



Combustion Byproducts Recycling Consortium

Combustion Byproducts Recycling Consortium

**Quarterly Project Status Report
for the period
July 2005 to September 2005**

Submitted to:

**U.S. Department of Energy
National Energy Technology Laboratory
P.O. Box 10940
626 Cochrans Mill Road
Pittsburgh, PA 15236-0940**

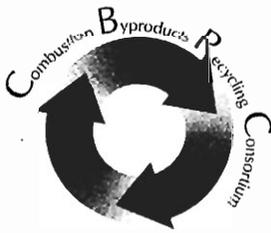
Submitted by:

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**Report Issued
October 2005**

DOE Award Number: DE-FC26-98FT40028

**Principal Investigator:
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Combustion Byproducts Recycling Consortium

a program of West Virginia University
in cooperation with the U.S. Department of Energy
National Energy Technology Laboratory

October 28, 2005

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To Whom It May Concern:

Enclosed please find 3 copies of the quarterly project status report for the reporting period of July 2005 to September 2005. I hope this report meets with your approval.

If you have any questions, please do not hesitate to contact me. I can be reached at (304) 293-2867 x5448 or through email at tvandivo@wvu.edu.

Sincerely,

Tamara Vandivort
Program Coordinator

Enclosures

Cc: Bill Aljoe, DOE-NETL Program Manager



U.S. DEPARTMENT OF ENERGY
FEDERAL ASSISTANCE PROGRAM/PROJECT STATUS REPORT

OMB Burden Disclosure Statement

Public reporting burden for this collection of information is estimated to average 47.5 hours per response, including the time for reviewing instructions, ing existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments reg this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Office of Information Resou Management Policy, Plans, and Oversight, Records Management Division, HR-422 - GTN, Paperwork Reduction Project (1910-0400), U.S. Departme Energy, 1000 Independence Avenue, S.W., Washington, DC 20585; and to the Office of Management and Budget (OMB), Paperwork Reduction Proje (1910-0400), Washington, DC 20503.

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4. Name and Address West Virginia University Research Corp. 886 Chestnut Ridge Road, Room 202, P.O. Box 6845 Morgantown, WV 26506-6845		5. Program/Project Start Date 9-24-1998
		6. Completion Date 10-26-05
7. Approach Changes <input checked="" type="checkbox"/> None		
8. Performance Variances, Accomplishments, or Problems Please see attached project status report <input checked="" type="checkbox"/> None		
9. Open Items <input checked="" type="checkbox"/> None		
10. Status Assessment and Forecast <input checked="" type="checkbox"/> No Deviation from Plan is Expected		
11. Description of Attachments <input type="checkbox"/> None		
12. Signature of Recipient and Date  10/26/05	13. Signature of U.S. Department of Energy (DOE) Reviewing Representative an	

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**Submitted by: Tamara Vandivort
Consortium Manager, CBRC**

**CBRC National Center Report
for
July - September, 2005**

Submitted by
**Tamara Vandivort
CBRC Consortium Manager**

Phase VI Proposal and Budget

A proposal package was completed for phase VI and submitted to U.S. DOE-NETL. Only \$10,000 of the requested \$1,499,998 was released to WVU September, 2005; the remainder is still pending.

Request for Pre-Proposals (RFP)

The deadline for receiving pre-proposals was set for July 31, 2005. Fifty-two pre-proposals were received. Pre-proposals were placed on a secure website. Reviewers (CBRC National Steering Committee members) who signed confidentiality agreements were given access to the web site to review the pre-proposals. Pre-proposals were available for review and instructions provided to the reviewers on ~August 5, 2005.

Pre-proposals Selected

Of the 52 pre-proposals received, 19 were selected. Attachment 1 is a list of those selected and invited to submit full proposals. The full RFP is available at a URL provided to those applicants. The deadline for receiving full RFPs is December 15, 2005.

National Steering Committee Meets

The CBRC National Steering Committee (NSC) met September 16, 2005 in Pittsburgh, PA. Those present included:

- Jim Rower, NSC Member, USWAG
- Paul Chugh, Director, Midwestern Region, SIUC
- William Aljoe, DOE-NETL COR
- Dave Meadows, USACE Huntington WV District
- Dan Wheeler, NSC Member, Illinois DCCA, Office of Coal
- Jim Hower, Director, Eastern Region, UK
- Paul Ehret, NSC Member, Interstate Mining Compact Commission
- Cheri Miller, NSC Eastern Regional Chair, TVA
- Kim Vories, NSC Member, U.S. Office of Surface Mining
- Dave Goss, ACAA

- Andy Wittner, EPA
- Paul Ziemkiewicz, National Center Director, WVU
- Tamara Vandivort, Consortium Manager, WVU

Those who participated via teleconferencing included:

- Debra Pflughoeft-Hassett, Director, Western Region, UND
- Jimmy Knowles, NSC Member, South Eastern Fly Ash Group (SEFA)
- Howard Humphrey, NSC Member, ACAA
- Rich Halverson, NSC Western Regional Chair, Headwaters Resources
- Bonnie Robinson, EPA

The agenda is listed below:

Combustion Byproducts Recycling Consortium
 National Steering Committee Meeting
 Friday, September 16, 2005
 8:00 AM - 3:00 PM
 Hyatt Regency
 Pittsburgh International Airport

Agenda

8:00 AM	Continental Breakfast Provided Welcome and Opening Remarks Explanation of the Day's Agenda Materials, Timeline, and Program Update	<i>Paul Ziemkiewicz, Director National Center</i> <i>Tamara Vandivort, Consortium Manager</i>
8:30 AM	Discussion of the Pre-proposals Western Region Midwestern Region Eastern Region	<i>Paul Ehret, NSC Chair Debra Pflughoeft-Hassett Paul Chugh Jim Hower</i>
11:30 AM	Working Lunch Provided	
1:00 PM	Selection of the Applicants to Invite to Submit Full Proposals	<i>Paul Ehret, NSC Chair</i>
2:00 PM	Other CBRC Business Full RFP Evaluation Criteria for Full Proposals Ashlines vs. Project Fact Sheets	<i>Tamara Vandivort, Consortium Manager</i>

3:00 PM Adjourn

Outreach Activities

Low-Cost, Reliable Energy and Chemical Feedstocks for Energy-Intensive Industry Clusters: Feasibility Study of a Coal-Fired Co-Generation Facility in Marshall County, WV

The energy balance for the industry cluster has been completed. A series of five energy generation case studies have been developed, ranging from conventional subcritical combustion units to advanced integrated gasification combined cycle (IGCC) technology. Generation of electrical energy is considered as the primary purpose of the power plant. Steam requirements for the energy cluster industries are provided by diverting steam streams from the power plant at appropriate pressure levels. When gasification of the coal occurs, the potential for replacing natural gas by diverting a slip stream of the synthesis gas from the gas turbines for use in the chemical process is also considered.

Capital cost estimates and energy input requirements were developed for each of these cases. Economic benefits for the various cases are currently under review. Preliminary results of the analysis indicate that the cases derived from the Leland Olds Station 2 re-powering project design study, which involves a hybrid gasification combined cycle unit, are economically superior to either an IGCC or a straight combustion unit for this particular industry cluster. The hybrid gasification system couples a partial gasification unit with a circulating fluidized bed combustion unit.

An overall energy balance for the cluster has been completed. Several generation options that, in most cases, would supply all of the steam and fuel gas requirements and over 50% of the total electricity requirements of the industry cluster have been developed.

Energy balances have been developed for 5 generation cases. The impact on electricity generation capacity of diverting steam streams from the power plant at appropriate pressure levels, and of diverting a slip stream of the synthesis gas from the gas turbines for replacing natural gas, has been estimated.

Web Page

The CBRC web page has been updated throughout the quarter with current events, the summer issue of *Ashlines*, and new project final reports that have been received.

Presentation Given at Pittsburgh Coal Conference

Paul Ziemkiewicz, Director, CBRC, gave a presentation on the CBRC program at the

2005 Pittsburgh Coal Conference, September, 2005. The presentation was based on a paper developed by Tamara Vandivort, Consortium Manager. A copy of the paper was sent to DOE-NETL COR, William Aljoe last quarter.

Summer, 2005 issue of *Ashlines*

The Summer, 2005 issue of *Ashlines* was completed (See Attachment 2.)

Project Final Reports and Papers

One final report on project 99-EC-E24, Use of Clean Coal Technology Products in the Construction of Low Permeability Liners, William Wolfe, Principal Investigator, was received. It can be found in Appendix A.

A paper on project 02-CBRC-M12, Commercial Production of Fired Bricks with Illinois Basin Class F Fly Ash, Melissa Chou, Principal Investigator, was received. This paper is to be given in December, 2005 at the International Congress on Fly Ash Utilisation, New Delhi, India. (See Appendix B.)

Plans for Next Quarter

Make preparations for NSC Meeting Set for February 2, 2006

A meeting will be held in conjunction with the American Coal Ash Association meeting February, 2006 in Austin, TX. The purpose of this meeting is to select from the full proposals received those to forward to U.S. DOE-NETL for funding consideration.

Full RFP

A full RFP was developed and reviewed by the NSC prior to release to the applicants invited to submit full proposals. A special URL was designated for applicants to use to download the RFP.

Ashlines

The Summer issue of *Ashlines* will be placed on the web page next quarter. E-mail notices will be sent to those on the CBRC *Ashlines* list serve. The Fall, 2005 issue of *Ashlines* under development this quarter will be completed and released next quarter. Due to delays from the current publisher in meeting deadlines, a new publisher will be solicited.

Coal-Fired Co-Generation Facility Feasibility Study

The economic analysis and comparison of the 5 generation cases will be finalized. A final report will be issued, and the results reviewed with U.S. DOE-NETL and industrial participants.

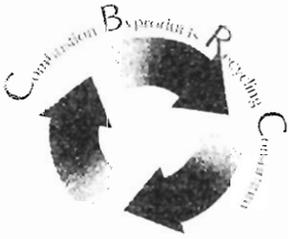
Attachment 1. List of pre-proposal applicants selected to submit full proposals.

Combustion Products Recycling Consortium
 Pre-proposal received in Response to RFP 2005
 SELECTION RESULTS

Proposal Number	Invite (Y/N)	Project Title	PI	Affiliation	Regional Priority	National Priority	Project Duration (Months)	CBRC Funds Requested	Proposer Funds	Other Funds	Total Project Value	Cost Share Required (25% of Total Project Value)	Cost Share Commitment
02-CBRC-M12	YES	Manufacturing fired bricks with fly ash and advanced CCBs	Chou	Illinois State Geological Survey	M1	N3	12	86,985.00	61,524.00	10,000.00	158,509.00	39,627.25	71,524.00
02-CBRC-W09	YES	Power Plant Combustion Byproducts for Improved Crop Productivity of Agricultural Soils (Phase II)	O'Neill	New Mexico State University	W1	N3	36	210,000.00	40,000.00	30,000.00	280,000.00	70,000.00	70,000.00
05-CBRC-E01	YES	Integrated Pilot Plant for CCB Conversion	Mensah-Biney	NC State Minerals Research Lab	E1	N3	24	112,300.00	190,000.00	247,700.00	550,000.00	137,500.00	437,700.00
05-CBRC-E08	YES	National Network of Research and Demonstration Sites for Agriculture and Other Land Application Uses of FGD Products	Dick	Ohio State University	E1	N4	36	250,000.00	21,000.00	216,370.00	487,370.00	121,842.50	237,370.00
05-CBRC-E09	YES	Synthetic Soil for Carbon Sequestration Reforestation Projects	Ellman	Maryland Environmental Restoration Group, Inc.	E1	N2	36	66,000.00	20,000.00	22,000.00	108,000.00	27,000.00	42,000.00
05-CBRC-E15	YES	Development and Demonstration of Rotary Triboelectrostatic Separation Technology for Fly Ash Purification	Tao	University of Kentucky	E1	N2	24	250,000.00	15,000.00	235,000.00	500,000.00	125,000.00	250,000.00
05-CBRC-E17	YES	Reuse of High Carbon Content Class F Fly Ash in Remediation of Petroleum-Contaminated Soils	Aydilek	University of Maryland	E1	N3	24	65,000.00	15,000.00	20,000.00	100,000.00	25,000.00	35,000.00
05-CBRC-M01	YES	Field Relevant Leachability Mass Transfer and Dispersion Coefficients	Daniels	University of North Carolina-Charlotte	M3	N1	36	243,500.00	81,167.00	0.00	324,667.00	81,166.75	81,167.00
05-CBRC-M08	YES	Extraction of Magnetite and Possible Utilization of Non-Magnetic CCBs in Construction	Mohanty	Southern Illinois University - Carbondale	M4	N3	24	249,471.00	85,464.00	5,000.00	339,935.00	84,983.75	90,464.00

Proposal Number	Invite (Y/N)	Project Title	PI	Affiliation	Regional Priority	National Priority	Project Duration (Months)	CBRC Funds Requested	Proposer Funds	Other Funds	Total Project Value	Cost Sha. Required (25% of Total Project Value)	Cost Share Commitment
05-CBRC-M09	YES	Cold In-Place Recycling of Asphalt Pavements Using Self-Cementing Fly Ash: Analysis of Pavement Performance and Structure Number	Misra	University of Missouri	M1	N3	12	24,984.00	10,195.00	20,489.00	55,668.00	13,917.00	30,684.00
05-CBRC-M10	YES	Field Testing of Arsenic and Mercury Bioavailability Model from Land-Applied CCBs	Pier	Tennessee Valley Authority	M1	N1	24	46,500.00	46,500.00	0.00	93,000.00	23,250.00	46,500.00
05-CBRC-M16	YES	In Situ Stabilization of Gravel Roads with Fly Ash	Edil	University of Wisconsin-Madison	M1	N3	24	100,000.00	33,300.00	0.00	133,300.00	33,325.00	33,300.00
05-CBRC-M17	YES	Environmental, Geotechnical and Microstructural Evaluation of Stabilized FGD (wet scrubber sludges) for use as Fill Material in Coastal Protection Devices	Rusch	Louisiana State University	M1	N4	36	365,500.00	112,014.00	40,000.00	517,514.00	129,378.50	152,014.00
05-CBRC-M20	YES	New Technology Based Approaches to Advance Higher Volume Fly ash Concrete with Acceptable Performance	Obla	National Ready Mixed Concrete Association	M1	N3	24	200,000.00	70,000.00	0.00	270,000.00	67,500.00	70,000.00
05-CBRC-M22	YES	Community-based Social Marketing: the tool to get target audiences to use CCBs	Buggeln	University of Tennessee	M3	N5	36	150,000.00	60,000.00	0.00	210,000.00	52,500.00	60,000.00
05-CBRC-W01	YES	Market, Characterization and Design Guidance for use of FGD material in Highway Applications	Daniels	University of North Carolina-Charlotte	W1	N4	36	252,400.00	84,133.00	0.00	336,533.00	84,133.25	84,133.00
05-CBRC-W03	YES	Evaluation of CCBs for In Situ Treatment of Acid Mine Drainage	Canty	Environmental, LLC	W1	N1	24	26,940.00	8,980.00	3,800.00	39,720.00	9,930.00	12,780.00
05-CBRC-W04	YES	Using Class C Fly Ash to Mitigate Alkali-Silica Reactions in Concrete	Dockter	University of North Dakota	W4	N3	36	225,000.00	1,000.00	74,000.00	300,000.00	75,000.00	75,000.00
05-CBRC-W08	YES	Commercialization of 100 Percent Fly Ash Concrete	Stephens	Montana State University	W3	N3	24	102,000.00	14,000.00	20,000.00	136,000.00	34,000.00	34,000.00

Attachment 2. Summer Issue of *Ashlines*



Volume 6, Number 2

Summer 2005

COMBUSTION BYPRODUCTS RECYCLING CONSORTIUM

Ashlines

a program of the
National Mine Land
Reclamation Center at
West Virginia University
in cooperation with the
U.S. Department of
Energy - National Energy
Technology Laboratory
www.netl.doe.gov

To promote and support the commercially viable and environmentally sound recycling of coal combustion byproducts for productive uses through scientific research, development, and field testing.

CCB Utilization and Disposal: A State-by-State Comparison

Bruce A. Dockter, P.I.

Engineers, scientists, and regulators who work with coal combustion byproducts (CCBs) are familiar with their state CCB regulations and local utilization and disposal practices. But few have the time or resources to investigate CCB practices outside their own region—for example, to compare what different state agencies require or what technologies and innovative uses are employed in other parts of the country.

In 2004, the Combustion Byproducts Recycling Consortium (CBRC) funded a study by the University of North Dakota's Energy and Environmental Research Center to compare CCB practices around the nation. According to Bruce A. Dockter, principal investigator, the project had two main goals. The first was to present a state-by-state accounting of department of transportation (DOT) specifica-



Study compares state department of transportation specifications for CCBs.

tions governing the use of CCBs.

Because most transportation and materials engineers cannot fully research all the current coal ash utilization technologies, the study compiled this information to

allow these professionals to become familiar with other department practices and to identify areas where specifications need to be developed within their own transportation offices.

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CCB Utilization and Disposal: A State-by-State Comparison

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The results from this project will help familiarize DOT engineers and officials with coal ash use applications around the country. It also will help the coal ash industry to develop a plan to work with these departments and individuals in expanding their knowledge while expanding coal ash markets.

The second goal of the project was to establish a comparison of state environmental laws and regulations as they pertain to CCB utilization and/or disposal. As a result of the interpretation of the Bevill Amendment, CCB utilization and disposal are not regulated at the federal level, but instead have been left to the states. Many states have enacted laws and adopted regulations, or both, governing the utilization and disposal of CCBs. These laws and regulations vary widely.

As part of the study, a state-by-state survey of state laws and regulations authorizing beneficial reuse of CCBs was conducted. It provides an overview of state solid waste laws and regulations governing reuse of CCBs. Although not intended to identify landfill or similar disposal requirements, the results will be useful to persons familiar with "beneficial use" regulations for CCBs in their particular state and will assist in the exchange of regulatory guidance to enhance the use of CCBs.

Although the findings of both project objectives are similar in their presentation (state-by-state comparisons), their contents are very distinct. Therefore, the project findings are presented in a two-

volume final report. Both volumes can be downloaded in their entirety from the CBRC Web site at <http://www.wri.nrcce.wvu.edu/programs/cbrc/>. The following is a short summary of the project findings.

Survey of State DOT Specifications for CCBs

In August 1992, a survey letter was sent to all highway departmental offices in the U.S. and Canada to look at the differences between state and provincial DOT specifications for CCB utilization. Since that time, numerous changes have occurred in these departments, so it was decided that an update was needed. An extensive survey was begun in 2004 to obtain specifications from all state DOT offices. All information for the survey was obtained through Internet searches and personal contacts within departments.

Although specifications and practices varied among states, several similarities were noted. The specifications used in all reported cases for fly ash were ASTM International (American Society for Testing and Materials) C618 and AASHTO (American Association of State Highway and Transportation Officials) M295. The title for both specifications is "Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete." Under both classification systems, fly ash is defined as "a finely divided residue that results from the combustion of ground or powdered coal."

In addition to concrete, numerous states have used fly ash as a mineral filler in asphaltic concrete and soil stabilization, with many more states beginning to use fly ash in flowable mortar applications.

Another material often cited for use as a cement supplement was ground granulated blast furnace slag. At one time, slag was generally only used as a blasting grit, skid, or traction applications, or as aggregate in asphaltic concrete. However, now many DOTs allow its use in the production of Portland cement concrete.

Most states included specifications for the allowable use of blended hydraulic cements. The specifications for these were ASTM C595 and AASHTO M240. The descriptions and definitions of these cements varied considerably.

The use of silica fume was often grouped into the same category as fly ash and ground granulated blast furnace slag as a mineral admixture in Portland cement concrete. The specifications for silica fume are AASHTO M307 "Microsilica for Use in Concrete and Mortar" and ASTM C1240 "Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout." Generally very small amounts of silica fume were specified for used in a concrete mix design. These specified amounts were usually from 3 to 10 percent of the total cementitious material.

Methods

Specifications on the use of CCBs in their construction procedures were requested. As was

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CCB Utilization and Disposal: A State-by-State Comparison

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the case in the 1992 survey, there were three main specification criteria:

- physical and chemical specifications for CCBs,
- applications that utilize CCBs and their corresponding specifications,
- quantities of CCBs which may be allowed in each application

The first step was to evaluate existing specifications as they appeared on Internet Web sites. The most utilized Web site was <http://fhwapap04.fhwa.dot.gov/nhswp/index.jsp>, which is maintained by the U.S. Federal Highway Administration (FHWA). This site consists of a searchable library of highway specifications from across the country. It also features discussion forums to enhance communication and interaction in the development and use of various types of construction specifications.

The FHWA Web site is not necessarily complete with all specification updates, so other DOT sites had to be utilized. Two of these other Internet sources of DOT specifications were <http://www.transdata.com/dots.htm> and <http://www.fhwa.dot.gov/webstate.htm>. These sites established links directly to DOT offices.

These DOT Web sites were often a good source of establishing personal contacts as well as checking specification updates. A summary was made for each state as to its existing specifications for CCB utilization.

After a state summary was completed, an e-mail copy was

sent to an appropriate representative from that state. The e-mail message was designed to accomplish two objectives: the first was to determine if there were any current specification updates that were not reflected on the available Web sites, and the second was to establish a personal contact, with an e-mail address, within each transportation office.

The information is presented in two forms in the project report. First, specific guidelines are given in a summarized text format. Second, the data are also presented in a series of tables allowing quick reference between states and comparison of their different specifications. This facilitates evaluation of similarities and experiences in coal ash utilization on a state-by-state basis. This information is intended to be used as a means of basic comparison and not to serve as a comprehensive design manual. In addition, a contact name with personal information is included in the appendix for each DOT office.

Results and Discussion

As mentioned previously, although specifications and practices varied between states, several similarities were noted. The specifications used in all reported cases for fly ash were ASTM C618 and AASHTO M295. The title for both specifications is "Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete." Under both classification systems, fly ash is defined as "a finely divided residue that results from the combustion of ground or powdered coal." Likewise, pozzolans are defined as "siliceous or siliceous

and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form, and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties."

These materials are then divided into three classifications: Class N, Class F, and Class C. Class N materials are raw or calcined natural pozzolans which may or may not be processed by calcination to induce satisfactory properties. Class F fly ash is normally produced from burning anthracite or bituminous coal and has pozzolanic properties. Class C fly ash is normally produced from lignite or subbituminous coal. This last class of fly ash, in addition to having pozzolanic properties, also has some cementitious properties.

Excerpts from the two classification systems, ASTM C618 and AASHTO M295, are given in Tables 1 and 2, respectively. The specification from AASHTO M295 is based on a previous ASTM C618 specification from 1996. Since that time, ASTM C618 has been updated to the more recent version portrayed in this report.

Transportation departments will often change their specification from the indicated ASTM C618 and AASHTO M295 to reflect regional practices and preferences. One example of this is the requirement for loss on ignition (LOI). The lowest maximum level of LOI allowed by either specification is 5 percent.

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CCB Utilization and Disposal: A State-by-State Comparison

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Table 1—ASTM C618-03 Chemical and Physical Specifications

Chemical Requirements	Mineral Admixture Class		
	N	F	C
Silicon Dioxide, Aluminum Oxide, Iron Oxide (SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃), min., %	70.0	70.0	50.0
Sulfur Trioxide (SO ₃), max., %	4.0	5.0	5.0
Moisture Content, max., %	3.0	3.0	3.0
Loss on Ignition, max., %	10.0	6.0 ^A	6.0
^A The use of Class F pozzolan containing up to 12.0% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.			
Physical Requirements	N	F	C
Fineness: Amount Retained When Wet-Sieved on 45 μm (No. 325) sieve, max., % ^A	34	34	34
Strength Activity Index: ^B with Portland Cement at 7-day, min. % of control	75 ^C	75 ^C	75 ^C
28-day, min. % of control	75 ^C	75 ^C	75 ^C
Soundness Water Requirement, max., percent of control	115	105	105
Autoclave Expansion or Contraction, max., %	0.8	0.8	0.8
^A Care should be taken to avoid the retaining of agglomeration of extremely fine material.			
^B The strength activity index with Portland cement is not to be considered a measure of the compressive strength of concrete containing the fly ash or natural pozzolan. The mass of fly ash or natural pozzolan specified for the test to determine the strength activity index with Portland cement is not considered to be the proportion recommended for the concrete to be used in the work. Strength activity index with Portland cement is a measure of reactivity with a given cement and may vary as to the source of both the fly ash or natural pozzolan and the cement.			
^C Meeting the 7- or 28-day strength activity index will indicate specification compliance.			
^D If the fly ash or natural pozzolan will constitute more than 20% by weight of the cementitious material in the project mix design, the test specimens for autoclave expansion shall contain that anticipated percentage.			

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CCB Utilization and Disposal: A State-by-State Comparison

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Table 2—AASHTO M295-98 Chemical and Physical Specifications

Chemical Requirements	Mineral Admixture Class		
	N	F	C
Silicon Dioxide, Aluminum Oxide, Iron Oxide (SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃), min., %	70.0	70.0	50.0
Sulfur Trioxide (SO ₃), max., %	4.0	5.0	5.0
Moisture Content, max., %	3.0	3.0	3.0
Loss on Ignition, max., %	5.0	5.0	5.0
Available Alkalies, as Na ₂ O, max., percent ^A	1.5	1.5	1.5
^A Applicable only when specifically required by the purchaser for mineral admixture to be used in concrete containing reactive aggregate and cement to meet a limitation on content of alkalies.			
Physical Requirements	N	F	C
Fineness: Amount Retained When Wet-Sieved on 45 μm (No. 325) sieve, max., % ^A	34	34	34
Strength Activity Index: ^B with Portland Cement at 7 day, min. % of control	75 ^C	75 ^C	75 ^C
28 day, min. % of control	75 ^C	75 ^C	75 ^C
Soundness Water Requirement, max., percent of control	115	105	105
Autoclave Expansion or Contraction, max., %	0.8	0.8	0.8
^A Care should be taken to avoid the retaining of agglomeration of extremely fine material.			
^B The strength activity index with Portland cement is not to be considered a measure of the compressive strength of concrete containing the mineral admixture. The strength activity index with Portland cement is determined by an accelerated test and is intended to evaluate the contribution to be expected from the mineral admixture to the longer strength development of concrete. Strength activity index with Portland cement is a measure of reactivity with a given cement and may vary as to the source of both the mineral admixture and the cement.			
^C Meeting the 7- or 28-day strength activity index will indicate specification compliance.			
^D If the fly ash or natural pozzolan will constitute more than 20% by weight of the cementitious material in the project mix design, the test specimens for autoclave expansion shall contain that anticipated percentage.			

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CCB Utilization and Disposal: A State-by-State Comparison

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However, many states specified LOI values to be much lower. Delaware, New York, North Carolina, Rhode Island, and the District of Columbia indicated a maximum allowable LOI of 4 percent. Still others, such as Arizona, Hawaii, Indiana, Idaho, Illinois, Kentucky, Missouri, Minnesota, New Jersey, New Mexico, North Dakota, Oregon, Ohio, South Dakota, Utah, Washington, and Wisconsin, accepted even lower maximum LOI values.

A similar situation also existed in the case for maximum levels of moisture content and fineness in states where DOT specifications are more restrictive than ASTM C618 or AASHTO M295. According to these specifications, the maximum retainment allowed on the number 325 mesh sieve is 34 percent, and the maximum acceptable moisture content is 3.0 percent. Several states such as Alaska, Indiana, New Mexico, Oregon, and South Dakota, were more restrictive in either one or both of these parameters.

Additionally, state specifications may undergo a series of alterations dependent on changes in national standards and field experiences. Other isolated differences in state specifications from national standards included maximum allowable autoclave expansion, maximum level of magnesium oxide (MgO), and a minimum calcium oxide (CaO) level. In Colorado, fly ash would only be accepted from a preapproved source, not at all an unusual DOT requirement, but preapproval required submission of a report from the supplier documenting the

results of testing the fly ash from that source in accordance with the toxicity characteristic leaching procedure (TCLP).

Fly ash use as a partial cement replacement in concrete was the most frequently indicated application. In most instances, 15 percent partial replacement of cement in a concrete mixture is allowed. The amount of fly ash used in place of the cement would either be added on a pound-for-pound basis or as additional weight.

The most common practice was to replace 15 percent of the cement with 20 percent fly ash. This was a practice originally specified in FHWA publications many years ago and was commonly incorporated into state DOTs across the country. However, in the past several years, many states have allowed for larger levels of replacement, depending on the applications. Other partial replacement levels were based on weight ratios varying from 1.0 to 1.35 portions of fly ash for every 1.0 portion of cement.

In states that have access to both Class C and Class F fly ash, the percentage of partial replacement and the amount of fly ash used as the replacement material would often be dependent on the fly ash classification. It was also commonly specified that the blending of different ash sources was prohibited.

In addition to concrete, numerous states have used fly ash as a mineral filler in asphaltic concrete and soil stabilization, with many more states beginning to use fly ash in

flowable mortar applications.

In the cases of fly ash for use in asphalt, the test procedure ASTM D242, "Mineral Filler for Bituminous Paving Mixtures," was commonly cited. This specification assesses fly ash for retainment on the No. 30-, 50-, and 200-mesh sieves and for organic impurities and plasticity indexes.

In soil stabilization, ASTM C593, "Fly Ash and Other Pozzolans for Use with Lime," is generally cited as a material specification. ASTM C593 provides evaluation criteria for fly ash by durability testing according to compressive and vacuum saturation strengths. In soil stabilization applications, it is the CaO contained in the fly ash that is being exploited for its potential engineering use. Thus there is usually a minimum level of CaO associated with fly ash being used in this application.

There are several forms of what could be considered soil stabilization, such as cement treated base, subgrade stabilization, subbase stabilization, and base course. States with some type of specification for soil stabilization include Arkansas, Illinois, Indiana, Mississippi, Nebraska, North Dakota, Oklahoma, Pennsylvania, Tennessee, Texas, Virginia, and Wisconsin, as well as Washington, D.C., and the federal lands highways.

Flowable mortar fill, also known as controlled low-strength materials (CLSM) and control density fill, is a low-strength

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flowable slurry for use as an economical fill or backfill material. It is generally placed by pouring from a commercial ready-mix concrete truck. The applications of CLSM mixtures include sewer trenches, utility trenches, bridge abutments, conduit trenches, retaining walls, foundation subbases, subfootings, floor slab bases, abandoned underground storage tanks and wells, and voids under pavement.

Flowability can be measured by the standard slump cone method for concrete (ASTM C143) with measurements generally at 8 inches or higher. Another method of measuring flowability is ASTM C934, "Flow of Grout for Preplaced Aggregate Concrete Flow Cone Method). CLSM are self-leveling and can be placed with minimal effort and no vibration or tamping. Long-term compressive strengths can vary from 50 to 1,200 psi.

Flowable CLSM mixtures are an economical alternative because of the savings of labor and time over placing and compacting soil or granular materials. This technology was once considered relatively new, and few state transportation departments have specifications for flowable mortar applications. However, several now have standing specifications for CLSM and flowable density fills, which often specify the use of fly ash as one of the constituents.

Another material often cited for use as a cement supplement was ground granulated blastfurnace slag (GGBF slag). At one time, slag was generally only used as blasting grit, in skid or traction

applications, or as aggregate in asphaltic concrete. However, now many DOTs allow its use in the production of Portland cement concrete. The replacement levels of cement with GGBF slag varied from 20 to 50 percent. It was also not uncommon to allow it to be blended with fly ash in concrete.

The materials specification cited for GGBF slag was ASTM C989 or AASHTO M302, "Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars." Three main definitions are listed under this specification. Blast-furnace slag is the nonmetallic product that is developed in a molten condition simultaneously with iron in a blast furnace. Granulated blastfurnace slag is the glassy granular material formed when molten blast-furnace slag is rapidly chilled as by immersion in water. Slag is granulated blast-furnace slag that is ground to cement fineness.

The two most common specified grades of GGBF slag were Grades 100 and 120. Most states included specifications for the allowable use of blended hydraulic cements. The specifications for these were ASTM C595 and AASHTO M240. The descriptions and definitions of these cements varied considerably.

A Type IS cement (Portland blast-furnace slag cement) was an intimate blending of cement and granulated blast-furnace slag in which the slag constituent is between 25 and 70 percent of the mass of Portland blast-furnace slag cement. A Type I(SM) cement

(slag-modified Portland cement) is a cement in which the slag constituent is less than 25 percent of the mass of the slag-modified Portland cement.

A Portland-pozzolan (Type IP) cement consisted of an intimate and uniform blend of Portland or Portland blast-furnace slag cement and fine pozzolan, in which the pozzolan constituent is between 15 and 40 percent of the mass of the Portland-pozzolan cement. A Type I (PM) cement (pozzolan-modified Portland cement) is a blend of Portland cement, or Portland blast-furnace slag cement and fine pozzolan, in which the pozzolan constituent is less than 15 percent of the mass of the Portland-modified Portland cement.

The use of silica fume was often grouped into the same category as fly ash and GGBF slag as a mineral admixture in Portland cement concrete. The specifications for silica fume are AASHTO M307, "Microsilica for Use in Concrete and Mortar," and ASTM C1240, "Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout." Generally very small amounts of silica fume were specified for use in a concrete mix design. These specified amounts were usually from 3 to 10 percent of the total cementitious material.

Several states made references to not allowing the blending of two or more sources of fly ash and to only allowing the use of ash that had been evaluated by Cement and Concrete Reference Laboratories

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(CCRL). It is customary for DOTs to use the CCRL evaluation report as a means of rating their own laboratory testing capabilities and personnel. In several state DOTs, it is a customary practice to use cutoff dates for when fly ash is not to be used in concrete pavements. The cutoff dates are dependent on the region of country but can generally begin in early fall and extend to late spring.

DOT Survey Project Conclusions

All states had in place specifications pertaining to CCBs and their applications. The single most noted application is the partial replacement of cement in concrete. For this reason, the most commonly referenced specifications were ASTM C618 or AASHTO M295. Both are designed as methods of verifying if an ash can be used as a partial cement replacement in concrete. It was common practice for transportation departments to often change their specification from the indicated ASTM C618 and AASHTO M295 to reflect regional practices.

The most significant changes in DOT specifications from 1992 were the additions of specifications for CLSM, GGBF slag, and blended cements. During the earlier comparison study, most states were aware of CLSM applications, but few had in-place specifications for its uses. The specified use of blended cements is an indication of the increased use of fly ash within the cement industry, as is also the case for GGBF slag.

