustion is to occur. Sufficient oxygen must be present and is supplied as ambient air or as pure oxygen through an injection system.

4.3.1.2. Advantages and Limitations

The advantage of incineration is that it can reduce the concentrations of almost all organic contaminants in soils to very low levels. Furthermore, it destroys and converts the contaminants to carbon dioxide and water. This feature makes it a suitable treatment technology for soil or sludges that contain high levels of organic contaminants, with a wide range of chemical and physical properties. Incineration is a common remediation technology at former MGP sites. However, the presence of some inorganic compounds, such as sulfur and nitrogen and certain heavy metals can yield emissions in the incinerator.

Apart from the advantages of the incinerator, this process is mainly suited for the highly contaminated and low volume residuals such as pumpable or non-pumpable free phase hydrocarbons, or sludges that are present at an MGP site. The type of waste that an incinerator can handle depends on the type of incineration equipment, the requirements of the facility air permits, the hazardous waste classification of the material, and the nature of the contaminants or concern. The combustion of most of the MGP site residuals in these units should not be a problem although it is likely that trace metal, cyanide, and sulfur content of these materials will be closely scrutinized. This may result in the imposition of the surcharges or possible rejection of the purifier box wastes since the wastes have been documented to contain relatively high concentrations of inorganic and heavy metal contaminants.

4.3.1.3 Performance

Removal and thermal treatment of coal tar contaminated soils from MGP sites have proven to be both a cost efficient and an environmentally effective treatment. The incineration method was applied to contaminated soils at former coal gasification sites in downtown Milwaukee. Treatment efficiency for solids has been reported as high as 99.99 percent for variety organic contaminants including VOCs and PAHs [39].

Treatment efficiencies for inorganic contaminants are also very high. As for metals, the removal percentage is dependent upon the chemical and physical properties of the individual compounds.

A former MGP site in Waterloo, Iowa treated the coal tar contaminated soil using thermal treatment. The primary contaminants of concern were the 16 U.S. EPA priority pollutant polycyclic aromatic hydrocarbons (PAHs). The initial total PAH concentrations in the soil feedstock varied between about 500 mg/kg and 3000 mg/kg. The soil was treated to about 600°C to 660°C in the primary unit to successfully achieve a less than 5 mg/kg total PAH treatment standard [40].

4.3.2 Chemical Oxidation

Chemical oxidation is another technology that is considered to be use at Solvay Coke. This technology might be use to treat the heavily contaminated soil around the condensing and byproduct houses.

4.3.2.1. Chemical Oxidation Description

Chemical oxidation is an in-situ technology that can be used to remediate contaminated soil, sediment, and groundwater. Some of the target contaminants include: VOCs, PAHs, and phenolics. This in-situ oxidation system is capable of complete, non-selective oxidation of organic compounds in soil and groundwater.

Chemical oxidation of organic contaminants is accomplished by injection of chemical oxidants and a catalyst formulation into the soil at various depths under carefully controlled conditions. With chemical oxidation, organic contaminants can be converted to carbon dioxide and water given sufficient reaction time and oxidant dosage.

Hydrogen peroxide is the most common oxidant that is used to treat soil. This is due to its relative stability compared to other oxidants (e.g., potassium permanganate and ozone). Iron sulfate is often combined with the hydrogen peroxide (known as Fenton's reagent) to enhance the treatment that is achieved by hydrogen peroxide alone.

The Fenton's reaction is: $H_2O_2 + Fe^{+2} \rightarrow OH^- + Fe^{+3}$ [41]

The Fenton's reaction shows that when hydrogen peroxide reacts with iron ion, the hydrogen peroxide will oxidize to hydroxyl. The free radical hydroxyl (OH^-) is an extremely powerful oxidizer of organic compounds. Residual hydrogen peroxide is rapidly decomposed to water and oxygen in the subsurface environment. During the reaction sequence, the organic compounds are successively converted to shorter chain fatty acids. These compounds are non-hazardous, naturally occurring substances, and are further degraded into carbon dioxide and water by subsequent reactions [42].

It should be noted that prior to applying chemical oxidation, bench and pilot scale testing is required to provide accurate oxidant application.

The cost of treatment using chemical oxidation can be substantial in addition to significant capital and operating costs. The operating costs are driven by the contaminant concentrations that are presented in the soil and water.

4.3.2.2.Advantages and Limitations:

The primary advantage of chemical oxidation is the ability of oxidizing agents to degrade organic compounds, theoretically to carbon dioxide and water. The limitation of this treatment process is that inaccurate calculation of the oxidant requirement can cause less effective treatment. Adequate oxidant and operating conditions (i.e., temperature, pH, and contact time) must be present to facilitate a complete reaction. The success of in-situ chemical oxidation will be largely dictated by the movement of the injected chemicals through the soil and groundwater. Another limitation of this cleanup method is the cost of chemical.

4.3.2.3 Performance:

Chemical oxidation reduces VOCs, PAHs, and phenolics to greater than 95 percent of the initial concentration providing that the appropriate dose of the oxidant is used and that sufficient mixing and contacting of the oxidant and contaminant occurs [43]. Excessive doses of the oxidant may be required to achieve the treatment of the target contaminants if other chemicals that are present in the water also react with the oxidant.

The chemical oxidation effectiveness depends upon:

- The oxidant dosage
- The initial chemical concentrations in the solution
- Their molecular structure

The process effectiveness decreases as the turbidity of the water increases. The process appears to be well suited for reduction of phenolics, PAHs, and cyanide.

