University of Louisville

ThinkIR: The University of Louisville's Institutional Repository

Electronic Theses and Dissertations

5-2006

Analysis of landfills C-746-S and C-746-T at the Paducah Gaseous Diffusion Plant.

Paul Jacob Cooper 1981-
University of Louisville

Follow this and additional works at: <https://ir.library.louisville.edu/etd>

Recommended Citation

Cooper, Paul Jacob 1981-, "Analysis of landfills C-746-S and C-746-T at the Paducah Gaseous Diffusion Plant." (2006). *Electronic Theses and Dissertations*. Paper 275.
<https://doi.org/10.18297/etd/275>

This Master's Thesis is brought to you for free and open access by ThinkIR: The University of Louisville's Institutional Repository. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of ThinkIR: The University of Louisville's Institutional Repository. This title appears here courtesy of the author, who has retained all other copyrights. For more information, please contact thinkir@louisville.edu.

ANALYSIS OF LANDFILLS C-746-S AND C-746-T AT
THE PADUCAH GASEOUS DIFFUSION PLANT

By

Paul Jacob Cooper
B.S., University of Louisville, 2005

A Thesis
Submitted to the Faculty of the
University of Louisville
Speed School of Engineering
As Partial Fulfillment of the Requirements
For the Professional Degree

MASTER OF ENGINEERING

Department of Civil and Environmental Engineering

May 2006

ANALYSIS OF LANDFILLS C-746-S AND C-746-T AT THE
PADUCAH GASEOUS DIFFUSION PLANT

Submitted by: _____
Paul Jacob Cooper

A Thesis Approved on

Date

By the Following Reading and Examination Committee:

D.J. Hagerty, Thesis Director

James C. Watters

J.P. Mohsen

ABSTRACT

Contamination can be very difficult to remove from water. Once this water seeps into the ground, the difficulty grows exponentially. The Paducah Gaseous Diffusion Plant, located in Paducah, Kentucky, has contaminated the groundwater. The contaminants that pose an environmental threat are Trichloroethylene and Technetium-99. Trichloroethylene is used as a degreasing solvent, while Technetium-99 is a by-product of enriching uranium.

This study involves investigating potential sources of Trichloroethylene and Technetium-99. The potential sources are two landfills, the C-746-S landfill and the C-746-T landfill. Data from monitoring wells located around the two landfills were analyzed to determine if the two landfills are sources of contamination. Data from leachate reports were compared to monitoring well data to investigate the possibility of leakage from the landfill containing Trichloroethylene or Technetium-99.

TABLE OF CONTENTS

APPROVAL PAGE	ii
ABSTRACT	iii
LIST OF FIGURES	vi
I. INTRODUCTION	1
II. SITE INFORMATION	9
A. SITE GEOLOGY	9
B. GROUNDWATER FLOW	12
C. LANDFILL DATA	18
D. PRINCIPAL CONTAMINANTS	20
E. OTHER POTENTIAL CONTAMINANTS: LANDILL LEACHATE CHEMICALS AND TOXINS	23
III. ANALYSIS OF DATA	27
A. PARAMETERS ANALYSIS VERSUS TIME	28
B. PARAMETERS ANALYSIS VERSUS TIME AND SPACE	36
IV. CONCLUSIONS	50
V. REFERENCES	52

APPENDIX A – TYPICAL CHEMICAL ANALYSIS OF
GROUNDWATER SAMPLES54

APPENDIX B – LEACHATE ANALYSIS 57

VITA 68

LIST OF FIGURES

Figure 1A. Location of PGDP	2
Figure 1B. Area of Investigation at PGDP	3
Figure 2. Geologic Cross-section Beneath PGDP	5
Figure 3. TCE Plume Map	7
Figure 4. TC-99 Plume Map	8
Figure 5. Hydrogeologic Units at PGDP	14
Figure 6. Hydraulic Conductivities	15
Figure 7. Well Group 1	28
Figure 8. TCE Well Group 1 Plot of Concentration versus Time	29
Figure 9. TC-99 Well Group 1 Plot of Activity versus Time	30
Figure 10. Well Group 2	31
Figure 11. TCE Well Group 2 Plot of Concentration versus Time	32
Figure 12. TC-99 Well Group 2 Plot of Activity versus Time	33
Figure 13. Well Group 3	34
Figure 14. TCE Well Group 3 Plot Concentration versus Time	35
Figure 15. TC-99 Well Group 3 Plot Activity versus Time	36
Figure 16. TCE Surfer Plot 1988	38
Figure 17. TCE Surfer Plot 1991	38
Figure 18. TCE Surfer Plot 1994	39
Figure 19. TCE Surfer Plot 1997	39

Figure 20. TCE Surfer Plot 2000 40

Figure 21. TCE Surfer Plot 2001 40

Figure 22. TCE Surfer Plot 2002 41

Figure 23. TCE Surfer Plot 2003 41

Figure 24. TC-99 Surfer Plot 1994 43

Figure 25. TC-99 Surfer Plot 1997 43

Figure 26. TC-99 Surfer Plot 2000 44

Figure 27. TC-99 Surfer Plot 2001 44

Figure 28. TC-99 Surfer Plot 2002 45

Figure 29. TC-99 Surfer Plot 2003 45

Figure 30. MW 179 and MW 275 Location 47

Figure 31. TC-99 Activity Plot of MW 179 and MW 275 47

I. INTRODUCTION AND OVERVIEW OF THE PADUCAH GASEOUS DIFFUSION PLANT

Located 10 miles west of Paducah, Kentucky, the Paducah Gaseous Diffusion Plant (PGDP) began operations in 1954. Figure 1A maps the location of the PGDP, while Figure 1B provides a closer image of the plant location. The plant initially produced enriched uranium that was enriched further at the Portsmouth Gaseous Diffusion Plant in Ohio. The Paducah Plant soon expanded to include nuclear weapons disassembly and disposal, uranium milling and disposal, and exotic metals recovery. The plant in 2006 produced uranium for commercial reactors, and used the uranium by-products for armor plating and anti-tank penetrators. The 2006 missions for the PGDP included: fuel production for commercial power reactors; environmental restoration of the site; and storage of depleted uranium hexafluoride.

The site is located on a large 3,422-acre complex, with 750 acres enclosed with fences. There are approximately 100 small lakes and ponds, with 7 settling basins and 17 gravel pits. Two major channels carry water: Bayou Creek is located on the west side of the site, with Little Bayou Creek located on the east side.

Figure 2 shows a geologic cross-section beneath the PGDP. Underneath the PGDP are three major geologic layers. The Upper Continental Recharge System (UCRS) consists

of clayey silts with interbedded sands and gravels. The UCRS is approximately 60 feet thick. Beneath the UCRS is the 30-40 feet thick Regional Gravel Aquifer System (RGA). The RGA contains discontinuous sands along with lower continental deposits. Located underneath the RGA is the semi-permeable McNairy formation. The groundwater flow has been determined to be approximately 3 ft/day, with a general flow direction of north-northeast.

Figure 2 – Geologic Cross-section Beneath PGDP (DOE 1997b)

The PGDP site has been identified as the source of groundwater contamination. The groundwater has been contaminated with TCE and TC-99. The plume maps for TCE and TC-99 are shown in Figures 3 and 4, respectively.

The problem addresses the C-746-S and C-746-T landfills. The landfills are located north of the plant, as shown in the area of investigation in Figure 1B. By transposing Figure 3 and Figure 4 on top of Figure 1B, the landfill site was located within the TCE and TC-99 plume. The question becomes, “Are the landfills the source of the TCE and TC-99 contamination?” The following sections address this issue. This document presents the general site characteristics. These include geology, groundwater flow, landfill contents, and information on the principal contaminants. The thesis then provides a description on the analysis of the data of groundwater contaminant and their levels. Finally the thesis includes three conclusions to answer the question.

2

FIGURE No. c5ac90001sk099.apr
DATE 08-12-01

Figure 3 – TCE Plume Map (Bechtel Jacobs Company LLC)

2

FIGURE No. c5ac90001sk099.apr
DATE 08-12-01

Figure 4 – TC-99 Plume Map (Bechtel Jacobs Company LLC)

II. SITE INFORMATION

This section addresses site characteristics. The geology and groundwater flow conditions are summarized. The geology of the site was used to develop the groundwater flow model, identify important chemical properties of the soil, and predict potential contamination problems. The groundwater flow model was used to determine the dispersion of the principal contaminants, along with leachate chemicals and toxins. The landfill contents also are addressed in this section. The landfill contents allowed insight into the possibility of the principal contaminants being present. The principal contaminants and leachate chemicals and toxins at the PGDP site also follow.

A. Site Geology

The geologic makeup of a site provides important data to an investigation. The geology provides information used to develop groundwater models, identify important chemical properties of the soil, and predict potential contamination problems. Critical features include geologic structures such as faults, and geologic units, particularly units defined on the basis of groundwater hydrology.

Outcrop maps of Southern Illinois show traces of faults and related structures. The same faults and related structures are expected in the PGDP area. The Illinois Geological Survey has identified faults and grabens within the PGDP area (DOE 1997b). The Kentucky Geologic Survey also has identified possible problems with two lineaments or fracture zones mapped through the PGDP area (DOE 1997b). The stratigraphic relationships also point to faulting that has continued into the Pleistocene age. The consistent elevation of the

depositional horizons indicates that faulting is absent in the continental deposits. The boreholes drilled at the site have returned no evidence of faulting in the surficial deposits.