Some states have or are currently in the process of adopting updated specifications for utilizing CCBs. Differences between DOT specifications still varied greatly between states, even neighboring ones. A transition in material specifications to performance specifications will gradually blur the lines between state specifications.

State Environmental Regulations Survey

Extensive research for part two of this project began in 2004, and information was obtained from numerous sources through February 2005. The laws and regulations of each state were reviewed to identify statutory or regulatory provisions authorizing the beneficial reuse of CCBs. Information was collected through Internet and Westlaw searches.

Additionally, a survey letter was sent to all the states requesting copies of any legal authority upon which the state relies to authorize beneficial reuse of CCBs. In many cases, personal contact was also made with state agencies.

Based on the information obtained, a summary of the CCB laws and regulation in each state was prepared and presented in volume 2 of the final project report, available with volume 1 for download from the CBRC Web site. The report provides an overview of state solid waste laws and regulations governing reuse of CCBs. It will be useful to persons familiar with "beneficial use" regulations for CCBs in their particular state and will assist in the exchange of regulatory guidance to enhance the use of CCBs.

Disclaimers

The report also includes several disclaimers. It is not intended to identify landfill or similar disposal requirements. Although the report seeks to accurately describe authorized CCB reuses in the states, the reader is cautioned to seek appropriate technical, environmental, and legal advice with respect to any actions that may be undertaken concerning the management and use of CCBs in any state. The report does not constitute legal or technical advice. Further, it is not intended to advise the reader regarding legal or regulatory requirements applicable to CCB reuse projects in any state and should not be relied upon for this purpose.

The report summarizes state laws, regulations, policies, and/or agency guidance regarding the use of CCBs. It is important the reader recognize that information presented in this section of the report is merely a summary overview of various state requirements. The reader should carefully review and understand the briefly stated limitations of this report as well as the formal disclaimer of warranties and limitation of liabilities.

States Define CCBs Differently

For consistency, this report utilizes the term CCBs. The term is intended to generically refer to fly ash, bottom ash, boiler slag, flue gas desulfurization sludge, or fluidized-bed combustion material. The reader must recognize that

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each state has different approaches to classification of CCBs and that these respective classifications may limit or expand allowable uses of CCBs.

For example, in Pennsylvania, CCBs are referred to as coal ash, which is defined to include fly ash, bottom ash, and boiler slag. Conversely, some states include within the definition of CCB wastes that have been combusted with other materials, such as petroleum coke, tire-derived fuel, and/or wood. In some cases, these distinctions are noted in the report. However, the reader should not assume that use of the term CCB infers that all types of CCBs are included within the scope of a particular state's regulations.

Summary of State CCB Regulations

CCB reuse options are determined by state law. CCBs are generally exempt from hazardous waste regulations, and the states have elected to regulate these materials as solid, special, or industrial wastes. States that do not exempt CCBs from hazardous waste regulations require testing to determine hazardousness, and if shown to be nonhazardous, the CCBs are regulated as solid waste.

Most states currently do not have specific regulations addressing the use of CCBs, and requests for CCB uses are handled on a case-by-case basis or under generic state recycling laws or regulations. Many states have "generic" laws and regulations that authorize limited reuse and recycling of hazardous and/or solid wastes.

These generic laws do not apply specifically to CCBs or any other materials. In general, under these regulations, materials are not considered solid wastes when they can be recycled by being:

- used or reused as ingredients in an industrial process to make a product, provided the materials are not being reclaimed;
- used or reused as effective substitutes for commercial products; or
- returned to the original process from which they are generated, without first being reclaimed. (The materials must be returned as a substitute for raw materials feedstock, and the process must use raw materials as principal feedstocks.)

A number of states have adopted laws and regulations or issued policies and/or guidance specifically pertaining to CCB use. The CCB uses authorized within these states vary widely. Some states authorize liberal use of CCBs, while others authorize CCB use only in limited applications. In addition, the level of regulatory control and oversight varies significantly.

CCB uses presenting the greatest concern to state regulators are those which involve land application, such as use of CCBs in agricultural applications, structural fills, mine applications, and embankments. Some states consider these applications to be waste disposal and not reuse or recycling.

Finally, other states have elected to adopt "industrial solid waste beneficial use" rules intended to authorize use of a variety of materials such as coal ash, paper mill sludge, and foundry sand. These reuse rules with application to multiple materials may represent a growing trend.

Table 1 in volume 2 of the final report summarizes the use of CCPs that are "authorized" or "allowed" on a state-by-state basis. A detailed, state-by-state summary and discussion as presented in the remainder of this report.

Results and Discussions Federal Regulation of CCBs

The principal federal statute under which hazardous and solid wastes are regulated is the Resource Conservation and Recovery Act (RCRA), 42 U.S.C. § 6901-6991. RCRA establishes a comprehensive cradle-to-grave system for regulating hazardous wastes. Specifically, Subtitle C of RCRA and its implementing regulations impose requirements on the generation, transportation, storage, treatment, and disposal of hazardous wastes. To trigger these requirements, a material must be a "solid waste," and the solid waste must be "hazardous."

Subtitle D of RCRA pertains to State or Regional Solid Waste Plans. Wastes that are not considered hazardous under Subtitle C fall under Subtitle D and are subject to regulation by the states as solid waste. As originally drafted, RCRA did not specifically

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address whether CCBs fell under Subtitle C as a hazardous waste or Subtitle D as a solid waste.

In 1980, Congress enacted the Solid Waste Disposal Act Amendments to RCRA. Under the amendments, certain wastes, including CCBs, were temporarily excluded from Subtitle C regulation. This regulatory exemption is commonly referred to as the "Bevill Exemption," 42 U.S.C. §6921(b)(3)(A)(i). As a result, CCBs fell under Subtitle D and became subject to regulation under state law as solid waste.

As the Bevill Exemption was temporary, the amendments further directed that the U.S. Environmental Protection Agency (EPA) produce a report regarding CCBs and to pursue appropriate regulation, 42 U.S.C. §6982(n). In accord with this mandate, EPA issued its first report to Congress in 1988 titled *Waste from the Combustion of Coal Electric Utility Power Plants* (EPA/5-30-SW-88-002). This EPA report concluded that CCBs generally do not exhibit hazardous characteristics, and that regulation of CCBs should remain under state Subtitle D authority.

Following litigation against EPA by the Bull Run Coalition because EPA failed to timely issue a regulatory determination as stated in its 1988 report to Congress, EPA entered into a consent decree with the Bull Run Coalition which included a time frame for EPA to issue a formal recommendation regarding regulation of CCBs. Pursuant to the consent decree, EPA issued a final regulatory determination applicable to fly ash, bottom ash,

boiler slag, and FGD material which became effective September 2, 1993, 58 *Federal Register* 42, 466 (August 9, 1993). The rule states that regulation of CCBs generated by coal-fired electric utilities and independent power producers as hazardous waste is unwarranted and that the materials will remain exempt from regulation as a hazardous waste under RCRA.

EPA has narrowly interpreted this exemption. According to EPA, the exemption applies only to coal-fired electric utilities and independent power producers. It does not include CCBs generated at any other industrial activity (in *re: Wheland Foundry*, EAB, No. 93-2, December 22, 1993). Further, fluidized-bed combustion wastes, low-volume wastes (boiler blowdown, coal pile runoff, cooling tower blowdown, demineralizer regenerant rinses, metal and boiler cleaning wastes), and pyrites and comanaged wastes (referred to as remaining wastes) are not covered by the rule. EPA decided that more study was needed on these remaining wastes before an exemption determination could be made.

EPA was initially scheduled to complete a study of remaining wastes by September 30, 1998, and issue a final regulatory determination regarding these wastes by April 1, 1999, pursuant to the consent decree in the Bull Run Coalition litigation. Based on this obligation, EPA's study of fluidized-bed combustion wastes, low-volume wastes (boiler blowdown, coal pile runoff, cooling tower blowdown, demineralizer

regenerant rinses, metal and boiler cleaning wastes), and pyrites and comanaged wastes (referred to as remaining wastes) were subsequently discussed in a March 31, 1999, Report to Congress. The report indicated that fluidized-bed combustion wastes, low-volume wastes, and remaining wastes should continue to maintain their "Bevill Exemption" and that regulation under Subtitle C was not warranted.

Based on extensions of the consent decree mentioned above, EPA was to issue a final regulatory determination addressing fluidized-bed combustion wastes, low-volume wastes, and remaining wastes by April 10, 2000. In early March, EPA circulated a draft regulatory determination which indicated that, contrary to the 1999 Report to Congress, these wastes would be regulated under Subtitle C. EPA's stated basis for this shift in position was that remaining wastes did present environmental concerns, particularly concerns regarding groundwater leaching and the effects on drinking water standards, as well as effects associated with mercury exposure.

The ACAA, as well as other shareholder groups, did not agree that regulation of CCBs as hazardous was warranted and met with EPA to discuss concerns associated with the draft approach. After much debate and discussion among EPA, industry, and environmental groups (as well as an extension of the consent decree), EPA issued its final regulatory

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determination April 25, 2000, which was published in the *Federal Register* on May 22, 2000 (65 *Federal Register* 32213).

The final regulatory determination states that fluidized-bed combustion wastes, comanaged wastes, and coal combustion wastes from nonutilities, petroleum coke combustion wastes, coburning of coal and fuel, and oil and natural gas combustion will not be regulated under Subtitle C and would continue to maintain their "Bevill Exemption."

However, in determining if low-volume wastes are subject to Subtitle C regulation, EPA divided the low-volume wastes into two new categories: uniquely associated wastes and nonuniquely wastes. EPA took the position that when uniquely associated low-volume wastes are comanaged, those wastes would continue to be exempt from regulation under Subtitle C. However, if these wastes are managed independently and if they exhibit hazardous characteristics, they are subject to Subtitle C regulation. EPA defined these uniquely associated low-volume wastes to include coal pile runoff, coal mill rejected and waste coal, air heater and precipitation wastes, flow and yard drains and sumps, wastewater treatment sludge, and boiler fireside chemical cleaning waste.

EPA defined nonuniquely associated wastes as boiler

blowdown, coal pile runoff, cooling tower blowdown, demineralizer regenerant rinses, metal and boiler cleaning wastes (which was the historical definition for all low-volume wastes). Under EPA's final regulatory determination, when these nonuniquely associated wastes are comanaged or managed independently, they are not automatically exempt from regulation under Subtitle C, but must rather go through a RCRA hazardous waste determination.

The determination also indicated that EPA would be looking to the states to ensure proper regulation for certain CCB applications. In particular, EPA expressed the view that CCBs disposed in landfills or surface impoundments, or used to fill surface or underground mines, should be regulated by the states. Alternatively, EPA stated it would develop federal regulations of these applications under Subtitle D of RCRA. EPA indicated in the regulatory determination that, in developing/reviewing regulations, it would look at the extent to which CCBs caused actual or potential damage to human health and/or the environment, the environmental effects of filling mines with CCBs, the adequacy of existing regulations, and the effects of mercury exposure from these activities. EPA further indicated any federal regulations would be developed through notice and comment rulemaking.

State Regulation of CCBs

As a result of the federal law developments described above, CCB reuse options are determined by state law. CCBs are generally exempt from hazardous waste regulations, and the states have elected to regulate these materials as solid, special, or industrial wastes. States that do not exempt CCBs from hazardous waste regulations require testing to determine hazardousness, and if shown to be nonhazardous, the CCBs are regulated as solid waste.

Most states currently do not have specific regulations addressing the use of CCBs, and requests for CCB uses are handled on a case-by-case basis or under generic state recycling laws or regulations. Many states have "generic" laws and regulations, which authorize limited reuse and recycling of hazardous and/or solid wastes. These generic laws do not apply specifically to CCBs or any other materials. In general, under these regulations, materials are not considered solid wastes when they can be recycled by being:

- used or reused as ingredients in an industrial process to make a product, provided the materials are not being reclaimed;
- used or reused as effective substitutes for commercial products; or
- returned to the original process from which they are generated,

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without first being reclaimed. (The materials must be returned as a substitute for raw materials feedstock, and the process must use raw materials as principal feedstocks.)

The following materials remain regulated solid wastes, even if the recycling involves use, reuse, or return to the original process:

- materials used in a manner constituting disposal or used to produce products that are applied to the land;
- materials burned for energy recovery, used to produce a fuel, or contained in fuels;
- materials accumulated speculatively; and
- inherently waste-like materials.

In addition, there is little consistency among the states regarding the use of CCBs in mine applications. Some states have detailed regulations for reuse of CCBs in mine applications (some of which are discussed in the project report). Other states address this common use of CCBs by reference to fly ash and flue gas desulfurization (FGD) material as materials, which may be permitted as "discharges" to the mine upon approval by the state mining agency.

In general, the legal and technical requirements for mine applications are complex. For this reason, these regulations are not discussed in detail in the final report but are noted so further research can be done in the event the reader is interested in the potential application of these regulations to a proposed project. There may be significant changes in the regulations applicable to mine reuse applications. EPA has identified this as an area where greater regulation is warranted.

State Regulations Survey Project Conclusions

A number of states have adopted laws and regulations or issued policies and/or guidance specifically pertaining to CCB use. The CCB uses authorized within these states vary widely. Some states authorize liberal use of CCBs, while others authorize CCB use only in limited applications. In addition, the level of regulatory control and oversight varies significantly.

CCB uses presenting the greatest concern to state regulators are those which involve land application, such as use of CCBs in agricultural applications, structural fills, mine applications, and embankments. Some states consider these applications to be waste disposal and not reuse or recycling.

Finally, other states have elected to adopt "industrial solid waste beneficial use" rules intended to authorize use of a variety of material such as coal ash, paper mill sludge, and foundry sand. These reuse rules with application to multiple materials may represent a growing trend.

Acknowledgements

This project was made possible through funding from the National Energy Technology Laboratory Combustion Byproducts Recycling Consortium (NETL CBRC) with industry support from the American Coal Ash Association (ACAA) and the Utility Solid Waste Activities Group (USWAG). Diana M. Jagiella of Howard & Howard Law for Business provided her expertise and assistance with the preparation of the final project report.

For more information about this project (#02-CBRC-W12), or to view the final report, please visit the CBRC Web site at <http://www.wri.nrcce.wvu.edu/programs/cbrc/>. Or contact the CBRC at cbrc@wvu.edu.



CBRC CONTACTS

Calendar of Events

November 29–30, 2005

2005 Byproducts Beneficial Use Summit
Philadelphia, Pennsylvania
Contact:
info@byproductsummit.com
www.byproductsummit.com/
2005\

December 4–7

International Congress Fly Ash India 2005
New Delhi, India
Contact:
flyash.conference@gmail.com,
www.flyashindia.tifac.org.in

December 6–8

Power-Gen International 2005 Conference & Exhibition
Las Vegas, Nevada
Contact:
http://pgi05.events.pennnet.com/

April 11–15

World of Coal Ash—2005
Lexington, Kentucky
Contact:
Gretchen Tremoulet
(859) 257-0355
gtremoulet@caer.uky.edu
www.worldofcoalash.org/

April 22

The Ohio State University Coal Combustion Products Extension Program Seminar
Columbus, Ohio
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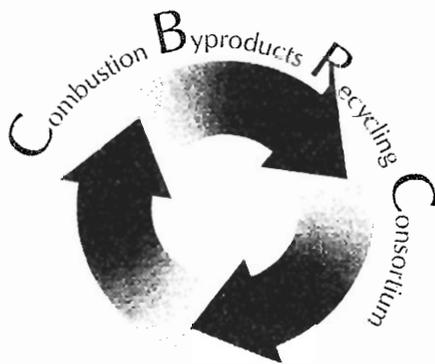
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EASTERN CENTER QUARTERLY PROGRESS REPORT

Submitted by: Jim Hower
Director, CBRC Eastern Regional Center

From: Jim Hower <hower@caer.uky.edu>
To: "Tamara Vandivort" <Tamara.Vandivort@mail.wvu.edu>
Date: 10/10/2005 9:28:25 AM
Subject: Re: CBRC Update

quarterly:

The primary focus for the quarter was the reading of the pre-proposals and the group evaluation of the pre-proposals in Pittsburgh on September 16th.

I will be giving the seminar in the geology department on Wednesday afternoon.
Jim

Midwest Center Quarterly Progress Report

**Submitted by: Yoginder P. Chugh
Director, CBRC Midwestern Regional Center**

**Combustion Byproducts Recycling Consortium (CBRC)
Midwestern Regional Center
Quarterly Progress Report July 1, 2005 – September 30, 2005**

**Submitted by
Yoginder P. Chugh
CBRC Midwestern Regional Center
On 10/11/05**

Task Description

The Midwestern Regional Center (MRC) will perform two primary tasks:

1. Technical administration of CBRC projects in the Midwestern region, including
 - Participation in National CBRC steering meetings, conference calls, and other communications.
 - Facilitating communication within the region with the Regional Chair and Review Committees.
 - Facilitating the proposal submittal and review process.
 - Facilitating project activities and reporting and coordinating with the national CBRC office
2. Financial Administration of the research contracts awarded in the midwestern region during the first round regional and national competitions.

Accomplishments for the Period

1. Worked with the National Center to review preproposals.
2. Attended the CBRC National Steering Committee Meeting on September 18 in Pittsburgh to select preproposals that should be invited as full proposals.
3. Continued to assist with utilization strategies for IGCC byproducts.
4. Assist with development of low permeability material for engineered caps and liners for mine reclamation.

Status of Ongoing Projects

- **ECM-07 “Industry – Government – University Cooperative Research Program for Development of CCBs-Based Light Poles For Electric Utility Industry,” (Y.P. Chugh, Southern Illinois University)**

The project has been completed. Trinity Industries has made a decision to not commercialize the project. Efforts are underway to develop final report for the project. The final report should be submitted by November 15, 2005.

- **CBRC M-9 “Environmental Performance Evaluation of Filling and Reclaiming A Surface Coal Mine with Coal Combustion Byproducts,” (Ish Murarka, ISH, Inc.)**

The staff has not been able to contact the PI. This project is very important to the Midwestern Region and efforts should be made to get the final report completed on this project.

- **CBRC M-04 “Crushed Aggregates from Class C Fly Ash,” (Anil Misra, University of Missouri – Kansas City).**

This project is almost complete. The PI has met requirements of the contract. However, product potential for commercialization is very low.

- **CBRC M-23 “Quantifying CCBs for Agricultural Land Application” (David Hassett, University of North Dakota)**

The project continues to make good progress.

- **CBRC M-21 “The Impact of Adsorption on the Mobility of Arsenic and Selenium Leached from Coal Combustion Products” (Dr. Bradley Paul, Southern Illinois University)**

Dr. Paul should be submitting his final report to CBRC soon. I talked to him on October 12.

- **02-CBRC-M12, “Manufacturing Fired Bricks with Class F Fly Ash from Illinois Basin coals”, (Dr. Mei-In Melissa Chou, Illinois State geological Survey)**

Ameren CIPS is actively involved in commercializing the project. The project continues to make progress.

Plans for the Next Quarter

- Continue to provide technical and coordination support to different projects within the region.
- Continue to provide support to industrial groups in the region.

Western Center Quarterly Progress Report

**Submitted by: Debra F. Pflughoeft-Hassett
Director, CBRC Western Regional Center**

**Combustion Byproducts Recycling Consortium (CBRC)
Western Regional Center
Quarterly Progress Report July 1 – September 30, 2005**

**Submitted by
Debra F. Pflughoeft-Hassett, Director
CBRC Western Regional Center**

Task Description

The Energy & Environmental Research Center (EERC) will perform two primary tasks as the CBRC Western Regional Center:

1. Technical administration of CBRC projects in the Western Region, including:
 - Participating in national CBRC meetings, conference calls, and other communications.
 - Facilitating communication within the region with the Regional Chair and Review Committees.
 - Facilitating the proposal submittal and review process.
 - Facilitating project activities and reporting and coordinating with the national CBRC office.
2. Financial administration of the research contracts awarded in the Western Region during the first-round regional and national competition and review.

Accomplishments for the Quarter

A brief summary of the status of Western Region CBRC projects follows:

ECW05 – “Promote Increased Use of Coal Combustion Products to State Regulators and Government Agencies,” Ish Inc.

The project draft final report was accepted as submitted. The status of this final report is in negotiation with the national CBRC office.

02-CBRC-W9 – “Power Plant Combustion Byproducts for Improved Crop Productivity of Agricultural Soils,” Agricultural Science Center at Farmington, New Mexico State University (NMSU)

Most samples of coal combustion byproducts (CCBs), soil, and leaf tissue from three hybrid poplar container studies were analyzed for chemical composition. Stem material from these studies is being processed for future determination of metal content. Available data are currently being compiled for statistical analysis. The soil column study was terminated in mid-August, and soil samples were removed for future analysis. A fourth pilot greenhouse study growing sorghum in CCB-amended soil was terminated in mid-September.

02-CBRC-W12 – “Engineering and Environmental Specifications of State Agencies for Utilization and Disposal of Coal Combustion Products,” University of North

Dakota EERC

The project final report was submitted. This project is complete, and no further quarterly reports are expected. This project will be removed from the Western Region quarterly report after this report.

Western Region Directorate Administrative Activities

The Western Region Director reviewed preproposals submitted under the current request for proposal (RFP) with Western Region priorities noted. Comments were prepared and submitted. All Eastern and Midwestern preproposals were also reviewed in preparation for the National Steering Committee meeting on September 16, 2005. The Western Region Director participated in that meeting via telephone. Comments were revised and resubmitted.

Technical Progress

ECW05 – “Promote Increased Use of Coal Combustion Products to State Regulators and Government Agencies,” Ish Inc.

The draft final report was accepted. No quarterly report is expected.

02-CBRC-W9 – “Power Plant Combustion Byproducts for Improved Crop Productivity of Agricultural Soils,” Agricultural Science Center at Farmington, NMSU

The greenhouse studies have been completed using a soil from Farmington amended with fly ash, bottom ash, or scrubber material at two rates: 10 and 20 T/acre. Hybrid poplar cuttings and sorghum plant types were studied, with the Sorghum tests being completed most recently. Soil is being analyzed for soil salinity, sodium adsorption ratio (SAR), pH, nitrate, soil macro and micro elements, and trace metals. Plant sections (leaves, stems, and roots) were taken from each study for biomass measurements (height, basal stem diameter, total leaf area, and dry weights of each plant part). Analysis of leaf tissue macro and trace elements, including metal content, was completed for the earliest study and is under way for later tasks. Stem samples are being prepared for a determination of the potential accumulation of trace metals. The leachate column study to evaluate the same soil amended with the same CCBs was completed in mid-August. Leachate was collected over the 5-month experimental period and analyzed for electroconductivity, pH, and trace element and heavy metal content. Leachate pH initially dropped because of the high content of soluble salts flushing through the soil but then gradually rose as salinity decreased as the study progressed. Soil from the 30-cm-long columns was removed in September by dissecting each column in 2.5-cm sections. Soil samples were air dried for future analysis.

02-CBRC-W12 – “Engineering and Environmental Specifications of State Agencies for Utilization and Disposal of Coal Combustion Products,” University of North Dakota Energy & Environmental Research Center

The Final Report was submitted. No quarterly report is expected, and no further reporting will be done of this project in the Western Region quarterly reports.

Plans for the Next Quarter

The Western Region Director will participate in a Western Region Ash Group meeting in October and report on the status and remaining schedule of the CBRC RFP. When full proposals are received in December, review will be initiated.

Financial Information

A financial report is being submitted under separate cover.

Eastern Regional Projects
Active Projects:

01-CBRC-E10

02-CBRC-E6

02-CBRC-E10

**Full-Scale Testing of Coal Combustion Product Pavement Sections
Subjected to Repeated Wheel Loads**

01-CBRC-E10

Tarunjit Butalia

01-CBRC-E10 Quarterly Report

Project Title: Full-Scale Testing of Coal Combustion Product Pavement Sections
Subjected to Repeated Wheel Loads

Reporting Period: July 1, 2005 – September 30, 2005

Prepared by: Dr. Tarunjit S. Butalia (614-688-3408), The Ohio State University
Professor William E. Wolfe (614-292-0790), The Ohio State University

1. Introduction

The objective of this research project is to conduct accelerated load testing of full-scale pavements constructed of coal combustion products (CCPs) and compare their performance with sections constructed with conventional materials. As a part of the overall project, an innovative mechanics based approach will be developed for designing of pavements constructed of coal combustion products (CCPs). The pavement will be modeled as an elastic (or visco-elastic) multi-layered system placed on an elastic (or visco-elastic) foundation. Resilient modulus testing will be carried out for cohesive and non-cohesive CCPs and soils, and granular materials to be used in the pavement system. The material property database information will be used as input to the finite element multi-layered models to predict the stress, strain, and displacements at various points within or below the pavement structure. This will allow the research team to accurately model the response of the pavement when subjected to loading. The stress, strain, and displacement predictions from the mechanics model will be compared with the actual measurements made from the pavement sections (in year 2 and 3) subjected to accelerated loading at the OSU/OU Accelerated Pavement Load Facility in Lancaster, Ohio.

2. Task Description

- Task 1: Develop innovative mechanics based approach
- Task 2: Pavement modeling
- Task 3: Resilient modulus laboratory testing
- Task 4: Additional laboratory testing
- Task 5: Develop material property database for CCP and natural materials
- Task 6: Conduct existing empirical design
- Task 7: Determine thickness of pavement layers and their constituents
- Task 8: Comparison of mechanics based predictions with field observations

3. Summary of Period's Accomplishments & Significant Events

Analysis of data collected during loading of concrete and asphalt sections up to 20 years of State Highway traffic (135,000 cycles) was carried out. Laboratory samples collected during the construction of the full-scale pavement sections were tested in the laboratory and compared with design mix values. The pavements were saturated with water and the pavements were loaded for an additional 5 years of highway traffic.

4. *To Date Accomplishment*

	Completed
Task 1: Develop innovative mechanics based approach	70%
Task 2: Pavement modeling	70%
Task 3: Resilient modulus laboratory testing	90%
Task 4: Additional laboratory testing	70%
Task 5: Develop material property database for CCP and natural materials	70%
Task 6: Conduct existing empirical design	100%
Task 7: Determine thickness of pavement layers and their constituents	100%
Task 8: Comparison of mechanics based predictions with field observations	50%

5. *Technical Progress*

The technical data will be included in the final report

6. *Plans for Next Quarter*

The concrete and asphalt pavements (CCP and control sections) will be loaded up to another 135,000 cycles, i.e. another 20 years of state highway traffic while the pavement subgrade, base, and subbase are infiltrated with water and the air temperature is cycled to simulate the effects of freeze-thaw cycling. Elevated temperature testing will be used for the asphalt pavement testing. The pavement response will be measured. Laboratory testing of samples collected during the pavement construction will be continued.

7. *Financial Report to date*

<u>Fund Source</u>	<u>Project budget</u>	<u>Expenditures to date</u>	<u>Expenditures as % of budget</u>
CBRC	\$70,000	\$ 31,557.65	45.1%
OSU	\$233,685	\$389,262.54	166.6%
OCDO	\$230,258	\$688,960.05	299.2%
Total	\$533,943	\$1,109,780.20	207.8%

Prediction of the Effects of Placing CCBs in Contact with Mine Spoil

02-CBRC-E06

Richard Herd

Prediction of the Effects of Placing CCBs in Contact with Mine Spoil

CBRC Project 02-CBRC-E6

Combustion Byproducts Recycling Consortium
National Mine Reclamation Center
West Virginia University

Introduction

Uncertainty regarding the leachability and mobility of toxic ions from CCBs is the most significant deterrent to wide spread use of coal ash in large scale mine reclamation and other beneficial use projects.

The objective of this project is to determine if the mine water leaching procedure (MWLP) is effective in predicting the ability of mine spoil to retard toxic ion mobility at proposed CCB mine beneficial use sites. The secondary objective is to quantify the magnitude of retardation for various ions and to translate the results into protective recommendations for field deployment.

Five different treatment ratios of both CCB (class F) and FBC ash and neutral, non-pyritic mine spoil (sandstone and shale) will be subjected to MWLP in accordance with the protocol shown below and analyzed for trace elements, pH, alkalinity and acidity to determine leachable element adsorption to mine spoil.

Task Descriptions

Task 2. Conduct sequential leachings on CCB/spoil mixtures

The MWLP sequential leachings of the fly ash/sandstone and fly ash/shale spoil mixtures in the variable combination ratios contained in the proposal were completed. Initial results were inconclusive therefore a new experimental design has been devised (see below). The MWLP sequential leachings of the class F ash with both sandstone and shale at the new experimental ratios are underway.

Task 3. Leachate collection and analysis

Task 4. Data entry and analysis

The fly ash/sandstone and fly ash/shale spoil leachate mixtures were analyzed and data entered into an Excel worksheet.

Summary of Accomplishments and significant events

The initial MWLP treatments of both sandstone and shale/CCB mixtures produced inconclusive results as presented in last quarters report. Based on these preliminary results the experimental design has been modified in accordance with the spoil and CCB treatment mixture combinations as shown below:

MWLP . All data are in grams

	Treatment				
	PCF/SS 1	PCF/SS 2	PCF/SS 3	PCF/SS 4	PCF/SS 5
class F	100	100	100	100	0
sandstone	0	25	50	75	100
total solids	100	125	150	175	100
AMD T&T	1000	1250	1500	1750	1000
solid/liquid	10%	10%	10%	10%	10%

	Treatment				
	PCF/SH 1	PCF/SH 2	PCF/SH 3	PCF/SH 4	PCF/SH 5
class F	100	100	100	100	0
shale	0	25	50	75	100
total solids	100	125	150	175	100
AMD T&T	1000	1250	1500	1750	1000
solid/liquid	10%	10%	10%	10%	10%

	Treatment				
	FBC/SS 1	FBC/SS 2	FBC/SS 3	FBC/SS 4	FBC/SS 5
FBC ash	100	100	100	100	0
sandstone	0	25	50	75	100
total solids	100	125	150	175	100
AMD T&T	1000	1250	1500	1750	1000
solid/liquid	10%	10%	10%	10%	10%

	Treatment				
	FBC/SH 1	FBC/SH 2	FBC/SH 3	FBC/SH 4	FBC/SH 5
FBC ash	100	100	100	100	0
shale	0	25	50	75	100
total solids	100	125	150	175	100
AMD T&T	1000	1250	1500	1750	1000
solid/liquid	10%	10%	10%	10%	10%

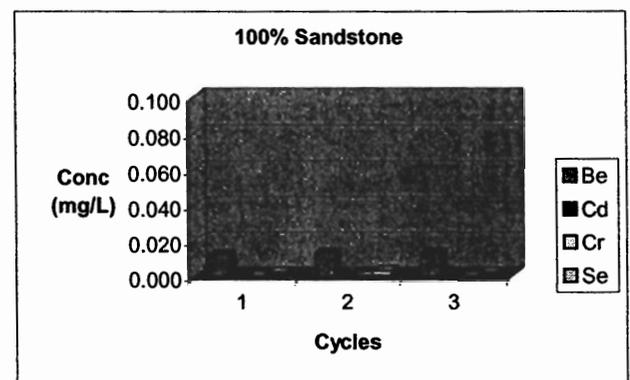
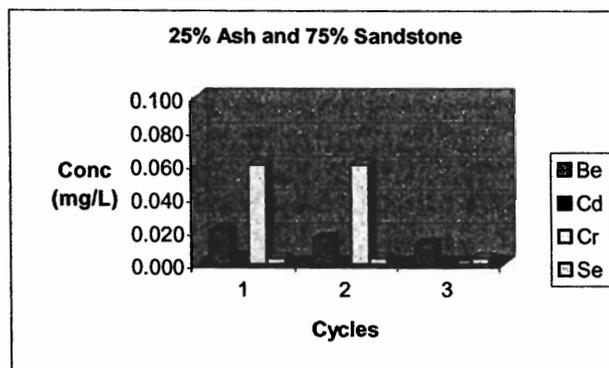
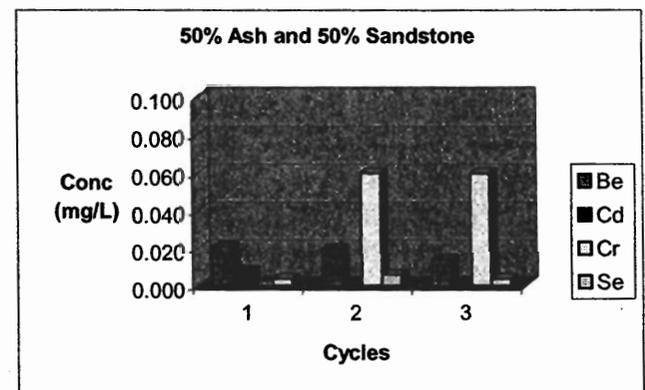
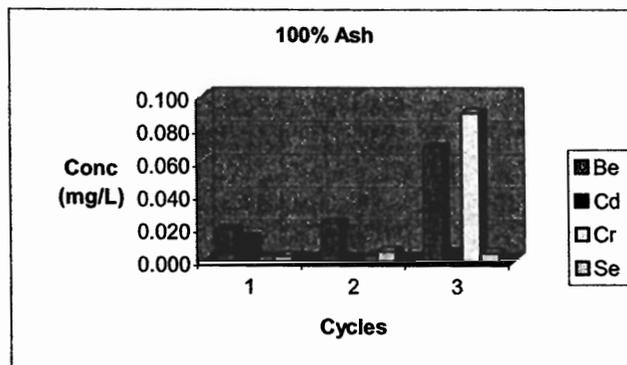
To-Date Accomplishments

Based on the expanded experimental design, tasks 2, 3 and 4 are approximately 25% complete.

Technical Progress

Initial MWLP sequential leaching results for the variable ratios of Class F ash and sandstone were reported in the previous quarters report (shown below).

The graphs below show preliminary fly ash/sandstone mixture MWLP leachate results for the trace elements beryllium, cadmium, chromium and selenium. Sandstone spoil appears to increase the rate at which chromium is leached. Both beryllium and cadmium had an affinity for adsorption by sandstone spoil. Selenium leachate concentrations remained relatively under various treatment ratios of sandstone spoil indicating little if any adsorption activity. The leaching rate of arsenic copper, nickel and zinc present in fly ash did not appear to be influenced by addition of spoil material.



The variable nature of these results dictated a modification of the experimental design as shown above. The new design will maintain a constant (100g) amount of ash in each sequential leaching as opposed to varying the amount of ash and FBC as originally proposed.

Plans for Next Period

Complete Sequential MWLP of the four treatments shown in the modified experimental design shown above.