A former MGP site in the City of Burlington, owned by the Wisconsin Electric Power Company (WEPCO), is undergoing remediation. A number of studies conducted by WEPCO showed that the Geo-Cleanse® in-situ chemical oxidation treatment process, which has been used successfully to clean up many other contaminated sites, was the most cost effective process to successfully treat the soil and groundwater at the Burlington site. Based on the results of the bench and pilot tests, an oxidant (50% hydrogen peroxide) to contaminant ratio ranging from 10:1 to 40:1 was determined for the site. Assuming the site contained approximately 50,000 pounds of organic contaminants (BTEX and PAHs) and an average reagent to contaminant ratio of 25:1, a total of 1,250,000 pounds or 125,000 gallons of reagent was estimated to be required for the full scale treatment of the site [44].

As of the end of October 2000, approximately 70,000 gallons of 50% hydrogen peroxide have been injected into the soil and groundwater at the Burlington site during three months of injection operations. Based on the groundwater performance, peroxide has been found throughout the groundwater in the treatment zone with the proper levels of iron and the desired slightly acidic pH of the groundwater. These are the proper conditions for oxidation to occur as is confirmed by the associated carbon dioxide increase and VOC decreases in the vent/monitoring points. On the other hand, contaminant mass in soil showed an average reduction by approximately 40% with a greater reduction occurring form BTEX compounds (60%) than for PAH compounds (35%) [43]. This case study result indicated that the usage of chemical oxidation in treating MGP site contaminants proven to be successful.

4.3.3 Capping

Capping is one of the technologies selected and recommended to be use in this project. Cap is used primarily to reduce percolation of surface water into the contaminated soil zone to minimize the amount of leachate generated.

4.3.3.1 Description of Cap

The goals of cap design are to prevent surface water 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 cap also acts as a physical barrier to keep subsurface wastes isolated from the ground surface and prevent migration of contaminant –laden surface dust. Site capping design is based on site specific and depend on the intended or existing use of the former MGP site.

The design of the cap depend on the several factors: [45]

1. Slope of the cap, which is used to control water runoff velocity to minimize erosion;
2. An outer layer of soil is placed to support a growth of selected shallow-rooting grasses fro wind and water erosion control;
3. An inner compacted clay layer is typically placed to achieve a permeability of 10-7 cm/second or less to resist water infiltration from the soil layer
4. Sand and/or gravel layers or a synthetic drainage net may be placed between the soil and clay layers if the cover is extensive to facilitate runoff of water infiltration from the soil layer.

For the Solvay Coke site, it was assumed that a two feet clay cap with one foot of soil cover would be placed over the site.

4.3.3.2 Advantages and Limitations

Soil capping is generally more cost effective than other treatment technologies and requires shorter installation times. Capping also prevents infiltration of water into wastes and subsequent vertical migration of contaminants. However, this remediation method requires periodic inspection for settlement, ponding of liquids, erosion, and naturally occurring invasion by deep-rooted vegetation.

4.3.3.3 Performance

The performance of soil capping has been proven to eliminate a potential for direct human contact hazard poses by PAHs present in subsurface soils and fill materials at concentrations in excess and limit the leaching of PAHs to groundwater.

Capping may also be used to control the emission of gases and odors, reduce erosion, and improve aesthetics. Capping provides a stable surface which prevents direct contact with wastes, and is necessary when contaminated materials are to be buried or left in place at a site.

4.3.4 Natural Attenuation

Natural attenuation has become an acceptable method to address residual organic contaminats in the groundwater after source remediation is completed

4.3.4.1 Natural Attenuation Process Description

Natural attenuation, also known as passive bioremediation, is a passive remedial approach that depends upon natural processes to degrade and dissipate constituents in soil and groundwater. Natural attenuation includes several natural processes – such as dilution, dispersion, volatilization, biodegradation, adsorption, and chemical reactions with soil materials – where contaminant concentrations are reduced to acceptable levels.

Under appropriate site conditions, natural attenuation can reduce the potential impact of contaminant release either by preventing constituents from being transported to sensitive receptors or by reducing constituents concentrations to less harmful levels. The rates of natural processes are typically slow; contaminant levels may not be reduced to acceptable levels for years. Long-term monitoring is necessary to demonstrate that contaminant concentrations are continually decreasing at a rate sufficient to ensure that potential receptors are not adversely affected.

Groundwater contamination at MGP sites typically persists for decades because of the slow, continuous dissolution of PAHs from subsurface coal tar. These compounds have complex molecular structures and low water solubility, and they tend to adsorb strongly to soil in the subsurface. However, because PAHs dissolve slowly, natural attenuation can control the contamination even if biodegradation is slow, as long as it occurs at the same rate as or faster than dissolution.

The fate of PAHs in subsurface system is governed largely by their hydrophobic nature. PAH molecules that are held within NAPLs or are adsorbed onto surfaces cannot be biodegraded.

Studies have indicated that some microorganisms can metabolize dissolved PAHs composed of up to five benzene rings. Microorganisms generally use oxygenase enzyme to initiate the biodegradation. These reactions require the presence of oxygen. However, microbial degradation of PAHs with lower molecular weight can occur under nitrate-reducing (McNally et al., 1998; Mihelcic and Luthy, 1988) and sulfate-reducing conditions (Coates et al., 1997; Zhang and Young, 1997) [46].

4.3.4.2 Advantages and Limitations:

Natural attenuation, compared to most conventional remedial alternatives, pump-and-treat systems, provides the cost effective and requires minimal maintenance. On the other hand, natural attenuation is not effective where constituents' concentrations are high. There is potential for some migration of constituents to occur. The remediation period is varying depending on the condition of the contaminations and may not always achieve the desire cleanup levels within a reasonable length of time.

4.3.4.3 Performance:

Target contaminants for natural attenuation are VOCs, SVOCs and fuel hydrocarbons. The appropriate natural attenuation evaluation is to make the determination that the transformation processes are taking place at a rate that is acceptable for an acceptable period of time. In some cases, natural attenuation is used to manage the remaining contamination after an engineered system has removed the bulk of contamination.