The upper bedrock beneath the PGDP consists of Mississippian limestone and chert. A north regional dip towards the Illinois Basin exists. The units of the Mississippi Embayment and the Gulf Coastal Plain Province form a regional unconformity at the top of the bedrock. The Mississippi Embayment sediments belong to the Cretaceous McNairy Formation, the Paleocene Porters Creek Clay, and undifferentiated Eocene sands of the Wilcox Formation and Claiborne Group. The site is located on the northern tip of the Mississippi Embayment. Sands and gravels of the alluvial fan, located in parts of southern Illinois, were eroded and replaced by sediments of the Tennessee River basin. During the Pleistocene, the top of the McNairy Formation was disturbed by the Tennessee River. The ancestral river carved a basin in the shallow sediments. The Ohio River tends to follow the course taken by the ancestral river, but is displaced to the north of a loop in the ancestral river. The ancestral Tennessee River valley is filled with Pleistocene river and lake deposits, as shown in Figure 2, presented in Chapter I.

The following is an explanation of the different stratigraphic sections, shown in Figure 2, in chronological order, from oldest to youngest.

Mississippian Limestone – The Mississippian limestone forms the bedrock beneath the site. The limestone contains chert nodules with a gray tint. The limestone has been suggested to be cavernous from the information contained in the drillers' logs.

Rubble Zone – The rubble zone consists of chert and limestone gravels. The zone also contains limestone boulders embedded in sands or clays. The thickness of the rubble zone varies from 10 to 45 feet.

McNairy Formation – The thickness of the Cretaceous McNairy Formation ranges from 221 to 247 ft. The formation can be classified into three different layers, the lower, middle and upper. The upper layer ranges from 60 to 69 ft in thickness. The layer consists mainly of interbedded silts and fine sands. The middle layer contains thick silt and clay beds, ranging from 56 to 62 ft in thickness. The lower layer ranges from 100 to 120 ft in thickness and contains silt and clay beds with well-sorted fine sands between the silt and clay strata. Because of chemical weathering and physical erosion, the top layer of the McNairy Formation has less silt and clay content.

Porters Creek Clay – The thickness of this clay layer is approximately 100 ft. This massive glauconitic clay contains interbeds of sand. The clay represents a layer of ancestral Tennessee River sediments.

Eocene Sands – The thickness of this sand layer is approximately 100 ft. The sand overlays the Porters Creek Clay south of the PGDP.

Pliocene Gravels – The thickness of this layer can range from zero to 30 ft. The gravel consists of angular and sub-angular pieces. The gravel contains poorly sorted silty sands south of the plant. The age of the gravel ranges from Miocene to Pleistocene. The southeast quadrant of the plant overlies this gravel.

Lower Continental Deposits – The deposits have an average thickness of 30 ft, with a bottom of approximately 60 ft. The deposits consist of medium to coarse sand and chert gravel.

Upper Continental Deposits – Three depositional layers have been classified out of the total deposit. A basal sand defines the lower unit. The sand becomes siltier as it approaches the middle unit. The middle unit consists of fine-textured sediments. The

thickness of the middle unit ranges from 10 to 40 ft. The upper unit contains sand and gravel. The sand and gravel varies greatly in texture and sorting. Frequent vertical fracture traces are present within the deposit. The fractures are filled with silt or clay.

Loess – The loess is typically 10 to 15 ft thick beneath the PGDP. The silt facies from the upper continental deposits make the loess deposits difficult to differentiate. The loess has been replaced with fill material for construction of building supports in many places.

B. Groundwater Flow

Once a contaminant enters the ground, groundwater flow can disperse the contaminant. In order to determine the dispersion, a groundwater flow model must be developed. The model must define accurately the soil layers present, the hydraulic properties of the soil layers, and the possible connectivity of the layers. Once the model has been completed, then the contaminant can be tracked and possible solutions for the containment and cleanup of the contaminant can be proposed.

In order to develop an accurate conceptual model for the PGDP site, lithologic and geologic units were grouped together according to flow characteristics. The grouping of strata is called a hydrogeologic unit. The PGDP area can be represented by six defined hydrogeologic units. These units are defined as:

HU 1 – Loess

HU 2 – Permeable lenses (UCRS or Terrace Deposits)

HU 3 – UCRS lower confining unit

HU 4 – Regional Groundwater Aquifer (upper zone)

HU 5 – Regional Groundwater Aquifer (lower zone)

HU 6 – McNairy Formation Flow System.

Figure 5 gives a graphical representation of the hydrogeologic units. Figure 6 presents low, high and mean values for hydraulic conductivity of the units, where available. The loess is not an aquifer at the PGDP site.

Figure 5 – Hydrogeologic Units at PGDP (DOE 1997b)

Table 3-1. Hydraulic Conductivity Data

Hydrogeologic Unit	Low	Mean	High	Type of Test and Reference
UCRS - K_h				
(cm/sec) (ft/day)	1.02×10^{-8} 2.90×10^{-5}		6.93×10^{-4} 1.96	Slug tests (CH2M HILL, 1992)
HU 3 - K_v				
(cm/sec) (ft/day)		2.00×10^{-4} 0.57		Pumping test at C-404 (Terran, 1990)
(cm/sec) (ft/day)	1.06×10^{-7} 3.00×10^{-4}		5.19×10^{-7} 3.00×10^{-1}	Pumping test at C-333 (Terran, 1992)
RGA (K_p)				
(cm/sec) (ft/day)	3.26×10^{-5} 0.09		5.16×10^{-3} 146	Slug tests (CH2M HILL, 1992)
(cm/sec) (ft/day)	1.87×10^{-7} 53		3.77×10^{-3} 107	Pumping test at C-404 (Terran, 1990)
(cm/sec) (ft/day)	3.53×10^{-3} 100		5.29×10^{-1} 150	Pumping test at C-537 (CH2M HILL, 1992)
(cm/sec) (ft/day)	3.53×10^{-1} 1,000		4.23×10^{-1} 1,200	Pumping test at C-333 (Terran, 1992)
(cm/sec) (ft/day)	0.95 2,686		2.01 5,700	Pumping test at Northwest Plume north containment well field (LMES, 1996b)
McNairy (K_h)				
(cm/sec) (ft/day)	2.88×10^{-4} 0.08		1.84×10^{-4} 0.52	Slug tests (CH2M HILL, 1992)

K_h = horizontal hydraulic conductivity

K_v = vertical hydraulic conductivity

Figure 6 – Hydraulic Conductivities (DOE 1997b)

Upper Continental Recharge System

The upper continental recharge system (UCRS) defines the uppermost water-bearing layer. The layer contains lenses of sand and gravel material. The layer contains two hydrogeologic subunits, HU 2A and HU 2B. HU 2A is the uppermost unit, while HU 2B

defines the lower unit. A continuous clay layer separates the two subunits. Each layer also shows different head values, corresponding to different water elevations. Each unit does show a strong downward vertical gradient. The hydraulic conductivity of the two layers can be variable. Slug tests reveal an average hydraulic conductivity for HU 2A of 4.24×10^{-5} cm/sec and 7.41×10^{-4} cm/sec for HU 2B (DOE 1997b). According to McConnell (1992), the vertical hydraulic conductivity can be approximated by $1/10^{\text{th}}$ the horizontal conductivity. The dominant flow in the layers is downward.

The site lacks the historical data to determine accurately the hydraulic conductivity field. The hydraulic conductivity field can be better understood by performing a geostatistical evaluation. DOE (1997a) used experimental semivariograms to evaluate the hydraulic conductivity field. The analysis was performed on layers HU 2A and HU 2B. The geostatistical analysis determined the spatial correlation structure of hydraulic conductivity. The semivariogram analysis determined the spatial distribution of lithologic classes. Semivariogram analysis was conducted for indicator-transformed data. Lithologic Class 3 and Class 4 were defined by semivariograms used to evaluate the spatial correlation structure. Class 2 was unable to be designated due to limited data. To evaluate the site thoroughly, multiple direction semivariogram analysis was performed. At large distances, hydraulic conductivity, lithology, and facies were spatially correlated. Four key conclusions came from the semivariogram analysis. First, the HU 2A and HU 2B are spatially connected as shown by correlated structures. The semivariograms show omnidirectional and directional correlation. The lithologic classes are also spatially correlated. The second key conclusion states the best model for Lithologic Class 3 in HU 2A is a pure nugget model. That model shows the clayey and silty sand in HU 2A is not spatially correlated; i.e., the fine soils are

present in lenses, not continuous layers. Thirdly, the north-south and northeast-southwest directions show the best spatial correlation. The last key conclusion involves the accuracy of the data. The correlation in HU 2A ranges from 45.7 to 228.6 meters. A majority of the data correlated with HU 2A is less than 91.4 meters. The correlation in HU 2A can be assumed to be less than 91.4 meters.