Financial Report

Expenditures = \$ 20,644.54

**Commercialization of Production Foundry Molds Made from CCBs for
High Volume Automotive Applications**

02-CBRC-E10

Robert Purgert

A draft final report has been prepared. That report and patent clearance form will be submitted next quarter.

Midwestern Regional Projects
Active Projects:

99-EC-M07

00-CBRC-M9

01-CBRC-M21

01-CBRC-M23

02-CBRC-M12

Development of Coal Combustion Products Based Transmission Poles

99-EC-M07

Y. Paul Chugh

QUARTERLY TECHNICAL REPORT

July 1, 2005 through September 30, 2005

Project Number: ECM07

Project Title: INDUSTRY-GOVERNMENT-UNIVERSITY
COOPERATIVE RESEARCH PROGRAM FOR
DEVELOPMENT OF COAL COMBUSTION BY-
PRODUCTS-BASED LIGHT POLES FOR ELECTRIC
UTILITY INDUSTRY

Principal Investigator: Dr. Y. P. Chugh

Other Investigator: Jinrong Ma, Department of Mining and Mineral Resources
Engineering, Southern Illinois University at Carbondale

PROGRESS REPORT

1. During past three months, Trinity Industries has evaluated the market data for poles. Although we have no written letter from them yet, it appears that they will not fund the capital for commercialization of the project.
2. Final report preparation for the project is progressing. The PI plans to submit the final report by November 15, 2005.
3. Mr. Jim Cutney, a consultant in Indiana, has indicated that there may be market for fly ash based poles in Gulf States area. The PI plans to approach Trinity Industries again with this information to see if they will fund capital for commercialization.

**Environmental Performance Evaluation of Filling and Reclaiming a
Surface Coal Mine with Coal Combustion Byproducts**

00-CBRC-M09

Ishwar Murarka

No Report Received

**The Impact of Adsorption on the Mobility of Arsenic and Selenium
Leached from Coal Combustion Products**

01-CBRC-M21

Bradley Paul

**The Impact of Adsorption on the Mobility of Arsenic and Selenium
Leached from Coal Combustion Products**
(Time Period July 2005 to Sept 2005)

CBRC Project No.: 0-1-CBRC-M21

P.I.- Dr. B. C. Paul

Introduction

Regulatory frameworks effect the disposal and beneficial use of coal combustion products. Regulatory structures put in place for disposal often impact the perception of risk in beneficial use projects. Regulatory structures placed to “protect” the public during disposal encourage parallel regulations for beneficial use projects that will steer potential customers clear of recycling of combustion products in favor of less restrictive virgin materials.

Most fears about coal combustion products center on a belief that trace elements present in coal combustion products (and in fact naturally occurring rock in general) will leach into the groundwater supply where they will become a danger to public and environmental health. That trace elements are present in coal combustion products or that the can be leached is not a real question since water can leach trace elements from almost anything. The focus of this project is that environmental and public health risks that are based only on the presence of leachable trace elements will probably be overstated because the mere fact that something enters the water supply is no guarantee that it will remain there. Many of the trace elements in coal and consequently the ash that remains originated by water borne trace elements being adsorbed by clays or organic materials in ancient swamps. These same adsorption processes are active today and may remove trace elements from solution before they can be transported or dispersed any distance in the groundwater supply. Indeed EPA has developed standard methodologies for determining the amount of trace element adsorption that can be expected by soils, clays and other natural strata materials. Where this methodology was applied to boron using mine and road cut spoils and soils the results showed that only very small boron leachate plumes extending a few hundred feet could ever develop. This is in contrast to very large plumes extending for miles being predicted by models that failed to consider the existence of adsorption. While boron lacks the low level toxicity of arsenic and selenium, most previous work suggests that the adsorption of arsenic and selenium will be 10 times stronger than for boron.

This project will measure the adsorption of arsenic and selenium by soil and spoil material and examine the impact to be anticipated in terms of toxic plumes forming from coal combustion products contacting ground water. The results to be reported will go directly to the question of whether trace element exposure risks from combustion product leaching are accurately reported or overstated.

Task Description

The project involves 9 task steps.

Task #1 – With consultation from the advisory board select the samples to be studied for their adsorption properties.

Task #2 – Collection of samples chosen by the advisory board but not already available.

Task #3- Sample preparation.

Task #4 – Test concentrations of Arsenic and Selenium will be determined in cooperation with the Industrial Advisory Board.

Task #5 – Running the actual test batteries.

Task #6 – Running Analysis.

Task #7 – Running basic modeling.

Task #8- Feed back and reporting.

Task #9- Conference Reporting.

Efforts this past quarter have been in the areas of compiling the completed results and running and verifying the computer models of this work which are being used for a near complete Ph.D. dissertation.

Summary of this Quarters Accomplishments and Significant Events

Work on this project and the grant period was completed during this quarter at the end of July. Mr. Shei Chen completed his dissertation on the work done for this project and is preparing for a formal defense. The draft of the final report has been completed, but editing is still needed to provide a clear and smooth flowing report.

To Date Accomplishments

The work on this project has been completed except that the draft final report is being edited into the final report.

Technical Progress

Because a final report is almost finished the technical discussion will be deferred at this time.

Plans for Next Period

The dissertation based on this work should be defended and a Ph.D. degree either issued or scheduled for the next commencement. Editing of the report to final form is expected.

Quantifying CCBs for Agricultural Land Application

01-CBRC- M23

David Hassett

Qualifying CCBs for Agricultural Land Application
01-CBCR-M23
July 1 – September 30, 2005

Introduction

Agricultural application is one of the largest potential unrealized uses for coal combustion by-products (CCBs). This project will determine the appropriateness of mixed CCBs (bottom and fly ash and flue gas desulfurization [FGD] material) recovered from wet storage for agricultural land application. The CCBs reclaimed from disposal, individual ash samples before wet storage, untreated and field-treated soil samples, and Duck Creek Power Station ash pond water will be evaluated in a laboratory setting. A specified mixed ash will be evaluated, but the project is directed at developing and testing a process of qualifying ash for use as an agricultural soil amendment that will be broadly applicable.

Task Description

Task 1. Review of Existing Information

This task consists of obtaining and assembling all existing information on AmerenCILCO Duck Creek Station CCBs. Information on Illinois regulations concerning CCBs will also be obtained. This information will aid in directing the remaining research effort. Much of this information is already in the possession of Energy & Environmental Research Center (EERC) research staff.

Task 2. Sampling

Duck Creek Station personnel will obtain both solid and liquid samples. Solid samples will include soil, fly ash, bottom ash, FGD material, and as-managed CCBs. Two samples each of treated and untreated soil will be collected during the project. One sample each of fly ash, bottom ash, and FGD material will be collected in locations before entry to the wet disposal pond. Three samples of as-managed CCBs as well as one sample of pond water will be collected. Guidance for sampling protocols will be provided by EERC researchers.

Task 3. Laboratory Analysis

Solid materials will have major, minor, and trace constituents determined. Major and minor constituents include silicon, aluminum, iron, calcium, magnesium, sodium, potassium, titanium, manganese, phosphorus, strontium, barium, and sulfur and loss on ignition. A list of trace elements of concern will be developed and will include, but not be limited to, antimony, arsenic, boron, cadmium, chromium, cobalt, copper, lead, mercury, nickel, selenium, thallium, and zinc. In addition to these 13 trace elements, up to four additional elements may be added based on a proton-induced x-ray emission analysis, which determines the elements from sodium through uranium. Sulfite/sulfate ratios will be done because of phytotoxicity.

Additionally, limited work on oxidation rates of sulfite will be performed. The solid samples will consist of one fly ash, one bottom ash, one scrubber sludge, two treated soil, two untreated soil, and three as-managed CCB samples.

Solid samples will be leached for 18 hours using the synthetic groundwater leaching procedure (SGLP). The samples subjected to leaching will be the three as-managed CCBs and the four soil samples. The resulting leachate liquids as well as collected ash pond water will be analyzed for the same parameters as the solid samples.

Task 4. Data Interpretation

Using the information collected in Task 1, a list of appropriate limits for analytical parameters will be developed. Application practices and rates will be determined and summarized. Beneficial properties of the ash will be identified. Results from Task 3 will be compared to these.

Task 5. Reporting and Technology Transfer

Project reporting will include required quarterly progress and financial reports. A comprehensive final report as well as a write-up for a CBRC newsletter will also be completed. The key deliverables for this effort will be:

- 1) A report to the Illinois Environmental Protection Agency facilitating its determination on the appropriateness of AmerenCILCO Duck Creek Power Station mixed ash for agricultural application in Illinois.
- 2) A generic document detailing the process for qualifying CCBs for agricultural application.

Summary of This Quarter's Accomplishments and Significant Events

Data interpretation and reporting efforts continued.

To-Date Accomplishments

Task 1 is 100% complete.
Task 2 is 100% complete.
Task 3 is 100% complete.
Task 4 is 50% complete.
Task 5 is 50% complete.

Plans for Next Period

Data interpretation and report writing will be completed. The final report will be submitted.

**Manufacturing Fired Bricks with Class F Fly Ash from Illinois Basin
Coals**

02-CBRC-M12

Melissa Chou

CBRC Technical Progress Report (July 1, 2005 – September 30, 2005)

Project Title: Manufacturing Fired Bricks with Class F Fly Ash from Illinois Basin Coals

Project Number: 02-CBRC-M12 (DOE SIUC 05-13)

Introduction

More than six million tons of Class F fly ash are generated from burning about one hundred million of Illinois Basin coal each year. Most of this fly ash has been ponded or landfilled, and is readily available for making fired bricks. Nevertheless, until the brick industry gains more confidence in using fly ash as a raw material for their brick production, evaluation and testing will be needed on a case-by-case basis. The purpose of this project is to determine if the Class F fly ash produced by Cinergy PSI's Cayuga power generation station (CPSIC) is a viable raw material for brick production at Colonial Brick Company (CBC), a brick plant in Indiana near the Illinois border. CBC is located less than five miles from CPSIC, which burns Illinois Basin coals from both Illinois and Indiana.

Task Description

This project has eight tasks.

Task 1: Sample acquisition.

Task 2: Characterization of raw materials, intermediates, and final products.

Task 3: Producing bench-scale commercial-size green bricks and conducting preliminary in-plant firing evaluations.

Task 4: Commercial-scale production. Up to four commercial test runs will be conducted for process optimization.

Task 5: Economic assessment. The critical economic factors in using fly ash as a raw material for brick making will be evaluated.

Task 6: Environmental feasibility study.

Task 7: Public outreach.

Task 8: Quarterly and final reports.

Summary of this Quarter's Accomplishments and Significant Events

All of the pre-cursor tests making mold-pressed paving bricks and building bricks for preliminary in-plant firing evaluations were concluded in this quarter. For the paving brick studies, bricks containing fly ash at 10, 20, 30, 40, and 50 % by volume were successfully fired as a part of commercial firing. In this quarter, engineering tests were conducted on a set of fired paving bricks with fly ash inputs of 40 and 50 vol% to provide requisite engineering data. For building brick studies, commercial-size three-hole green building bricks were produced by mold-press for preliminary in-plant firing evaluations to determine formulations that would best be suited for the scale-up test runs. These mold-pressed three-hole building bricks were made with fly ash inputs up to 60 vol% by volume, and

were successfully fired as part of the commercial firing at CBC. Also, in this quarter, four commercial-scale extrusion test runs, at about 2000 bricks per run, making three-hole green building bricks were completed. These extrusion tests successfully produced attractive and strong green building bricks with fly ash inputs at levels of 0, 20, 30, and 40 vol%. The run without fly ash was included as a standard run. Drying and firing evaluations, including shrinkage measurements, of these four batches are in progress.

To-Date Accomplishments

The completion of each task in percentage is indicated as follows.

Task 1 - 95% Task 2 - 80% Task 3 -100 % Task 4 - 80%
 Task 5 -10 % Task 6 - 10% Task 7 - 70% Task 8 - 75%

Technical Progress

Pre-cursor tests (Task 3) were conducted to determine the best suitable formulation, additives, and/or parameters prior to conducting scale-up production test runs. Pre-cursor test runs for the paving brick studies were completed in this quarter. Engineering tests were conducted on fired paving bricks with fly ash inputs of 40 and 50 vol% in order to provide additional typical engineering data. One set of paving bricks made with fly ash inputs at levels of 40 and 50 vol% was blended with shale only, and another set of bricks made with fly ash inputs at the same level was blended with a mix of clay and shale. Firing of these two sets of paving bricks was conducted first at the ISGS bench scale facility and then as a part of commercial firing at CBC. The engineering properties of the bricks fired at ISGS are shown in Table 1, and those fired at CBC are shown in Table 2. The engineering tests included initial suction rate, cold and boiling water absorption measurements, and compressive strength determinations.

Table 1: Engineering Properties of Mold-Pressed Paving Bricks fired at ISGS Bench-Scale Facility

Brick Composition, vol%		CiPFA 40 CBCS 46.7 CBCC 13.3	CiPFA 50 CBCS 36.7 CBCC 13.3	CiPFA 40 CBCS 60	CiPFA 50 CBCS 50
Max. water absorption	Cold water 24 hr, %	8.15	8.77	9.85	10.05
	Boiling water 5 hr, %	11.51	12.62	13.35	13.70
Suction, gm wt gain/minute		12.12	13.29	25.05	23.74

CiPFA: Cinergy Poned Fly Ash; CBCS: CBC Shale; CBCC: CBC Clay

A general trend was observed for the water absorption capacity of these mold-pressed bricks. The bricks with a greater fly ash input tend to absorb more water. This may be related to the large water holding capacity of the original fly

ash samples. However, the cold water and boiling water absorption capacities increase proportionally so the saturation coefficient remains nearly constant for each case. Another general trend was observed, which was expected, in which the bricks with clay tend to have a lower water absorption capacity than their shale-only counterparts. This may be due in part to the fact that the particle sizes of the clay material are much finer than those of the shale and fly ash materials, and also may form a tighter brick body during the vitrification process.

No definite trend was observed for the compressive strength data of these bricks related to the fly ash content and clay content. Since the bricks were individually pressed, the compaction cannot be controlled exactly the same for all the brick samples produced. Some trends observed in fired bricks produced with an extrusion technology may not be repeated in fired bricks made with a mold-pressed method. Despite the fact that a clear trend was not observed for the compressive strength of these mold-pressed bricks related to fly ash content and clay content, all of the bricks have met ASTM specifications for severe weather (8000 psi). Also, the commercial firing appears to produce relatively harder bricks than the ISGS bench-scale firing.

Table 2: Engineering Properties of Mold-Pressed Paving Bricks Fired as Part of CBC's Commercial Firing

Brick Composition, vol%		CiPFA 40 CBCS 46.7 CBCC 13.3	CiPFA 50 CBCS 36.7 CBCC 13.3	CiPFA 40 CBCS 60	CiPFA 50 CBCS 50
Max. water absorption	Cold water 24 hr, %	6.59	8.15	8.20	8.84
	Boiling water 5 hr, %	10.10	12.04	11.86	12.64
Suction, gm wt gain/minute		5.60	6.72	9.48	11.93

CiPFA: Cineroy Pondered Fly Ash; CBCS: CBC Shale; CBCC: CBC Clay

In this quarter, pre-cursor tests with building bricks were conducted by making three-hole building bricks with increased fly ash inputs of 40, 50, and 60 vol%. Each formulation contained a constant level of clay material (16.7 vol%). These bricks were successfully fired as part of the commercial firing at CBC.

ISGS met with the industry partners and discussed the project progress regarding a plan for the building brick scale-up test runs. The discussions centered on determining which final products could be the most readily adaptable to commercial production while still using a significant amount of fly ash. During this quarter, four scale-up extrusion test runs were conducted at CBC and the chemical compositions of the fly ash sample from the 40-ton lot, and the clay and shale used for the extrusion tests were analyzed. These extrusion tests

successfully produced attractive and strong green bricks (Figure 1) with fly ash input at 0, 20, 30, and 40 vol% for Run No.1, Run No.2, Run No.3, and Run No.4 respectively. Run No. 1 was conducted as a standard run and included no fly ash input. Each scale-up extrusion run produced about 2000 building bricks, and a total of about 8000 three-hole building bricks were produced for continued scale-up drying and firing evaluations.



Figure 1: Conducting scale-up extrusion testing at CBC and producing three-hole green building bricks (700 bricks per car).

In addition, the economic and environmental studies were initiated this quarter.

Plans for Next Period

Task 1 will pertain to receiving the final products from the scale-up runs in order to test their engineering properties and determine whether they meet ASTM commercial building brick specifications. Task 2 will continue, as engineering tests will be performed on the final products from the commercial-scale runs (Task 4). Task 4 will be concluded with the firing of the bricks that were extruded at CBC. Tasks 5 and 6 will be continued in the next quarter with evaluations on the economic and environmental impacts of producing the fly ash containing bricks commercially. A manuscript for the International Congress Ash Conference will be completed and preparation of the final report of the project will be initiated (Task 8). PI (M Chou) will attend and give an oral presentation of the project research to the International Congress Ash Conference to be held

December 4-7, 2005 in New Delhi, India (Tasks 7 and 8).

Expenditures Above \$500

The cost for M Chou's travel to attend and present project research to the International Congress Ash Conference to be held December 4-7, 2005 in New Delhi, India, was estimated at \$3325. The current project travel money (about \$2200) cannot fully support the trip. However, by conducting tests, such as SEM analysis, by ourselves using the equipment available to us with little to no equipment time charges, the project direct cost originally budgeted for these tests will save about \$1500. The money thus saved from project direct cost can be moved to project travel to fully support M. Chou's trip to the conference in India.

Western Regional Projects
Active Projects:

02-CBRC-W09

**Power Plant Combustion Byproducts for Improved Crop Productivity
of Agricultural Soils**

02-CBRC-W09

Michael O'Neill

TECHNICAL PROGRESS REPORT

Power Plant Combustion Byproducts for Improved Crop Productivity of Agricultural Soils

*New Mexico State University, Agricultural Science Center at Farmington
Mick O'Neill (PI)*

Reporting period ending October 15, 2005

ACRONYM LIST

CCBs	Coal Combustion Byproducts – specifically referring to fly ash, bottom ash, and scrubber slurry obtained from Four Corners Power Plant, Farmington, New Mexico.
EC	Electrical Conductivity
NAPI	Navajo Agricultural Products Industry
NMSU ASC	New Mexico State University Agricultural Science Center at Farmington
NMSU Agro/Hort	New Mexico State University Department of Agronomy and Horticulture, Las Cruces, New Mexico
SAR	Sodium Adsorption Ratio
SWAT Lab	Soil, Water, and Air Testing Lab, NMSU, Las Cruces, NM

INTRODUCTION

Two coal combustion power plants in the Four Corners region consume approximately 14.5 million metric tons of sub-bituminous coal on an annual basis for the generation of electricity. In addition to electricity, these power plants also generate substantial coal combustion byproducts (CCBs) in the form of 3.4 million metric tons of ash and 0.39 million metric tons of flue gas desulfurization (FGD) materials. Near the two power plants is the Navajo Agricultural Products Industry (NAPI), a large commercial farm currently operating nearly 600 automatic center pivot irrigation systems on 25,000 ha of farmland. Soil texture on the NAPI farm is generally sandy to sandy loam with limited water-holding capacity, low inherent nutrient status, and elevated pH. The addition of bottom ash, fly ash, and/or FGD materials to agricultural soils may increase water-holding capacity and contribute to the soil pool of micronutrients available for plant uptake.

This project is designed to 1) identify potentially beneficial and harmful constituents of CCBs; 2) characterize the water-holding capacity of CCB-amended soils; and 3) to demonstrate potential increased productivity of these soils with the addition of

CCBs from local coal combustion power plants. This study is a collaborative project with New Mexico State University, the Navajo Agricultural Products Industry, and the Arizona Public Service (APS) Four Corners Power Plant. The demonstration of environmentally sound management strategies for applying CCBs to agricultural lands would address regional and national priorities established by the U.S. Department of Energy National Energy Technology Laboratory and the Combustion Byproducts Recycling Consortium for the increased utilization of these products.

TASK DESCRIPTION JULY 15 – OCTOBER 14, 2005 REPORTING PERIOD

The following is a list of tasks and accomplishments outlined below initiated or completed during this reporting period.

#	TASK	STATUS	Institution/Location
1.	Recruit a graduate student into the NMSU Department of Agronomy and Horticulture soil science program	Completed	NMSU Agro/Hort
2.	Obtain start-up funds/lab inspection and quality assurance compliance	Completed	NMSU Agro/Hort
3.	Characterize CCBs obtained from Four Corners Power plant, Farmington for agriculturally significant macro and micro-nutrient content.	Completed	NAPI Lab
4.	Establish Hybrid Poplar pilot container of study utilizing CCBs as soil amendment at application rates of 10 and 20 tons/acre.	Completed	NMSU ASC
5.	Establish Hybrid Poplar container greenhouse trial utilizing CCBs as soil amendment at application rates of 10 and 20 tons/acre.	1. Study terminated 2. Lab analysis ongoing	NMSU Agro/Hort and NAPI Lab
6.	Establish second Hybrid Poplar greenhouse trial utilizing fly ash.	1. Study terminated 2. Lab analysis ongoing	NMSU Agro/Hort and NAPI Lab
7.	Establish Sorghum container greenhouse trial utilizing CCBs as soil amendment at application rates of 10 and 20 tons/acre.	1. Study terminated 2. Lab analysis ongoing	NMSU Agro/Hort and NAPI Lab
8.	Establish Column leachate study utilizing CCBs. Methodology established to simulate field conditions at the NMSU ASC with soil amended	1. Study terminated 2. Lab analysis ongoing	NMSU Agro/Hort and SWAT Lab

with CCBs at 10 and 20 ton/acre application rates.

- | | | |
|---|-------------|----------------|
| 9. Establish moisture release curves with soil amended with CCBs at 10 and 20 ton/acre application rates. | Not Started | NMSU Agro/Hort |
|---|-------------|----------------|
-

SUMMARY OF THIS QUARTER'S ACCOMPLISHMENTS & SIGNIFICANT EVENTS

Most samples of CCBs, soil, and leaf tissue from three hybrid poplar container studies have been chemically analyzed. Stem material from these studies is being processed for future chemical analysis by EPA Method 3051A to determine metal content. Data that has been generated is being compiled for statistical analysis. A fourth pilot greenhouse study using sorghum grown in soil amended with the various CCBs was terminated in mid September. The soil column study was terminated in mid August and soil samples were removed for future analysis.

TECHNICAL PROGRESS

The greenhouse studies have been completed. In these trials, a Doak sandy loam soil from Farmington was amended with either Fly Ash, Bottom or Scrubber Slurry at two rates: 10 and 20 T/ acre. Hybrid Poplar cuttings were cultivated in three of the studies under the amended soil (Tasks 4, 5, and 6). A fourth pilot study initiated May 15 (Task 7) using Sorghum (*Sorghum bicolor*) sown in CCB amended soil was terminated in mid September. Soil from all studies was removed from containers and has or currently is in the process of being analyzed for soil salinity, sodium adsorption ratio (SAR), pH, nitrate, soil macro and micro elements and trace metals (by ICP). Non-destructive measurements using a Minolta SPAD 502 meter were also made throughout the studies to monitor leaf chlorophyll status. Upon termination of each study, plants were sectioned into leaves, stems, and roots for biomass measurements (height, basal stem diameter, total leaf area, and dry weights of each plant part). Leaf tissue macro and trace elements, including metal content, was completed for Task 5 and is underway for Task 6. Stem samples from the hybrid poplar studies (Task 5 and 6) are currently being ground to a fine powder at the NMSU Soils Group laboratory in Las Cruces for future acid digestion using EPA Method 3051A described for other plant samples mentioned above to determine the potential accumulation of trace metals. The NAPI lab at Farmington will analyze these samples.

The Leachate column study (Task 8) of 27 columns filled with a Doak sandy loam soil amended with the various CCBs was terminated in mid August (Figure 1). Leachate was collected over the 5 month period (beginning March 30) every other day after irrigations and analyzed for EC, pH and trace element and heavy metal content. Leachate pH initially dropped because of the high content of soluble salts flushing through the soil but then gradually rose as salinity decreased as the study progressed (Figure 2 and 3). Soil from the 30 cm long columns was removed in September by dissecting each column in 2.5 cm sections. Soil samples were air dried and will be analyzed for salinity, SAR,

pH, macro and micro elements and trace metal content according to methods described previously in order to determine the adsorption or movement of any potentially hazardous element within the experimental soil profile.

**ADDITIONAL WORK PLANS FOR OCOBER 15-JANUARY 14, 2005
REPORTING PERIOD**

Chemical analysis for Tasks 5-8 will be completed. Data will be analyzed in SAS to determine any significant differences in chemical content versus the controls. Results of these studies are now pending the completion of chemical analysis currently ongoing at both the NAPI lab and NMSU Soils group lab or the compellation of data generated up to this point.

Moisture release curves (Task 9) will be initiated to establish water holding capacity of soil amended with agricultural rates of the various CCBs. This data will be combined with soil and biomass data generated from the greenhouse studies to begin to establish agricultural utilization significance of CCBs in the Four Corners region.

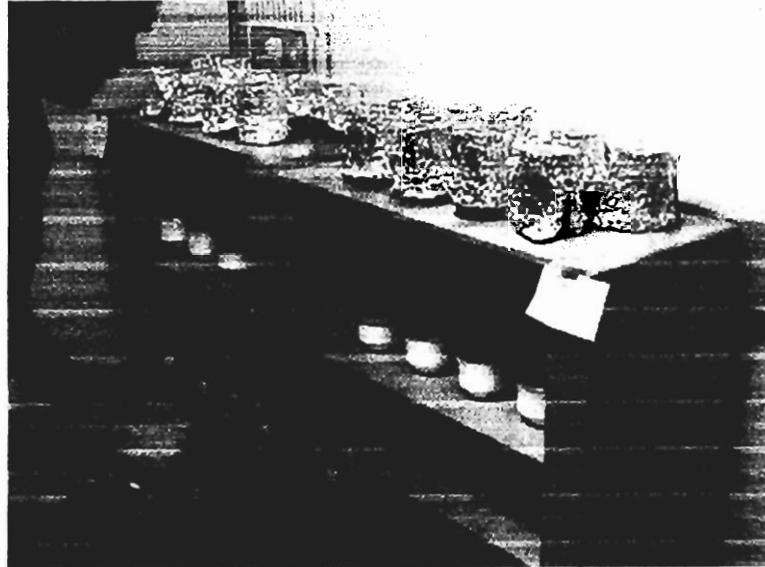


Figure 1. Leachate column study (Task 8). Collection of leachate for analysis of salinity, pH, and volume content.

Leachate pH Over Time

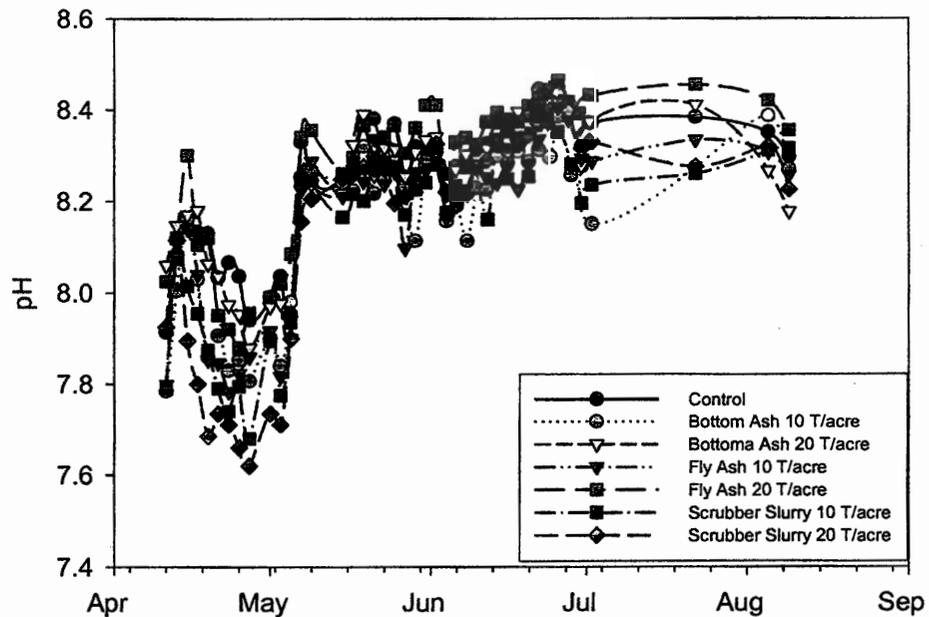


Figure 2. Leachate pH over time from Soil Column Study (Task 8). The pH of the leachate water slightly drops as salts flush through the system then slightly increases over time (see Figure 3).

Salinity Over Time

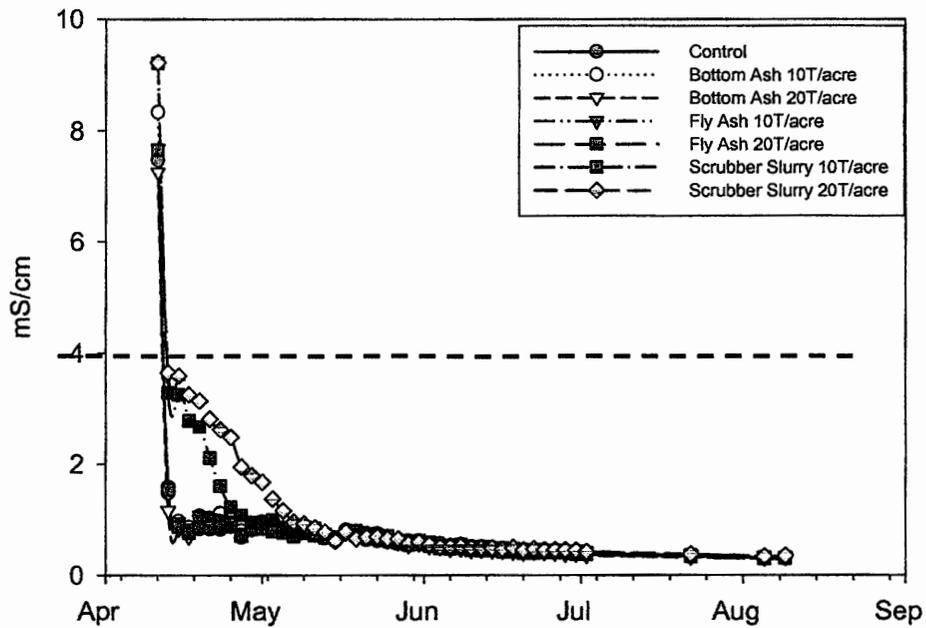


Figure 2. Leachate water collected from the soil columns. Salinity is initially high in salts for all CCB treatments and the control but fall below levels considered detrimental for plants (> 4 mS/cm) after two irrigations.

Appendix A

**Final Report
99-EC-E24**

**Use of Clean Coal Technology Products in the
Construction of Low Permeability Liners**

William Wolfe

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A. CONTRACTOR ACTION (CONTRACTOR COMPLETES PART A. 1-5)

- Document Title: Re-Use of Clean Coal Technology By-Products in the Construction of Low Permeability Lines
- Type of Document: Technical Progress Report Topical Report Final Technical Report
 Abstract Technical Paper Journal Article Conference Presentation
 Other (please specify): _____
- Date clearance needed: _____

◆4. Patent information.

- Yes No
- Is any patentable subject matter disclosed in the report?
- If so, has an invention disclosure been submitted to DOE Patent Counsel?
If yes, identify disclosure number or DOE Case Number _____
- Are there any patent-related objections to the release of this report? If so, state the objections.

◆5. Signed T.S. Butalia (Contractor) Date 7/28/05

Name & Phone No. Dr. T.S. Butalia, 614-688-3408

Address 770 Hitchcock Hall, 2070 Neil Av., Columbus, OH-43210

B. DOE PATENT COUNSEL ACTION

- Patent clearance for release of the above-identified document is granted.
- Other: _____
- Signed _____ Date _____

(Patent Attorney)

◆ Must be completed by the contractor.

99-EC-E24

Re-Use of Clean Coal Technology By-Products in the Construction of Low Permeability Liners

CBRC Project # ECE24

Final Report

Reporting Period Start Date: 1/3/00

Reporting Period End Date: 6/30/05

**William E. Wolfe, Ph.D., P.E.
Tarunjit S. Butalia, Ph.D., P.E.
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William Mitsch, Ph.D.**

July 15, 2005

DE-FC26-98FT40028



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ABSTRACT

This final project report presents the results of a research program conducted at The Ohio State University from January 3, 2000 to June 30, 2005 to investigate the long-term use of stabilized flue gas desulfurization (FGD) materials in the construction of low permeability liners for ponds and wetlands. The objective of the research program was to establish long-term field-verified time-dependent relationships for the performance of liners constructed from stabilized FGD by-products generated in Ohio. The project objective was accomplished with a coordinated program of testing and analyzing small-scale laboratory specimens under controlled conditions, medium-scale wetland experiments, and monitoring of a full-scale FGD-lined pond facility. Although the specific uses directly addressed by this report include liners for surface impoundments, the results presented in this study are also useful in other applications especially in the design of daily covers and liners for landfills, seepage cutoff walls and trenches, and for nutrient retention and pollution mitigation wetlands.

The small-scale laboratory tests and monitoring of the full-scale FGD lined facility (capacity of one million gallons) shows that stabilized FGD materials can be used as low permeability liners in the construction of water and manure holding ponds. Actual long-term permeability coefficients in the range of 10^{-7} cm/sec (3×10^{-9} ft/sec) can be obtained in the field by compacting lime and fly ash enriched stabilized FGD materials. Leachate from the FGD material meets Ohio's non-toxic criteria for coal combustion by-products, and for most potential contaminants the national primary and secondary drinking water standards are also met. The low permeability non-toxic FGD material investigated in this study poses very minimal risks, if any, for groundwater contamination. The FGD wetland experiments indicated no significant differences in phosphorus retention between the clay and FGD-lined basins. The FGD-lined basins had a greater richness of plant species but lower total plant productivity than did the clay-lined basins.

Future research work investigating the use of FGD materials in the construction of landfill caps and liners, and wetland experiments at the medium to full-scale level is recommended.