4.3.5 Vertical Containment

According to the USEPA, 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 [47]. If source control and natural attenuation is not adequate at the Solvay Coke site, vertical containment could be implemented.

Vertical containment methods are used to prevent or significantly reduce migration of contaminants in soils or groundwater and to prevent human or animal exposure to contaminants.

4.3.5.1 Description

Physical barriers, including slurry walls, sheet piles, and grout barriers, have been used as means to manage contaminated areas. Slurry walls and sheet piles are the most commonly used physical barriers. Slurry walls are used to provide a barrier to control the lateral migration of contaminated fluids and are designed to impede or direct migration of contaminants. The construction of the walls consist of low permeability materials, which are compatible with the waste constituents.

These subsurface barriers consist of excavated trenches filled with slurry. The slurry, usually a mixture of bentonite and water, hydraulically shores the trench to prevent collapse and retards groundwater flow. Slurry walls are often used where the waste mass is too large for treatment and where soluble and mobile constituents pose an imminent threat.

Slurry walls have been used for decades as long-term solutions for controlling seepage. They are often used in conjunction with capping. Most slurry walls are constructed of a soil, bentonite, and water mixture. The bentonite slurry is used primarily for wall stabilization during trench excavation. Walls of this composition provide a barrier with low permeability and chemical resistance at low cost.

Slurry walls are typically placed at depth up to 30 meters (100 feet) and are generally 0.6 to 1.2 meters (2 to 4 feet) in thickness. The most effective application of the slurry wall is to base the slurry wall 0.6 to 0.9 meters (2 to 3 feet) into a low permeability layer such as clay or bedrock [48]. This installation provides an effective foundation with minimum leakage potential.

4.3.5.2 Advantage and Limitation:

The advantage of slurry walls is that it is a relatively inexpensive means of reducing groundwater flow in unconsolidated materials. On the other hand, the limitation of slurry walls is that the walls only contain contaminants within a specific area and it does not actually reduce contaminant concentrations. In contaminated groundwater applications, specific contaminant types may degrade the slurry walls components and reduce the long-term effectiveness.

4.3.5.3 Performance:

Slurry walls have demonstrated an effectiveness in containing greater than 95% of contaminant sources. In general, in-situ containment used in MGP site must be compatible to the waste and groundwater characteristics and to the site geology structure for satisfactory performance.

Section 5

Conceptual Model For Site Remediation

5.1 Introduction

A conceptual plan for remediating the Solvay Coke site was developed using the technologies discussed in the previous section. The plan was designed based on the currently available information for the site. However, future environmental assessments will be required to obtain more accurate site data and to verify the assumptions made in this section.

This section introduces the proposed site cleanup plan, which includes the remediation plan and estimates for the area and volume of materials likely requiring treatment.

5.2 Proposed Site-Cleanup Model

The proposed conceptual remediation plan consists of:

- Excavation and onsite thermal treatment for are of the site that most likely contains coal tars and/or sludge residuals.
- In-situ chemical oxidation to threat the contaminated soil and groundwater.
- Capping for containing lightly contaminated soil and residual contaminants remaining after soil/groundwater remediation.

- Natural attenuation for residual contaminants in the groundwater after active remediation is completed, and
- Slurry wall for containing the groundwater if natural attenuation is not sufficient to address groundwater issues.

Areas requiring these specific treatments were estimated from the information available and Sanbron maps. Figures 19 and 20 present the proposed remediation plan. The following sections describe these technologies in more detail. Table 3 summarizes the estimated area and volume of contamination for each media.

5.2.1 Remediation of Coal Tar/ Sludge

Coal tar residues and sludges, a mixture of coal tars and soils, are likely to be found in tar pits near the tar tanks, gas tanks, and near the coke oven as shown on Figure 19. The soil near the coke ovens is likely contaminated by coal tar residue.

The coal tar residues and sludges will be treated by incineration. The contaminated soil will be excavated to a depth of 15 feet around the tanks and 8 feet (the depth to groundwater) around the coke ovens. According to the site map, the total volume of soil that would need to be excavated is 18,400 cubic yards.

5.2.2 Remediation of Heavily Contaminated Soil

Heavily contaminated soil is assumed to be in the areas of the condensing houses, the by-product house, and several ammonia tanks, where the raw coal gas was condensed and the by-products were stored.

Chemical oxidation would be use to treat heavily contaminated areas. The volume of this heavily contaminated soil is calculated to be 37,000 cubic yards, assuming that the soil will be treated to a depth of 20 feet.

5.2.3 Remediation of Lightly Contaminated Soil

Lightly contaminated soil is assumed to be found throughout the site due to the storage of coal throughout the site. Most of the site likely contains soil with PAH concentrations exceeding the WDNR direct contact cleanup levels.

To prevent direct contact with the contaminated soil, a three feet thick clay cap would be placed on the entire site. The total area that will be covered by the clay cap is about 46 acres.

5.2.4 Remediation of Groundwater

Groundwater contamination likely occurred throughout the site, with the highest concentration being in the area where the soil is most heavily contaminated. After thermal treatment and in-situ chemical oxidation, most sources of groundwater contamination would likely have been eliminated. Remaining contaminated groundwater would be addressed through natural attenuation. The area which will be remediated covers the total area of the site.

5.2.5 Additional Treatment for Remediation of Groundwater

Slurry walls could be built surrounding the Solvay Coke site in case of natural attenuation does not perform as well as expected or there is an unacceptable amount of contaminated groundwater migrating offsite. The slurry walls are estimated to have a wall thickness of 3 feet and depth of 35 feet. The total length would be 5,200 feet.