The UCRS shows steep vertical hydraulic gradients. These vertical hydraulic gradients range from 0.5 to 1 meter/meter. The large gradients make the analysis of the water table difficult. The water table has a broad trough located in the northeast and central areas. There is also a ditch in the northwest quadrant, representing a linear discharge area. The west side of the PGDP has a hydraulic gradient toward Bayou Creek in the UCRS.

To summarize, the UCRS contains many discontinuous zones of clay and silt embedded in sandy layers, as well as some continuous fine-grained strata. Gradients indicate overall downward flow, but local flow could be horizontal on the upper surfaces of clay or silt lenses.

Regional Gravel Aquifer

The HU 4 and HU 5 hydrogeologic units define the Regional Gravel Aquifer (RGA). The two units generally work together. The lower continental deposits define HU 5, while discontinuous sand makes up HU 4. The two units showed no water elevation change in nested wells, revealing that the two units are hydraulically connected.

As stated before, the RGA ranges in thickness from 3 to 17 meters. Figure 6 shows the results from conductivity tests performed in the RGA. These tests include aquifer tests by Terran (1990), CH2M Hill (1992), and LMES (1996). Each test returned different values for hydraulic conductivity, ranging from 0.09 ft/day to 5700 ft/day.

HU 3 provides a confining layer for the RGA. HU 3, the lower unit of the UCRS, consists of silt and clay facies. These facies restrict the vertical flow of groundwater. The layer is continuous over the site. The Ohio River influences the groundwater flow in the RGA. When the stage of the Ohio River is low, the groundwater in the RGA flows north to northeast. During high stages of the Ohio River, it is possible for the groundwater flow to slow or even reverse direction.

McNairy Formation

The hydraulic gradient in this formation is toward the Ohio River. The slope of the gradient is almost parallel to that in the RGA. The Porters Creek Clay layer caps the formation, making recharging of the formation minimal. However, the clay layer is absent around the PGDP, so the RGA and McNairy Formation hydraulically are connected. Monitoring wells have measured the vertical gradient to be 0.03 meter/meter. The McNairy Formation does have a high hydraulic potential near the Ohio River from a steeper potentiometric surface of the RGA. The hinge line, along which the vertical hydraulic gradient does not exist, runs parallel to the Ohio River at the northern boundary of the site. The Upper and Levings Members of the McNairy formation show very low conductivities. It would take approximately 12,000 years for water to flow vertically through the 125-ft thick layer.

C. Landfill Data

The C-746-S and C-746-T landfills are located on an older solid waste management unit, SWMU 145, which is located just beneath the S&T landfills. The SWMU is approximately 44 acres in size. The units were constructed in the early 1950's. A report

from Union Carbide in 1973 contains indications of what is in the units (Union Carbide 1973). The report states that the site contractor at that time would discard all types of scrap and waste materials into the landfills. The collection of construction waste continued until the late 1980's. Once a year, the scrap would be moved into piles or depressions, and covered with soil. Previous site investigations discovered materials such as roofing, construction debris, and flyash in the landfills (DOE 2001). No reports state that TCE or TC-99 was placed in the landfill.

A report found within files of the Division of Waste of the Department of Environmental Protection in Frankfort provides some insight into the S landfill contents. The 1980 report provides information on operators, refuse path, landfill operation, and landfill contents. The landfill was operated and maintained by the Plant Services Department. Special pans were located throughout the plant, labeled "Sanitary Landfill Only". Input to the pans was limited to paper, rags, wood, floor sweepings, garbage, paint and soft drink cans. The refuse was taken to the landfill, where it was placed with fly and bottom ash from the C-600 Steam Plant. The refuse was placed in a trench of ash, then backfilling over the refuse was done with ash. Dirt and clay was placed over the ash to facilitate runoff and prevent erosion and leaching. Daily disposals were about 2.7 tons of refuse and 15.9 tons of ash. Cover material was applied only weekly.

Ash provides most of the input to the landfill. Approximately 5,800 tons per year of ash were added to the sanitary landfill. Paper provided the second highest flow, at 650 tons each year. Wood, metal, garbage, and miscellaneous refuse provided about 100 tons each per year. Hazardous waste was taken to the sanitary landfill as well. Approximately five tons per year of transite sheeting were deposited in the S landfill. Transite sheeting contains

asbestos. The cooling tower fill deposited in the landfill contained vinyl chloride, asbestos and organics. Hazardous fill provided an extra 2.5 tons per year. The wood used for the cooling tower contained arsenic and pentachlorophenate, which prevents fungus growth. The wood accounted for 0.5 ton per year of weight. A percent breakdown of materials disposed at the landfill also was provided in the report. Approximately 42 percent of materials were cardboard, while 35 percent of materials were paper. Only 13 percent of the actual material going to the landfill was characterized as garbage, while small wood pieces and miscellaneous items accounted for the remaining 10 percent.

Notice of violation was given to the Plant Services Department in 2005. The violations included failure to characterize waste found in newly discovered solid waste management units, and failure to make a determination as to the hazardous or nonhazardous character of wastes deposited in the S&T landfills.

D. Principal Contaminants

Trichloroethylene

Trichloroethylene (TCE) is a blue or colorless organic liquid. TCE has a distinct chloroform-like odor. Trade names and synonyms include Benzinol, Lethurin, Philex and Vitran. The TCE EPA hazardous waste number is U228, and the Hazardous Substance Data Bank code for TCE is 133(ASTDR, p.182). TCE is used commonly to degrease fabricated metal parts and also in some textiles. TCE can be used also in dry cleaning solvents and a refrigerant/heat exchange liquid. The Safe Drinking Water Act sets the Maximum Contaminant Level for TCE in source water at five parts per billion (ppb). (NPDWR)

A toxic release inventory conducted between 1987 and 1993 shows Pennsylvania releasing the most TCE into water and land with 33,450 pounds per year. Most of the contaminant released into the water comes from industrial organics industry, releasing 27,708 pounds per year. The steel pipe/tube industry pollutes the land with TCE, at a total of 39,288 pounds per year. The car parts, plating, and wool fabric industries also contributed to the contamination of the land with 19,920, 20,100, and 18,081 pounds, respectively.

(NPDWR)

TCE is classified as a highly volatile compound, with vapor pressure of 69.0 mm Hg at 25 degrees Celsius. TCE also is denser than water, having a specific gravity of 1.464. Air-born TCE has a residence time of 5-7 days, and degrades to phosgene, dichloroacetyl chloride, and formyl chloride. (ATSDR, p.182-184)

The LC₅₀ is the measure of an instantaneous lethal dose to laboratory animals. The dose amount will result in 50 percent death of the population of laboratory animals within four hours after dosing. Siegel (1971) reported the LC₅₀ dose for TCE at 12,500ppm. Kylin (1962) studied mice exposed to four hours of TCE at a concentration of 6400ppm. A 20 percent death rate occurred. Most deaths were caused from depression of the central nervous system. Prendergast (1967) reported laboratory animals have survived doses from 35ppm for 90 days up to 700ppm for 6 weeks. TCE also causes respiratory problems when victims are exposed through inhalation. Villas (1991) reported that when victims are exposed to 500ppm for 30 minutes, Clara cells in the bronchial tree showed vacuole formation and endoplasmic reticulum dilation. In a study by Windemuller and Ettema (1978), 15 males showed no adverse effects from exposure of 200ppm for 2.5 hours. Other reports from Milby, Sidorin, Bell and Smith have shown adverse reactions to exposure to TCE. (ATSDR, p. 11-19)

Since TCE is denser than water, it is classified as a dense nonaqueous phase liquid, better known as a DNAPL. A DNAPL solution, such as TCE, tends to travel along water channels within the subsurface until it meets an impervious obstacle. The impervious obstacles that TCE encounter at PGDP are thin clay lenses in the UCRS and in the bottom of the RGA.

Technetium-99

Technetium-99 (TC-99) occurs naturally in very small amounts in the earth's crust. TC-99 is mostly made artificially during enrichment of uranium and plutonium for nuclear reactors. TC-99 was first produced from neutron or deuteron bombardment of molybdenum sheets. TC-99 also is produced by spontaneous fission of uranium, which occurs in atmospheric nuclear weapons tests. (Peacock 1966)

The main source of TC-99 is from fission product wastes. The yield percent for technetium 99 from thermonuclear fission of uranium 235 is 6.06 percent (Till 1984). In a report with data from 1975 to 1982, the Portsmouth, Ohio plant in 1977 released 31 Ci into water that year (Union Carbide Corp. 1979). Oak Ridge recorded the largest amount of Technetium released into air with 6.8 Ci in 1976 (Union Carbide Corp. 1977).

TC-99, like many radioactive elements, exists as different isotopes. The most common isotope of technetium, TC-99m, is used in the medical field. By injecting technetium into the body, it is possible to produce images from certain organs in the body. (For Example, Figure 20.1 in Ebbing's *General Chemistry* book shows an image of the entire body made using TC-99m (Ebbing, p.836).) The half-life of TC-99m is approximately 6 hours. The half-life for TC-99, like at PGDP, is 212,000 years.