ACKNOWLEDGEMENTS

This report was compiled as a part of a research project entitled *Use of Clean Coal Technology Products in the Construction of Low Permeability Liners* (CBRC Grant ECE24 & OCDO Grant CDO/D-98-19) and was performed at The Ohio State University. The principal sponsors of the research project were the Ohio Air Quality Development Authority's Ohio Coal Development Office, Coal Combustion Byproducts Recycling Consortium of USDOE, and The Ohio State University. The additional co-sponsor was American Electric Power. Support and encouragement for the project work was provided by Carmeuse North America, Ohio Department of Natural Resources, Ohio Farm Bureau, Ohio Pork Producers Council, Ohio Cattlemen's Association, Ohio Poultry Association, and BBC&M Engineering, Inc. The cooperation of AEP staff is valued and appreciated. The assistance provided by the OARDC Western Branch staff during the monitoring of the full-scale facility is appreciated. The corporate support of Zande & Associates, particularly Tom Flippo, for the design, engineering, and general assistance in the construction of the wetland experiments is appreciated. The assistance of Cheri Higgins, Changwoo Ahn, and Li Zang in conducting the wetland experiments is appreciated. More information on this research initiative may be obtained from the Internet web address: **<http://ccpohio.eng.ohio-state.edu/liner/>**. Additional information on the use of coal combustion products can be accessed at: **<http://ccpohio.eng.ohio-state.edu>**.

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EXECUTIVE SUMMARY

The objective of this research was to establish long-term field-verified time-dependent relationships for the performance of liners constructed from stabilized FGD by-products generated in Ohio. The project objective was accomplished with a coordinated program of testing and analyzing small-scale laboratory specimens under controlled conditions, medium-scale wetland experiments, and monitoring of a full-scale FGD-lined pond facility.

It was shown that lime and fly ash enriched stabilized FGD materials can be compacted in the laboratory using standard soil testing procedures to obtain long-term permeability coefficients that are in the 10^{-8} to 10^{-9} cm/sec range, which is lower than the 1×10^{-7} cm/sec value typically recommended by USEPA for constructing liners for waste containment facilities.

Four FGD test pads were constructed at the Conesville landfill of AEP in Fall of 2002. Each test pad used a different stabilized FGD material recipe and was instrumented at its center with a Boutwell apparatus immediately after the construction of the test pad. As in the previous study (Wolfe et al., 2000), we found that the Boutwell tests carried out on field constructed FGD material test pads did not provide a satisfactory correlation with laboratory permeability values.

The permeability and strength development of low fly ash content FGD and clay mixtures were studied to obtain mixture permeability values in the 10^{-7} cm/sec range. It was found that as the FGD:clay ratio decreased, the permeability reduced. As the FGD:clay ratio decreases, the rate of decrease of permeability with curing time increases. FGD:clay mixtures of 25:75 achieve 10^{-7} cm/sec range permeabilities within 7 to 28 days of curing. FGD:clay mixtures of 50:50 exhibit 10^{-7} cm/sec range permeabilities within 60 to 90 days of curing. The unconfined compressive strength of the clay samples is very low (25-35 psi) and is unaffected by curing time. The FGD material containing samples exhibit significant strength gains with curing time, and the amount of strength gain with curing time increases as the FGD:clay ratio increases.

The leaching potential of stabilized FGD material was evaluated using TCLP and modified TCLP testing procedures. The TCLP testing program conducted on the stabilized FGD material indicates that the stabilized FGD material tested in the laboratory is a relatively clean material, non-toxic and poses very minimal risks, if any, for groundwater contamination. Leaching results vary considerably depending on the leaching solution. In general, citric acid and ammonium citrate resulted in the largest leachate values for most elements. Ammonium oxalate generally resulted in the lowest leachate values. Results of the leaching kinetic studies show that the leaching process of stabilized FGD material conducted in a flow-through-rotating disk shows an independent relationship of leaching kinetics on hydrodynamic condition suggesting the leaching process is controlled largely by surface reaction.

Pilot-scale wetland experiments were carried out in four small created wetland basins at the Olentangy River Wetland Research Park in Columbus, Ohio, USA. Stabilized FGD material, received from the Conesville power plant of America Electric Power, was used as the liner for FGD basins, while local clay soil was used as a liner for the two control basins. Higher concentrations of elements common in FGD-liner material were found in leachate water in the FGD basins, suggesting that introduced river water was transported through the liners in these basins to the leachate collection system. The FGD mixture as implemented in this project did not serve as an effective aquiclude to water movement. It was about 20 times more permeable than the clay liner material. There were no significant differences in phosphorus retention between the clay and FGD-lined basins during the high-phosphorus pulsing period, refuting the hypotheses generated by earlier small-scale mesocosm wetland studies. Plant productivity was

lower in the FGD-lined wetland basins than in the clay-lined. The FGD-lined basins, which were stressed by low water levels, had a greater richness of plant species than did the clay-lined basins that had higher water levels. The clay-lined basins showed greater total plant productivity but with fewer plant species.

A million-gallon FGD-lined pond facility constructed in 1997 at South Charleston was monitored for a total period of about 5 ½ years. The full-scale permeability of the facility was evaluated to be 9.1×10^{-7} cm/sec at a curing time of one month. The permeability coefficient continued to reduce over time (due to curing of FGD) and stabilized at approximately 4×10^{-7} cm/sec at about 150 days of curing. Beyond 150 days, the permeability of the FGD material liner has been maintained at around 4×10^{-7} cm/sec till 5 ½ years of monitoring of the facility. The FGD permeability coefficient data range obtained from the full-scale tests is comparable to typical clays used in the construction of compacted liners. It is important to note that the actual measured field permeability values of the full-scale FGD liner are an order of magnitude higher than laboratory measured values. The water quality monitoring program showed that the leachate from the FGD lined facility needs to meet OEPA's non-toxic criteria. All the non-toxic parameters measured for the FGD facility while holding water and swine manure were much lower than OEPA's non-toxic criteria. It should be noted that the leachate from the full-scale FGD-lined facility meets most of the National Primary Drinking Water Regulations (NPDWR) limits. From a regulatory perspective, the leachate from the FGD material is not required to meet any of the NSDWR limit values, yet the leachate concentration levels measured from the FGD lined facility are generally lower or comparable to the NSDWR limits for most potential contaminants of concern.

In conclusion, long-term actual permeability coefficients in the range of 10^{-7} cm/sec (3×10^{-9} ft/sec) can be obtained in the field by compacting lime and fly ash enriched stabilized FGD materials. Leachate from the FGD material meets Ohio's non-toxic criteria for coal combustion by-products, and for most potential contaminants the national primary and secondary drinking water standards are also met. The low permeability non-toxic FGD material investigated in this study poses very minimal risks, if any, for groundwater contamination. Medium-scale FGD wetland experiments indicated higher concentrations of elements common in FGD-liner material in the leachate water in the FGD basins. The FGD mixture as implemented in the wetland experiments did not serve as an effective aquiclude to water movement. There were no significant differences in phosphorus retention between the clay and FGD-lined basins during the high-phosphorus pulsing period. Plant productivity was lower in the FGD-lined wetland basins than in the clay-lined basins. The FGD-lined basins had a greater richness of plant species than did the clay-lined basins that had higher water levels. The clay-lined basins showed greater total plant productivity but with fewer plant species.

Although the specific uses directly addressed by this report include liners for surface impoundments, the results presented in this study are also be useful in other applications, especially in the design of daily covers and liners for landfills, seepage cutoff walls and trenches, and for nutrient retention and pollution mitigation wetlands. The results obtained from this study are being incorporated into a revised draft ASTM standard guide for the use of FGD materials in the construction of liners and encapsulations.

Future research work is recommended to extend the knowledge developed in this project to the use of FGD materials in the construction of landfill caps and liners, where the cost saving to the utility are significant and the clay borrow sources can be preserved.

1 INTRODUCTION

1.1 Background and Objectives

In the past two decades, restrictions on the emission of sulfur dioxide from coal-fired power plants have been increasingly stringent in the United States. In response to these developments, power plants have had to remove increasing amounts of SO₂ from the flue gases before releasing them to the atmosphere. This process typically involves the injection of a reagent into the flue gases to form a solid by-product, which can then be collected. This solid by-product is commonly referred to as Flue Gas Desulfurization (FGD) material. Its principal constituents are varying amounts of sulfates and / or sulfites of the reagent, unreacted lime and fly ash. The FGD material may be dry or wet depending on the desulfurization process. The wet scrubbing process, which is commonly used by large electric utilities in Ohio, involves the injection of a reagent (typically hydrated quicklime) into the flue gases. The wet product generated (commonly referred to as FGD filter cake) is a dewatered mixture of sulfites and sulfates of the reagent, unreacted reagent, and some water. Calcium sulfite content is typically greater than 70% while the calcium sulfate content is approximately 10%. Fly ash and additional quicklime are added to stabilize the FGD filter cake. This stabilized (fixated) FGD material is gray in color and looks like silty clay. Currently more than 25 million tons of FGD material is generated annually in the US and this annual production rate is expected to increase significantly in the next several years.

In the past, FGD material has generally been treated as a waste product and landfilled. But the increasing cost of landfilling as well as the scarcity of landfill space have led utility companies to look into the beneficial re-use of this by-product. Several researchers at The Ohio State University have led efforts to use FGD materials for land application (Stehouwer et al. 1991, 1998; Dick et al. 1998). They identified a number of agricultural and engineering properties of both wet and dry clean coal technology by-products. Encouraged by the promising results obtained by the above listed studies, a research program was developed at The Ohio State University to study the suitability of compacted stabilized FGD materials as low permeability liners. Results from the Phase I study (OCDO Project CDO/D-95-19) have been published in Wolfe, et al., 2000. Phase I work showed that FGD material liners exhibit short-term characteristics that are suitable for liner applications.

The objective of the Phase II research program, co-funded by CBRC, presented in this report was to establish long-term field-verified time-dependent relationships for the performance of liners constructed from stabilized flue gas desulfurization by-products generated in Ohio. The project objective was accomplished with a coordinated program of testing and analyzing small-scale laboratory specimens under controlled conditions, medium-scale wetland experiments, and monitoring of a full-scale FGD-lined pond facility. Although the specific uses directly addressed by this report include liners for surface impoundments, the results presented in this study will also be useful in other applications, especially in the design of daily covers and liners for landfills, seepage cutoff walls and trenches, and for nutrient retention and pollution mitigation wetlands.

1.2 Outline of Report

Chapter 1 presents an introduction to the report. The small-scale laboratory testing program presented in Chapter 2 consists of long-term permeability characterization, comparison of laboratory and field (Boutwell) permeability procedures, permeability and strength development of FGD-clay mixtures, evaluation of leaching potential, and the implications of leaching tests for stabilized FGD pond liners. The construction and monitoring of medium-scale FGD-lined wetlands at the Olentangy River Wetland Research Park is discussed in Chapter 3. Chapter 4 presents a nearly six-year performance evaluation of the full-scale FGD lined facility (capacity of one million gallons) constructed in 1997 at the Ohio Agricultural Research and Development Center Western Branch in South Charleston. Summary and conclusions are presented in Chapter 5. Chapter 6 includes a list of references.

2 LABORATORY TESTING PROGRAM

2.1 Introduction

In order to evaluate the potential use of stabilized FGD materials for liner applications, it is important to characterize the material under standard laboratory testing procedures so that the response of the material under a controlled environment can be ascertained. The four main technical issues relating to low permeability FGD liners are permeability, strength, leachate potential, and durability of the material. In this chapter, we present the results of laboratory investigations of the long-term hydraulic conductivity, strength, and leaching potential of stabilized FGD materials.

2.2 Long-Term Permeability Characteristics

In order to characterize the long-term permeability of stabilized FGD materials, a set of experiments were conducted to evaluate the effect of more than 5 years of curing time on the laboratory permeability of material.

The material used in preparing the samples was generated by American Electric Power's Plant near Conesville, Ohio. At this plant, a lime-enriched wet scrubbing process is used to remove the SO₂ from the flue gases. The filter cake (FC) obtained in this process is mixed with Class F fly ash (FA) and lime (L) to produce the stabilized FGD. The FGD material is stored on a

temporary curing pad for 3-4 days to reduce the moisture content and allow for some curing. This permits the material to be handled more easily and subsequently it can be hauled to the plant landfill.

The FGD material used in the construction of the full-scale FGD lined facility was investigated for the long-term permeability study. The FGD material tested had a target FA:FC ratio of 1.8:1 and lime content of 8% as per power plant control operations. The material was generated at the power plant and transported within 12-24 hours of its production to the South Charleston facility under construction. Bucket samples of the FGD material were transported within 12 hours to the Soil Mechanics Laboratory at The Ohio State University. The material was generally compacted within 24 hours of delivery at the laboratory.

Four permeability samples were prepared using standard proctor test guidelines (ASTM D698, 1997) at as received moisture contents. It can be observed from Tables 2.1 that the as received moisture contents varied from 49 to 62 % while the compacted dry densities ranged from 9.6 to 11.6 KN/m³.

The coefficient of permeability was measured in the laboratory using a falling head test (ASTM D5084, 1996; ASTM D5856, 1996) for short curing times (7, 28, 60 days) and long curing times (150, 580, 980, 1960 days).

It can be observed from Table 2.1 that the coefficient of permeability for all the four samples tested in the laboratory decreased with curing time. The rate of decrease in permeability of the

samples was much greater at shorter curing times as compared to longer curing times. At 60 days of curing, all the samples exhibited permeability values in the 10^{-7} to 10^{-8} cm /sec range. At 1960 days (5 years and 4 ½ months) of curing, the permeability values were in the 10^{-8} to 10^{-9} cm/sec range.

It can be concluded from Table 2.1 that lime and fly ash enriched stabilized FGD materials can be compacted in the laboratory using standard soil testing procedures to obtain long-term permeability coefficients that are in the 10^{-8} to 10^{-9} cm/sec range, which is lower than the 1×10^{-7} cm/sec value typically recommended by USEPA for constructing liners for waste containment facilities (Goldman, et al., 1988).

Table 2.1 Long-Term Permeability of Stabilized FGD Material

ID	Sampling Location	Sampling Date	w (%)	γ_d (KN/m ³)	Coefficient of Permeability (cm/sec)						
					7 day	28 day	60 day	150 day	580 day	980 day	1960 day
P1	Pond Bottom 1st Lift	8/11/97	49.0	11.0	4.99×10^{-7}	1.38×10^{-7}	2.08×10^{-7}	1.87×10^{-7}	1.58×10^{-7}	1.12×10^{-7}	2.79×10^{-8}
P2	Pond Sides 2nd Lift	8/12/97	61.8	11.6	2.30×10^{-6}	2.57×10^{-7}	1.16×10^{-7}	1.64×10^{-7}	7.80×10^{-8}	3.84×10^{-8}	1.61×10^{-8}
P3	Pond Bottom 3rd Lift	8/13/97	52.0	10.5	6.96×10^{-7}	7.63×10^{-8}	4.19×10^{-8}	3.57×10^{-8}	2.35×10^{-8}	1.64×10^{-8}	3.45×10^{-9}
P4	East Side of Pond & Test Pad 1	8/15/97	62.0	9.6	1.48×10^{-6}	1.24×10^{-7}	2.68×10^{-8}	2.33×10^{-8}	1.68×10^{-8}	9.59×10^{-9}	4.72×10^{-9}

$1 \text{ KN/m}^3 = 6.366 \text{ lb/ft}^3$

$1 \text{ cm/sec} = 0.0328 \text{ ft/sec}$

2.3 Comparison of Laboratory & Field Test Pad Measured Permeability

In Phase I of this study, Wolfe et al., 2000 observed significant disagreements between permeability of laboratory samples and Boutwell test values measured on test pads. In the previous study, the size of the test pads was comparable to the compaction equipment and hence it was suspected that inadequate compaction could have contributed to the disagreement in the data sets.

In this study, four FGD test pads (approximately 60 feet long, 15 feet wide, and 5 feet high) were constructed at the Conesville landfill of AEP in August and September of 2002. Each test pad used a different stabilized FGD material recipe as shown in Table 2.2. The lime content ranged from 4.5 to 10% and the fly ash to filter cake ratio (FA:FC) ranged from 1:1 to 1.5:1. The as received moisture contents ranged from about 50 to 72%.

Each FGD material recipe was used to construct a test pad. Compaction of each pad was achieved by using a compaction roller that is routinely used at the landfill and it was operated by landfill staff. Each test pad was instrumented at its center with a Boutwell apparatus (Boutwell, 1992) by a technician from BBC&M Engineering immediately after the construction of the test pad. Samples of the FGD material used in the construction of the test pads were brought to the Soil Mechanics Laboratory of The Ohio State University and laboratory permeability samples prepared using Standard Proctor compactive effort. The Boutwell apparatuses installed in the field test pads were used to measure the field permeability of the compacted test pads, while

falling-head permeability tests carried out on laboratory compacted samples measured the laboratory controlled values. All laboratory tests were carried out by OSU staff, while the Boutwell test measurements were carried out jointly by OSU and AEP staff.

Table 2.3 shows the comparison of the laboratory and field test pad (Boutwell) permeability values for curing times of 7, 28, and 60 days. Samples with higher moisture contents (Test Pads 1 and 2) showed good agreement between laboratory and field (Boutwell) permeability values at longer curing times, while samples with lower moisture contents (Test Pads 3 and 4) showed poor correlation of the Boutwell permeability with the laboratory measured values for all curing times. As expected, the laboratory permeability values were the lowest for Test Pad 3 (since this sample has the highest lime and FA:FC content). However, this Test Pad gave the highest field (Boutwell) permeability values. Test Pad 4 standpipe for Boutwell test did not hold water for long so no significant test measurements could be made. However, the laboratory samples for Test Pad 4 exhibited permeability values in the 10^{-5} to 10^{-6} cm/sec range.

In these experiments, the test pads were wide enough as compared to the compaction equipment and the compaction of the test pads was carried out by landfill staff who had several years experience in compacting the FGD material at the landfill. Inadequate compaction of test pads is not the likely source of the discrepancy of results for the field permeability tests carried out in this study. As in the previous study (Wolfe et al., 2000), the Boutwell tests carried out on field constructed FGD material test pads did not provide a satisfactory correlation with control laboratory permeability values.

Table 2.2 FGD Test Pads Mixes Constructed at Conesville Landfill

Designation	FGD Test Pad 1	FGD Test Pad 2	FGD Test Pad 3	FGD Test Pad 4
Date sample collected	8/13/02	8/20/02	8/27/02	9/3/02
Amount (# of buckets)	2	2	2	2
Lime (%)	4.54	6.82	10.0	6.79
Fly Ash : Filter Cake	1.04:1	1.07:1	1.46:1	1.45:1
Description of material	STP produced material of 1.04/1.00 Fly ash/Filter cake with 4.54% lime on August 10, 2002 (6AM – 6PM). Pad constructed on August 13, 2002. (800 tons +/-)	STP produced material of 1.07/1.00 Fly ash/Filter cake with 6.82% lime on August 17, 2002 (6AM – 6PM). Pad constructed on August 20, 2002. (800 tons +/-)	STP produced material of 1.46/1.00 Fly ash/Filter cake with 10.0% lime on August 24, 2002 (6AM – 6PM). Pad constructed on August 27, 2002. (800 tons +/-)	STP produced material of 1.45/1.00 Fly ash/Filter cake with 6.79% lime on August 31, 2002 (6AM – 6PM). Pad constructed on September 3, 2002. (800 tons +/-)
As received moisture content	71.9 %	63.5 %	53.1 %	49.8 %

Table 2.3 Comparison of Laboratory and Field (Boutwell) Permeability Values

Sample	L, FA:FC	w (%)	Laborator y γ_d (kN/m ³)	Laboratory Permeability (cm/sec)			Field (Boutwell) Permeability (cm/sec)		
				7 days	28 days	60 days	7 days	28 days	60 days
Test Pad 1	4.54%, 1.04:1	71.9	8.43	1.84E-05	1.19E-05	1.04E-05	9.17E-06	1.71E-05	1.29E-05
Test Pad 2	6.82%, 1.07:1	63.5	8.82	1.71E-05	8.59E-06	5.40 E-06	4.07E-06	2.68E-06	1.92E-06
Test Pad 3	10.0%, 1.46:1	53.1	9.30	8.01E-06	7.28E-06	2.29E-06	2.40E-04	1.96E-04	1.82E-04
Test Pad 4	6.79%, 1.45:1	49.8	9.58	1.21E-05	1.02E-05	7.23E-06	pipe won't hold	pipe won't hold	pipe won't hold

L: Lime

FA: Fly Ash

FC: Filter Cake

2.4 Permeability & Strength Development of FGD-Clay Mixtures

Past research conducted on the potential use of FGD material as a low permeability liner has shown that lime and fly ash enriched FGD materials with FA:FC ratio of 1.8:1 or more and lime contents of at least 8% exhibit laboratory permeability values in the 10^{-8} to 10^{-9} cm/sec range. Stabilized FGD materials with lesser amounts of fly ash (FA:FC ratio of 1.5:1 or less) typically exhibit permeability values in the 10^{-6} cm/sec range. In this section, we present the results of a study carried out to explore mixtures of low fly ash content stabilized FGD and clay to obtain mixture permeability values in the 10^{-7} cm/sec range. The strength of such FGD-clay mixtures is also investigated.

The FGD materials used in the construction of test pads at the Conesville landfill, as elaborated in Section 2.3 earlier, were combined with clay being used at the landfill as a final cap material (permeability in the 10^{-8} cm/sec range). The FGD:clay ratios (on a dry weight basis) tested were 100:0 (FGD material only), 75:25, 50:50 (equal parts of FGD and clay), 25:75, 0:100 (clay only). All samples were compacted using Standard Proctor compactive effort.

Tables 2.4 and 2.5 show the permeability and unconfined compressive strength, respectively, for the four FGD:clay ratios (100:0, 75:25, 50:50, 25:75, and 0:100) and the four types of FGD recipes (FA:FC=1.04:1 with 4.54%L, FA:FC=1.07:1 with 6.82%L, FA:FC=1.46:1 with 10%L, and FA:FC=1.45:1 with 6.79%L) for curing times of 7, 28, 60, and 90 days.

It can be seen from Table 2.4 that as the FGD:clay ratio decreases, the permeability reduces. The permeability of the clay only samples remains the same with curing time, while the permeability of the FGD material reduces significantly with curing time. The mixtures of clay and FGD exhibit reduction in permeability values with curing time. As the FGD:clay ratio decreases, the rate of decrease of permeability with curing time increases. FGD:clay mixtures of 25:75 achieve 10^{-7} cm/sec range permeabilities within 7 to 28 days of curing. FGD:clay mixtures of 50:50 exhibit 10^{-7} cm/sec range permeabilities within 60 to 90 days of curing.

As seen in Table 2.5, the unconfined compressive strength of the clay samples is very low (25-35 psi) and is unaffected by curing time. The FGD containing samples exhibit significant strength gains with curing time, and the amount of strength gain with curing time increases as the FGD:clay ratio increases.

Table 2.4 Permeability of FGD-Clay Mixtures

	FGD: CLAY (dry weight basis)	w (%)	γ_d (kN/m ³)	k (cm/sec)			
				7 day	28 day	60 day	90 day
FGD 1 (4.54%L, FA:FC=1.04:1)	100:0	71.9	8.43	1.84E-05	1.19E-05	1.04E-05	1.04E-05
	75:25	51.5	10.58	8.57E-06	3.23E-06	2.92E-06	2.72E-06
	50:50	37.9	12.72	3.20E-06	1.98E-06	NT	NT
	25:75	28.3	14.87	5.17E-07	4.50E-07	4.71E-07	2.33E-07
	0:100	21.1	17.01	3.13E-08	2.77E-08	2.36E-08	2.30E-08
FGD 1 (6.82%L, FA:FC=1.07:1)	100:0	63.5	8.82	1.71E-05	8.59E-06	5.40 E-06	5.73E-06
	75:25	46.9	10.87	1.18E-05	6.71E-06	3.79E-06	2.87E-06
	50:50	35.6	12.92	5.43E-06	2.42E-06	2.87E-06	8.39E-07
	25:75	27.3	14.97	4.14E-07	3.53E-07	4.78E-07	2.77E-07
	0:100	21.1	17.01	3.13E-08	2.77E-08	2.36E-08	2.30E-08
FGD 1 (10.0%L, FA:FC=1.46:1)	100:0	53.1	9.30	8.01E-06	7.28E-06	2.29E-06	3.91E-06
	75:25	41.0	11.23	7.02E-06	4.63E-06	4.66E-06	NT
	50:50	32.4	13.16	4.41E-06	3.45E-06	2.54E-06	NT
	25:75	26.0	15.08	9.84E-07	1.11E-06	5.38E-07	NT
	0:100	21.1	17.01	3.13E-08	2.77E-08	2.36E-08	2.30E-08
FGD 1 (6.79%L, FA:FC=1.45:1)	100:0	49.8	9.58	1.21E-05	1.02E-05	7.23E-06	6.07E-06
	75:25	39.1	11.44	5.21E-06	4.02E-06	NT	NT
	50:50	31.4	13.30	4.48E-06	2.76E-06	NT	NT
	25:75	25.6	15.16	2.46E-06	8.31E-07	NT	NT
	0:100	21.1	17.01	3.13E-08	2.77E-08	2.36E-08	2.30E-08

L: Lime FA: Fly Ash FC: Filter Cake NT: Not Tested

Table 2.5 Unconfined Compressive Strength of FGD-Clay Mixtures

	FGD: CLAY (dry weight basis)	w (%)	γ_d (kN/m ³)	q_u (psi)			
				7 day	28 day	60 day	90 day
FGD 1 (4.54%L, FA:FC=1.04:1)	100:0	71.9	8.43	32	52	89	88
	75:25	51.5	10.58	27	34	30	39
	50:50	37.9	12.72	23	29	29	32
	25:75	28.3	14.87	NT	37	27	36
	0:100	21.1	17.01	26	24	27	33
FGD 1 (6.82%L, FA:FC=1.07:1)	100:0	63.5	8.82	85	234	399	379
	75:25	46.9	10.87	55	129	168	204
	50:50	35.6	12.92	54	70	94	98
	25:75	27.3	14.97	42	39	52	54
	0:100	21.1	17.01	26	24	27	33
FGD 1 (10.0%L, FA:FC=1.46:1)	100:0	53.1	9.30	156	298	316	NT
	75:25	41.0	11.23	90	88	170	NT
	50:50	32.4	13.16	57	80	96	NT
	25:75	26.0	15.08	34	37	46	NT
	0:100	21.1	17.01	26	24	27	33
FGD 1 (6.79%L, FA:FC=1.45:1)	100:0	49.8	9.58	147	321	229	395
	75:25	39.1	11.44	70	164	188	NT
	50:50	31.4	13.30	56	70	79	106
	25:75	25.6	15.16	38	40	55	54
	0:100	21.1	17.01	26	24	27	33

L: Lime FA: Fly Ash FC: Filter Cake NT: Not Tested

2.5 Leaching Potential

2.5.1 TCLP

The leaching potential of the stabilized FGD material was evaluated using standard 20:1, 18 hour leaching tests as per USEPA Toxicity Characteristic Leaching Procedure (TCLP) dilute acetic acid method 1311 (United States Environmental Protection Agency, 1991). Two liters of the extractant was added to 100g of FGD material in a Teflon bottle. The extractant consisted of 5.7 ml of glacial acetic acid diluted to 1 liter with de-ionized water ($\text{pH} = 2.88 \pm 0.05$). Bottles were placed on a rotary shaker (30 rpm) for 18 hours at 25°C. Leachates were filtered and analyzed for pH, total dissolved solids, acidity, alkalinity, conductivity, and 20 elements by ICP and graphite furnace atomic absorption (GFAA) spectrophotometry.

A total of five stabilized FGD material samples from Conesville power plant were collected over a four-week period, and analyzed according to USEPA TCLP Method 1311. The results are presented in Table 2.6. For each constituent, its range and mean value were calculated and are reported in Table 2.7. The Table also presents a comparison of the TCLP results with appropriate regulatory levels. Two types of regulatory levels are listed for comparison. First, Ohio EPA's non-toxic criteria, which is generally 30 times selected national primary drinking water standards, is the regulatory level needed for the FGD material to be considered as non-toxic in the state of Ohio. Second, the national drinking water standards are also listed in Table 2.7. These consist of the National Primary Drinking Water Regulations (NPDWR or primary

standards) and the National Secondary Drinking Water Regulations (NSDWR or secondary standards). The primary standards are legally enforceable standards that apply to all public water systems that protect drinking water quality by limiting the levels of specific contaminants that can adversely affect public health. The secondary standards are non-enforceable non-health related guidelines regulating contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as color, odor, or taste) in drinking water.

It can be observed from Table 2.7 that the FGD leachate data for various constituents studied do not vary over a wide range and are bracketed within a reasonably small range of values. The mean values calculated for the potential contaminants are very low. A comparison of the FGD leachate data with Ohio EPA non-toxic criteria shows that for the contaminants studied, the FGD material meets all the criteria specified by the Ohio EPA by a large factor of safety and hence the stabilized FGD material used in the study can be characterized to be non-toxic. The range and mean values for all constituents are lower than the primary standards (NPDWR). As an example, for Arsenic, the concentration values ranged from 0.004 to 0.008 mg/l with a mean value of 0.006 mg/l, which is less than one-eighth the primary standard value of 0.05 mg/l. Hence, the leachate from stabilized FGD material studied in this investigation meets all the National Primary Drinking Water Regulations. In general, the FGD leachate concentration levels are also lower than the secondary (non-health and unenforceable) standards. The exceptions being pH (mean value of 11.08) and Aluminum (mean value of 5.114 mg/l). The TCLP testing program conducted on the stabilized FGD material indicates that the stabilized FGD material tested in the laboratory is a relatively clean material, non-toxic and poses very minimal risks, if any, for groundwater contamination.

Table 2.6 TCLP Results

Analyte	Units	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Acidity	mg/L	<1	<1	<1	<1	<1
Alkalinity	mg/L	198	174	268	149	212
Aluminum	mg/L	5.54	5.72	4.66	4.37	5.28
Arsenic	mg/L	0.005	0.008	0.004	0.005	0.008
Barium	mg/L	0.188	0.047	0.204	0.151	0.214
Beryllium	mg/L	< 0.0002	<0.0002	< 0.0002	< 0.0002	< 0.0002
Cadmium	mg/L	< .0005	0.001	< 0.0005	0.001	< 0.0005
Chloride	mg/L	36	46	30	34	43
Chromium	mg/L	0.004	0.002	0.002	0.004	0.002
Conductivity	umhos/cm	946	950	1320	828	1120
Copper	mg/L	< 0.001	< 0.001	0.003	< 0.001	< 0.001
Flouride	mg/L	0.2102	0.1387	0.2102	0.1605	0.2129
Iron	mg/L	0.03	0.01	0.02	0.02	< 0.01
Lead	mg/L	< 0.002	< 0.002	< 0.002	< 0.002	<0.002
Manganese	mg/L	< 0.01	<0.01	< 0.01	< 0.01	< 0.01
Mercury	mg/L	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002
Nickel	mg/L	< 0.003	0.014	< 0.003	< 0.003	< 0.003
pH	s.u.	11.0	11.0	11.2	11.0	11.2
Filterable TDS	mg/L	430	402	447	404	450
Selenium	mg/L	0.014	0.007	0.006	0.008	< 0.005
Silver	mg/L	<0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002
Sodium	mg/L	10.5	11.1	9.1	9.6	12.2
Sulfate	mg/L	79	71	49	94	68
Vanadium	mg/L	0.028	0.033	0.021	0.029	0.03
Zinc	mg/L	0.025	0.022	0.028	0.024	0.029

Table 2.7 Comparison of TCLP Results with Regulatory Standards

Constituent	Units	Range for FGD materials tested	Mean value for FGD materials tested	Ohio EPA Non-Toxic Criteria	National Drinking Water Standards
Acidity	mg/L	-	<1	-	-
Alkalinity	mg/L	149 - 268	200.2	-	-
Aluminum	mg/L	4.37 - 5.72	5.114	-	0.05 - 0.2**
Arsenic	mg/L	0.004 - 0.008	0.006	1.5	0.05*
Barium	mg/L	0.047 - 0.214	0.1608	60	2*
Beryllium	mg/L	-	<0.0002	-	0.004*
Cadmium	mg/L	<0.0005 - 0.001	-	0.15	0.005*
Chloride	mg/L	30 - 46	37.8	-	250**
Chromium	mg/L	0.002 - 0.004	0.0028	3	0.1*
Conductivity	umhos/cm	828 - 1320	1032.8	-	-
Copper	mg/L	-	<0.001	-	1.0**
Fluoride	mg/L	0.1387 - 0.2129	0.1865	-	4.0* , 2.0**
Iron	mg/L	<0.01 - 0.03	<0.018	-	0.3**
Lead	mg/L	-	<0.002	1.5	0.015***
Manganese	mg/L	-	<0.01	-	0.05**
Mercury	mg/L	-	<0.0002	0.06	0.002*
Nickel	mg/L	<0.003 - 0.014	-	-	-
pH	s.u.	11.0 - 11.2	11.08	-	6.5 - 8.5**
Filterable TDS	mg/L	402 - 450	426.6	-	500**
Selenium	mg/L	<0.005 - 0.008	<0.008	1	0.05*
Silver	mg/L	-	<0.0002	-	0.1**
Sodium	mg/L	9.1 - 12.2	10.5	-	-
Sulfate	mg/L	49 - 94	72.2	-	250**
Vanadium	mg/L	0.021 - 0.033	0.0282	-	-
Zinc	mg/L	0.022 - 0.029	0.0256	-	5.0**

* : National Primary Drinking Water Regulation (NPDWR)

** : National Secondary (Non-health related) Drinking Water Regulation (NSDWR)

***: Action Level

2.5.2 Modified TCLP

Other leaching solutions (citric acid, ammonium citrate, oxalic acid, ammonium oxalate, acetic acid, and pond water) were also applied to study the leaching potential of the stabilized FGD material. Citric and oxalic acids were chosen because their abundance in many types of natural waters and sedimentary basin fluids with the concentration range from the scale of $\mu\text{g/L}$ to mg/L (Thurman, 1985). Both acids were also found in fresh and decomposed manure with the concentrations ranged from 5.88 to 69.17 mmol/g (Baziramakenga and Simard, 1998). Their ability to form complexes with metal cations has led to many studies of their roles in mineral dissolution, trace element mobility, and trace element bioavailability and toxicity (Prapaipong et al., 1999). Ammonium citrate and ammonium oxalate were applied to evaluate the effect of citrate and oxalate ligands without the influence of proton. Pond water was used to assess the leaching potential under the specific environment as in this project.