Section 6

Cost Estimate

The nature of site remediation can vary from containment of the source contaminants to complete excavation of the site and the treatment of groundwater. The cost of the site remediation depends upon the site remediation goal and the future use of the site. Assuming that in the near future the site will be used as an industrial area, the site remediation can be performed to less stringent standards. However, if the site will be used as a residential area, the cost of remediating the site will escalate due to the fact that a residential area would need to achieve lower cleanup standards.

As discussed previously in this report, the assumed remediation plan incorporated remediation technologies typically used in other MGP sites in Southeast Wisconsin. Likewise, the cost estimate for remediating the Solvay Coke site is based on costs for applying the same technologies at other sites in Southeast Wisconsin. The cost estimate, like the remediation plan, is very preliminary but does provide insight into the order of magnitude costs likely to be incurred in the remediation of the site. A more formal preliminary cost estimate would need to be completed after the site investigation, and a final cost estimate completed after the design of a specific remediation plan.

The approach used in this cost estimate was to use unit costs that are inclusive of material handling, treatment, sampling, and disposal. For example, the pre cubic yard cost for incineration includes material excavation, thermal treatment, sampling after treatment, and disposal. Based on the estimated quantities presented in Section 5, a total capital cost was developed. Table 4 presents the cost estimate for remediating the Solvay

Coke site. The cost for building demolition was obtained from the City of Milwaukee and was added to the overall remediation costs. An estimate for the site investigation was also added to the overall capital cost. After a total capital cost estimate was obtained, allowances for engineering, permitting, oversight during construction, and a construction allowance were added to the total. Some of the costs used in calculating the capital costs were acquired from vendors and contractors based on today's costs.

The estimated cost for remediating the Solvay Coke site, using the recommended technologies, is $10,400,000.00. This includes the capital cost and allowances for the site investigation, building demolition, thermal treatment of the coal tar and sludge, in-situ chemical oxidation in heavily contaminated soil, capping the site, and natural attenuation for groundwater.

As stated in Section 5, if additional groundwater containment were required to prevent offsite discharge contaminated groundwater, a slurry wall could be built around the site. This report includes a slurry wall as a contingency for the overall remediation. The cost for a slurry wall is estimated to be $1,280,000.00.

Endnotes

1. Fischer, C.L.J, Schmitter, R.D, Lane, E.O. November 1999. "Manufactured Gas Plants: The Environmental Legacy." Technical Outreach Services of Communities Program South & Southwest Center. Georgia Institute of Technology. Atlanta, Georgia.

2. Gas Research Institute. *Management of Manufactured Gas Plant Sites: Volume I Wastes and Chemicals of Interest.* October 1987. (Chicago: Gas Research Institute).

3. Salcedo, Rudy. "Phase I Environmental Investigation: Former Milwaukee Solvay Coke & Gas Co. Site (311 E. Greenfield Avenue)". City of Milwaukee – Health Department. October 20, 1993.

4. Newport Company History. 1921. "The Milwaukee Coke and Gas Company." Published Brochure. A copy of this article is in the possession of University of Wisconsin – Milwaukee.

5. Milwaukee Solvay Quarter Century Club. [Internet,WWW]. Address: http://www.uwm.edu/Library/arch/finaids/uwmmss57.htm. pp 1-2. [Access: January 29, 2001]

6. Salcedo, Rudy. "Phase I Environmental Investigation: Former Milwaukee Solvay Coke & Gas Co. Site (311 E. Greenfield Avenue)". City of Milwaukee – Health Department. October 20, 1993.

7. Milwaukee Solvay Quarter Century Club. [Internet,WWW]. Address: http://www.uwm.edu/Library/arch/finaids/uwmmss57.htm. pp 1-2. [Access: January 29, 2001]

8. Milwaukee Solvay Quarter Century Club. [Internet,WWW]. Address: http://www.uwm.edu/Library/arch/finaids/uwmmss57.htm. pp 1-2. [Access: January 29, 2001]

9. Milwaukee Metropolitan Sewerage District. October 1988. "Kinnickinnick/ Lake Michigan Tunnel System Geotechnical Report."

10. Milwaukee Metropolitan Sewerage District. October 1988. "Kinnickinnick/ Lake Michigan Tunnel System Geotechnical Report."

11. Menomonee Valley Partners. November 2000. "An Aerial Wide Approach for Groundwater Management in Menomonee Valley." Draft.

12. Menomonee Valley Partners. November 2000. "An Aerial Wide Approach for Groundwater Management in Menomonee Valley." Draft.

13. Menomonee Valley Partners. November 2000. "An Aerial Wide Approach for Groundwater Management in Menomonee Valley." Draft.

14. Milwaukee Metropolitan Sewerage District. October 1988. "Kinnickinnick/ Lake Michigan Tunnel System Geotechnical Report."

15. Gas Research Institute. *Management of Manufactured Gas Plant Sites: Volume I Wastes and Chemicals of Interest.* October 1987. (Chicago: Gas Research Institute).

16. Gas Research Institute. "Historical Overview of Manufactured Gas Plant Sites". [Internet,WWW]. Address:http://www.gri.org/pub/oldcontent/tech/e+s/mgpsites/history.htm. [Access: December 12, 2000].

17. Salcedo, Rudy. October 20, 1993. City of Milwaukee – Health Department. "Phase I Environmental Investigation: Former Milwaukee Solvay Coke & Gas Co. Site (311 East Greenfield Avenue)."

18. Gas Research Institute. "Historical Overview of Manufactured Gas Plant Sites". [Internet,WWW]. Address:http://www.gri.org/pub/oldcontent/tech/e+s/mgpsites/history.htm. [Access: December 12, 2000].

19. Gas Research Institute. "Historical Overview of Manufactured Gas Plant Sites". [Internet,WWW]. Address:http://www.gri.org/pub/oldcontent/tech/e+s/mgpsites/history.htm. [Access: December 12, 2000].