E. Other Potential Contaminants: Landfill Leachate Chemicals and Toxins

A number of chemicals, including potentially toxic compounds and elements, are present typically in landfill leachate. The presence of such chemicals in groundwater under the S&T landfills would indicate the landfills were possible sources for contaminants such as TCE and TC-99. Among the elements found in landfill leachate are cadmium, iron, lead, and zinc (Tchobanoglous et al 1993, p.419). Various chlorides also are commonly found at significant concentrations in landfill leachate. Leachate also typically shows high chemical oxygen demand values (Tchobanoglous et al 1993, p.418).

Cadmium

Cadmium is a naturally occurring element present in the earth's crust. Cadmium cannot exist in the environment in a pure form; it must bind with oxygen, chlorine or sulfur. Cadmium is dangerous because it is not odiferous and is readily soluble in water. Release of the toxin is estimated at 4,000 to 13,000 tons per year in the United States. Cadmium is the by-product of production of metals such as zinc, lead, and copper. Cadmium is found in batteries, some metal alloys, and metal coatings. (ATSDR)

Cadmium seems to show the most potential for problems through inhalation exposure. Accidental acute exposure by inhalation has been recorded. Typical symptoms do not occur until days later, when severe pulmonary edema and chemical pneumonitis cause death (Beton et al, 1966). Measurements of concentrations where death has occurred have ranged from 1.5 µg/g of wet lung tissue to 4.7 µg/g. (ATSDR)

Chlorides

Chlorine is the most important and widely distributed halogen in natural water (Hem, p.170). Chlorine is present in various types of rocks, although in low concentrations.

Chlorine is typically present as the chloride ion, Cl^- . Over 75 percent of the total amount of chlorine is present in the earth's crust. Rainwater around the ocean falls with a concentration around 1 mg/L.

Chloride ions do not enter into oxidation or reduction reactions and are not significantly adsorbed on mineral surfaces. Kaufman and Orlob (1956) found that chloride ions move with water through most soils tested. Landfills greater than 10 years old have chloride concentrations ranging from 100 mg/L to 400 mg/L (Tchobanoglous et al., p.418).

Iron

EPA classifies iron as a secondary contaminant, setting the standard to 0.3 mg/L maximum contaminant level. When the iron enters the groundwater, it forms ferrous iron II. Iron II does not cause a problem, but it does form iron III. Iron III reacts with oxygen or bacteria and forms insoluble hydroxides. These cause blockages in pipes and pumps, and eventually attract bacteria. The bacteria cause odor and blockage problems also (Lenntech). Landfills over 10 years old have iron concentrations ranging from 20 mg/L to 200 mg/L (Tchobanoglous et al., p.418).

Lead

Lead is a naturally occurring element in the Earth's crust. Lead normally does not occur in pure form; rather it stabilizes with two or more elements to form lead compounds. Lead presents itself in typical everyday objects such as batteries, pipes, and munitions. Before the 1980's lead also was found in paints and ceramic glazes. Lead has been banned in gasoline. (ATSDR)

When lead is released into the ground, it adheres to soil particles. It is released only when it is exposed to acidic water. Lead enters the human body through ingestion of lead-

ridden foods or lead-contaminated water. Water can be contaminated by lead through groundwater contamination or lead pipes existing in the structure. Lead is also found in cigarettes, lead solder, and high exposure near busy highways. About 99 percent of the lead taken in by an adult leaves the body, while only 32 percent leaves children. (ATSDR)

Lead attacks the body in the same way whether it is ingested or inhaled. Lead disrupts the nervous system by reducing its effectiveness, causing weakness in fingers, hands, and toes. High exposure causes fatal brain and kidney damage. Lead can also cause reduced sperm production in males and miscarriages in females. (ATSDR)

Zinc

Zinc is one of the most abundant naturally occurring metals. Zinc is present in almost all foods. Zinc commonly protects steel from corrosion when steel is galvanized. Zinc is used in products ranging from shampoos to sun block. Zinc usually adheres to soil particles and is insoluble in water, but some types of zinc compounds have the ability to transfer to the groundwater. Fish also absorb zinc. (ATSDR)

The recommended daily allowance of zinc for men is 11 mg/day, while women are allowed 8 mg/day. Adverse reactions for exposure ten to fifteen times RDA such as vomiting, nausea, and stomach cramps occur. Health effects such as reduced HDL cholesterol and pancreas damage occur when subjects are exposed to zinc over a long period of time. (ATSDR)

Chemical Oxygen Demand

Chemical Oxygen Demand (COD) is the measurement of oxygen required to oxidize wastes chemically. COD is calculated when compounds present in a water sample resist degradation by biologic activity. Typical COD values for landfills older than 10 years range

from 100 mg/L to 500 mg/L (Tchobanoglous et al., p.418). The test involves mixing known quantities of sulfuric acid reagent containing silver sulfate, and potassium dichromate, with the sample. The mixture is vaporized and condensed for two hours, with condenser attached. The following chemical equation shows the process.

The amount of excess dichromate is measured by titration with ferrous ammonium sulfate. A sample of distilled water is tested to repeat the procedure to check for errors caused by organic matter present in the reagents. The COD can be calculated using Equation 2. (Viessman, Jr. and Hammer 1998)

$$\text{COD} = \frac{(a - b) \times (\text{normality_of_Fe})(\text{NH}_4)_2(\text{SO}_4)_2 \times 8000}{V} \quad (2)$$

where

COD = chemical oxygen demand, mg/l

a = amount of ferrous ammonium sulfate titrant added to blank, ml

b = amount of titrant added to sample, ml

V = volume of sample

Section II provided site information for PGDP. The geology of the site provided information about the potential paths by which the contaminants can disperse. The groundwater flow direction from the model is north-northeast. The primary contaminants present very serious health concerns for people. The leachate chemicals and toxins provide secondary checks for landfill leakage. Section III analyzes the data in order to investigate the landfill problem. Only data for the monitoring wells provided within the investigation area were analyzed. Bechtel-Jacobs Company LLC provided the data via an FTP site.

III. ANALYSIS OF DATA

Groundwater chemical analysis samples for the site were collected by different companies responsible for the site at different times. Each sample had a full analysis performed. TCE concentrations were reported with detection limits. Technetium-99 activities included detection limits, along with an error inherent in the radiation measurement technique. Sample data sheets are shown in Appendix I.

Data Sorting Method

Each measurement value of TCE was accompanied by its detection limit. The detection limit is the lowest possible value that the test method allows. If a concentration value was at or below the detection limit, then the concentration value could be taken to be the detection limit, or it could have been discarded. A problem occurs with discarding data because the test did detect some source of contaminant. By excluding the data, any statistical analysis program will perceive that value as zero, instead of the possible detection limit. As the detection limit increases, the error in excluding the data increases. Also, as the concentration value approaches the detection limit, the data results can be skewed due to the exclusion. The dilemma caused by excluding data could have been serious for plots based on statistics. The patterns of the derived contaminant plumes would have been affected by the plot of zero values or the detection limit. Therefore, all data values were included, whether they were above, at, or below the detection limit.

A. Parameter Analysis versus Time

Well Groups

Assuming the groundwater flow model developed was correct, three groups of wells were chosen. Each group served its own purpose to investigate possible transport paths for the contaminants.

Group 1

The first group of wells was MW263, MW179, and MW264. Figure 7 shows the well locations in reference to the landfills. This group of wells is located approximately the same distance north of the landfills. Since the groundwater flow is generally assumed to be north-northeast, these wells should show any transport of contaminants from the landfill.

Figure 7 – Well Group 1

Trichloroethylene Plots-Group 1

Figure 8 shows a plot of the concentration of TCE versus time at wells 179, 263, and 264. If the landfills are sources of TCE, then TCE concentrations in each MW should peak

at approximately the same time. MW263 records the greatest value for the well group in July 2001 at 23 µg/L. MW179 also peaks during July 2001 at 9 µg/L. During July 2001, MW264 recorded a concentration of 4 µg/L. MW264 peaks during October 2000 at 6 µg/L. MW179 and MW264 show a considerable difference from MW263 during July 2001. If the landfills are sources of TCE, then the concentrations of the well group should be very similar. The well group data do not show any hard evidence of a possible TCE leak from the landfills.

Figure 8 – TCE Well Group 1 Plot of Concentration versus Time

Technetium-99 Plots-Group 1

Figure 9 shows a plot of the concentration of TC-99 versus time in group #1 wells. MW263 and MW264 show no relative increase during the period. The highest value for MW263 occurs on October 1999; the concentration of TC-99 was recorded at 48.3 pCi/L. MW264 shows a peak value of 121 pCi/L in November 1994. MW179 shows two distinct peaks. The first peak occurs in July 1998, while the other larger peak occurs in July 2001. The concentration values are 451.8 pCi/L and 506 pCi/L, respectively. According to the

location of the wells, data from MW263 and MW 264 should mimic these two peaks. The graph shows good evidence that the landfills are not sources of TC-99.

Figure 9 – TC-99 Well Group 1 Plot Activity versus Time

Group 2

The second group of wells is MW353, MW267, MW179, and MW273. The wells are plotted in Figure 10, showing their orientation to the landfills. These monitoring wells are located along the assumed groundwater flow direction north-northeast. Each well bottoms in the middle of the RGA.