The fixated FGD material used in this study was manufactured in the lab by mixing filter cake (FC) and fly ash (FA) from AEP's coal-fired power plant near Conesville, Ohio, with a FA:FC ratio of 1.5:1 (dry weight basis). Milli-Q water and an additional 6% of total weight of quicklime were added to produce a final mixture with 30% moisture content. Fixated FGD material prepared by the above composition ratio was found to have the best engineering performance for low permeability liner applications (Butalia and Wolfe, 1999). The mixture was then compacted to a disk with dimensions of 3.18 cm and 0.8 cm in diameter and thickness, respectively, and then cured in a 100 % humidity room. After being cured for 28 days, the fixated FGD material disk was oven-dried at 60°C over night and then stored in a vacuumed desiccator containing

diphosphorus pentoxide (P_2O_5) to terminate the hydration process. Three randomly selected samples were tested for dried density and the result, $11.85 \pm 0.06 \text{ kN/m}^3$, agrees well with what was found by Butalia and Wolfe, 1999.

Leaching tests were carried out by following the standard USEPA Toxicity Characteristic Leaching Procedure (TCLP), method 1311; with the exception of the leaching solution. Oxalic acid, citric acid, ammonium oxalate, and ammonium citrate at a concentration 0.1M were used as leaching reagents. Two liters of the leaching reagent was added to 100g of ground stabilized FGD material in a Teflon bottle. Pond water collected on Feb 12, 2002 was used as one of the leachants. Standard TCLP with 0.1 M acetic acid solution was also conducted for comparison purposes. The starting pHs of acetic acid, oxalic acid, citric acid, ammonium oxalate, ammonium citrate, and pond water were 2.83, 1.28, 2.01, 6.39, 4.99, and 7.66, respectively. Bottles were placed on a rotary shaker (30 rpm). Ten milliliter of leachate was collected periodically from each bottle for a total period of 168 hours. A total volume of 100 mL leachate was collected from each bottle during the whole period. Each collected leachate was filtered with 0.7 mm TCLP filters and analyzed for 23 elements by ICP.

The leaching results of all elements from the modified TCLP test are shown in Table 2.8. It can be seen that the leaching results vary considerably depending on the leaching solution. In general, citric acid and ammonium citrate resulted in the largest leachate values for most elements. Ammonium oxalate generally resulted in the lowest leachate values. It should be emphasized, however, that none of the concentration of these elements exceeds the nontoxic criteria levels established by OEPA.

After 18 hours of leaching, the concentration levels of 5 selected nontoxic criteria parameters (As, Ba, Cr, Pb, and Se) from each extraction batch are shown in Figure 2.1 to 2.5. The concentration levels of Cd and Hg were too low to be detected by ICP-AES and, therefore, no data are shown. The pH values in acetic acid, oxalic acid, ammonium oxalate, citric acid, ammonium citrate, and pond batches after 18 hours of leaching were 5.41, 4.03, 8.97, 3.72, 7.13, and 8.39, respectively. In the pond water batch, all the concentration levels of nontoxic criteria parameters were below respective detection limits. Citric acid and ammonium citrate batches had the highest concentration levels for all selected elements, except for Se. In the case of Se, oxalic acid has slightly higher leaching results than citric acid. Due to lower pH, citric acid and oxalic acid both have higher extraction results when compared to ammonium citrate and ammonium oxalate, respectively. The proton effect seems to be more significant in oxalate than in citrate for all of the selected elements with the exclusion of As. Ba concentration in the oxalic acid batch was about an order of magnitude higher than in ammonium oxalate, but only about 1.5 time higher when comparing the concentration level in citric acid to the concentration level in ammonium citrate.

Figure 2.6 shows the leaching profiles of selected nontoxic criteria parameters from the batch where the standard TCLP test with acetic acid was conducted. Concentration levels of Pb in this batch were undetectable. At the beginning of leaching, concentration levels of Ba increased dramatically and reached its maximum value within 6 hours. After 6 hours, concentrations of Ba started decreasing and stabilized after 48 hours. The concentration levels of As kept very low over the leaching period. Detectable concentrations were found during the first 6 hours with a

maximum concentration of 5 μ g/L. Selenium and chromium concentrations fluctuated throughout the leaching period. Results from this figure indicate that 18 hours of leaching may not generate the maximum or equilibrium concentrations for the above-mentioned elements.

The leaching profiles of selected elements in pond water are shown in Figure 2.7. Different from the standard TCLP test, the concentrations levels of As, Se, Cr, and Ba increased slightly during the first 28 hours of the leaching period. After 28 hours, all concentration levels remained constant throughout the leaching process. All the concentration levels of nontoxic criteria parameters were very low.

Table 2.8 Modified TCLP Results

	Acetic Acid	Oxalic Acid	Ammonium Oxalate	Citric Acid	Ammonium Citrate	Pond Water	
						Leachate	Water*
Al	521	14240	11	33400	24400	74	216
As	<10	16	19	130	87	<10	<35
B	940	1050	960	1440	1550	1076	2115
Ba	56.83	131.8	8.75	280	206.3	<30	14
Be	0.64	4.5	<0.2	6.1	4.53	<0.2	-
Ca [†]	230.5	190	1.136	533	228.3	158.8	164.9
Cd	<10	<10	<10	<10	<10	<10	<2
Co	2.4	4.2	<1	10.6	8.0	<1	-
Cr	1.6	23.5	2.4	38.8	34.7	<1	10
Cu	13.1	27.1	16.0	79.8	68.8	15.3	10
Fe	70	6551	3.2	12400	10360	50	3000
K [†]	71.5	78.0	48.6	94.1	86.1	362	366
Mg	18460	26300	5200	29500	25600	8760	69000
Mn	87.8	99.9	1.55	137.8	104.2	3.2	100
Ni	14.2	23	0.2	31	29.4	2.8	10
P	ND	70	86	940	440	-	49000
Pb	<2	<2	<2	27	14	<2	<20
S	6746	25970	18580	21320	7860	-	170400
Se	<20	45.6	21.5	42.6	29.9	<20	<100
V	<3	52.1	9.3	114	97.6	5.4	30
Zn	25.4	58.5	<20	110	71.3	<20	40

Unit: µg/L

[†]Unit: mg/L

* Results obtained from full-scale FGD liner water quality monitoring

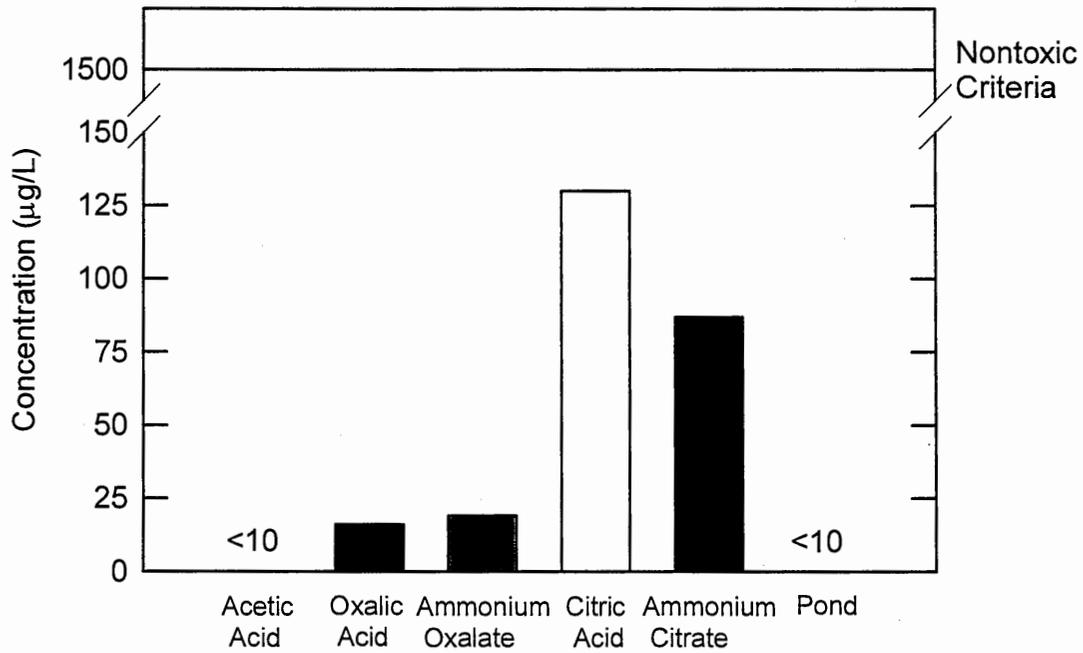


Figure 2.1 Concentration of Arsenic from modified TCLP test

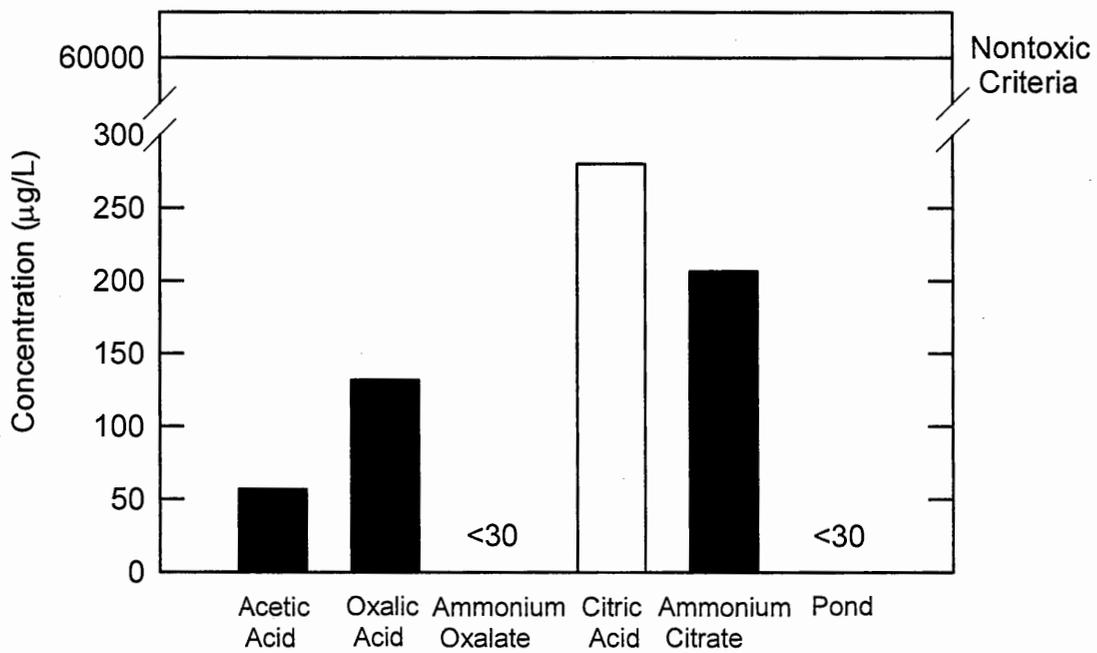


Figure 2.2 Concentration of Barium from modified TCLP test

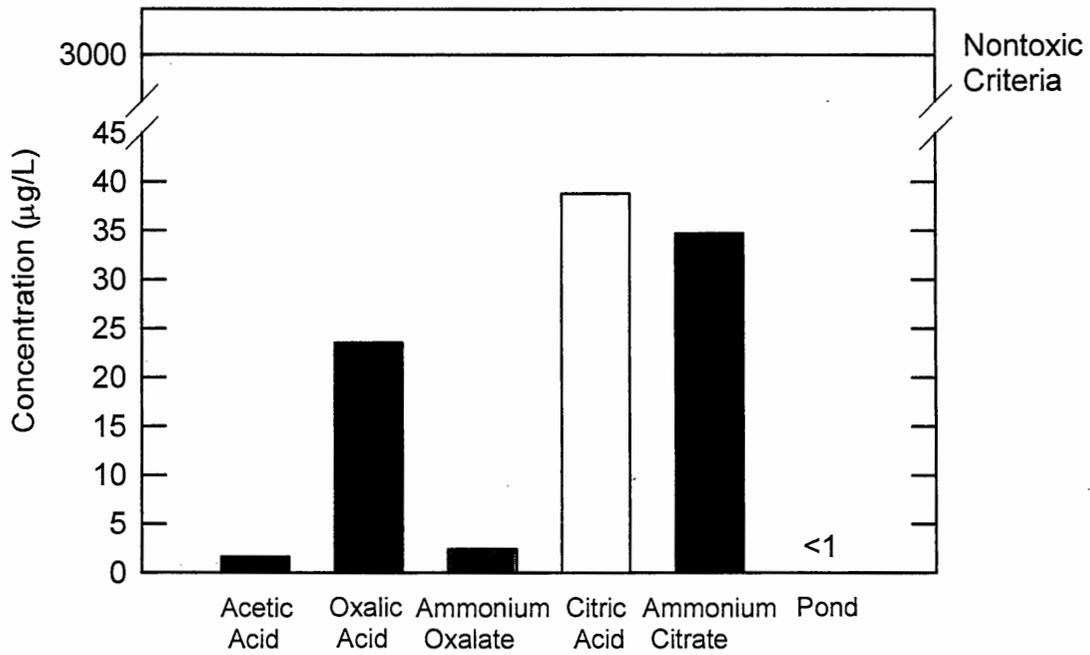


Figure 2.3 Concentration of Chromium from modified TCLP test

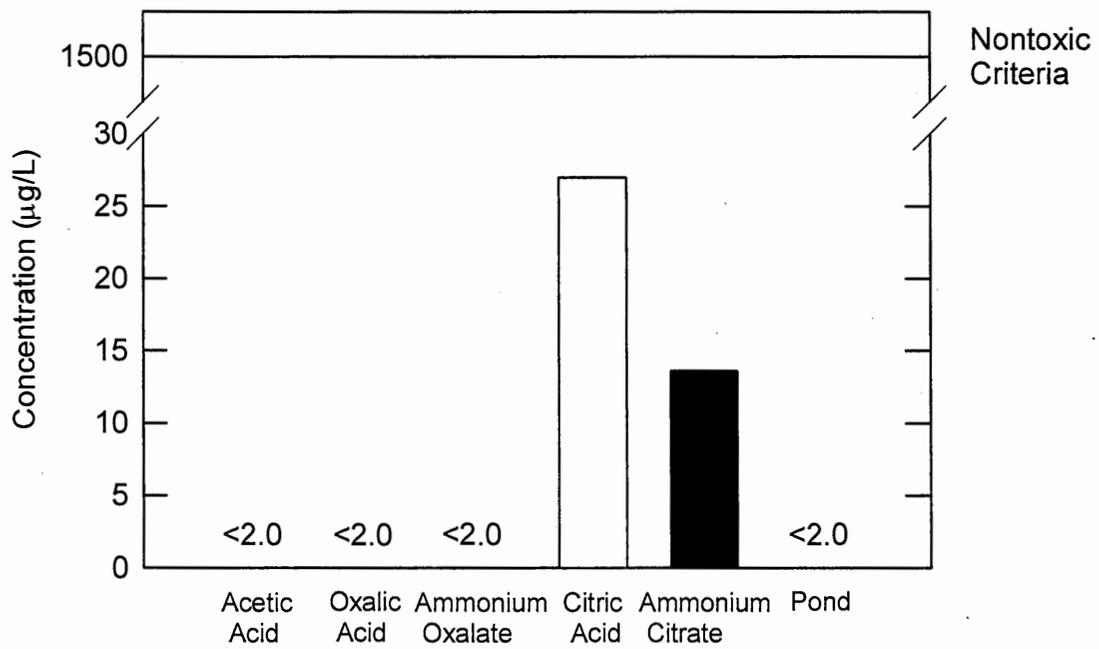


Figure 2.4 Concentration of Lead from modified TCLP test

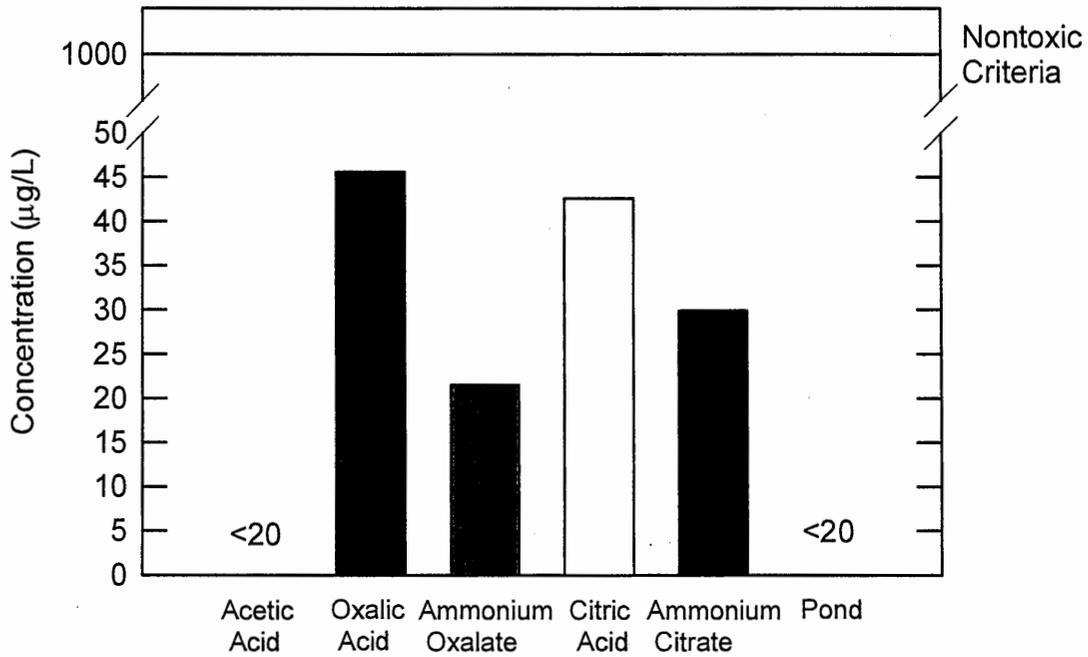


Figure 2.5 Concentrations Se from the modified TCLP test

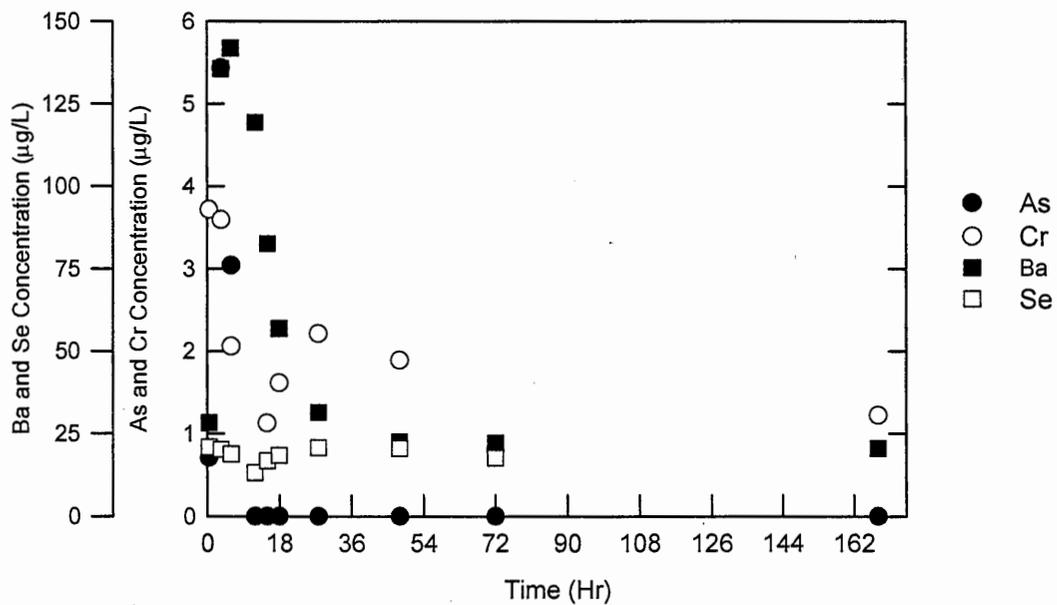


Figure 2.6 Concentration profiles of nontoxic criteria parameters from standard TCLP test

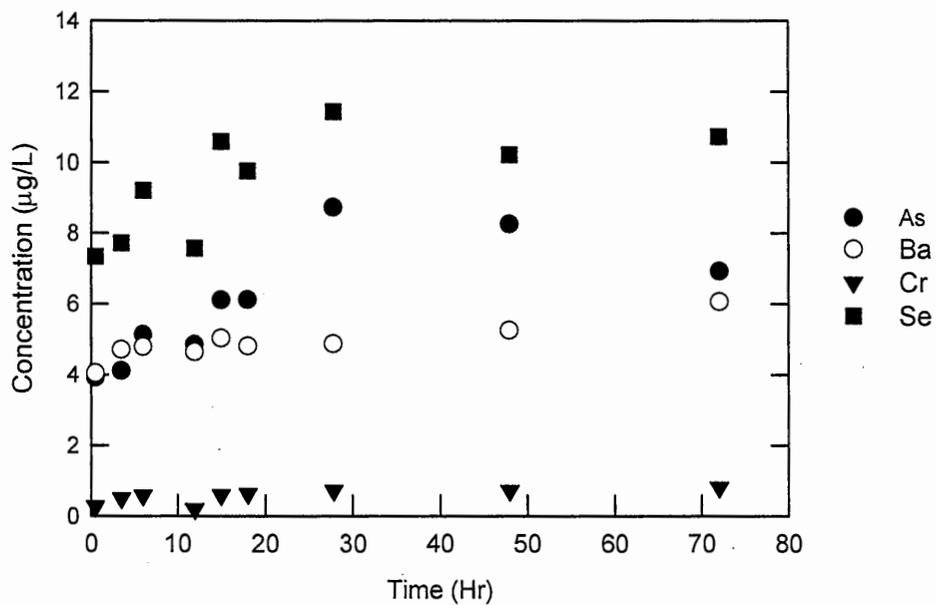


Figure 2.7 Concentration profiles of (a) nontoxic criteria parameters and (b) selected elements from leaching test with 2/12/2002 pond water

2.5.3 Effect of pH on Leaching Kinetics

According to the TCLP and modified TCLP studies conducted in this study, the leaching results are highly dependent on the particular conditions of the leaching tests. Kim (2003) reviewed fly ash leaching studies conducted during the past 25 years and found those reviewed data were highly variable and cannot be applied to predict field leachate concentrations. The only qualitative trend shown in the review is that most cations in fly ash are more soluble in acid solution. However, no quantitative description of the acidity effect is available. Lack of the knowledge about the mechanisms affecting the leaching process prevents us from understanding and predicting the leaching behavior of this material in field applications.

To develop a better understanding of the leaching behavior of fixated FGD material, a leaching kinetic study was conducted to (1) determine whether the leaching kinetics of specific elements are transport- or reaction-controlled, (2) elucidate the role of pH on controlling the leaching kinetics of stabilized FGD material, and (3) propose leaching models for specific elements that take into account the effect of pH.

2.5.3.1 Experimental

The stabilized FGD material used in this study was manufactured in lab by following the method describes in Section 2.5.2. Leaching solution was prepared by adding sodium nitrate (Fisher Scientific) into de-ionized water to a final concentration of 0.01 M.

Complete elemental analysis of fixated FGD material was accomplished by following the guideline of EPA method 3052, in which microwave heating method was applied. About 300 mg of the fixated FGD material sample was first heated in a digestion solution of a mixture of 10-mL deionized water, 6-mL nitric acid, 2-mL hydrochloric acid, and 2-mL hydrofluoric acid. Then, the sample was heated a second time with additional 20-mL of boric acid. Coal fly ash, 1633b, provided by the National Institute of Standards and Technology (NIST) was digested along with fixated FGD material samples for analytical quality control.

The leaching experiments were carried out in a flow-through-rotating-disk system as schematically shown in Figure 2.8. This system was chosen because (1) the flux of reagents (e.g., protons) to the FGD by-product surface can be conveniently controlled by changing the rotation speed of the disk; (2) an exact solution to the Navier-Stokes equation describing the hydrodynamics of this system exists; and thus (3) allowing for the precise prediction of transport-controlled rates of reactants and products, to and from, the disk surface. In this system, a fixated FGD material disk was attached to the Teflon-lined rotator with an acrylic sample holder. The distance from the disk surface to the bottom of the vessel was kept constant at 8 cm. Temperature was controlled by a thermo-regulated water bath at $25.0 \pm 0.1^\circ\text{C}$. The pH in the reactor was adjusted by a pH-stat autotitrator with trace-metal grade nitric acid with a relative standard deviation less than 1%. The rotating speed of the disk was controlled by a motorized mixer.

In each leaching experiment, a leaching condition with constant pH and disk rotating speed was maintained. Five different acidic leaching conditions ranging from pH 2.2 to 6.8 were tested. A

rotating speed of 60 rpm was applied to each acidic leaching condition. Other rotating speeds were also carried out in pH 2.2 and 5.0. The surface roughness of the fixated FGD material disk was kept constant by polishing the surface with 320 grit size waterproof silicon carbide paper before every experiment began. Samples were collected periodically until the leaching process reached steady state (i.e., the relative standard deviation of element concentrations from the last four successive effluent samples was less than 10%).

Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) was applied to analyze major and minor elements; i.e., Al, Ca, Fe, S, Si, and Mg. The specific surface area of each leached fixated FGD material disk was characterized with the BET technique by determining the quantity of a gas that adsorbs as a single layer of molecules on a sample. A tailor-made monolith holder allows the analysis to be done without breaking disk samples. The change of mineral phases and morphology on the surface of the fixated FGD material disk before and after leaching were studied with X-ray diffraction (XRD) and scanning electronic microscopy (SEM).

The experimentally determined leaching rate (e.g., $\mu\text{mole cm}^{-2} \text{min}^{-1}$) of a selected element i was calculated as:

$$R_i = \frac{\bar{C}_{i,eff} \times \bar{Q}}{A} \quad (1)$$

where $\bar{C}_{i,eff}$ is the mean concentration value of the last four successive samples collected after steady state is reached (e.g., $\mu\text{mole L}^{-1}$), \bar{Q} is the average value of the last four measurements of the flow rates (e.g., L min^{-1}), and A is total surface area of fixated FGD material after leaching

(e.g., cm²). The error in the calculated rates were estimated by the Gaussian error propagation method (Barrante, 1974; Cama et al., 2000):

$$\Delta R_i = \sqrt{\left(\frac{C_i}{A}\right)^2 \times \Delta q^2 + \left(\frac{q \times C_i}{A^2}\right)^2 \times \Delta A^2 + \left(\frac{q}{A}\right)^2 \times \Delta C_i} \quad (2)$$

where Δ represents uncertainty of each parameters with a 95% confidence interval.

2.5.3.2 Data Interpretation

The equation to describe the mass transfer in the vicinity of a rotating disk can be obtained by solving the convective-diffusion equation with corrected Schmidt number (Gregory and Riddiford, 1956; Levich, 1962; Newman, 1966). The mass flux of reactant, which is the proton in this study, from the bulk solution to the disk surface, J (e.g., mole dm⁻² sec⁻¹), is given by:

$$J = \frac{0.62048 Sc^{-2/3} \sqrt{\nu \omega}}{1 + 0.2980 Sc^{-1/3} + 0.1451 Sc^{-2/3}} ([H^+]_{Bulk} - [H^+]_{Surface}) \quad (3)$$

where k_d is transport rate constant (e.g., dm sec⁻¹); Sc is the Schmidt number (e.g., ν/D); ν is kinematic viscosity (e.g., dm² sec⁻¹); D is diffusion coefficient (e.g., dm² sec⁻¹); $[H^+]_{Bulk}$ is the concentration of proton in the bulk solution (e.g., mole L⁻¹); and ω is angular velocity (e.g., rad sec⁻¹).

If the leaching process is limited by rate of mass transport, all proton molecules approaching the surface react spontaneously; therefore, $[H^+]_{Surface}$ can be assumed to be zero. At steady state, the leaching rate is equal to the transport rate of proton. $R_{i,H}$ then is rewritten as:

$$R_{i,H} = k'_{i,H} = \frac{0.62048Sc^{-2/3} \sqrt{\nu\omega}}{1 + 0.2980Sc^{-1/3} + 0.1451Sc^{-2/3}} [H^+]_{Bulk} \quad (4)$$

Equation 4 indicates the magnitude of $R_{i,H}$ is proportional to the square root of the angular velocity at a fixed $[H^+]_{bulk}$ value.

If the leaching process is limited by the kinetics of the surface reaction, $R_{i,H}$ is independent of the mass flux of proton and therefore independent of the rotating speed. In such case, the concentration of proton in the entire solution can be assumed to be constant (Levich, 1962; Morgan and Stumm, 1990) and the rate of the leaching process is determined by:

$$R_{i,H} = k'_{i,H} [H^+]_{bulk}^n \quad (5)$$

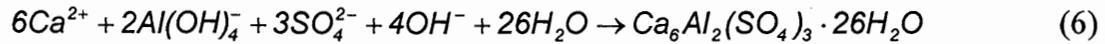
If the rate of leaching is controlled by both mass transport and reaction kinetics, the boundary condition is more complicated and is discussed by Levich, 1962.

2.5.3.3 Results and Discussion

2.5.3.3.1 Change of Morphology And Mineral Phases After Leaching

Figure 2.9 shows the XRD diffraction patterns and SEM micrographs of the constituents of fixated FGD material; i.e., lime (Figure 2.9a), filter cake (Figure 2.9b), and fly ash (Figure 2.9c), and the fixated FGD material samples before (Figure 2.9d) and after (Figure 2.9e) the leaching process had been conducted. Lime (CaO) and portlandite (Ca(OH)₂) are the main mineral phases found in the additional lime. The mineral composition of filter cake is dominated by flask shape

hannebachite ($\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$). The mineral phases of fly ash are more complicated. Alluminosilicates (i.e., mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$) and sillimanite (Al_2SiO_5)), iron oxides (i.e., magnetite (Fe_3O_4), hematite (Fe_2O_3)), and quartz (SiO_2) are the observed crystalline minerals. The non-flat baseline in Figure 2.9c(II) indicates amorphous glass also presented. Except lime and portlandite, the fixated FGD material is composed of the minerals observed in those constituents. Besides, a secondary mineral, ettringite ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$), was also found. The presence of needle-shape ettringite might be result from the following hydration reaction (McCarthy and Solem-Tishmack, 1994):



which explains the formation of net structure between the flask hannebachite and spherical fly ash particle (Figure 2.9d(I)). After leaching, the absence of net and flask structures (Figure 2.9e (I)) agrees with the XRD diffraction pattern (Figure 2.9e(II)), in which the mineral phases are identical to what were observed in fly ash (Figure 2.9c(II)).

2.5.3.3.2 Leaching Profile

Figure 2.10 presents the mass flux profiles of (1) selected elements over the leaching process under the leaching condition of pH 2.2 and angular velocity of 60 rpm (Figure 2.10a); (2) Ca under various acidic leaching conditions with rotating speed of 60 rpm (Figure 2.10b); and (3) Ca under three rotating speeds with pH of 2.2 (Figure 2.10c). The mass fluxes of elements was calculated by:

$$q = C_{i,eff} \times Q \quad (7)$$

where $C_{i,eff}$ is effluent concentration of element i (e.g., $\mu\text{mole L}^{-1}$), Q is flow rate of leachant solution flow through the reactor (e.g., L min^{-1}). As can be seen in Figure 2.10a, b, and c, the mass fluxes of different elements and different leaching conditions exhibit the same pattern: a rapid release at the early stage of the leaching process followed by an exponential decrease.

The observed transients are possibly the results of the following mechanisms. (1) The existence of ultra-fine particles created naturally or from the surfacing procedure when the samples were prepared (Samson and Eggleston, 1998). (2) A higher initial density of active sites (Wehril, 1989) shows the mole fractions of more active sites; such as adatom, ledge, and kink sites, are higher on the initial surface than on the steady-state surface. (3) The presence, and subsequent depletion, of more soluble mineral phases. The relatively constant stoichiometric ratios of Ca to S over a wide range of leaching conditions (Figure 2.11a) indicate the release of Ca and S is controlled by certain mineral phases over leaching processes. Therefore, the third mechanism is unlikely the cause of the transient phenomena for Ca and S. However, the slow increase of Al to Si ratio (Figure 2.11b) indicates either the mineral phases controlling the leaching at the early stage were different from the steady state or there was an initial stage of incongruent dissolution.

2.5.3.3 Controlling Mechanisms of Leaching Kinetics

Figure 2.12 shows the leaching rates of Ca, S, Al, Si, Fe, and Mg at pH of 2.2 as a function of the square root of the disk rotating speed, $\omega^{1/2}$. In this figure, dissolution rates were normalized by the dissolution rate observed at the angular velocity of 6 rpm, the lowest speeds utilized in these experiments. The solid reference line shows relationship of the rate and $\omega^{1/2}$ when dissolution is

purely transport-controlled. As can be seen in Figure 2.12, the increase of rotating speeds did not increase the leaching rate of all selected elements in the leaching condition of pH of 2.2.

This observation indicates that a change of hydrodynamics of the system has no effect on the leaching kinetics of fixated FGD material for all selected elements, and hence a surface reaction mechanism controls the leaching kinetics.

2.5.3.3.4 Effect of Protons on Leaching Kinetics

For a surface-controlled leaching kinetics, Eq.5 can be used to express the pH effect on the leaching kinetics. In Figure 2.13, the leaching rates of selected elements are plotted as a function of pH.

The leaching rates of selected elements were constant at pH 6.8 and 5 indicating the overall leaching kinetics was controlled by intrinsic hydration mechanism at near neutral pH conditions.

When pH was below 3.7 (5.0 for Mg and Fe), leaching rates started increasing indicating the proton-promoted leaching process was dominating. Therefore, the overall leaching rate law of each element can be determined by attempting the linear regression at the ascending part of the logarithmic plot. The overall leaching rate ($\mu\text{mole cm}^{-2} \text{min}^{-1}$) can be written as:

$$R_i = R_{i,H_2O} + k'_{i,H} a_H^n \quad (8)$$

where $k'_{i,H}$ is the rate constant ($\mu\text{mole cm}^{-2} \text{min}^{-1}$) and a_H is proton activity (dimensionless).

Regression results were summarized in Table 2.9. It is found that the reaction orders are very close to 0.5 and 0.75 for divalent ions; such as Ca, S, and Mg, and trivalent ions; i.e., Al and Fe, respectively. The mathematical model indicates the leaching rates of divalent and trivalent cations increase 3.2 and 5.2 times, respectively, when pH decreases 1 unit.

2.5.3.4 Conclusions

The leaching process of stabilized FGD material conducted in a flow-through-rotating disk shows an independent relationship of leaching kinetics on hydrodynamic condition suggesting the leaching process is controlled by surface reaction.