20. Newport Company History. 1921. "The Milwaukee Coke and Gas Company." Published Brochure. A copy of this article is in the possession of University of Wisconsin – Milwaukee.

21. Newport Company History. 1921. "The Milwaukee Coke and Gas Company." Published Brochure. A copy of this article is in the possession of University of Wisconsin – Milwaukee.

22. Newport Company History. 1921. "The Milwaukee Coke and Gas Company." Published Brochure. A copy of this article is in the possession of University of Wisconsin – Milwaukee.

23. United States Environmental Protection Agency. February 1988. Hazardous waste Engineering Research Laboratory. Office of Research and Development. "U.S. Production of Manufactured Gases: Assessment of Past Disposal

Practices." Washington, DC. EPA/600/2-88/012.

24. Spiros L. Fafalios. *The Application of Steam-Enhanced Extraction for In-situ Remediation of Coal Tar Residues at a Former Manufactured Gas Plant Site.* Milwaukee, Wisconsin. May 1998.
25. Spiros L. Fafalios. *The Application of Steam-Enhanced Extraction for In-situ Remediation of Coal Tar Residues at a Former Manufactured Gas Plant Site.* Milwaukee, Wisconsin. May 1998.
26. Allen Hatheway, July 1997, "King Coal's rude resurrection". Civil Engineering News [Internet, WWW]. Address: http://www.cenews.com/feat797.htm
27. Gas Research Institute. "Remediation alternatives and Costs for The Restoration of MGP Sites". March 1990. (Chicago: Gas Research Institute)
28. Management of Manufactured Gas Plant Sites. Volume I Wastes and Chemicals of Interest. Gas Research Institute. October 1987 (Chicago: Gas Research Institue). pp x.
29. United States Environmental Protection Agency. February 1988. Hazardous waste Engineering Research Laboratory. Office of Research and Development. "U.S. Production of Manufactured Gases: Assessment of Past Disposal Practices." Washington, DC. EPA/600/2-88/012.
30. Murarka, Ishwar P. September 1990 "Land and Water Quality Research: Manufactured Gas Plant Site Investigations." Electric Power Research Institute Journal, pg 40-44.
31. Electric Power Research Institute. December 18, 1990. "Remediation Strategies for Source Materials and Contaminated Media at Manufactured Gas Plant (MGP) Sites." (Palo Alto: Electric Power Research Institute).
32. Hatheway, Allen W. Nov 1997. "Manufactured Gas Plant: Yesterday's pride, today's liability." Civil Engineering. New York. Vol 67 (11), pp. 38-41.
33. Gas Research Institute. *Management of Manufactured Gas Plant Sites: Volume I Wastes and Chemicals of Interest.* October 1987. (Chicago: Gas Research Institute).
34. Luthy, Richard G., David A. Dzombak, Catherine A. Peters, Sujoy B. Roy, Anuradha Ramaswami, David V. Nakles, and Babu R. Nott. September 1994. "Remediating Tar-Contaminated Soils at Manufactured Gas Plant Sites." Environmental Science and Technology. Vol 28 (6), pp 266A-276A.
35. United States Environmental Protection Agency. September 1999. Office of Research and Development . Office of Solid Waste and Emergency Response.

"Groundwater Issue: Microbial Processes Affecting Monitored Natural Attenuation of Contaminants in the Subsurface." Washington, DC. EPA/540/S-99/001.

36. Luthy, Richard G., David A. Dzombak, Catherine A. Peters, Sujoy B. Roy, Anuradha Ramaswami, David V. Nakles, and Babu R. Nott. September 1994. "Remediating Tar-Contaminated Soils at Manufactured Gas Plant Sites." Environmental Science and Technology. Vol 28 (6), pp 266A-276A.

37. United States Environmental Protection Agency. Solid Waste and Emergency Response. 1998. *On-Site Incineration: Overview of Superfund Operating Experience.* Washington, DC. EPA-542-R-97-012.

38. United States Environmental Protection Agency. Solid Waste and Emergency Response. 1998. *On-Site Incineration: Overview of Superfund Operating Experience.* Washington, DC. EPA-542-R-97-012.

39. Electric Power Research Institute. D.V. Nakles. *Remediation Strategies for Source Materials and Contaminated Media at manufactured Gas Plant (MGP) Sites.* December 1994. (Palo Alto: Electric Power Research Institute).

40. Golchin, J., Juhlin, S.A, Kjartanson, B.H., Stenback, G.A., and Stryker, R.C. "Reuse of Thermally Desorbed Soils from Former Manufactured Gas Plant Sites". In Gas Technology Institute Conference. 4 –7 December 2000. *Site Remediation Technologies & Environmental Management Practices in the Utility Industry. Proceedings of the 13th Gas Technology Institute Conference.* Orlando, Florida. pp 2.

41. Hellman, E, Lingle, J., Noel, M., and Wilson, J. "Full Scale Chemical Oxidation of Manufactured Gas Plant Hydrocarbons in Soil and Groundwater Using Fenton's Reagent." In Gas Technology Institute Conference. 4 –7 December 2000. *Site Remediation Technologies & Environmental Management Practices in the Utility Industry. Proceedings of the 13th Gas Technology Institute Conference.* Orlando, Florida. pp 2.

42. Hellman, E, Lingle, J., Noel, M., and Wilson, J. "Full Scale Chemical Oxidation of Manufactured Gas Plant Hydrocarbons in Soil and Groundwater Using Fenton's Reagent." In Gas Technology Institute Conference. 4 –7 December 2000. *Site Remediation Technologies & Environmental Management Practices in the Utility Industry. Proceedings of the 13th Gas Technology Institute Conference.* Orlando, Florida. pp 2.