○ **273**

Figure 10 – Well Group 2

Trichloroethylene Plots-Group 2

The TCE concentrations in the well group were plotted versus time in Figure 11. MW353 and MW267 show detection limit readings throughout the sampled time. MW179 data show considerable fluctuation and increase. The concentration fluctuates between 1 $\mu\text{g/L}$ and 9 $\mu\text{g/L}$ during the study period. MW 273 should mimic these fluctuations, if TCE is coming from the landfills because of the location of MW 273 down gradient from MW 179. MW273 shows no fluctuations, staying at the detection limit during the study time. Data from this well group are inconclusive.

Figure 11 – TCE Well Group 2 Plot of Concentration versus Time

Technetium-99 Plots-Group 2

Technetium-99 activities are plotted versus time in Figure 12 for Group 2 wells. Data from MW353 and MW267 would show any TC-99 that may enter the study area through contamination sources located south of the landfills. MW267 shows no TC-99 moving into the area. MW353 shows some signs of a contaminant moving into the area. MW179 data show the same signature twin peak shown in Figure 9, while MW273 data show little activity. If the landfills were a source of contaminant, then a moving peak would be present on the plot as shown by peaks at different times in different wells. With the high activities of TC-99 in MW179 data not showing in MW273 data, it is highly probable that the landfills are not a source of TC-99 contamination.

If a spike on the plot in Figure 12 represents the passage of a slug of contaminant through the RGA, from MW 353 toward MW 179, the data suggest that a slug of TC-99 passed from MW 353 to MW 179 in about 21 months. With the distance between those two

wells being 2150 feet, it is possible to estimate the rate of contaminant travel as about 3 ft/day, which is consistent with estimates from groundwater studies done at PGDP.

Figure 12 – TC-99 Well Group 2 Plot of Activity versus Time

Group 3

The third group of wells is MW266, MW275, and MW272, shown in Figure 13. The group also is aligned with the assumed groundwater flow direction. The sampling zones in these wells are located in the lower RGA.

○ **272**

○ **275**

Figure 13 – Well Group 3

Trichloroethylene Plots-Group 3

With TCE being a DNAPL, it is more likely that the contaminant would be transported along the bottom of the RGA. Also, if the landfill is a true source of TCE, then the well cluster data should show some increased concentrations. Figure 14 shows a plot of the well cluster concentrations of TCE versus time. The concentration of TCE increases to a peak concentration of 16 µg/L in April 2001, then decreases. MW275 and MW272 record detection limit concentrations during the study period. Data from MW266 indicate that the landfills could be a source of TCE. However, concentration from MW266 should show on

MW275 and MW272 if the landfills are a true source, and no such increase is shown.

Figure 14 – TCE Well Group 3 Plot Concentration versus Time

Technetium-99 Plots-Group 3

Data from MW266 show the best evidence, in combination with data from MW275 and MW272, that the landfills are not a source of TC-99. MW266 shows a peak activity of 19.6 pCi/L during April 1998, as shown in Figure 15. MW275 shows the highest activity of 231 pCi/L. MW272 also shows high activity of TC-99, increasing to 78.6 pCi/L. If the landfills are a source of TC-99, then MW266 should show the peak values that occur at MW275 and MW272. Without a large activity in the data for MW266, the plot shows strong evidence of no TC-99 leak.

Figure 15 – TC-99 Well Group 3 Plot Activity versus Time

B. Parameter Analysis versus Time and Space

Surfer Analysis

Surfer is a program developed by Golden Software (2002). The program has the ability to plot data at Cartesian coordinates at a particular elevation. The program can be used to plot concentration and activity values. The user-friendly interface allows importing Excel files for easy plotting. In general, the darker the color, the higher the concentration or activity.

Trichloroethylene Plots

Surfer plots were generated for TCE around the area of the S&T landfills by year, and by elevation. The years chosen were 1988, 1991, 1994, 1997, 2000, 2001, 2002, and 2003. Figures 16 through 23 show plots for those years. Figure 16, the 1988 plot of the

concentration of TCE in the RGA, suggests two possible sources of contaminant. The apparent source southeast of the landfills has a higher concentration of TCE than does the apparent source northwest of the landfills. The shape of the southeast "hot spot" is interesting. The plume of contaminant is elongated almost perpendicular to groundwater flow. The northwest hot spot also elongates perpendicular to the groundwater flow. The 1991 plot of TCE concentration, Figure 17, shows the 1988 southwest plume apparently has grown. The size and concentration have increased. The 1988 northeast plume has reduced in size and concentration. The pattern formed by the 1988 and 1991 plots shows the contaminant moving in the east-southeast direction. This direction implies flow perpendicular to the accepted groundwater model flow directions. Furthermore, the plots of TCE concentration shown in Figures 18 through 23 show an apparent irregular disappearance and reappearance of implied sources of TCE northwest and southeast of the S&T landfills. All of these plots suggest sources of TCE outside the landfills, with implied movement of TCE perpendicular to the most likely direction of groundwater flow.

Figure 16 – TCE Surfer Plot 1988

Figure 17 – TCE Surfer Plot 1991

Figure 18 – TCE Surfer Plot 1994

Figure 19 – TCE Surfer Plot 1997

Figure 20 – TCE Surfer Plot 2000

Figure 21 – TCE Surfer Plot 2001

Figure 22 – TCE Surfer Plot 2002

Figure 23 – TCE Surfer Plot 2003

Technetium-99 Plots

Figures 24-29 show Surfer plots of TC-99 activities in the RGA, for 1994, 1997, 2000, 2001, 2002, and 2003, respectively. The 1994 plot of TC-99 activities, Figure 24, shows two apparent sources, or “hot spots”. One hot spot is located to the northeast of the landfills, while the other hot spot is located southwest of the landfills. The 1997 plot, Figure 25, reveals the disappearance of the two hot spots. The hot spots are replaced by an increased activity of TC-99 from the northeast to the southwest. The 2000 plot, Figure 26, shows the return of the southwest hot spot. The plume formation implies a groundwater flow perpendicular to the accepted groundwater flow direction of north-northeast. The 2001 plot, Figure 27, shows a decrease in activity at the southwest hot spot. The northeast hot spot returns with another hot spot located farther to the northeast. The 2002 plot, Figure 28, shows a reduction of activity around the landfills, with a reduction in activity of the new northernmost hot spot. The 2003 plot, Figure 29, shows a complete site reduction in activity around the landfills. None of the original hot spots are present. The sequence of plots shows no real pattern of activity of TC-99 in the RGA below the landfills. If the landfills were a source of TC-99, then the Surfer plots should show a corresponding plume originating at the landfills.

Figure 24 – TC-99 Surfer Plot 1994

Figure 25 – TC-99 Surfer Plot 1997

Figure 26 – TC-99 Surfer Plot 2000

Figure 27 – TC-99 Surfer Plot 2001

Figure 28 – TC-99 Surfer Plot 2002

Figure 29 – TC-99 Surfer Plot 2003

Groundwater Flow Direction Accuracy

The results from the Surfer plots put in question the accuracy of the groundwater flow model. Surfer plots at different times show plume patterns different from those expected from the assumed north-northeast flow direction. Two wells show some evidence of the north-northeast flow direction. Figure 30 shows the locations of MW179 and MW275. The sampling zone for MW179 is located in the middle depth of the RGA, while the sampling zone for MW275 is located in the lower RGA. When the activity of TC-99 was plotted versus time in Figure 31, the pattern expected from the location of the two wells was found. MW179 shows a distinct peak activity in July 1998. MW275 shows a distinct peak during July 2001. The distance between the wells is 1570 feet, and the time for the contaminant plug to travel is 36 months. Therefore the contaminant plug velocity is 1.5 ft/day. This result agrees with the accepted values of effective porosity, gradient, groundwater flow direction and contaminant transport velocity.

○ 275

Figure 30 – MW 179 and MW 275 Location

Figure 31 – TC-99 Activity Plot of MW 179 and MW 275

Leachate Analysis

If the landfills are leaking, then it is appropriate to examine concentrations of contaminants other than just TCE and TC-99. If no contaminated material, such as TCE and TC-99, was placed in the landfills, then there would be no proof of leakage from the concentration and activity analyses. The leachate reports used for the analysis are provided in Appendix B. The following constituents were examined: Cadmium, Chlorides, COD, Iron, Lead, Sulfates, TOC, and Zinc.

Cadmium provides little to no evidence of landfill leakage. The maximum concentration measured in samples from the monitoring wells is 0.01 mg/L. The average reading of Cadmium concentration is 0.005 mg/L, or 5 µg/L, in groundwater samples. The maximum leachate concentration for Cadmium is 3.4 µg/L. The detection limit for the leachate sample is 5 µg/L. Typical values of Cadmium in landfill leachate range from 0 to 0.6 mg/L, or 0 to 60 µg/L. (Vesilind et al., p.127). Therefore, Cadmium cannot provide any evidence of landfill leakage.

Chlorides averaged 39 mg/L in groundwater samples from the monitoring wells. The monitoring well samples showed a maximum chloride concentration value of 316 mg/L. Typical values for chlorides in landfill leachate range from 6.2 to 67,000 mg/L (Vesilind et al., p. 127). Once again, the chlorides fall in the lower range of concentration, providing no evidence of landfill leakage.