Therefore, the leaching rate, R_i , of a selected element can be written as:

$$R_i = R_{i,H_2O} + k'_{i,H} a_H^n \quad (9)$$

The regression result obtained from the plot of $\log R_i$ as a function of pH establishes a complete mathematic model describing the effect of pH on the release of the selected elements. The model suggests the leaching rates of divalent and trivalent cations increase 3.2 and 5.2 times, respectively, when pH decreases by 1 unit.

Table 2.9 Numerical results of pH effect on selected elements

pH of solution	- log a _{H⁺}	Leaching Rate ($\mu\text{mole cm}^{-2} \text{min}^{-1}$)					
		Ca ²⁺	S ²⁻	Al ³⁺	Si ²⁺	Mg ³⁺	Fe ³⁺
2.2	2.24	13±2	9±1	1.3±0.2	1.0±0.1	0.45±0.06	0.26±0.04
2.9	2.94	6±1	3.8±0.8	0.38±0.06	0.47±0.09	0.18±0.03	0.08±0.02
3.7	3.74	2.4±0.4	1.3±0.2	0.10±0.02	0.22±0.05	0.06±0.03	0.015±0.004
5.0	5.04	1.7±0.2	0.7±0.2	0.10±0.02	0.2±0.1	0.013±0.006	0.002±0.002
6.8 ¹	6.84	1.4±0.2	0.8±0.1	0.09±0.01	0.13±0.02	0.010±0.002	0.0016±0.0005
		1.1±0.1	0.60±0.07	0.08±0.01	0.12±0.02	0.007±0.0008	0.0014±0.0005
$R_{\text{H}_2\text{O}}$ ($\mu\text{mole cm}^{-2} \text{min}^{-1}$)		1.4±0.3	0.7±0.2	0.9±0.3	0.2±0.1	0.01±0.007	0.0015±0.0006
k^{H} ($\mu\text{mole cm}^{-2} \text{min}^{-1}$)		166.3	155.3	55.8	9.6	7.7	13.1
n		0.50	0.55	0.73	0.44	0.56	0.76
r ²		0.9997	0.9992	0.9997	0.998	0.998	0.994

1 Duplicate data is shown

2 Regression ranges from pH 3.7 to 2.2

3 Regression ranges from pH 5.0 to 2.2

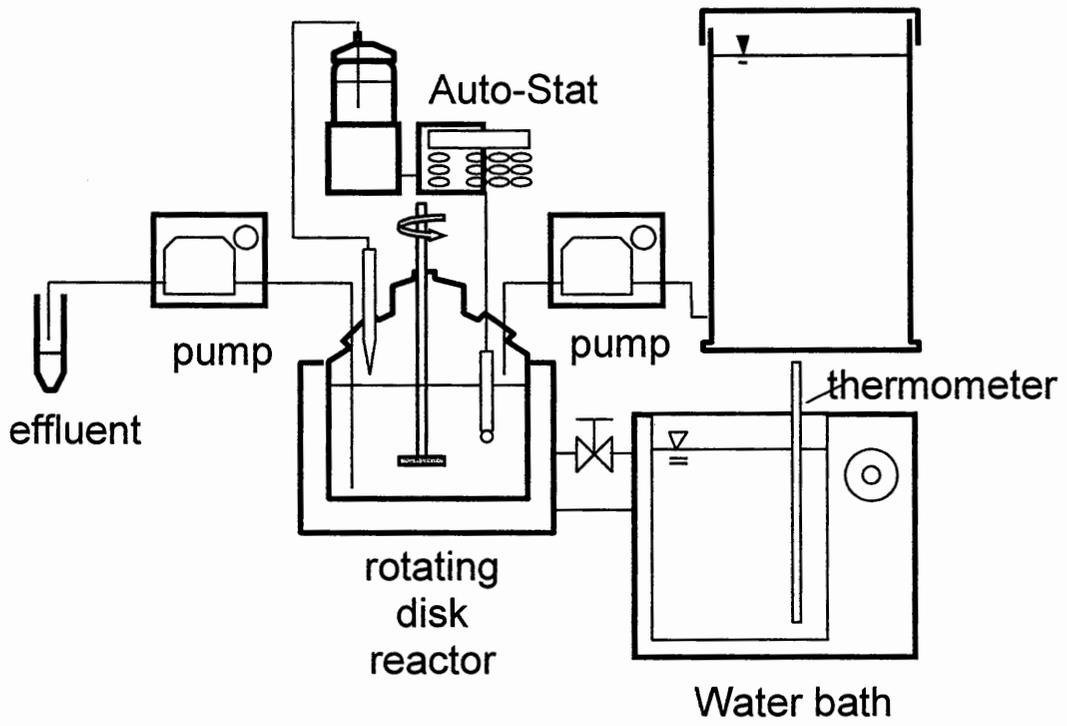


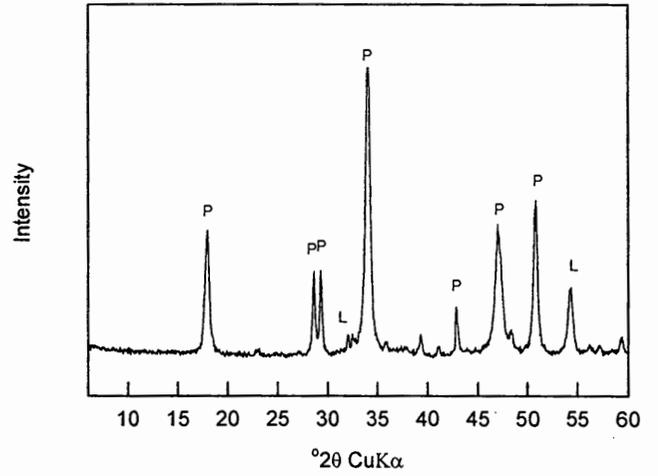
Figure 2.8 Schematic diagram of the apparatus

a (I)



3 μ m

a (II)

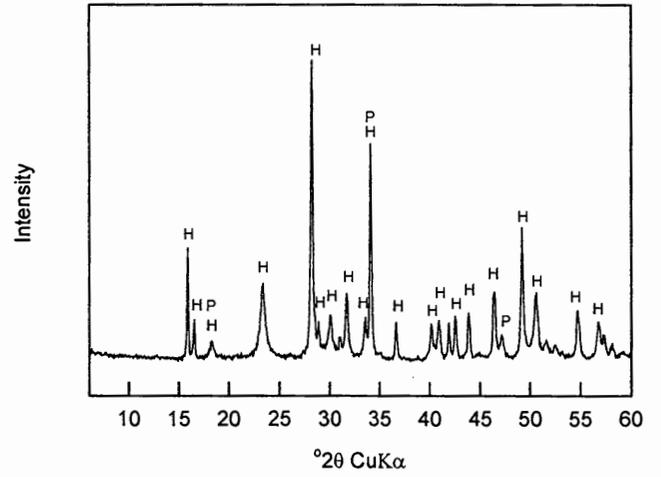


b (I)

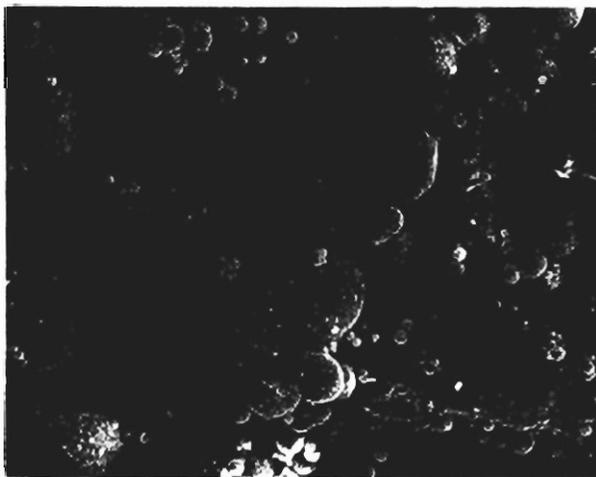


4 μ m

b (II)

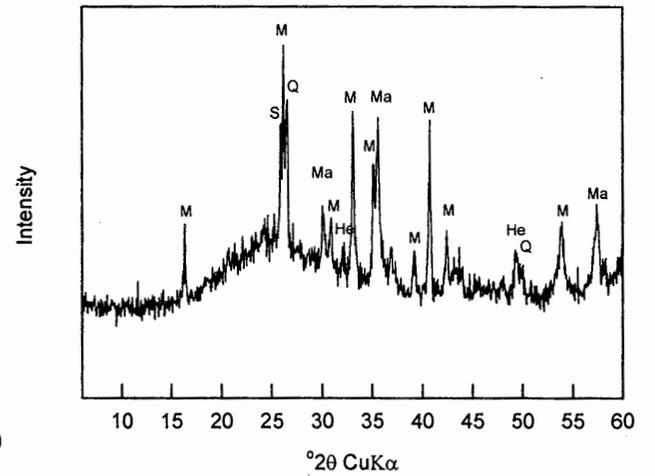


c (I)

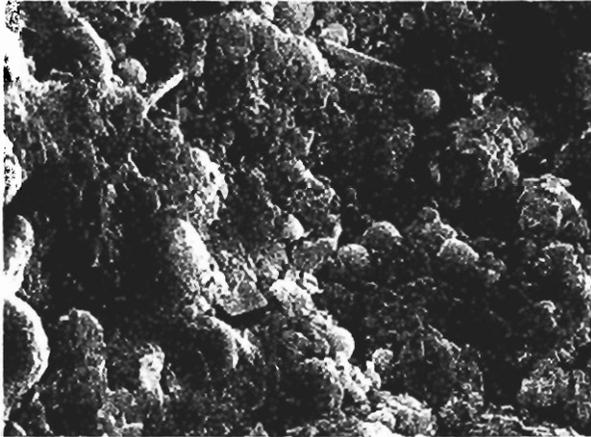


30 μ m

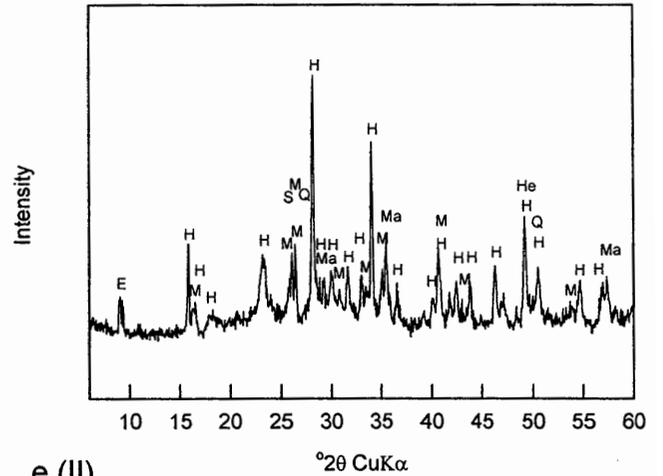
c (II)



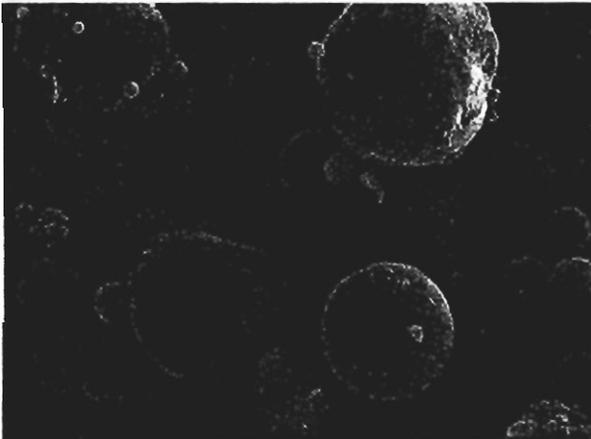
d (I)



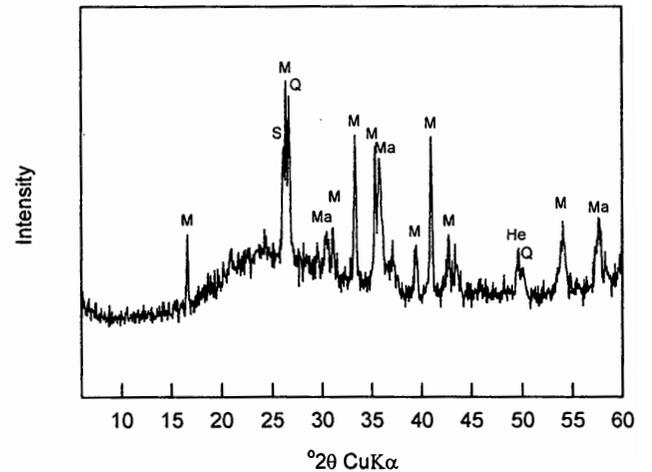
d (II)



e (I)



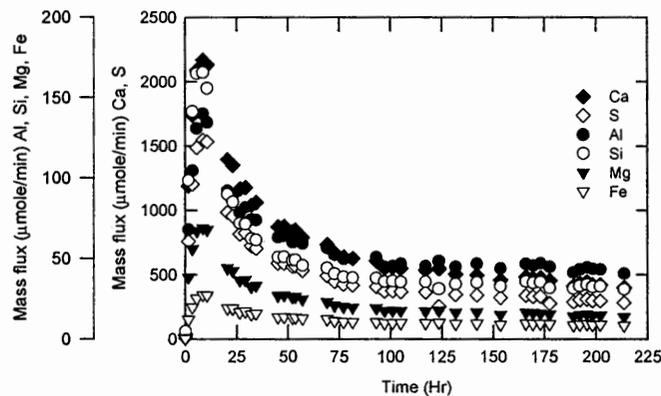
e (II)



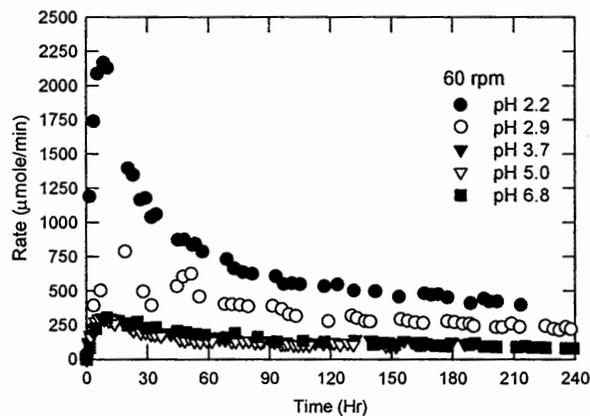
P=portlandite; L=lime; M=mullite; S=sillimanite; Q=quartz; He=hematite; Ma= magnetite; H=Hannebachite; E=ettringite.

Figure 2.9 SEM micrographs(I) and (II) X-ray diffraction patterns of (a) lime, (b) filter cake, (c) fly ash, (d) 28days-cured fixated FGD material before leaching, and (e) 28days-cured fixated FGD material after 240 hours leaching.

(a)



(b)



(c)

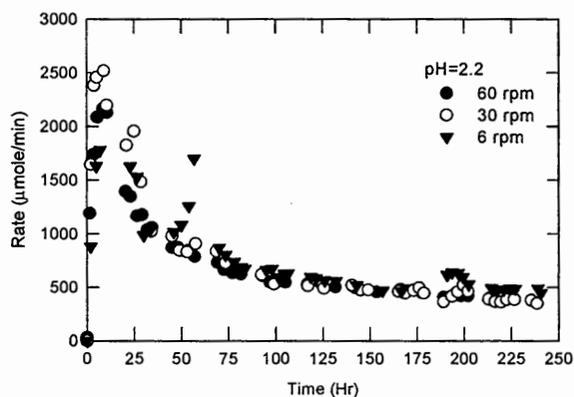
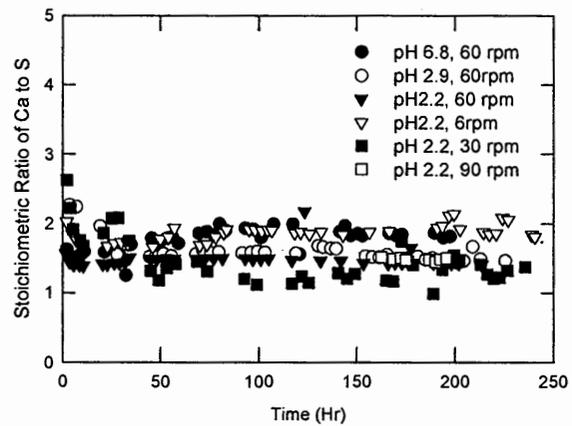


Figure 2.10 Mass flux profiles of (a) selected elements over the leaching process under the leaching condition of pH 2.2 and angular velocity of 60 rpm; (b) Ca under various acidic leaching conditions with angular velocity of 60 rpm; and (c) Ca under various angular velocity of 60 rpm with acidic leaching condition of pH 2.2

(a)



(b)

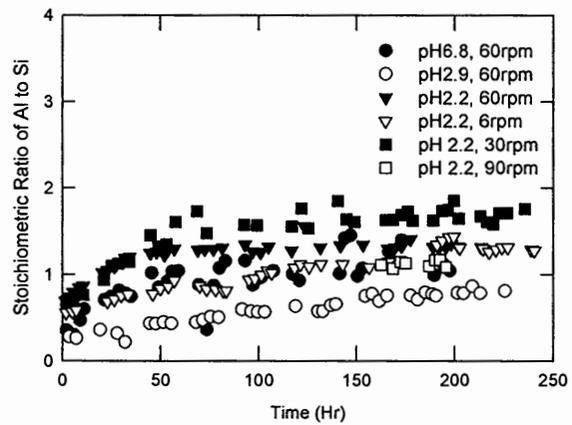


Figure 2.11 Stoichiometric ratio profiles of (a) Ca to S and (b) Al to Si during various leaching processes.

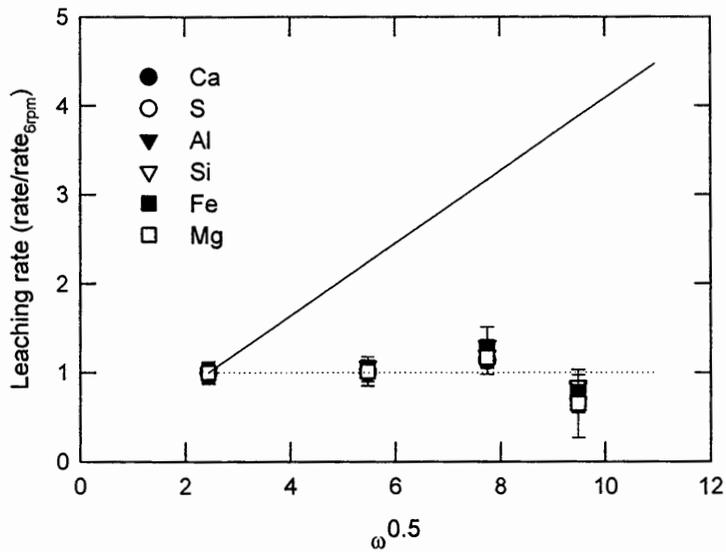


Figure 2.12 Leaching rates as a function of rotating speed under leaching condition of pH2.2.

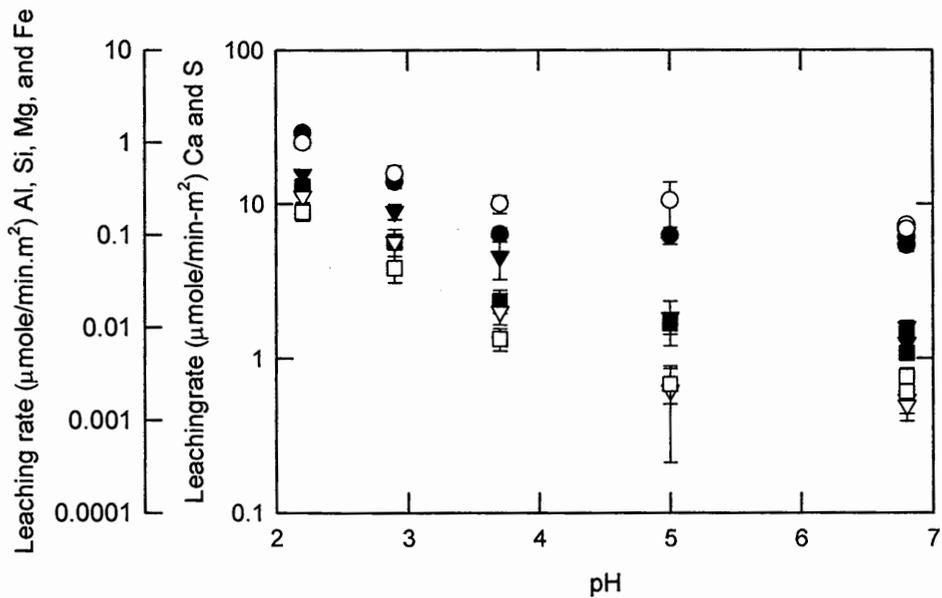


Figure 2.13 Leaching rates as a function of proton activity

2.6 Implication of Leaching Tests for Stabilized FGD Pond Liners

Table 2.10 lists the leaching concentrations of selected elements from the standard TCLP test and the maximum concentrations observed in the sump leachates from the water quality monitoring of the facility (refer to Chapter 4 for complete data set). By comparing the two sets of concentrations, we found the leaching potentials of As, Cd, Cr, and Se, obtained from the standard TCLP test do not represent the maximum limits for the concentrations observed in the sump leachates. In fact, most of the TCLP results were lower than the observed maximum concentrations at the facility. The observation suggests the standard TCLP test may underestimate the leaching potentials of some elements under the field condition at the site. Results obtained from modified TCLP tests suggest a higher leaching potential of stabilized FGD material could be established by using oxalic and citric acids as the leaching solutions when evaluating the environmental impact. However, these leaching solutions overestimated the extent of leaching for a number of elements. Modified TCLP leaching tests with pond water appeared to provide the closest representation of leaching in the field as seen in Table 2.11. However, leaching tests carried out with pond water significantly under predicted the concentrations of Al, Fe, Mg, Mn, Ni, and V. It should be noted that these conclusions regarding the TCLP test may not be applicable to other systems, such as FGD material landfills.

Both batch leaching studies and field data demonstrated that the extent of leaching is time dependent. As concluded earlier, the standard TCLP test may not produce maximum concentrations at 18 hours for the stabilized FGD material. As can be seen in Figure 2.6, where the leaching profiles of selected elements in the standard TCLP test were shown, the

concentrations levels kept changing over first 18 hours. The attenuation of dissolved elements might be due to other chemical phenomena; e.g., adsorption, complexation, or/and formation of secondary mineral phases. Similar mechanisms might explain the concentration profiles in the sump leachates observed over time at the field site. Many of the maximum concentrations in the sump leachates occurred right after filling the facility with water; e.g., As, Al, Cr, Ba, dissolved and total Fe, Cu, dissolved and total Mn, K, and Mg. The leaching kinetic study found (Figure 2.10) that high leaching rates can be observed during the initial stages of the leaching process. The kinetic study implied (1) the existence of ultra-fine particles created naturally (Samson and Eggleston, 1998), (2) a higher initial density of active sites (Wehril, 1989), and (3) the presence, and subsequent depletion, of more soluble mineral phases. These mechanisms may also influence the time dependent leaching in the field.

Table 2.11 displays the comparison of results obtained from the modified TCLP test carried out with pond water and water quality monitoring conducted at the facility on 2/14/2004. It can be seen that the leaching results varied somewhat compared to the observed concentration levels in the sump. However, the leaching results suggest the stabilized FGD material is not a source for many elements. In fact, the lag of the concentration profiles in the sump (when compared to the profile of the pond) suggest the stabilized FGD liner could be a sink for As (Figure 4.9), V (Figure 4.18), Mn (Figure 4.22), B (Figure 4.24), Mg (Figure 4.26), and Ni (Figure 4.30).

The surface-controlled mechanism determined by the leaching kinetic study suggests the hydrodynamic conditions in the field (e.g., flow rate through the liner) should not greatly affect the leaching rate of elements from the full-scale stabilized FGD material pond liner.

Table 2.10 Comparison of leaching concentrations from TCLP test and the observed maximum concentrations in sump leachates

	Standard TCLP test	Maximum concentration in sump leachates
Aluminum	5.1±0.6	5.505
Arsenic	0.006±0.002	0.145
Barium	0.16±0.07	0.100
Cadmium	0.0007±0.0002	0.004
Chromium	0.003±0.001	0.087
Copper ¹	0.014±0.009	0.018
Iron	0.018±0.008	0.120
Lead ¹	<0.02	<0.020
Manganese ¹	<0.01	0.114
Nickel	0.005±0.005	0.012
Selenium	0.009±0.003	0.187
Sodium	10.5±1.2	317.55
Sulfate	70±20	485.532
Vanadium	0.028±0.004	0.035
Zinc	0.027±0.003	0.531

Units: µg/mL

¹ data obtained from the acetic acid batch in modified TCLP test

Table 2.11 Comparison of results from pond water leaching and water quality monitoring

	Modified TCLP with 2/14/2002 pond water	Water quality on 2/14/2002	
		Sump	Pond
Aluminum	74	321	216
Arsenic	<10	101	ND
Boron	1076	2349	2115
Barium	<30	73	14
Calcium	158800	115130	164900
Cadmium	<10	<2	<2
Chromium	<1	<5	10
Copper	15.3	<10	11
Iron	50	2300	3000
Magnesium	8768	6838	69000
Manganese	3.2	5	100
Nickel	2.8	11	13
Selenium	<20	<100	<100
Vanadium	5.4	15	32
Zinc	3.1	38	38

Unit: µg/L

3 MEDIUM-SCALE WETLAND EXPERIMENTS

3.1 Introduction

Engineered wetlands have provided natural alternatives for wastewater treatment, storm water storage, and flood diversion (Mitsch and Gosselink, 2000; Mitsch and Jorgensen, 2004). A new market is evolving around the use of natural landscapes as beneficial and cost effective treatment alternatives. Recent advances in wastewater treatment follow this trend to avoid more typical chemical and energy intensive methods. Research attempting to characterize and quantify the range of nutrient and pathogen removal has resulted in a highly variable range of efficiencies (Werker et al, 2002). A perceived niche for small-scale decentralized wastewater treatment wetlands encourages the development of more predictable and sustainable solutions to water quality management.

Researchers at the Olentangy River Wetland Research Park (ORWRP) have experimented with the use of clean coal technology by-products as liners to prevent groundwater contamination and retain water in the wetland basins. Early studies at the ORWRP using small (1 m²) mesocosm tubs showed that while there was some minor effect of coal combustion product liners on plant growth, phosphorus retention in the mesocosms lined with the material were effective in removing phosphorus from flow-through river water (Wolfe et al., 2000; Ahn et al., 2001; Ahn and Mitsch, 2002a; Ahn and Mitsch, 2002b). Stabilized flue gas desulfurization (FGD) material is a solid form of sulfur oxides precipitated by lime scrubbing techniques in coal-fired electric

plants and mixed with fly ash and lime. Principally composed of sulfites, un-reacted lime, fly ash, and water, the FGD material should fit well in the role of reducing phosphates in municipal or agricultural wastewater because of the high concentrations of calcium carbonate and lime, both of which have an affinity for phosphorus.

Laboratory experiments have shown a range of permeability characteristics for stabilized FGD materials (Butalia and Wolfe, 1999). These findings encouraged field studies using compacted FGD material as liners for treatment wetlands at the mesocosm (1m^2) scale (Wolfe et al., 2000; Ahn et al., 2001). Results from our mesocosm experiments found greater removal of total phosphorus and soluble reactive phosphorus in mesocosms lined with FGD material than unlined mesocosms.

Our current research used FGD liner material to construct treatment wetlands at a pilot medium-scale (12 m^2) scale over three growing seasons (2001-2003). Basins lined with FGD material were compared to similar basins lined with clay to test the hydrologic and ecological efficacy of FGD-liners in constructed wetlands. Objectives to meet that goal included: investigating the effect of FGD liner on water quality, plants and soil chemistry, and examining the hydrologic efficacy of FGD liners compared to clay liners in treatment wetlands. If techniques such as using FGD material for wetland liners can be perfected, then significant expenses could be saved in creating wetlands for cleaning up wastewater.

3.2 Methods

3.2.1 Basin Construction

The pilot-scale experiments were carried out in four created 12-m² wetland basins in the northwest corner of the Olentangy River Wetland Research Park in Columbus, Ohio, USA (Figures 3.1, 3.2, and 3.3). Construction on the wetlands (Figures 3.4 to 3.11) began on August 30, 2000 after permits were obtained from Ohio EPA to allow minor on-site discharge of water from the wetland basins. Four basins were excavated and lined with HDPE plastic liner material. The HDPE plastic liner (Figure 3.6) served as an impervious liner between the wetland and the underlying soil and water table and captured and contained any water that leached through the experimental liners. One foot of pre-washed river gravel was placed in a trench at the bottom of each basin and covered with Geonet fabric to form a leachate collection system. Two separate extensions of PVC pipe were inserted at opposite ends of gravel-filled trenches and extended up above the ground surface. These collection wells were used to access samples of leachate from the underlying gravel trenches. Stabilized FGD material, received from the Conesville power plant of America Electric Power, was compacted in a six-inch layer above the Geonet fabric in the two FGD-lined basins (Figure 3.7), and local clay soil was compacted in a six inch layer similarly in the two clay-lined basins. The Geonet layer kept the respective liner materials from mixing into the interstitial spaces of the gravel filled layer. Compaction in both clay and FGD basins was done with a vibratory compactor (Figure 3.8). The compactor was used in the FGD material only until it began sinking into the material. Compaction in the FGD basins was completed by using the bucket from a back hoe stabilized on the edge of the basins. Both FGD

and clay-lined basins were then filled with two feet of local topsoil suitable for wetland vegetation growth.

The initial elemental composition of the liner materials and topsoil is shown in Table 3.1. The FGD material is notably more alkaline than the clay because it is treated with lime as a part of the stabilization process. The FGD material is relatively high in concentrations of S as well as Ca from the unreacted lime. Higher concentrations of metals Mg, Ca, and metalloids Al and B were detected in the FGD material than in the clay liner material.

Flow systems were installed in April 2001 (Fig. 3.2 and 3.9). A Teel® 4RJ42 pump drew water from the Olentangy River inflow pipes that fed the two experimental wetlands nearby. The water was fed to four 500-gallon plastic tanks (Fig. 3.2). A network of poly vinyl chloride (PVC) piping gravity fed water from each drum to its respective basin. A 2-inch ball valve at the head of each pipe allowed control of inflow rates by loosening or tightening. T-branch end pieces were fitted to the opening of each inflow pipe to reduce erosion on basin topsoil. Standpipes controlled the outflow of each basin allowing waters above 13 cm to drain out through an underground pipe into a landscape trench. The outflow trenches lie below the elevation of the basins. Staff gages were installed in each basin to display basin water level.

Two species of bulrush were planted in the topsoil of each basin in July 2001. Twenty root bundles of *Scirpus americanus* were planted in the outflow half of each basin, and twenty root bundles of *Schoenoplectus tabernaemontani* were planted in the inflow half of each basin. Both rhizomatous perennials are common in shallow marshes, and fluoresce June through September.

The relatively shallow growth pattern of the rhizomes and roots of these wetland plants should minimize the possibility of roots penetrating 2 feet to the liner material.

Initial design conditions were to add water at a hydraulic loading rate (HLR) of 5.5 cm/day during each growing season. This is a typical rate for surface flow treatment wetlands and was designed to result in a water retention rate in the basins of 3 days.

3.2.2 Data Collection and Analysis

3.2.2.1 Hydrology

River water was first introduced to the four basins on April 23, 2001. Inflow valves were initially manipulated to achieve a hydrologic loading rate (HLR) in a range of 10-15 cm/week. On alternating days, river water was pumped into each of the four 500-gallon drums at the head of each hydrologic flow system. Each basin flooded freely up to the height of the standpipe outflow (12.8 cm). When water was deeper than 12.8 cm it discharged out of the standpipe to a low-lying ditch, and eventually returned to groundwater. The 500-gallon inflow from the hydrologic flow system took about 8.5 hours to flow into the wetland. By the first week of the study FGD-lined basins showed a shorter retention time of standing water than the clay-lined basins.

Water levels were recorded weekly in each basin, both prior to loading and after loading of water. Water was added to the basins from filled water tanks, first on a weekly basis and, after it

was determined that standing water did not persist, on a more frequent basis. The overall number of water pulses added to the basins for each of the 3 years of study are shown in Table 3.2.

Leachate accumulated in the collection system and was purged on alternate months in 2001. The following two years (2002-2003) leachate was purged on alternate weeks as more leachate had accumulated than expected.

The pump system was dismantled during the freezing months of November 2002 - March 2003, and reassembled in early spring for each year of the study. On June 3, 2003 the outflow piping for basins 2 (clay-lined) and 3 (FGD-lined) were examined for leaks and the standpipes in both basins were refitted with adhesive. On June 7, 2002 and July 1, 2003 rodent holes on the perimeter of the basins were filled with local topsoil and manually compacted.

3.2.2.2 Water Quality

On-site water quality data were collected at the inflow, where waters from each of the four drums entered the respective basins, and outflow where waters exit the standpipe. A handheld YSI 600XL water quality monitor manually inserted into the overlaying waters of each basin for 1 minute to measure the following parameters: temperature, conductivity, dissolved oxygen, redox potential, and pH. During 2002 and 2003, a portion of the detector on the YSI malfunctioned, and reliable redox data were not recorded. One 500-mL sample of surface water

was collected at the inflow and outflow of each basin weekly from August 2001 to September 2003. No samples were taken in winter and surface plumbing was drained then to avoid ice damage. In 2003 sampling holes were drilled into the PVC pipes leading to the inflows of each basin and surface water samples were then collected just prior to exiting the pipe at the inflow of each basin. This minor change in inflow sampling was done to make it easier to minimize backwater effects on inflow sampling. The method for collecting water at the outflow remained the same throughout the study. Water was sampled just as it was leaving through the outlet structure in each basin.

Surface water samples were refrigerated or frozen until analysis. Two categories of sub-samples were prepared from the field-collected samples: inorganic and organic. Organic samples were preserved by adding 0.5 ml of H₂SO₄ to 100 ml of sample and frozen for no more than 10 days. Thawed samples were examined for Total Phosphorus concentration by spectrophotometric analysis using a Lachat 8000 series FIA⁺ after appropriate digestion. Inorganic samples were filtered through 0.5 um cellulose filters, and digested in a Lachat block digester BD-46 according to the Quik Chem® method (Lachat Instruments, 2000). Cooled samples were examined for SRP concentration using a Lachat spectrophotometer.