43. Hellman, E, Lingle, J., Noel, M., and Wilson, J. "Full Scale Chemical Oxidation of Manufactured Gas Plant Hydrocarbons in Soil and Groundwater Using Fenton's Reagent." In Gas Technology Institute Conference. 4 –7 December 2000. *Site Remediation Technologies & Environmental Management Practices in the Utility Industry. Proceedings of the 13th Gas Technology Institute Conference.* Orlando, Florida. pp 7.

44. Hellman, E, Lingle, J., Noel, M., and Wilson, J. "Full Scale Chemical Oxidation of Manufactured Gas Plant Hydrocarbons in Soil and Groundwater Using Fenton's Reagent." In Gas Technology Institute Conference. 4 –7 December 2000. *Site Remediation Technologies & Environmental Management Practices in the Utility Industry. Proceedings of the 13th Gas Technology Institute Conference.* Orlando, Florida. pp 9-13.

45. United States Environmental Protection Agency. Solid Waste and Emergency Response. 1999. *Groundwater Containment Remediation Technology. Slurry Walls.* Washington, D.C.

46. The National Academies. 2000. "Natural Attenuation for Groundwater Remediation." [Internet, WWW]. Address: http://www.nap.edu.

47. United States Environmental Protection Agency. Solid Waste and Emergency Response. July 2000. *A Resource of MGP Site Characterization and Remediation: Expedited Site Characterization and Source Remediation at Former Manufactured Gas Plant Sites.* Washington, D.C. EPA 542-R-00-005.

48. United States Environmental Protection Agency. Solid Waste and Emergency Response. 1999. *Groundwater Containment Remediation Technology. Slurry Walls.* Washington, D.C.

Bibliography

Allen Hatheway, July 1997, "King Coal's rude resurrection". Civil Engineering News [Internet, WWW]. Address: http://www.cenews.com/feat797.htm

Electric Power Research Institute. D.V. Nakles. *Remediation Strategies for Source Materials and Contaminated Media at manufactured Gas Plant (MGP) Sites.* December 1994. (Palo Alto: Electric Power Research Institute).

Electric Power Research Institute. December 18, 1990. "Remediation Strategies for Source Materials and Contaminated Media at Manufactured Gas Plant (MGP) Sites." (Palo Alto: Electric Power Research Institute).

Fischer, C.L.J, Schmitter, R.D, Lane, E.O. November 1999. "Manufactured Gas Plants: The Environmental Legacy." Technical Outreach Services of Communities Program South & Southwest Center. Georgia Institute of Technology. Atlanta, Georgia.

Gas Research Institute. *Management of Manufactured Gas Plant Sites: Volume I Wastes and Chemicals of Interest.* October 1987. (Chicago: Gas Research Institute).

Gas Research Institute. *Remediation alternatives and Costs for The Restoration of MGP Sites.* March 1990. (Chicago: Gas Research Institute).

Gas Research Institute. "Historical Overview of Manufactured Gas Plant Sites". [Internet,WWW]. Address:http://www.gri.org/pub/oldcontent/tech/e+s/mgpsites/history.htm. [Access: December 12, 2000].

Golchin, J., Juhlin, S.A, Kjartanson, B.H., , Stenback, G.A., and Stryker, R.C. "Reuse of Thermally Desorbed Soils from Former Manufactured Gas Plant Sites". In Gas Technology Institute Conference. 4 –7 December 2000. *Site Remediation Technologies & Environmental Management Practices in the Utility Industry. Proceedings of the 13th Gas Technology Institute Conference.* Orlando, Florida. pp 2.

Hatheway, Allen W. Nov 1997. "Manufactured Gas Plant: Yesterday's pride, today's Liability." Civil Engineering. New York. Vol 67 (11), pg 38-41.

Hellman, E, Lingle, J., Noel, M., and Wilson, J. "Full Scale Chemical Oxidation of Manufactured Gas Plant Hydrocarbons in Soil and Groundwater Using Fenton's Reagent." In Gas Technology Institute Conference. 4 –7 December 2000. *Site Remediation Technologies & Environmental Management Practices in the Utility Industry. Proceedings of the 13th Gas Technology Institute Conference.* Orlando, Florida. pp 2+.

Luthy, Richard G., David A. Dzombak, Catherine A. Peters, Sujoy B. Roy, Anuradha Ramaswami, David V. Nakles, and Babu R. Nott. September 1994. "Remediating Tar-Contaminated Soils at Manufactured Gas Plant Sites." Environmental Science and Technology. Vol 28 (6),. pp 266A-276A.

Menomonee Valley Partners. November 2000. "An Aerial Wide Approach for Groundwater Management in Menomonee Valley." Draft.

Milwaukee Metropolitan Sewerage District. October 1988. "Kinnickinnick/ Lake Michigan Tunnel System Geotechnical Report."

Milwaukee Solvay Quarter Century Club. [Internet,WWW]. Address: http://www.uwm.edu/Library/arch/finaids/uwmmss57.htm. pp 1-2. [Access: January 29, 2001]

Murarka, Ishwar P. September 1990 "Land and Water Quality Research: Manufactured Gas Plant Site Investigations." Electric Power Research Institute Journal, pg 40-44.

Newport Company History. 1921. "The Milwaukee Coke and Gas Company." Published Brochure. A copy of this article is in the possession of University of Wisconsin – Milwaukee.

Salcedo, Rudy. "Phase I Environmental Investigation: Former Milwaukee Solvay Coke & Gas Co. Site (311 E. Greenfield Avenue)". City of Milwaukee – Health Department. October 20, 1993.

Spiros L. Fafalios. *The Application of Steam-Enhanced Extraction for In-situ Remediation of Coal Tar Residues at a Former Manufactured Gas Plant Site.* Milwaukee, Wisconsin. May 1998.

The National Academies. 2000. "Natural Attenuation for Groundwater Remediation." [Internet, WWW]. Address: http://www.nap.edu.