The maximum concentration for iron from the monitoring well samples was 383 mg/L. The average concentration of iron was 3 mg/L. The maximum iron concentration from the leachate reports is 950 mg/L. Typical ranges for iron are 4 to 2200 mg/L in landfill leachate (Vesilind et al., p.127). The maximum concentration in groundwater is a fraction of

that in the leachate, but the average iron concentration was low. The iron data show no signs of leakage from the landfills.

The maximum lead concentration recorded in the monitoring wells was 0.235 mg/L, or 235 µg/L. The average lead concentration for the monitoring wells was 0.06 mg/L, or 60 µg/L. Typical values for leachate from landfills range from 0 to 2.55 mg/L, or 2550 µg/L. (Vesilind et al., p.127). The leachate from the S landfill had a maximum lead concentration of 89 µg/L. The leachate concentration was lower than the monitoring well concentrations. Data on lead do not support the theory of a leaking landfill.

The maximum zinc concentration for the monitoring well samples was 2 mg/L. The average concentration of zinc for the monitoring well samples was 0.12 mg/L. Typical values of zinc from landfill leachate range from 0.005 to 846 mg/L (Vesilind et al., p.127). The leachate report for the S landfill gives a zinc concentration of 0.9 mg/L. Zinc data could be interpreted as giving weak evidence of leakage from the landfills.

TCE and TC-99 levels reported in the leachate from the S landfill show that little contaminated refuse was placed in the landfills. The maximum TC-99 activity was 3 pCi/L. The maximum TCE concentrations present in the leachate do not exceed the detection limit. From these results, it can be concluded that there is little or no TCE or TC-99 present in the landfills.

The maximum value for Chemical Oxygen Demand, or COD, recorded in analysis of groundwater from around the S&T landfills was 254 mg/L. The average recorded COD for the monitoring well samples was 24.5 mg/L. Typical values of COD in landfill leachate range from 11 mg/L to 84,000 mg/L (Vesilind et al., p. 127). The average COD falls into the lower range of values for leachate. COD does not provide evidence for landfill leakage.

IV. CONCLUSIONS

The cumulative analysis of the data shows that there is a very high probability that the landfills have not leaked TCE and TC-99. There is a plethora of evidence pointing to this conclusion.

1. The concentration plots show evidence of the landfills not being a source of TCE or TC-99. Plots of TCE concentrations and TC-99 activities versus time for each monitoring well group enforce the conclusion. Data from one monitoring well group does support the assumed groundwater flow direction and velocity, but do not support the possibility of a leak.
2. The Surfer plots also show no evidence of TCE or TC-99 leakage. The Surfer plots show strange patterns when the data are compared over time. The locations of higher concentrations or activities move around the site, and sometimes completely disappear.
3. The leachate analysis was directed at the contents of the landfill, to try to discover any possible leakage of key leachate chemicals. None of the concentrations show solid proof of leakage from the landfill.

The Surfer plots show recurring high concentrations of TCE located close to the old north-south drainage ditch, which was located north of the landfills. TCE was used as a degreasing agent, which could have been washed down the drains without any regard. The source of TCE contamination around the landfills could be the north-south drainage ditch.

Figure 12 and Figure 31 suggest that plugs of TC-99 are travel from south of the landfills, across the landfills, and continue traveling in the groundwater flow direction. With the path of the slugs beginning south of the landfills, they cannot be sources of TC-99 contamination.

With the assumption of funds available for the project, better techniques are available to address the issue of possible leakage from the S&T landfills. A quick, accurate solution could be obtained by taking core samples in borings angled beneath the landfills. This method can provide groundwater for samples contaminant testing, to allow investigation of the effects of the landfill on groundwater quality and flow.

V. REFERENCES

- Agency for Toxic Substances and Disease Registry (ATSDR). 1997. Toxicological profile for trichloroethylene (TCE). Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.
- Department of Energy (1997a). *Progress Report, Characterization of Upper Continental Recharge System Heterogeneity and Uncertainty for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, JE/PAD/97-0137, United States Department of Energy, Paducah, KY, April 1, 1997.
- Department of Energy (1997b). *Ground-Water Conceptual Model for the Paducah Gaseous Diffusion Plant*, DOE/OR/06-1628&D0, United States Department of Energy, Paducah, KY, August 1997.
- Department of Energy (2001). *Old North-South Diversion Ditch Sampling Results, Paducah Gaseous Diffusion Plant, Paducah, Kentucky*. DOE/OR/07-1929&D1, United States Department of Energy, Paducah, KY, May 2001.
- Ebbing, D.D. (1996). *General Chemistry*, 5th Edition, Houghton Mifflin Company, Boston, 1087 pp.
- Goodyear Atomic Corporation (1978). Portsmouth Gaseous Diffusion Plant Environmental Monitoring Report for Calendar Year 1977, GAT-955.
- Hem, John D. (1978). *Study of Interpretation of the Chemical and Characteristics of Natural Water*, Second Edition. United States Government Printing Office, Washington.
- Howard, P. (1991). *Handbook of Environmental Fate and Exposure Data for Organic Chemicals, Volume II Solvents*, Lewis Publishers.
- Lenntech, www.lenntech.com/groundwater/iron.htm, April 11, 2006.
- McConnell, C.L. (1992). "A Steady State Computer Model of the C-404 Landfill Area," in *Resource Conservation and Recovery Act Part B Permit Modification for Inclusion of C-404 Low-Level Radioactive/Hazardous Waste Landfill*, KY/E-129, Martin Marietta Energy Systems, Inc., Paducah Gaseous Diffusion Plant.

- National Primary Drinking Water Regulations. www.epa.gov/safewater/mcl.html. February 28, 2006.
- Peacock, R.D., (1966) *The Chemistry of Technetium and Rhenium*, Elsevier Publishing Company, New York, NY.
- Surfer version 8.04, Golden Software, Inc., Golden, Colorado.
- Tchobanoglous, G., H. Theisen and S.A. Vigil (1993). *Integrated Solid Waste Management*. McGraw-Hill, New York, 978 pp.
- Terran Corporation (1990). *Groundwater Monitoring Phase II C-404 Aquifer Testing Program ESO 16749 Paducah Gaseous Diffusion Plant, Paducah, Kentucky.*, Report NO. TX-8925, Terran Corporation.
- Till, J.E., Source Terms for Technetium-99 from Nuclear Fuel Cycle Facilities, Radiological Assessments Corporation, Nesses, South Carolina.
- Union Carbide Corporation (1973). *The Discard of Scrap Materials by Burial at the Paducah Plant*, Paducah, KY, October.
- Union Carbide Corporation (1977). Environmental monitoring report. Oak Ridge Facilities for Calendar Year 1976, Y/UB-6.
- Vesilind, P. A., Worrell, W. A. and Reinhart, D. R. (2002). *Solid Waste Engineering*. Brooks/Cole, Pacific Grove, CA 428 pp.
- Viessman, Jr., W. and M.J. Hammer (1998). *Water Supply and Pollution Control*. Addison Wesley Longman, Inc., Menlo Park, 827 pp.

APPENDIX A - TYPICAL CHEMICAL ANALYSIS OF GROUNDWATER SAMPLES

STA_NAME	D_COLLECTED	LAB_MEAS_CHEMICAL_NAME	LAB_MEAS_RESULTS	LAB_MEAS_UNITS	DETECT_LIMIT	RAD_ERR
MW276	2-Apr-01	Cadmium	0.005	mg/L	0.005	
MW276	2-Apr-01	Iron	1.16	mg/L	0.2	
MW276	2-Apr-01	Lead	0.05	mg/L	0.05	
MW276	2-Apr-01	Zinc	0.2	mg/L	0.2	
MW276	2-Apr-01	Technetium-99	68.9	pCi/L	19.1	15
MW276	2-Apr-01	Trichloroethene	16	ug/L	1	
MW276	2-Apr-01	Chloride	48.7	mg/L	2	
MW276	2-Apr-01	Chemical Oxygen Demand (COD)	25	mg/L	25	
MW268	2-Apr-01	Zinc	0.2	mg/L	0.2	
MW268	2-Apr-01	Technetium-99	42.3	pCi/L	19.1	14.2
MW268	2-Apr-01	Chloride	21.1	mg/L	2	
MW268	2-Apr-01	Chemical Oxygen Demand (COD)	25	mg/L	25	
MW268	2-Apr-01	Cadmium	0.005	mg/L	0.005	
MW268	2-Apr-01	Trichloroethene	2	ug/L	1	
MW268	2-Apr-01	Iron	1.71	mg/L	0.2	
MW268	2-Apr-01	Lead	0.05	mg/L	0.05	
MW275	3-Apr-01	Zinc	0.2	mg/L	0.2	
MW275	3-Apr-01	Technetium-99	228	pCi/L	19.1	19.3
MW275	3-Apr-01	Trichloroethene	1	ug/L	1	
MW275	3-Apr-01	Chloride	37.8	mg/L	2	
MW275	3-Apr-01	Chemical Oxygen Demand (COD)	25	mg/L	25	
MW275	3-Apr-01	Cadmium	0.005	mg/L	0.005	
MW275	3-Apr-01	Iron	1.5	mg/L	0.2	
MW275	3-Apr-01	Lead	0.05	mg/L	0.05	
MW272	2-Apr-01	Zinc	0.2	mg/L	0.2	
MW272	2-Apr-01	Technetium-99	37.6	pCi/L	19.1	14
MW272	2-Apr-01	Chloride	53.4	mg/L	2	
MW272	2-Apr-01	Chemical Oxygen Demand (COD)	25	mg/L	25	
MW272	2-Apr-01	Trichloroethene	1	ug/L	1	
MW272	2-Apr-01	Cadmium	0.005	mg/L	0.005	
MW272	2-Apr-01	Iron	1.67	mg/L	0.2	
MW272	2-Apr-01	Lead	0.05	mg/L	0.05	
MW269	4-Apr-01	Iron	0.2	mg/L	0.2	
MW269	4-Apr-01	Lead	0.05	mg/L	0.05	
MW269	4-Apr-01	Cadmium	0.005	mg/L	0.005	
MW269	4-Apr-01	Zinc	0.2	mg/L	0.2	
MW269	4-Apr-01	Technetium-99	82.1	pCi/L	19.1	15.4
MW269	4-Apr-01	Chloride	30.6	mg/L	2	
MW269	4-Apr-01	Chemical Oxygen Demand (COD)	25	mg/L	25	