3.2.2.3 Wastewater Pulsing Experiment

High-phosphorus wastewater was simulated by adding phosphorus fertilizer to the inflow river water in the 2003 growing season. This was done because previous studies at the Olentangy River Wetland Research Park and supported by the Ohio Coal Development Office (Ahn et al.

2001; Ahn and Mitsch, 2002) suggested that small wetland mesocosms lined with FGD material has significantly higher phosphorus retention. Hi-yield® triple super Phosphate containing 0-45-0 Phosphorus Oxide (P_2O_5) was added to river water in the headwater drums to achieve two treatment regimes: (1) very high phosphorus inflow concentration of 120 mg-P/L, and (2) high concentration of 40 mg-P/L. Very high phosphorus concentration water was added to all four basins weekly between June 14, 2003 and August 1, 2003. Plain river water was added August 11, 2003, and high concentrations resulted for the period August 1 through September 11, 2003.

3.2.2.4 Vegetation

Number of stems for both of the planted species was recorded twice a month throughout the duration of the study. Stem length was measured for 40 random individuals of both planted species. Numbers of flowers were recorded from 20 subsamples to make inferences about plant maturation and species fecundity. In each basin, four 1 m² areas were harvested August 16, 2001, September 15, 2002, and September 15, 2003. Harvested plants were separated according to species, and weighed in bundles. A sub-sample of each bundle was dried at 60°C in a forced air oven for no more than two days, weighed, and ground to pass a 2 mm sieve. Ground plant tissue was analyzed for all major elements using spectrophotometric analysis by ICP at the STAR lab in Wooster. Several plant species not introduced during the study became established in the basins, particularly in the third growing season.. These colonizing plants were identified and included in total biomass harvesting. Flowering bodies were removed from the highly aggressive *Typha* sp. to suppress the spread to adjacent sites.

3.2.2.5 Soil

Local topsoil was sampled prior to completion of the basins in 2001. Local clay, used to line the control basins, and FGD material used to line the treatment basins were also sampled and analyzed. After the first and second full growing season (2002 and 2003), soil cores were collected at four points throughout each basin. Soil samples were air dried near 30°C, and ground to pass a 2 mm sieve. Complete element analysis by ICP spectrophotometer was conducted after microwave 3051 digestions, and according to the EPA standard method.

3.2.2.6 Leachate Water

At the onset of the study, water was not expected to leach through either liner materials. The leachate collection system was more of a precautionary device, and allowed leachate to be sampled prior to passing into groundwater. During the study, the leachate collection systems were estimated to have held up to 2000 liters per 7 days of basin inundation. The frequency of purging the leachate collection system was increased accordingly to remove water regularly and collect fresh sample of leachate. An Isco 150 portable pump was used to draw 500 ml water samples from each leachate well monthly in 2001, and biweekly in 2003. Leachate storage systems were completely purged after sampling. Water quality parameters were determined in the field with the YSI water quality monitor. Leachate samples were separated, treated and analyzed similarly to the surface water samples using the Lachat Quik Chem® method and ICP systems.

3.3 Observations and Results

3.3.1 Hydrology

The average HLRs (hydraulic loading rates) for the wetlands basins for each of the 3 years are illustrated in Table 3.2. During the last 2 years, a hydraulic loading rate of 6.8 cm/day was maintained, about 24% higher than proposed flow conditions. Water was added as 3 to 4 “pulses” per week rather than a continuous flow (Table 3.2), as flow as low as 0.1 gal/min were difficult to sustain. In addition, more water was added than originally designed to keep surface water in the more rapidly leaking FGD-lined basins. Water levels in the FGD-lined basins were consistently lower than clay-lined basins in 2001, and were statistically lower in 2002 and 2003 (Figure 3.12). This trend is because the permeability of the FGD-liner was higher than the permeability of the clay-liner.

A field infiltration study was conducted in the four wetland basins in July 2003 to verify the different hydrology in the FGD basins. The study showed that while the water level dropped at $4-6 \times 10^{-6}$ cm/sec in the clay-lined basins, it dropped 100 times faster (10^{-4} cm/sec) in the FGD lined basins (Figure 3.13). This validated the interpretation of the water level results described above. High permeability of the FGD liner prevented sufficient ponding in the FGD basins. Thus, effects that could be interpreted as being caused by the FGD liner could, in fact, be due to the consistently less water in the FGD-lined basins.

3.3.2 Surface Water Quality

Typical fluctuations in surface water quality were observed in the basins from inflow to outflow water in both treatments (Table 3.3). There were no significant differences in surface water outflows for clay-lined and FGD-lined basins in any of the 3 years for temperature dissolved oxygen, conductivity, pH, redox potential, and turbidity. Temperature increased across a spatial gradient, and pH ranged between neutral to slightly alkaline. Some fluctuations in turbidity may be due to sampling at low water levels that caused artificial turbidity in the samples. Conductivity was generally higher in water collected at the outflow of FGD-lined basins than clay-lined basins but the differences were not statistically significant ($\alpha = 0.05$). All of the reported dissolved oxygen levels in surface water surpass the current EPA water quality criteria of 5 mg O₂/L (US EPA, 1986).

3.3.3 Leachate Water Quality

Leachate water from the FGD-lined basins showed significantly higher conductivity than did leachate water from the clay-lined basins for all three years of the study (Table 3.3). Leachate water from FGD-lined basins was also consistently more alkaline than leachate in the clay-lined basins, but both systems were less in the last year of the study. pH was 7.7 to 8.1 in the clay-lined leachate in 2001-02 and lower at 6.6 in the third year. In contrast, pH averaged 9.4 to 9.8 in the FGD-lined basins in 2001-02 and 8.7 in the third year. The differences between clay and FGD remained 2.1 pH units from the first to third years, but the pH itself dropped 1.2 pH units over that time. In the third year of the experiment, leachate was significantly cooler below the

FGD-lined wetlands than below the clay-lined basins. This is probably due to the fact that water was retained longer in the clay basins and had more opportunity to be heated by sunlight and atmosphere.

Elemental analysis of leachate water shows significantly higher concentrations of K, Na, and Mo in the first year in leachate water from FGD-lined basins than clay-lined basins (Table 3.4). In the second year of sampling, K and Na continued to be higher in the leachate of the FGD basins but were joined by significantly higher concentrations of Ca, S, and B. The higher Ca, Na, and K are consistent with the significantly higher conductivity seen in the leachate (Table 3.3). The higher concentration of B in the leachate is worrisome and reflects a negative effect of the higher permeability of the FGD material in this experiment.

3.3.4 Nutrient Retention in Simulated Wastewater Treatment

There were no significant differences between the clay-lined and FGD-lined basins on retaining phosphorus when very high concentrations of phosphorus were added to all basins in the 2003 experiment (Table 3.5). We had hypothesized that there would be an effect based on the results of experiments with small (1 m²) mesocosms (Ahn et al., 2001; Ahn and Mitsch, 2001, 2002a). The phosphorus concentrations in the outflows of the FGD basins during the phosphorus additions were (average \pm std err.) 49 \pm 11 mg-P/L (n=24), and the outflow of the clay-lined basins were 41 \pm 10 mg-P/L (n=26). These outflow concentrations were only slightly lower than the average inflow concentrations of 54 \pm 12 mg-P/L (Table 3.5). Apparently the pulsed water did

not spend much time in the wetland basins but discharged quickly to the outflow (or to the leachate collection system with the FGD basins) without much biogeochemical activity. This was another disadvantage of the pulse-flow system we found it necessary to implement compared to a more desirable continuous-flow system. The only significant difference seen in nutrient retention was before the increased concentrations of phosphorus were added. During that period, the clay-lined wetlands discharged significantly lower concentrations of soluble reactive phosphorus (SRP), 0.10 mg-P/L, than did the FGD-lined basins (0.17 mg-P/L). This may reflect another effect of the differences in hydrology rather than the differences in the basins. The samples from the FGD basins were taken with lower water levels and thus contamination due to sediments getting into the sample bottles is much more likely.

3.3.5 Vegetation Productivity

Wetland plant biomass was used as an indicator of ecosystem productivity in the experiment. Higher biomass would indicate a less-stressed ecosystem. Plant biomass in the FGD-lined basins was consistently lower than wetland plant biomass in clay-lined basins for all three growing seasons, though only significantly different for 2001 and 2002 (Table 3.6; Figure 3.14). This was somewhat unexpected and is likely a function of the shorter hydrologic retention time in the FGD-lined basins as much or more than any adverse effect of elements leached from the FGD liner. During the first two years, all basins were dominated by the two sedges that were originally planted—*Schenoplectus tabernaemontani* (soft-stem bulrush) and *Scirpus americanus* (common three-square rush). During the third year, probably as a result of the very high levels of phosphorus added, both basins became dominated by *Typha* spp. (cattail). As shown in Figure

3.14, the FGD basin, while lower in productivity, had 5 species dominating while the clay basins had only 3 species dominating in 2003. Fewer stems were counted in the FGD-lined basins than the clay-lined basins, but greater richness of species was found in the FGD basins. There was substantially greater presence of the common marsh herbs *Eleocharis obtuse* and *Leersia oryzoides* in the FGD-lined basins implying that more species may have greater success in FGD-lined wetlands than in the clay basins during periods of high nutrients. But this conclusion is tempered by the point that the “stress” that caused lower productivity in the FGD basins is more likely low water levels than any chemical effects of the FGD material.

Some indicators of plant morphology illustrate differences between the clay and FGD basins (Table 3.7). There were significantly more plant stems in the clay basins in both 2001 and 2002. These data are reported for the two originally planted sedges *Scirpus americanus* and *Schenoplectus tabernaemontani*. By the third year, *Typha* sp. (cattails) dominated the system and a good comparison of stem lengths and heights was not possible.

3.3.6 Plant Tissue Analysis

Chemical concentration of plant material in the basins could serve as indicators of whether plant roots extended into the liner material. Plant tissue analysis comparison is reported here for two wetland plants that were found in abundance in both the clay-lined basins and FGD-lined basins in the third year of study 2003 (Table 3.8). Greater concentrations of Al and Fe were detected in three-square rush (*Scirpus americanus*) plant tissue samples from FGD-lined basins in year 2003. These elements were present in higher concentrations in the FGD liner material than in

the clay liner (Table 3.1), supporting the idea that some plant roots were able to reach through 2 feet (60 cm) of top soil and enter the liner material. This would be particularly the case if there were low water levels that would cause the plants to extend their roots deeper into the basins as was the case in the FGD basins. On the other hand, plants in the FGD basins did not have higher concentrations of Ca and B, two elements that are much higher in the FGD leachate. *Scirpus* had higher concentrations of Na, Mn and P in the clay-lined basins.

3.3.7 Soil

Topsoil was examined in both wetland basins in 2002 and 2003 to see if chemical analysis was different between the clay and FGD-line basins. A higher concentration after 2 or 3 years would indicate an upward movement of chemicals from the liners. Topsoil analysis after both full growing seasons (2002 and 2003) showed comparable concentrations of B between FGD-lined and clay lined basins (Table 3.9). Boron was an element of interest, as Ahn and Mitsch (2002a) and others have cautioned about the high concentration of B in FGD material. The concentrations of Ca and Mg were similar for topsoil in both treatment types. Topsoils from FGD-lined basins contained slightly greater concentrations of Fe and Mn during both years. There were statistically higher concentrations of S both years in the clay basins but the concentrations may not be ecologically different. After both full growing seasons (2002 and 2003), higher Mo was detected in the clay-lined basins than the FGD-lined basins (Table 3.9). This difference may be a reflection of the higher concentration of Mo in the clay-liner material (Table 3.1) although the clay-lined Mo concentration is only 12% higher than the FGD-lined Mo concentration.

3.4 Conclusions

Higher concentrations of elements common in FGD-liner material were found in leachate water in the FGD basins, suggesting that introduced river water was transported through the liners in these basins to the leachate collection system. Analysis of water level and seepage data supports this conclusion.

The FGD mixture as implemented in this project did not serve as an effective aquiclude to water movement. It was about 20 times more permeable than the clay liner material. Basins lined with the FGD material (vertical infiltration of 10^{-4} cm/sec) consistently showed lower water levels than basins lined with clay material (vertical infiltration of 5×10^{-6} cm/sec). These marked differences in hydrologic regime probably affected vegetative growth and nutrient removal.

Experiments with more impermeable FGD liners are needed to isolate the effects of the liner from the hydrologic effects observed in this study, some of which were due to different water levels.

There were no significant differences in phosphorus retention between the clay and FGD-lined basins during the high-phosphorus pulsing period, refuting the hypotheses generated by earlier small-scale mesocosm wetland studies. However these results cannot be firmly established because of three problems encountered in this study: 1) the phosphorus concentrations were 10 times those seen in wastewater wetlands; 2) the FGD basins were 20 times more permeable than

the clay-lined basins, and 3) pulsing flow conditions rather than continuous flow conditions were necessary because of the instability of continuous flow conditions.

Plant productivity was lower in the FGD-lined wetland basins than in the clay-lined basins but we believe that this difference was caused more by difference in hydrology than by any effect of FGD material on plant growth. This conclusion is supported by the lack of substantial differences in elemental concentrations in plant tissue and topsoil between the FGD-lined and clay-lined basins.

Tradeoffs exist between productivity and diversity in most ecosystems. Plant data comparing FGD and clay-lined basins support this theory. The FGD-lined basins, which were stressed by low water levels, had a greater richness of plant species than did the clay-lined basins that had higher water levels. The clay-lined basins showed greater total plant productivity but with fewer plant species.

Additional studies are needed with FGD material designed to achieve low permeabilities similar to the clay material. We also propose additional studies that mix the FGD material in the topsoil so as to investigate the effectiveness of a topsoil/FGD mix on water quality and the effect of the mixture on plant productivity and wetland ecosystem health.

Table 3.1 Element composition of liner materials (FGD and clay) and topsoil used in the wetland experiment, October 10, 2000

Elements	Liner material		
	FGD	Clay	Topsoil
pH	11.8	7.9	7.5
(mg /g)			
Al	19.5	<11	<11
Ca	167.4	10.0	4.3
Fe	49.1	34.3	39.0
K	2.74	9.0	10.1
Mg	8.3	4.0	4.6
S	86.0	0.6	0.3
N	0.18	1.53	1.39
(ug /g)			
B	342	38.1	41.6
Mn	130	655	990
Mo	4.0	9.7	8.4
Na	402	47.0	450
Ni	33.4	44.4	53.7
P	9.0	0.05	2.5

Table 3.2 Number of water pulses added to the experimental wetlands, 2001-2003 and average hydraulic loading rate (HLR) each year

Dates	Pulsing schedule				
	Pulses/week	Weeks	Number of Pulses	HLR cm/wk	HLR cm/day
8/10/01—11/15/01	4	12	48	63	9.0
3/18/02—8/8/02	3	20	60	47	6.8
5/13/03—9/11/03	3	18	54	47	6.8

Table 3.3. Weekly water quality parameters for surface water and leachate water in clay-lined and FGD-lined basins, asterisks denote significant differences (SD)

	Surface water			SD	Leachate		SD
	Inflow	Outflow clay-lined	Outflow FGD-lined		Clay-lined	FGD-lined	
First year (2001)							
Temperature (°C)	17.9 ± 0.0 (22)	18.8 ± 1.3 (13)	19.5 ± 1.5 (13)	—	20.2 ± 1.2 (21)	20.0 ± 1.6 (19)	—
DO (mg/L)	7.3 ± 0.7 (22)	6.19 ± 0.8 (13)	6.9 ± 1.0 (13)	—	4.3 ± 0.5 (21)	3.8 ± 0.5 (19)	*
Conductivity (µS/cm)	596 ± 29 (22)	597 ± 28 (13)	591 ± 35 (13)	—	1044 ± 78 (21)	1679 ± 199 (19)	*
pH	8.1 ± 0.2 (22)	7.9 ± 0.2 (13)	8.5 ± 0.2 (13)	—	7.7 ± 4.2 (21)	9.8 ± 0.5 (19)	*
Redox (mV)	219 ± 55 (13)	151 ± 32 (8)	173 ± 63 (6)	—	290 ± 32 (5)	294 ± 25 (4)	—
Turbidity (NTU)	34.8 ± 12.8 (17)	31.6 ± 21.8 (8)	39.7 ± 16.7 (6)	—	6.8 ± 1.7 (14)	12.9 ± 1.2 (15)	—
Second year (2002)							
Temperature (°C)	21.8 ± 2.0 (11)	21.6 ± 2.1 (6)	21.8 ± 2.2 (6)	—	23.2 ± 0.3 (10)	20.9 ± 0.19 (8)	—
DO (mg/L)	5.3 ± 1.1 (11)	5.2 ± 0.5 (6)	5.4 ± 0.6 (6)	—	2.0 ± 0.5 (10)	1.7 ± 0.5 (8)	—
Conductivity (µS/cm)	671 ± 13 (11)	666 ± 11 (6)	659 ± 8 (6)	—	1011 ± 232 (10)	2194 ± 320 (8)	*
pH	8.2 ± 0.6 (11)	8.1 ± 0.7 (6)	8.1 ± 0.6 (6)	—	8.1 ± 0.52 (10)	9.41 ± 0.12 (8)	*
Turbidity (NTU)	36.2 ± 1.4 (11)	27.4 ± 3.5 (6)	33.4 ± 1.8 (6)	—	8.3 ± 0.8 (13)	9.5 ± 1.5 (11)	—
Third year (2003)							
Temperature (°C)	22.9 ± 0.9 (31)	22.3 ± 2.2 (8)	23.0 ± 2.0 (8)	—	18.8 ± 1.2 (9)	16.3 ± 0.5 (8)	*
DO (mg/L)	6.5 ± 0.4 (24)	7.9 ± 0.6 (10)	7.3 ± 0.8 (10)	—	3.3 ± 1.16 (6)	2.43 ± 0.84 (8)	—
Conductivity (µS/cm)	537 ± 65 (23)	558 ± 73 (8)	628 ± 71 (8)	—	957 ± 162 (12)	1514 ± 358 (10)	*
pH	7.3 ± 0.2 (21)	7.9 ± 0.5 (8)	7.7 ± 0.5 (8)	—	6.6 ± 0.2 (12)	8.7 ± 0.2 (12)	*
Turbidity (NTU)	49.2 ± 14.8 (23)	30.2 ± 15.8 (8)	32.12 ± 14.92 (7)	—	7.4 ± 0.7 (4)	8.7 ± 0.6 (4)	—

Table 3.4 Elemental composition of leachate water for clay-lined and FGD-lined basins in years 2001 and 2002 (asterisks denote significance differences ($\alpha = 0.05$))

Element	First year (2001)		SD	Second year (2002)		SD
	clay-lined	FGD-lined		clay-lined	FGD-lined	
($\mu\text{g/mL}$)	N=4	N=4		N=4	N=4	
Al	0.02 \pm 0.0	2.6 \pm 0.9	—	0.02 \pm 0.00	0.09 \pm 0.03	—
Ca	104.6 \pm 6.4	152.5 \pm 42.2	—	104.6 \pm 6.4	438.8 \pm 14.6	*
K	3.3 \pm 0.9	837.1 \pm 190.5	*	1.08 \pm 0.08	30.9 \pm 7.3	*
Na	14.0 \pm 0.8	214.7 \pm 46.1	*	16.5 \pm 0.9	23.0 \pm 0.9	*
Mg	62.4 \pm 5.9	0.3 \pm 0.2	*	48.8 \pm 2.0	1.6 \pm 0.8	*
S	128.1 \pm 41.6	112.4 \pm 21.6	—	10.6 \pm 1.7	363.6 \pm 13.0	*
B	0.07 \pm 0.00	0.15 \pm 0.04	—	0.1 \pm 0.0	1.5 \pm 0.2	*
Ni	<0.1	<0.1	—	<0.1	<0.1	—
P	<0.1	<0.1	—	<0.1	<0.1	—
Mn	0.4 \pm 0.1	0.1 \pm 0.0	—	0.2 \pm 0.0	0.01 \pm 0.0	—
Mo	0.01 \pm 0.0	0.34 \pm .05	*	0.01 \pm 0.0	0.01 \pm 0.0	—
Fe	0.01 \pm 0.0	0.01 \pm 0.0	—	0.01 \pm 0.0	0.3 \pm 0.1	—

Table 3.5. Nutrient concentrations in surface water of clay-lined and FGD-lined basins before and after phosphorus addition.

	Surface water			SD
	Inflow	Outflow clay-lined	Outflow FGD-lined	
Before P addition				
SRP (mg-P/L)	0.17 ± 0.07 (15)	0.10 ± 0.04 (10)	0.17 ± 0.06 (8)	*
Total P (mg-P/L)	0.27 ± 0.01 (15)	0.26 ± 0.01 (7)	0.25 ± 0.07 (8)	—
NO3-N (mg-N/L)	0.29 ± 0.08 (16)	0.13 ± 0.05 (8)	0.10 ± 0.04 (5)	—
After P addition				
SRP (mg-P/L)	36.7 ± 9.4 (66)	26.8 ± 8.0 (28)	31.4 ± 10.0 (25)	—
Total P (mg-P/L)	53.8 ± 11.7 (61)	41.5 ± 10.5 (26)	49.2 ± 11.1 (24)	—
NO3-N (mg-N/L)	0.39 ± 0.15 (10)	0.31 ± 0.11 (8)	0.34 ± 0.16 (6)	—

** Significance level at p<0.05

Table 3.6. Plant biomass in clay-lined and FGD-lined experimental wetland basins (avg ± std err (# sample plots)).

	clay-lined	FGD-lined	SD
	g-dry wt/m ²		
2001	275 ± 21 (8)	93 ± 10 (8)	**
2002	531 ± 39 (8)	415 ± 45 (8)	**
2003	439 ± 56 (16)	329 ± 61 (16)	—

* Significance level at p<0.10

** Significance level at p<0.05

*** Significance level at p<0.01

Table 3.7. Average plant morphology and stem flowering in clay-lined and FGD-lined basins in 2001 and 2002 for planted vegetation *Schenoplectus tabernaemontani* and *Scirpus americanus*. SD = significant difference.

Element	First year (2001)			Second year (2002)		
	clay-lined	FGD-lined	SD	clay-lined	FGD-lined	SD
Ave. stem length, cm	139 ± 35	131 ± 34	—	334 ± 15	321 ± 20	—
Number of stems/ m ²	56 ± 5	33 ± 3	**	94 ± 13	60 ± 8	**
% of stems flowering	55	60	—	79	82	—

Table 3.8. Elemental composition of wetland plant tissue (*Typha* sp. and *Scirpus americanus*) in clay-lined and FGD-lined basins in 2003. SD = significant difference.

Element	<i>Typha</i>		SD	<i>Scirpus americanus</i>		SD
	clay-lined	FGD-lined		clay-lined	FGD-lined	
(µg/g)	n= 8	n= 11		n= 6	n= 7	
Al	26±4	18±4	—	34±7	169±62	*
B	9±1	8±1	—	17±2	18±3	—
Cu	4±1	5±1	—	2±0	4±1	—
Fe	49±8	36±6	—	79±10	218±65	*
Mn	217±17	167±14	**	482±24	381±34	**
Zn	9±1	8±0	—	12±1	12±1	—
(mg/g)	n= 8	n= 11		n= 6	n= 7	
P	1.2±0.1	0.9±0.1	—	1.2±0.0	1.1±0.0	*
K	13.0±2.4	12.3±1.5	—	17.9±1.4	16.4±1.9	—
Ca	10.9±1.2	12.0±0.9	—	5.4±0.2	5.8±0.5	—
Mg	1.5±0.3	1.2±0.1	—	1.8±0.1	1.7±0.1	—
Na	3.2±1.0	1.9±0.6	—	5.5±0.7	2.2±0.3	***

* Significance level at p<0.10

** Significance level at p<0.05

*** Significance level at p<0.01

Table 3.9 Elemental composition of topsoil in clay-lined and FGD-lined basins in years 2002 and 2003 (asterisks denote significance differences ($\alpha = 0.05$))

Element	Second year (2002)		SD	Third year (2003)		SD
	clay-lined	FGD-lined		clay-lined	FGD-lined	
($\mu\text{g/g}$)	N=8	N=8		N=8	N=8	
Cu	24.8 \pm 0.3	26.1 \pm 0.3	*	22.0 \pm 0.1	23.8 \pm 0.2	*
Mo	9.5 \pm 0.3	8.5 \pm 0.3	*	7.6 \pm 0.2	6.4 \pm 0.2	*
B	0.5 \pm 0.0	0.5 \pm 0.0	—	15.5 \pm 0.7	13.1 \pm 0.9	—
(mg/g)	N=8	N=8		N=8	N=8	
K	8.7 \pm 0.1	10.0 \pm 0.1	*	2.6 \pm 0.1	2.6 \pm 0.1	—
Al	31.3 \pm 0.3	36.2 \pm 15.2	—	13.5 \pm 0.4	14.8 \pm 0.4	—
Ca	5.3 \pm 0.7	4.1 \pm 0.0	—	4.3 \pm 0.1	4.2 \pm 0.4	—
Mg	4.3 \pm 0.3	4.1 \pm 0.0	—	2.8 \pm 0.1	2.9 \pm 0.2	—
Fe	30.6 \pm 0.2	32.4 \pm 0.4	*	25.7 \pm 0.1	28.7 \pm 0.3	*
Mn	0.6 \pm 0.0	0.7 \pm 0.0	*	0.5 \pm 0.0	0.6 \pm 0.0	*
S	0.4 \pm 0.0	0.3 \pm 0.0	*	0.4 \pm 0.0	0.3 \pm 0.0	*
P	0.6 \pm 0.0	0.6 \pm 0.2	*	0.6 \pm 0.0	0.5 \pm 0.0	*

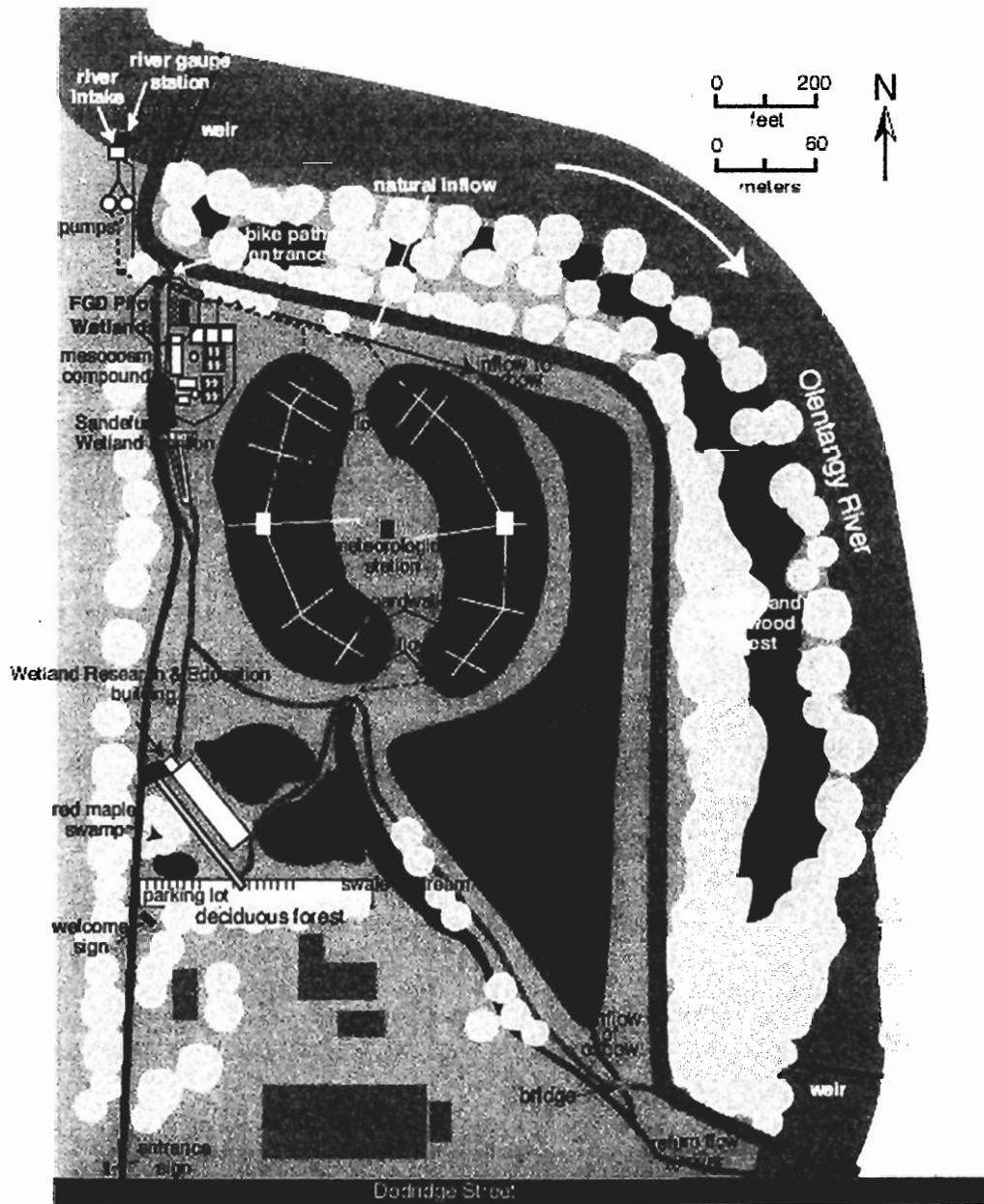


Figure 3.1 Olentangy River Wetland Research Park at The Ohio State University with location of FGD and clay-lined experimental wetland basins shown in the northwest corner of site.

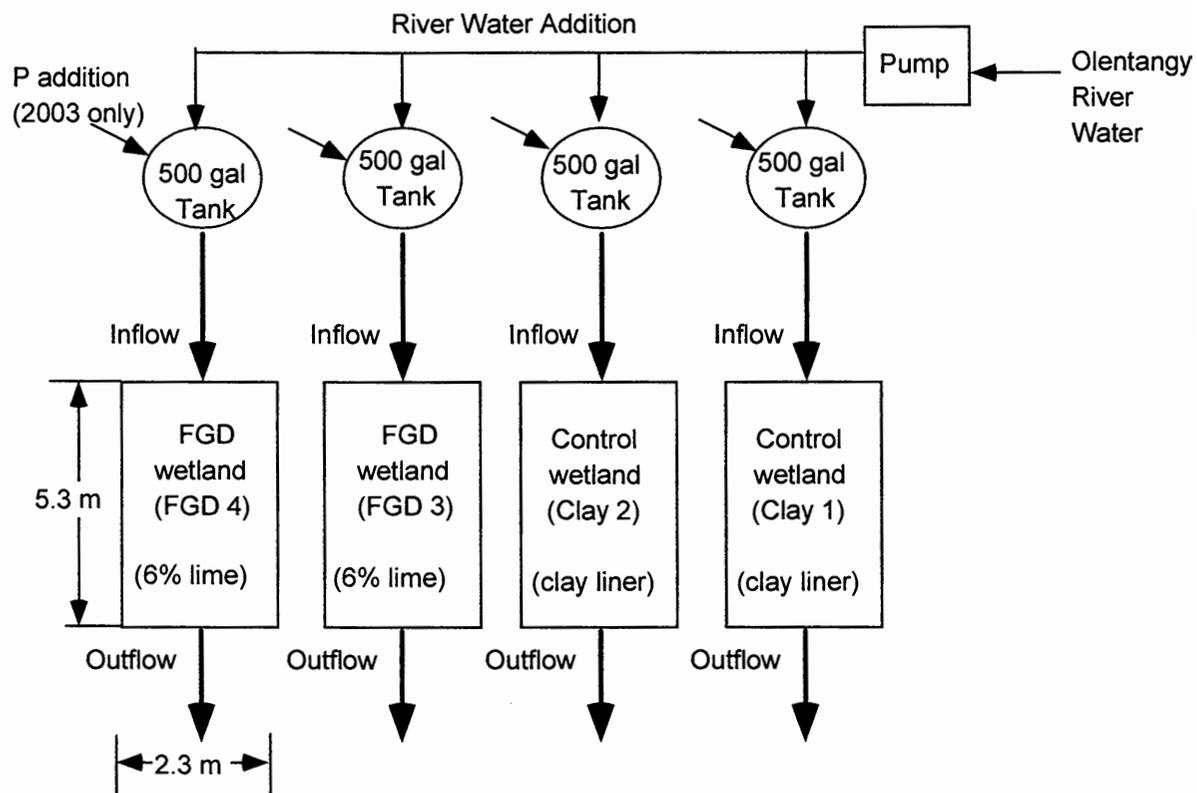


Figure 3.2. Schematic of medium-scale wetland experiments. Two basins were lined with FGD material and two basins were lined with clay.

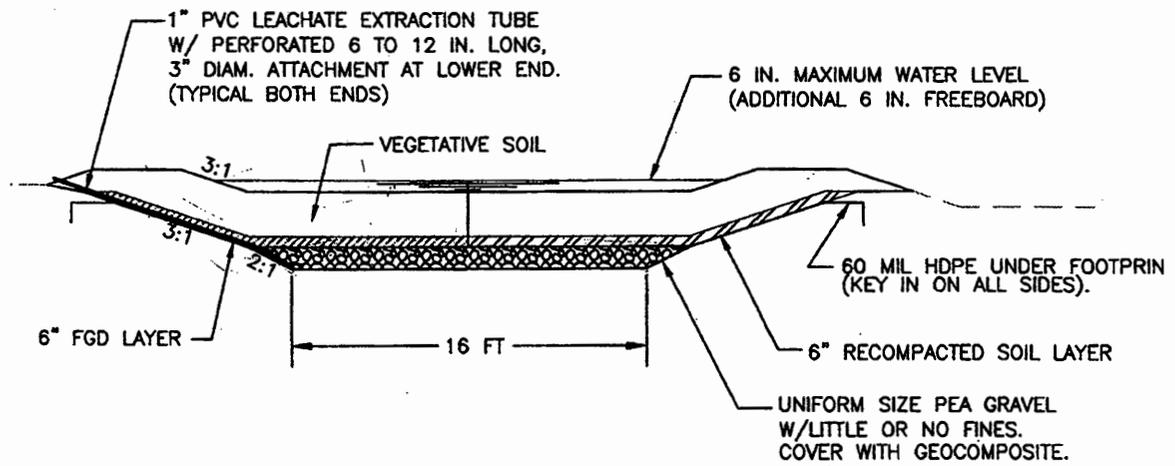


Figure 3.3 Construction cross-section of wetland basins used in this coal combustion project experiment.