United States Environmental Protection Agency. February 1988. Hazardous waste Engineering Research Laboratory. Office of Research and Development. "U.S. Production of Manufactured Gases: Assessment of Past Disposal Practices." Washington, DC. EPA/600/2-88/012.

United States Environmental Protection Agency. Solid Waste and Emergency Response. 1998. *On-Site Incineration: Overview of Superfund Operating Experience.* Washington, DC. EPA-542-R-97-012.

United States Environmental Protection Agency. Solid Waste and Emergency Response. 1999. *Groundwater Containment Remediation Technology. Slurry Walls.* Washington, D.C.

United States Environmental Protection Agency. September 1999. Office of Research and Development. Office of Solid Waste and Emergency Response. "Groundwater Issue: Microbial Processes Affecting Monitored Natural Attenuation of Contaminants in the Subsurface." Washington, DC. EPA/540/S-99/001.

United States Environmental Protection Agency. Solid Waste and Emergency Response. July 2000. *A Resource of MGP Site Characterization and Remediation: Expedited Site Characterization and Source Remediation at Former Manufactured Gas Plant Sites*. Washington, D.C. EPA 542-R-00-005.

Table 3. Estimated Volume of the Contaminated Areas

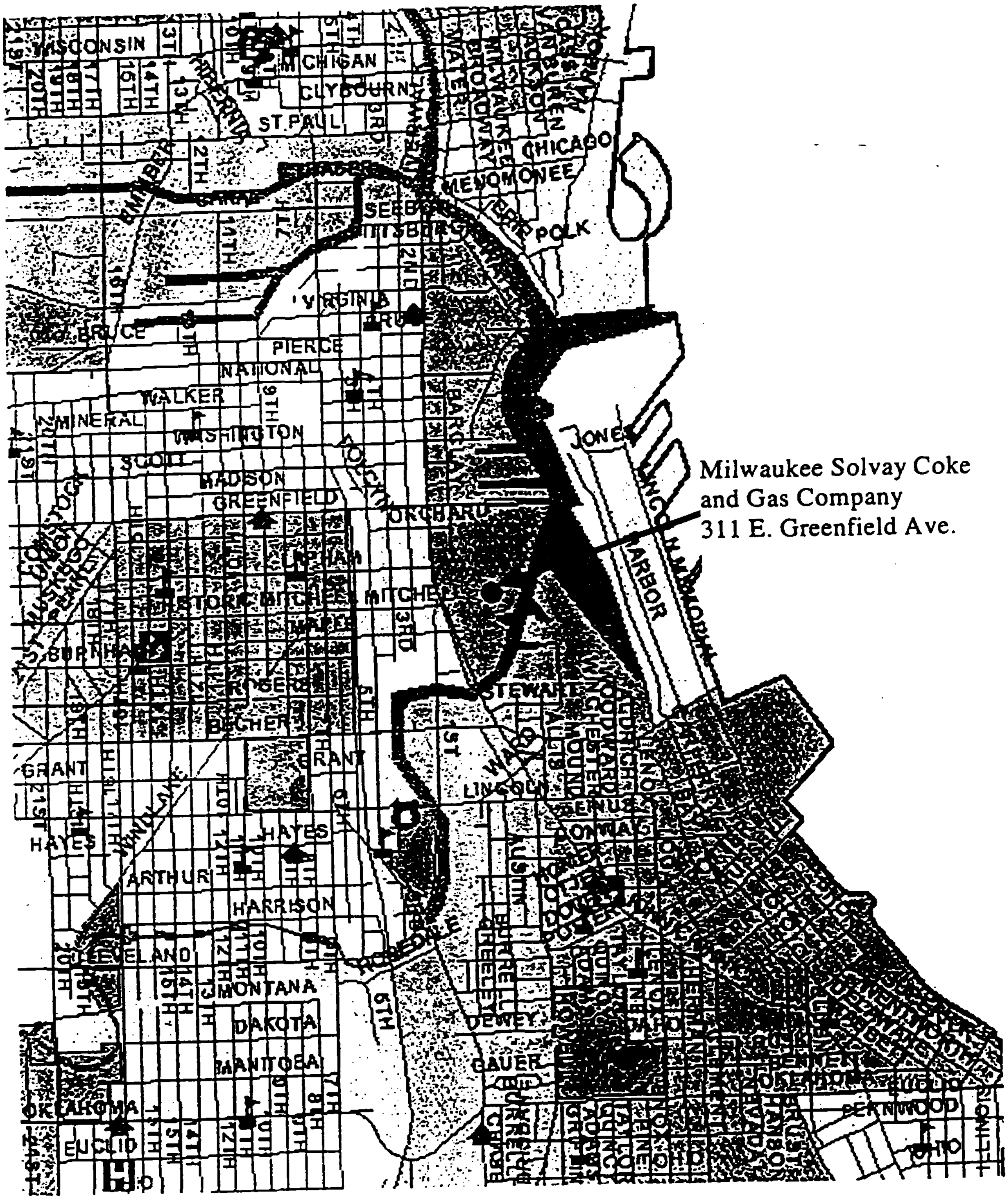
Item	Area [ft^2]	Volume [ft^3]	Volume [yd^3]
Coal Tar/ Sludge			
Tank #1	1,200	18,000	666
Tank #2	1,700	25,900	959
Tank #3	1,200	18,000	666
Tank #4	2,300	35,300	1,400
Area A	49,800	399,000	14,800
Total	56,300	496,000	18,400
Heavily Contaminated Area	49,800	996,000	36,900
Lightly Contaminated Area	2,069,200	6,207,000	230,000
Slurry Walls	181,800		