MW269	4-Apr-01	Trichloroethene	3	ug/L	1	
MW274	3-Apr-01	Chloride	40.5	mg/L	2	
MW274	3-Apr-01	Chemical Oxygen Demand (COD)	25	mg/L	25	
MW274	3-Apr-01	Cadmium	0.005	mg/L	0.005	
MW274	3-Apr-01	Iron	2.48	mg/L	0.2	
MW274	3-Apr-01	Lead	0.05	mg/L	0.05	
MW274	3-Apr-01	Zinc	0.2	mg/L	0.2	
MW274	3-Apr-01	Technetium-99	118	pCi/L	19.1	16.5
MW274	3-Apr-01	Trichloroethene	1	ug/L	1	
MW271	2-Apr-01	Chloride	25	mg/L	2	
MW271	2-Apr-01	Chemical Oxygen Demand (COD)	25	mg/L	25	
MW271	2-Apr-01	Cadmium	0.005	mg/L	0.005	
MW271	2-Apr-01	Iron	0.2	mg/L	0.2	
MW271	2-Apr-01	Lead	0.05	mg/L	0.05	
MW271	2-Apr-01	Zinc	0.2	mg/L	0.2	
MW271	2-Apr-01	Technetium-99	37.6	pCi/L	19.1	14.1
MW271	2-Apr-01	Trichloroethene	1	ug/L	1	
MW273	2-Apr-01	Zinc	0.2	mg/L	0.2	
MW273	2-Apr-01	Technetium-99	113	pCi/L	19.1	16.3
MW273	2-Apr-01	Trichloroethene	1	ug/L	1	
MW273	2-Apr-01	Chloride	37.2	mg/L	2	
MW273	2-Apr-01	Chemical Oxygen Demand (COD)	25	mg/L	25	
MW273	2-Apr-01	Cadmium	0.005	mg/L	0.005	
MW273	2-Apr-01	Iron	0.63	mg/L	0.2	
MW273	2-Apr-01	Lead	0.05	mg/L	0.05	
MW273	2-Apr-01	Cadmium	0.005	mg/L	0.005	
MW273	2-Apr-01	Iron	0.254	mg/L	0.2	
MW273	2-Apr-01	Lead	0.05	mg/L	0.05	
MW273	2-Apr-01	Zinc	0.2	mg/L	0.2	
MW273	2-Apr-01	Technetium-99	98.6	pCi/L	19.1	15.9
MW273	2-Apr-01	Trichloroethene	1	ug/L	1	
MW273	2-Apr-01	Chloride	37.2	mg/L	2	
MW273	2-Apr-01	Chemical Oxygen Demand (COD)	25	mg/L	25	

APPENDIX B - LANDFILL LEACHATE REPORTS

Landfill Leachate Report 080109 (C-746-S, Cell 2)

STL ST. LOUIS

COMMONWEALTH OF KENTUCKY

Client Sample ID: 080109

TOTAL Metals

Lot-Sample #...: F1H170127-002

Matrix.....: WATER

Date Sampled...: 08/14/01 14:25 Date Received...: 08/17/01

PARAMETER	RESULT	REPORTING LIMIT	UNITS	METHOD	PREPARATION- ANALYSIS DATE	WORK ORDER #
Prep Batch #...: 1233363						
Silver	ND N	10.0	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AM
		Dilution Factor: 1		Analysis Time...: 16:03		
Aluminum	160000 N	200	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AM
		Dilution Factor: 1		Analysis Time...: 16:03		
Arsenic	451	10.0	ug/L	SW846 6010B	08/21-08/25/01	EH6AV1AP
		Dilution Factor: 1		Analysis Time...: 00:00		
Barium	1920	200	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AQ
		Dilution Factor: 1		Analysis Time...: 16:03		
Beryllium	8.0	5.0	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AR
		Dilution Factor: 1		Analysis Time...: 16:03		
Calcium	348000	5000	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AC
		Dilution Factor: 1		Analysis Time...: 16:03		
Cadmium	2.3 B	5.0	ug/L	SW846 6010B	08/21-08/25/01	EH6AV1AT
		Dilution Factor: 1		Analysis Time...: 00:00		
Cobalt	228	50.0	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AU
		Dilution Factor: 1		Analysis Time...: 16:03		
Chromium	187	10.0	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AV
		Dilution Factor: 1		Analysis Time...: 16:03		
Copper	146	25.0	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AW
		Dilution Factor: 1		Analysis Time...: 16:03		
Iron	783000	500	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AX
		Dilution Factor: 5		Analysis Time...: 18:18		
Potassium	15000	5000	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AD
		Dilution Factor: 1		Analysis Time...: 16:03		
Magnesium	55800 E	5000	ug/L	SW846 6010B	08/21-08/27/01	EH6AV1AO
		Dilution Factor: 1		Analysis Time...: 16:03		

(Continued on next page)

LOT# F1H170127

STL ST. LOUIS

COMMONWEALTH OF KENTUCKY

Client Sample ID: 080109

TOTAL Metals

Lot-Sample #...: F1H170127-002

Matrix.....: WATER

PARAMETER	RESULT	REPORTING LIMIT	UNITS	METHOD	PREPARATION- ANALYSIS DATE	WORK ORDER #
Manganese	3860	15.0	ug/L	SW846 6010B	08/21-08/27/01	KH6AV1A9
		Dilution Factor: 1		Analysis Time...: 16:03		
Molybdenum	81.3	40.0	ug/L	SW846 6010B	08/21-08/27/01	KH6AV1A1
		Dilution Factor: 1		Analysis Time...: 16:03		
Sodium	43300	5000	ug/L	SW846 6010B	08/21-08/27/01	KH6AV1A8
		Dilution Factor: 1		Analysis Time...: 16:03		
Nickel	232	40.0	ug/L	SW846 6010B	08/21-08/27/01	KH6AV1A2
		Dilution Factor: 1		Analysis Time...: 16:03		
Lead	89.3	3.0	ug/L	SW846 6010B	08/21-08/25/01	KH6AV1A3
		Dilution Factor: 1		Analysis Time...: 00:00		
Antimony	ND	10.0	ug/L	SW846 6010B	08/21-08/25/01	KH6AV1A4
		Dilution Factor: 1		Analysis Time...: 00:00		
Selenium	9.6	5.0	ug/L	SW846 6010B	08/21-08/25/01	KH6AV1A5
		Dilution Factor: 1		Analysis Time...: 00:00		
Thallium	4.9 B	10.0	ug/L	SW846 6010B	08/21-08/25/01	KH6AV1A6
		Dilution Factor: 1		Analysis Time...: 00:00		
Uranium	ND	500	ug/L	SW846 6010B	08/21-08/27/01	KH6AV1AA
		Dilution Factor: 1		Analysis Time...: 16:03		
Vanadium	229	50.0	ug/L	SW846 6010B	08/21-08/27/01	KH6AV1A7
		Dilution Factor: 1		Analysis Time...: 16:03		
Zinc	902	20.0	ug/L	SW846 6010B	08/21-08/27/01	KH6AV1A8
		Dilution Factor: 1		Analysis Time...: 16:03		
Boron	210	200	ug/L	SW846 6010B	08/21-08/27/01	KH6AV1AF
		Dilution Factor: 1		Analysis Time...: 16:03		
Silicon	94800 N	2500	ug/L	SW846 6010B	08/21-08/27/01	KH6AV1AG
		Dilution Factor: 5		Analysis Time...: 18:18		

(Continued on next page)

LOT# F1H170127

35

STL ST. LOUIS

COMMONWEALTH OF KENTUCKY

Client Sample ID: 080109

TOTAL Metals

Lot-Sample #...: F1H170127-002

Matrix.....: WATER

PARAMETER	RESULT	REPORTING LIMIT	UNITS	METHOD	PREPARATION- ANALYSIS DATE	WORK ORDER #
Prep Batch #...: 1234181						
Mercury	ND B	0.20	ug/L	SW846 7470A	08/22/01	EH6AV1AH
		Dilution Factor: 1		Analysis Time..: 16:41		

NOTE(S):

N Spiked analyte recovery is outside stated control limits.