erest at MGP Sites

soil
essel, surface, and ground waters

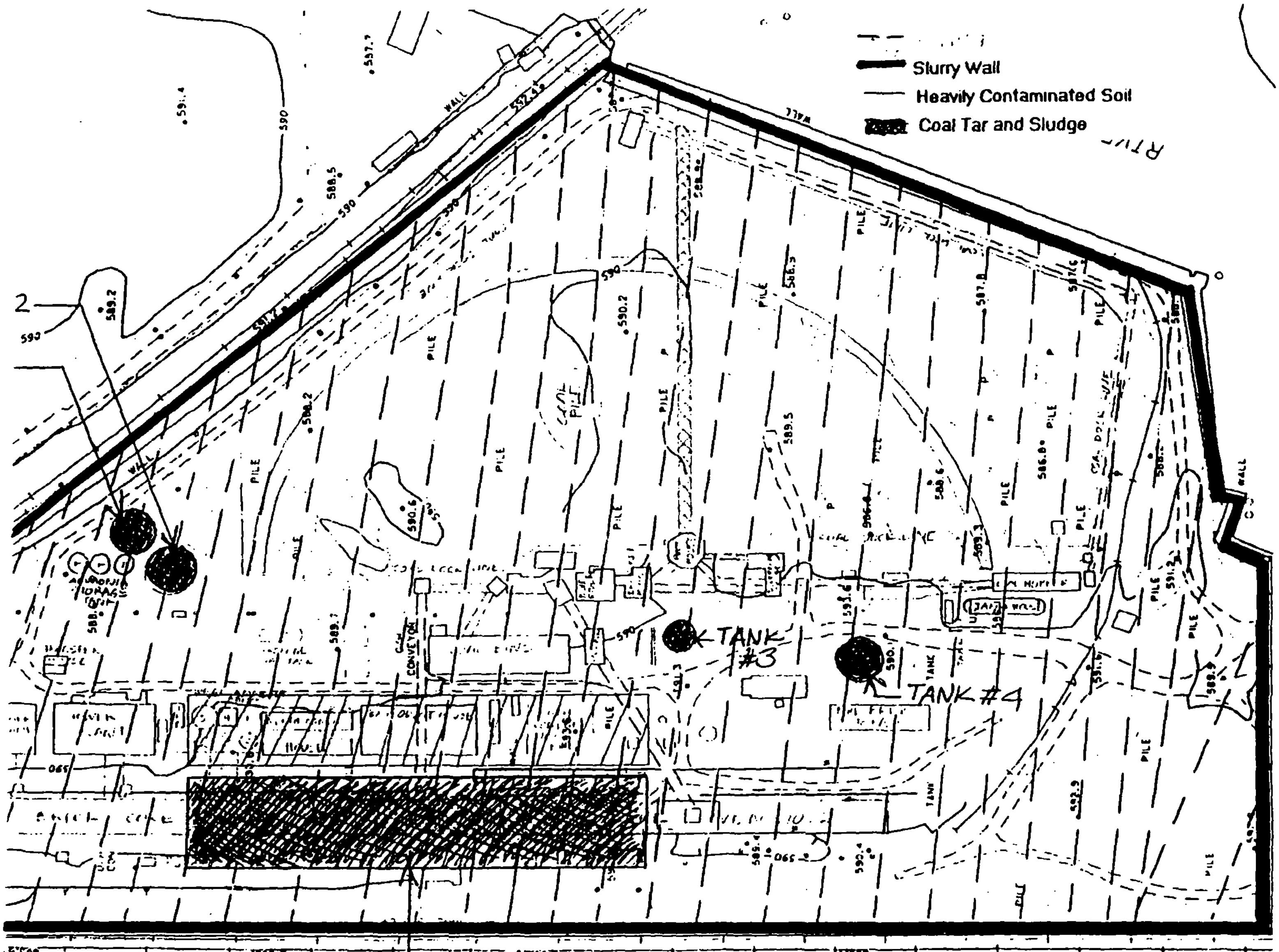
	Volatile Aromatics	Halogenated Volatiles	Phenolics	PAHs	Phthalates
	Benzene	Bromodichloromethane	Phenol	Acenapthene	Bis(2-ethylhexyl)phthalate
	Chlorobenzene	Chloroform	2,4-Dimethylphenol	Acenapthylene	Butyl Benzyl Phthalate
	Ethyl benzene	Methylene Chloride		Anthracene	Di-n-butylphthalte
	Nitrobenzene(b)	Tetrachloroethene		Benzo(a)anthracene	Di-n-Octyl Phthalate
	Toluene	Trans-1,2-Dichloroethene		Benzo(a)pyrene	Dimethyl Phthalate
	Total Xylenes	Trichloroethene		Benzo(b)fluoranthene	Diethylphthalate
	Trimethylbenzene	1,1,1-Trichloroethane		Benzo(b,k)perylene	
	1,2-Dichlorobenzene(b)	1,1,2,2-Tetrachloroethane		Chrysene	
ı	1,3-Dichlorobenzene(b)	1,1-Dichloroethane		Dibenzo(a,h)anthracene	
		1,1-Dichloroethene		Dibenzofuran	
		1,2-Dichloromethane		Dimethylnaphthalene	
		Cis-1,3-Dichloropropane		Fluoranthene	
		Cis-1,2-Dichloropropane		Fluorene	
m				Indeno(1,2,3-cd)Pyrene	
se				Napthalene	
				Phenanthrene	
				Pyrene	
ı				1-Chloronaphtalene	
				1-Methylnapthalene	
				2-Chloronapthalene	
				2-Methylnapthalene	
ı					

ed Gas Plant Sites
nterest. Gas Research Insitute. October 1987.



Milwaukee Solvay Coke
and Gas Company
311 E. Greenfield Ave.

Figure 1. Solvay Coke site location



MODEL OF THE CONTAMINATED AREA