B Estimated result. Result is less than RL.

E Matrix interference.

LOT# F1H170127

36

COMMONWEALTH OF KENTUCKY

Client Sample ID: 080109

GC/MS Volatiles

Lot-Sample #....: F1H170127-002 Work Order #....: EH6AV1AL Matrix.....: WATER

PARAMETER	RESULT	REPORTING LIMIT	UNITS
Iodomethane	ND	1.0	ug/L
Isobutanol	ND	50	ug/L
Methacrylonitrile	ND	1.0	ug/L
Methylene chloride	4.6 B	1.0	ug/L
Methyl methacrylate	ND	1.0	ug/L
Pentachloroethane	ND	1.0	ug/L
Propionitrile	ND	4.0	ug/L
Styrene	ND	1.0	ug/L
1,1,1,2-Tetrachloroethane	ND	1.0	ug/L
1,1,2,2-Tetrachloroethane	ND	1.0	ug/L
Tetrachloroethene	ND	1.0	ug/L
Toluene	ND	1.0	ug/L
1,1,1-Trichloroethane	ND	1.0	ug/L
1,1,2-Trichloroethane	ND	1.0	ug/L
Trichloroethene	ND	1.0	ug/L
1,2,3-Trichloropropane	ND	1.0	ug/L
Vinyl acetate	ND	2.0	ug/L
Vinyl chloride	ND	2.0	ug/L
Xylenes (total)	ND	1.0	ug/L

SURROGATE	PERCENT RECOVERY	RECOVERY LIMITS
4-Bromofluorobenzene	95	(72 - 116)
Toluene-d8	101	(79 - 124)
Dibromofluoromethane	97	(71 - 128)
1,2-Dichloroethane-d4	97	(65 - 126)

NOTE (S) :

J Estimated result. Result is less than RL.

B Method blank contamination. The associated method blank contains the target analyte at a reportable level.

LOT# F1H170127

17

STL ST. LOUIS

COMMONWEALTH OF KENTUCKY

Client Sample ID: 080109

Severn Trent Laboratories - Radiochemistry

Lab Sample ID: F1H170127-002
Work Order: EH6AV
Matrix: WATER

Date Collected: 08/14/01 1425
Date Received: 08/17/01 0900

Parameter	Result	Qual	Total Uncert. (2 σ +/-)	MDC	Prep Date	Analysis Date	Batch #	Yld %
TC-99 by LSC (Short CT)				pCi/L		TC-01 MOD		
Technetium 99	3.0	U	2.2	3.5	08/31/01	09/10/01	1243311	

NOTE(S)

Data are incomplete without the case narrative.

MDC is determined by instrument performance only.

Bold results are greater than the MDC

U Result is less than the sample detection limit.

LOT# F1H170127

19

STL ST. LOUIS

COMMONWEALTH OF KENTUCKY

Client Sample ID: 080110

TOTAL Metals

Lot-Sample #...: F1H170127-003

Matrix.....: WATER

PARAMETER	RESULT	REPORTING LIMIT	UNITS	METHOD	PREPARATION- ANALYSIS DATE	WORK ORDER #
Manganese	16100	75.0	ug/L	SW846 6010B	08/21-08/27/01	EH6A01A9
		Dilution Factor: 5		Analysis Time...: 18:22		
Molybdenum	127 B	200	ug/L	SW846 6010B	08/21-08/27/01	EH6A01A1
		Dilution Factor: 5		Analysis Time...: 18:22		
Sodium	3860 B	25000	ug/L	SW846 6010B	08/21-08/27/01	EH6A01A8
		Dilution Factor: 5		Analysis Time...: 18:22		
Nickel	397	200	ug/L	SW846 6010B	08/21-08/27/01	EH6A01A2
		Dilution Factor: 5		Analysis Time...: 18:22		
Lead	35.9	3.0	ug/L	SW846 6010B	08/21-08/25/01	EH6A01A3
		Dilution Factor: 1		Analysis Time...: 00:00		
Antimony	ND	10.0	ug/L	SW846 6010B	08/21-08/25/01	EH6A01A4
		Dilution Factor: 1		Analysis Time...: 00:00		
Selenium	20.4	5.0	ug/L	SW846 6010B	08/21-08/25/01	EH6A01A5
		Dilution Factor: 1		Analysis Time...: 00:00		
Thallium	219	50.0	ug/L	SW846 6010B	08/21-08/27/01	EH6A01A6
		Dilution Factor: 5		Analysis Time...: 18:22		
Uranium	ND	2500	ug/L	SW846 6010B	08/21-08/27/01	EH6A01AA
		Dilution Factor: 5		Analysis Time...: 18:22		
Vanadium	ND	250	ug/L	SW846 6010B	08/21-08/27/01	EH6A01A7
		Dilution Factor: 5		Analysis Time...: 18:22		
Zinc	812	100	ug/L	SW846 6010B	08/21-08/27/01	EH6A01A8
		Dilution Factor: 5		Analysis Time...: 18:22		
Boron	459 B	1000	ug/L	SW846 6010B	08/21-08/27/01	EH6A01AF
		Dilution Factor: 5		Analysis Time...: 18:22		
Silicon	67400 N	2500	ug/L	SW846 6010B	08/21-08/27/01	EH6A01AG
		Dilution Factor: 5		Analysis Time...: 18:22		

(Continued on next page)

LOT# F1H170127

38

STL ST. LOUIS

COMMONWEALTH OF KENTUCKY

Client Sample ID: 080110

TOTAL Metals

Lot-Sample #...: F1H170127-003

Matrix.....: WATER

PARAMETER	RESULT	REPORTING LIMIT	UNITS	METHOD	PREPARATION- ANALYSIS DATE	WORK ORDER #
Prep Batch #...: 1234181						
Mercury	ND	0.20	ug/L	SW846 7470A	08/22/01	EH6A01AH
		Dilution Factor: 1		Analysis Time...: 16.43		

NOTE(S):

- N Spiked analyte recovery is outside stated control limits.
B Estimated result. Result is less than RL.

LOT# F1H170127

39

STL ST. LOUIS

COMMONWEALTH OF KENTUCKY

Client Sample ID: 080110

GC/MS Volatiles

Lot-Sample #....: F1H170127-003 Work Order #....: EH6A01AL Matrix.....: WATER

PARAMETER	RESULT	REPORTING LIMIT	UNITS
Iodomethane	ND	1.0	ug/L
Isobutanol	ND	50	ug/L
Methacrylonitrile	ND	1.0	ug/L
Methylene chloride	3.8 B	1.0	ug/L
Methyl methacrylate	ND	1.0	ug/L
Pentachloroethane	ND	1.0	ug/L
Propionitrile	ND	4.0	ug/L
Styrene	ND	1.0	ug/L
1,1,1,2-Tetrachloroethane	ND	1.0	ug/L
1,1,2,2-Tetrachloroethane	ND	1.0	ug/L
Tetrachloroethene	ND	1.0	ug/L
Toluene	ND	1.0	ug/L
1,1,1-Trichloroethane	ND	1.0	ug/L
1,1,2-Trichloroethane	ND	1.0	ug/L
Trichloroethene	ND	1.0	ug/L
1,2,3-Trichloropropane	ND	1.0	ug/L
Vinyl acetate	ND	2.0	ug/L
Vinyl chloride	ND	2.0	ug/L
Xylenes (total)	ND	1.0	ug/L

SURROGATE	PERCENT RECOVERY	RECOVERY LIMITS
4-Bromofluorobenzene	92	(72 - 116)
Toluene-d8	93	(79 - 124)
Dibromofluoromethane	89	(71 - 128)
1,2-Dichloroethane-d4	87	(65 - 126)

NOTE(S) :

B Method blank contamination. The associated method blank contains the target analyte at a reportable level.

LOT# F1H170127

23

STL ST. LOUIS

COMMONWEALTH OF KENTUCKY

Client Sample ID: 080110

Severn Trent Laboratories - Radiochemistry

Lab Sample ID: F1H170127-003
Work Order: EH6A0
Matrix: WATER

Date Collected: 08/14/01 1530
Date Received: 08/17/01 0900

Parameter	Result	Qual	Total Uncert. (2 σ +/-)	MDC	Prep Date	Analysis Date	Batch #	Yld %
TC-99 by LSC (Short CT)				pCi/L		TC-01 MOD		
Technetium 99	2.1	U	2.3	3.8	08/31/01	09/10/01	1243311	

NOTE(S)

Data are incomplete without the case narrative.

MDC is determined by instrument performance only.

Bold results are greater than the MDC

U Result is less than the sample detection limit.

LOT# F1H170127

25

VITA

The author was born on January 14, 1981 in Hodgenville, Kentucky to David Cooper and Peggy Cooper. He graduated from LaRue County High School in May 1999. He received his Bachelor of Science in Civil and Environmental Engineering from the University of Louisville in May 2005 with Honors. In May 2006, Paul received the Master of Engineering Degree in Civil and Environmental Engineering from the University of Louisville. Paul was a member of Chi Epsilon, the University of Louisville American Society of Civil Engineers Student Chapter, and the University of Louisville Society of American Military Engineers Student Chapter. Paul enjoys fishing, hiking, and any outdoor activity.