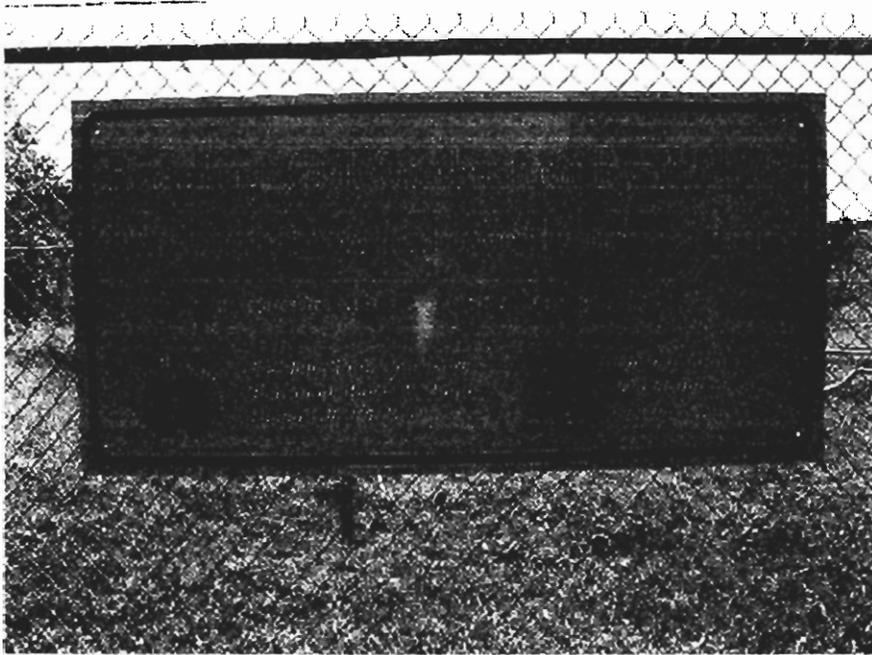


Figure 3.4 Sign at wetland experiment, Olentangy River Wetland Research Park summarizing OCDO support for this experiment



Figure 3.5 Excavation of wetland basins, August 30, 2000

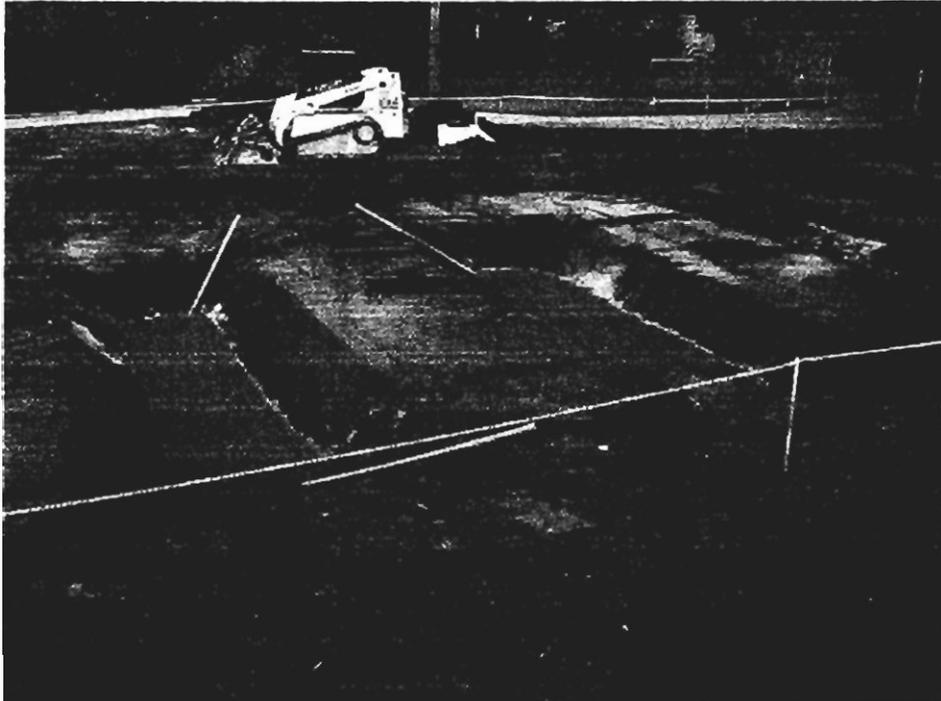


Figure 3.6 Placement of impervious liners and leachate collection system, September 1, 2000

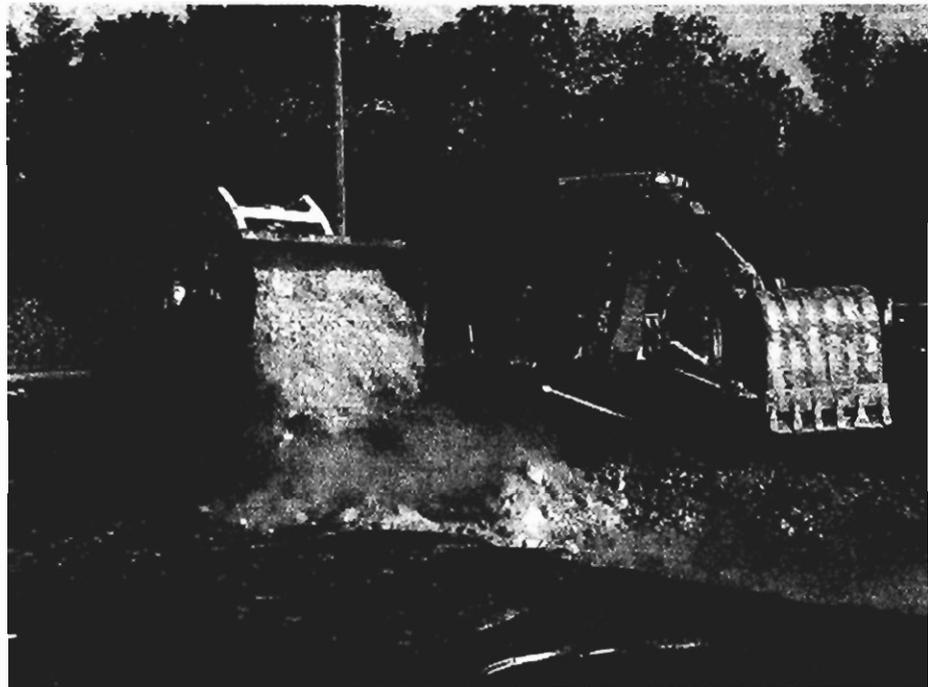


Figure 3.7 Addition of FGD material to two experimental wetland basins, September 13, 2000



Figure 3.8 Liner in FGD wetland basin showing initial compaction, September 13, 2000

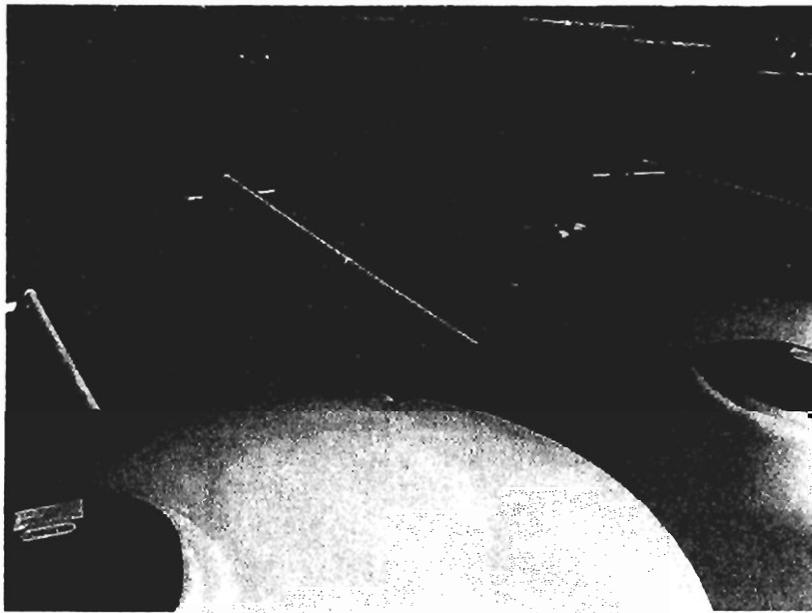


Figure 3.9 Installation of water delivery system to experimental wetland basins, April 25, 2001



Figure 3.10 FGD-lined basin after one growing season of planting, September 15, 2001



Figure 3.11 FGD-lined basins after three full growing seasons, August 6, 2003

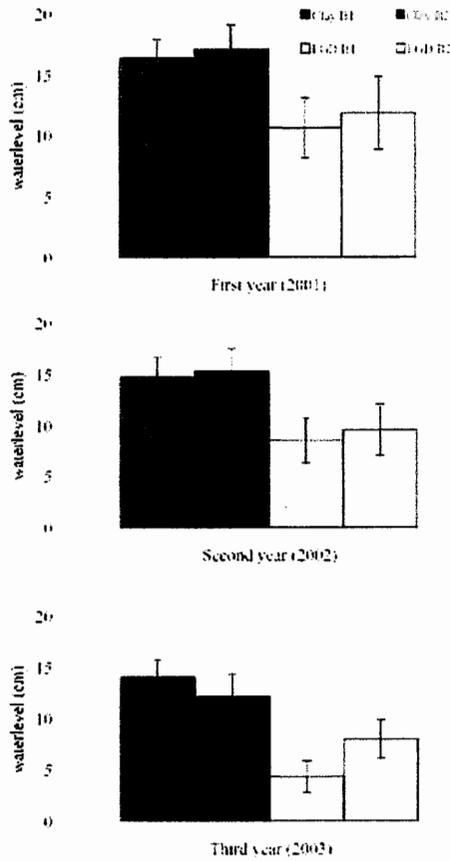


Figure 3.12 Average weekly water level in four pilot scale basins (2 clay-lined and 2 FGD-lined) for years 2001, 2002, and, 2003.

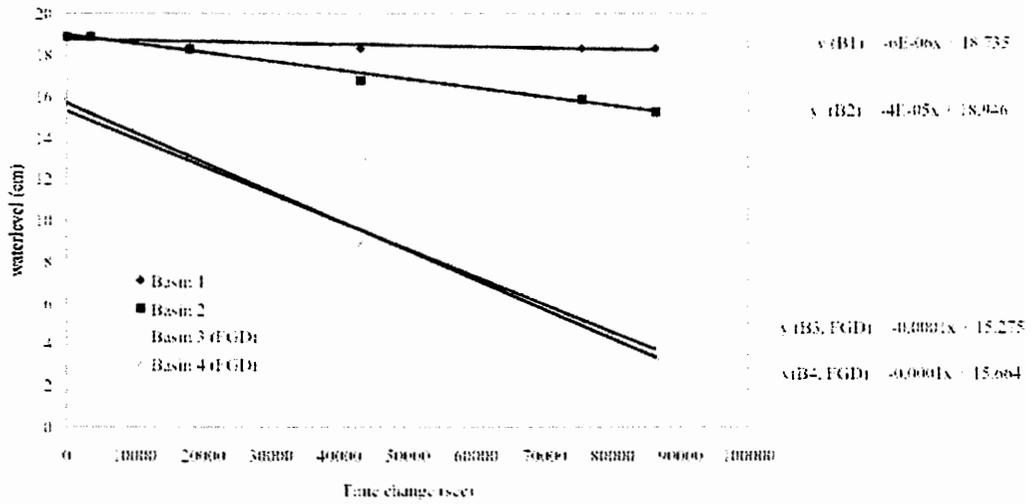


Figure 3.13. Water level decrease experiment of wetland basins, July 25, 2003.

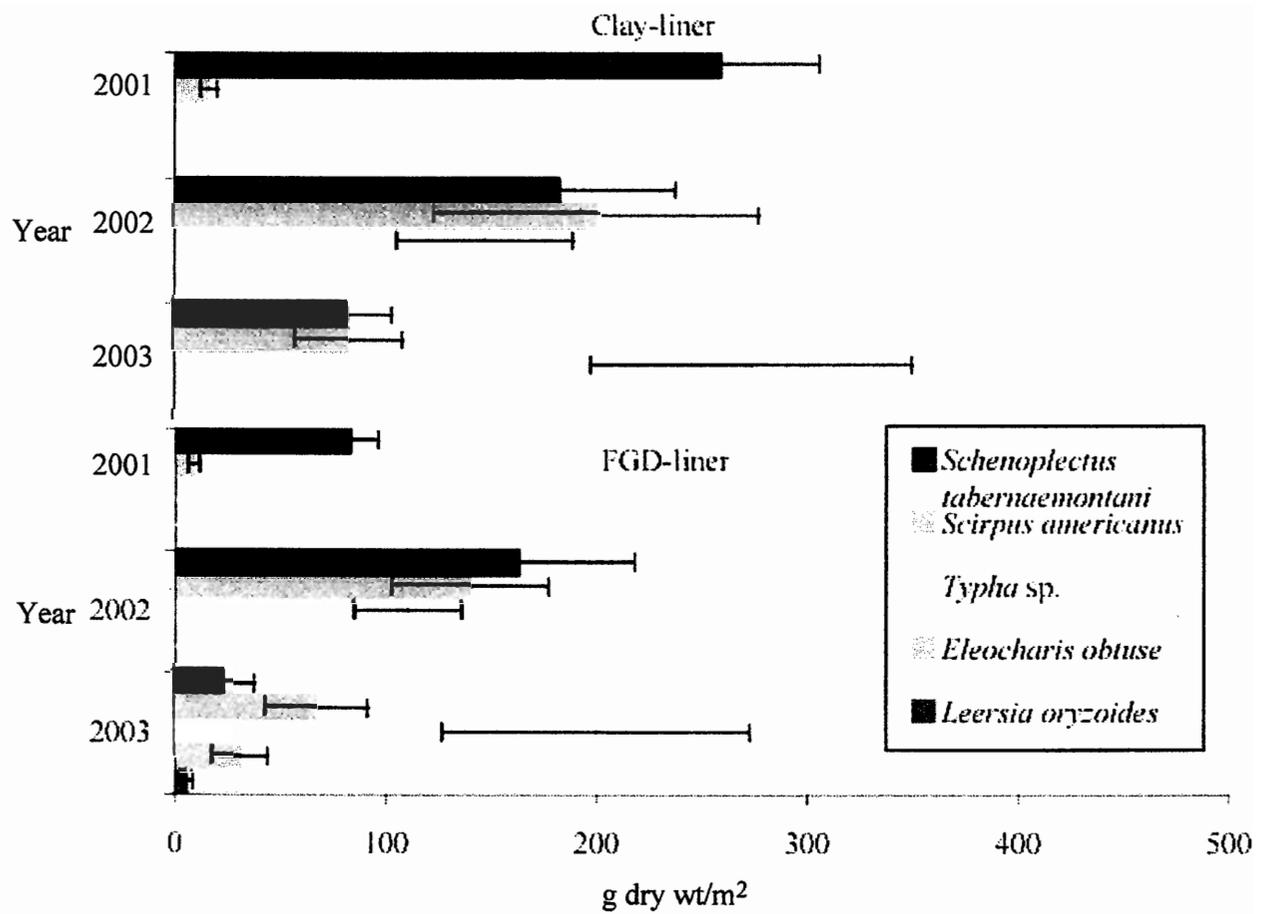


Figure 3.14 Annual peak biomass in clay-lined and FGD-lined basins for years 2001, 2002, and 2003

4 FULL-SCALE FGD-LINED STUDY

4.1 Introduction

Permeability of a field compacted FGD structure is a function of the construction process, and hence the field validation of properties obtained in the laboratory is an important part of the documentation process. In this chapter, we review the design and construction of the South Charleston FGD-lined pond facility that was constructed in August of 1997 and present monitoring results for the facility for a period of about 5 ½ years.

4.2 Background

A full-scale FGD-lined pond facility was constructed in 1997 (Wolfe et al., 2000) to address two critical questions about the behavior of stabilized FGD products constructed in the field, i.e. what is the permeability of a compacted engineered liner of known thickness and density, and what is the quality of the water that flows through the FGD liner.

The full-scale facility was designed and constructed at The Ohio State University's Ohio Agricultural Research and Development Center (OARDC) Western Branch in South Charleston (Clark County), Ohio. This site was chosen over other university sites because it had an abundance of clay onsite that was suitable for use as a secondary or outer liner to contain the primary FGD liner. The OARDC Western Branch facility is a swine and agronomic research

facility and, hence, it was decided to build a livestock manure storage facility that could be used by the center for storing swine manure after the completion of this research. The facility was designed for a capacity of approximately one million gallons (150,000 ft³) to provide six months storage for all liquid wastes from the swine onsite. A double-layered design was chosen with compacted stabilized FGD as the primary inner liner and the onsite clay (about 80 feet of grey glacial till) as the secondary outer liner. A leachate system was designed to be placed between the primary FGD liner and secondary clay liner to collect in a sump any water passing through the FGD fill. The sump was designed so that it could be used to collect leachate samples with ease and for conducting field permeability tests on the pond liner.

The detailed design and construction of the facility is documented in Wolfe et al., 2000. The facility is essentially rectangular in shape with overall dimensions of approximately 150 feet by 250 feet (including 8-foot wide berms), as shown in Figure 4.1. Three sides of the pond were constructed at 3:1 slope and the fourth (east) side slope at 7:1. The east side slope was designed to be less steep so as to allow for easy access to the pond bottom during and after construction. Cross-sections AA and BB which are presented as Figures 4.2 and 4.3, respectively, show the final elevations of the facility. As seen in Figures 4.2 and 4.3, the pond is 9 feet deep with a liquid freeboard of 2 feet. A berm of minimum 8-foot top width was added around the periphery of the pond to minimize the inflow of surface water. The natural clay at the site provided an outer liner that was at least 5 feet thick. The leachate collection system, which consisted of corrugated high-density polyethylene (HDPE) perforated pipes (with socks) and protected against crushing using #57 washed river gravel, was placed over the re-compacted clay. The bottom of the pond was then covered with 9 inches of sand. On top of the sand layer, an 18-inch

thick layer of compacted FGD material was placed. A plan view of the leachate collection system is shown in Figure 4.4. A typical detail of the perforated pipe embedded in the sand layer is shown in Figure 4.5. The pond facility was constructed in August of 1997 and by the third week of September the pond was filled with water up to a depth of approximately 9 feet as shown in Figure 4.6.

An outline of the test pads constructed at the pond site is shown in Table 4.1. The pads were constructed to avoid coring holes in the full-scale FGD liner for obtaining permeability samples. Four rectangular test pads (approximately 6 feet wide, 25-30 feet long and 3-4 feet deep) were installed. Each test pad was initially backfilled with 6 inches of sand to provide a permeable layer for drainage. The remainder of the excavation was filled with stabilized compacted FGD material. Each of the test pad was instrumented for Boutwell field permeability testing apparatuses (Boutwell, 1992). Details on the construction and monitoring of the test pads can be found in Wolfe et al., 2000.

The FGD lined facility was used to store water for the first year. In early September of 1998, some of the water was replaced with swine manure. Since then swine manure has continued to be added and removed from the facility on a regular basis depending on the manure storage vs. field spreading needs of the research farm. Monitoring of the site for field permeability and water quality was carried out for a period of about 5 ½ years. The average monitoring frequency was about three months. The monitoring program consisted of two main activities:

- 1) *Field Permeability Testing*: Full-scale falling head permeability tests on the facility were conducted by lowering the water level in the sump to create a head difference across the FGD

liner. The amount of time taken to increase the water in the sump to specific levels was observed. Knowing the thickness of the FGD liner and its plan view area, the effective permeability of the field compacted FGD-lined facility was calculated (refer Figure 4.7).

- 2) *Water Quality Monitoring Program:* Water quality monitoring of the site was conducted by collecting water samples from the pond, sump (leachate) and a vicinity well (or a vicinity tap). The first baseline water samples were collected on September 12, 1997 before any water was added to the facility. Only well and sump samples were collected. After the pond had been filled with water on September 23, 1997, water samples were collected from the pond, sump and well (or tap) on a regular basis. The water sampling program was conducted while the pond held water (until September 1998) and beyond at which time swine manure was added to the facility on a regular basis. All samples were tested for several constituents and properties including pH, electrical conductivity, alkalinity, acidity, total dissolved solids, aluminum, arsenic, boron, barium, calcium, cadmium, chromium, copper, iron, potassium, magnesium, manganese, sodium, nickel, phosphorous, lead, sulfur, selenium, silica, silver, vanadium, zinc, chloride, phosphate, sulfate, nitrate, ammonia and nitrogen. Although the vicinity well (or tap) was about 1,000 feet from the site and not necessarily hydrologically connected to the site, the well (or tap) samples were investigated so that potential contamination of the farm water supply from the FGD lined facility, if any, could be detected.

4.3 Monitoring Observations and Discussion

4.3.1 Permeability

After filling the full-scale facility with water, the actual field permeability of the FGD liner was measured by lowering the water level in the sump and taking readings of the water level rising in the sump at various time intervals (refer to Figure 4.7). The permeability coefficients were calculated using the bottom area of the pond as the effective leaching area for the FGD-liner.

Table 4.2 shows the effective coefficients of permeability obtained from full-scale permeability tests conducted on the pond facility. The permeability coefficient values listed in Table 4.2 are the average of several test readings that were measured at each curing time. The full-scale permeability of the facility was evaluated to be 9.1×10^{-7} cm/sec at a curing time of one month. The permeability coefficient continued to reduce over time (due to curing of FGD) and stabilized at approximately 4×10^{-7} cm/sec at about 150 days of curing. Beyond 150 days, the permeability of the FGD material liner has been maintained at around 4×10^{-7} cm/sec till 5 ½ years of monitoring of the facility. The FGD permeability coefficient data range obtained from the full-scale tests is comparable to typical clays used in the construction of compacted liners. The data presented in Table 4.2 includes the effect of freeze-thaw cycling on the actual permeability of the full-scale field compacted FGD liner. The actual area over which water flows through the FGD liner is greater than the bottom area of the pond (i.e., a significant amount of water may flow through the sides of the pond). Hence the full-scale permeability values presented in Table 4.2 should be taken to be an upper bound to the actual permeability of the field-compacted FGD

liner. The addition of swine manure to the facility (at 370 days of curing and thereafter) did not significantly affect the actual permeability of the liner.

The specific seepage rate (seepage volume below liner per unit liner area per unit time) for the full-scale facility can be obtained by multiplying the actual average coefficient of permeability with the hydraulic gradient across the liner. If no secondary liner were present at the site, the specific seepage rate for the 9 feet deep manure storage pond having an 18-inch thick FGD liner was calculated to be $0.095 \text{ in}^3/\text{in}^2/\text{day}$. Although currently Ohio does not provide guidance on maximum design seepage rate from lagoons, many states do specify maximum seepage rate values. For example, Kansas state regulations (Ham et al., 1998, 1999, 2000) allow for a maximum seepage rate of $0.25 \text{ in}^3/\text{in}^2/\text{day}$. Specific seepage rates less than $0.1 \text{ in}^3/\text{in}^2/\text{day}$ are considered to be very low seepage values. The long-term value for the full-scale FGD lined pond facility is $0.095 \text{ in}^3/\text{in}^2/\text{day}$. Hence, it can be concluded that if there was no secondary clay liner constructed for the facility (as would be the norm for typical FGD-lined pond and manure storage facilities), the seepage rate loss from such FGD facilities would be very low.

The actual field permeability data obtained from the full-scale pond tests was compared with a) laboratory tests conducted on several laboratory compacted samples collected during pond construction, b) laboratory tests conducted on field compacted samples cored from test pads installed at the site, and c) field permeability tests (Boutwell) conducted on the test pads TP1, TP2, and TP3. TP4 was not considered for comparison because this test pad was constructed using FGD material that was lower in lime content and fly ash to filter cake ratio compared to the material used in the construction of the full-scale facility. Figure 4.8 shows the time history

comparison of the full-scale permeability test values with permeability coefficients obtained from a) laboratory tests on laboratory compacted samples, b) field tests (Boutwell) conducted on test pads, and c) laboratory tests conducted on samples cored from test pads. All the test procedures showed decreasing permeability coefficient with increasing curing time. It was observed that the laboratory compacted samples had permeability coefficients which were an order of magnitude lower than the full-scale testing values. Permeability values obtained from Boutwell tests and cored samples tested in the laboratory were in close agreement with each other but were one to three orders of magnitude higher than the full-scale tests. The test pad sample permeability values (Boutwell tests and cored sample testing) indicated a large scatter in the data. The permeability coefficients varied from 10^{-4} cm/sec (3×10^{-6} ft/sec) to 10^{-7} cm/sec (3×10^{-9} ft/sec) with average permeability value in range of 10^{-5} cm/sec (3×10^{-7} ft/sec). This may be due to the unsuitable compaction achieved for the test pads. Furthermore, the Boutwell test procedure relates infiltration rate with permeability coefficient by assuming certain direction and boundary conditions of flow, which are nearly impossible to control in the field. However, it is important to note that the actual measured field permeability values of the full-scale FGD liner are an order of magnitude higher than laboratory measured values.

4.3.2 Water Quality

Table 4.3 lists the measured concentration levels of pH, electrical conductivity, alkalinity, acidity, total dissolved solids, aluminum, arsenic, boron, barium, calcium, cadmium, chromium, copper, iron, potassium, magnesium, manganese, sodium, nickel, phosphorous, lead, sulfur, selenium, silica, silver, vanadium, zinc, chloride, phosphate, sulfate, nitrate, ammonia, and

nitrogen.. The time history for various water quality measurement parameters is shown in Figure 4.9 through Figure 4.43. The concentration level of various analytes (pH, electrical conductivity, alkalinity, Ag, Al, Ca, Cl, PO_4^{-3} , Cr, K, Mg, Na, and Si) in the sump (leachate) increased suddenly following the filling of the facility with water. Thereafter, the concentration levels reduced rapidly. The leachate from the FGD lined facility needs to meet OEPA's non-toxic criteria. All the non-toxic parameters (Arsenic, Barium, Cadmium, Chromium, Lead, Selenium) measured for the FGD facility while holding water and swine manure were much lower than OEPA's non-toxic criteria. It should be noted that, in general, the leachate from the full-scale FGD-lined facility meets the National Primary Drinking Water Regulations (NPDWR) limits. However, the value or concentrations of pH, Al, and Cl were observed constantly higher than the NPDWR limits. It was also found the concentrations of other elements exceeded the limits in some of the sampling events, such as the total and dissolved Fe on Nov. 12th 2001, Ag on Sept. 28th 1997, sulfates on Nov. 7th 2002 and April 2nd 2003, and nitrates on Sept. 12th 1997 and Jun. 8th 2001. NSWDR limits are non-enforceable non-health related guidelines regulating potential contaminants that may cause cosmetic or aesthetic effects in drinking water. From a regulatory perspective, the leachate from the FGD material is not required to meet any of the NSDWR limit values, yet the leachate concentration levels measured from the FGD lined facility are generally lower or comparable to the NSDWR limits for most potential contaminants of concern. The following paragraphs describe the concentration profiles of monitored elements and aquatic parameters.

Arsenic concentration levels of the pond and sump samples were very low (lower or close to $0.035\mu\text{g/mL}$, the detection limit) in the first year (Figure 4.9) of monitoring. Upon addition of

swine manure to the facility (in early September, 1998), the concentration level of Arsenic in the pond increased gradually to a maximum value of 0.18 $\mu\text{g}/\text{mL}$ over a two-year period and then fractured. The increase in As concentration immediately following addition of swine manure may have resulted from the presence of As in the manure, though no analysis of the manure was conducted. Another possibility is that changing chemical conditions in the pond due to addition of manure increased the leaching of As. The Arsenic concentrations in sump samples were close to the detection limit for the first four years of sampling (from September 1997 to February 2001), but a noticeable increase was found in the recent sampling events (October 2001~April 2003). It should be noted, however, arsenic levels in the sump and pond have remained lower than Ohio EPA's non-toxic regulatory value of 1.5 $\mu\text{g}/\text{ml}$ for the duration of the project.

Barium concentrations of all samples collected from sump, pond, and well/tap (ranged from 0.009 to 0.089 $\mu\text{g}/\text{mL}$) were significantly lower than the primary drinking water standards (2.0 $\mu\text{g}/\text{mL}$) (Figure 4.10). It was found that the barium concentrations in the sump were slightly higher than in the pond, but both were lower than in the well.

Cadmium concentrations (Figure 4.11) have generally been at the detection limit (0.002 $\mu\text{g}/\text{mL}$) and lower than the NPDWR (0.005 $\mu\text{g}/\text{mL}$) during the monitoring period. Detectable cadmium concentration values are found in all of the samples collected from the 10/2/98 sampling event and in the well sample collected from the 10/11/01 sampling event. The sudden increase in those samples seems to be erroneous. *Chromium* concentration in sump and pond samples has been lower than NPDWR except when the facility was just filled with water (Figure 4.12). However, because the observed high concentrations in sump and pond are associated with abnormal high

concentration in the well, some inaccuracy might be involved. Both cadmium and chromium concentration levels are far below the OEPA's non-toxic criteria (0.15 and 3.0µg/mL, respectively).

Lead concentration levels for sump and pond have been at or near the detection limit (Figure 4.13) for the duration of the project. The lead level in well samples is elevated, perhaps due to the use of lead pipes to convey water from the bottom of the well to the sampling point. No lead concentration levels are observed to exceed the Ohio EPA's non-toxic criteria (1.5µg/mL).

Selenium concentration levels are generally at the detection limit of 0.1µg/mL. No sample had Se concentration higher than Ohio EPA's non-toxic criteria (1µg/mL). Due to a higher detection limit provided by the applied analytical technique, no evidence has been shown that the Se concentration levels are below the NPDWR value of 0.05 µg/ml (Figure 4.14). A sudden increase in all Selenium measurements for 3/16/99 seems to be erroneous.

Copper concentrations have been significantly lower than the USEPA Action Level of 1.3µg/ml and NSDWR limit of 1.0µg/ml (Figure 4.15). No increase in copper concentration level is observed in the sump during the monitoring period.

The concentration levels of dissolved *Aluminum*, *Zinc*, and *Vanadium* in the sump samples increased significantly during the filling of the pond (Figure 4.16, 4.17, and 4.18). However soon after filling the facility, concentration levels of these three elements in the sump dropped significantly. The concentrations of dissolved Aluminum and Zinc have been around or far

below the NSDWR limits (0.2 and 5µg/ml), respectively. No increase in the concentration levels for these three elements is observed as the monitoring project went on.

Dissolved and *total Iron* levels for the sump samples are quite low (Figure 4.19 and 4.20). Both iron levels are lower than NSDWR (0.3µg/ml). After swine manure was added into the facility, both dissolved and total iron concentration levels in the pond increased. The concentration levels in the sump were constant over the monitoring period.

Total Manganese level for the sump is lower than or comparable to the NSDWR limit value (Figure 4.21). Pond samples show a steady increase in total manganese concentrations right after the addition of swine manure to the pond. The concentration levels of *dissolved Manganese* present a very similar pattern as total manganese (Figure 4.22).

After filling of the facility with water, *Silver* concentrations increased significantly and exceeded the NSDWR (0.1µg/ml), but a rapid decrease was found over the next two sampling events (Figure 4.23). After the 7/9/98 sampling event, the silver concentration levels were generally below the detection limit (0.008µg/ml) through the rest of the monitoring period.

Boron, elevated levels of which can be phytotoxic to plant growth, generally had lower concentration levels in the sump than the pond during the early and middle stages of the monitoring period (Figure 4.24). This may be due to adsorption of some Boron by the FGD liner. However, at the last three sampling events, the concentration levels of Boron in the pond and sump were similar. Similar adsorption phenomena can also be observed in the concentration

profiles of *Calcium*, *Magnesium*, and *Silica* (Figure 4.25, 4.26, and 4.27). After swine manure was added into the facility, rapid increases of Si, Mg, and Ca concentrations in the pond were shown, but relatively constant concentration levels were maintained in the sump except for Calcium. Calcium level in the sump continued to increase slightly.

The *Sodium* concentration in the sump increased sharply right after filling the facility with water (Figure 4.28) and decreased to a constant level before swine manure was added into the facility. After the addition of swine manure, the concentration level of sodium in the sump started increasing slightly throughout the monitoring period. Pond samples showed a steady increase in sodium concentrations right after the addition of swine manure and then the concentration remained at a relatively constant level. The sodium concentration levels in the sump were found generally higher than in the pond. *Potassium* showed a similar concentration patterns as sodium (Figure 4.29). The concentration levels in the sump and the pond were similar during the late stage of the monitoring period.

No detectable *Nickel* concentrations were found before swine manure was added into the facility (Figure 4.30). After the addition of swine manure, the nickel concentrations in the pond started increasing and reached a maximum concentration of 0.035 $\mu\text{g}/\text{mL}$. After then, the concentrations of nickel in the pond declined sharply and almost were not detectable in the last two sampling events. The nickel concentrations in the sump were at the detection limit for the duration of the monitoring period.

On filling the pond, the *Chloride* concentration in the sump increased to about four times over the NSDWR limit (Figure 4.31), but decreased after reach a maximum value of about 1000 $\mu\text{g}/\text{ml}$ to a level lower or slightly higher than the NSDWR regulation limit (250 $\mu\text{g}/\text{ml}$). The chloride concentrations in the sump were generally higher than the concentrations in the pond for the duration of the project. *Total Sulfur* concentrations in the sump increased noticeably during the monitoring period (Figure 4.32). Since the concentration levels of sulfur in the pond were constantly lower than the levels in the sump after swine manure was added into the facility, the FGD liner seems to be a source of Sulfur. *Sulfate* levels in the sump have generally been within the NSDWR limit, except for the sample collected in the last sampling event (Figure 4.33).

The *total Nitrogen* concentrations in the sump remained constant and were higher than the concentration levels in the pond before the facility was filled with swine manure (Figure 4.34). After the addition of swine manure, the concentration levels of total nitrogen in the pond increased dramatically and remained at a constant level. With the increase concentration levels of total nitrogen in the pond, the total nitrogen concentrations in the sump also increased. In general, *Nitrate* levels (Figure 4.35) in the sump leachate were low compared to the NPDWR value of 10 $\mu\text{g}/\text{ml}$. However, there were two sampling events where the nitrate concentrations exceeded the NPDWR value. In the last two sampling events, both nitrogen concentrations in the pond and sump showed an increasing trend. *Ammonia* levels (Figure 4.36) increased in pond with addition of swine manure. This resulted in an increase in the concentration of ammonia in the sump leachate. Ammonia, which can be converted to soluble nitrate in the presence of oxygen (non-saturated conditions), may be a concern during the cleaning and removal of manure storage facilities (irrespective of whether the facility is constructed with clay or FGD).

Phosphorous concentration in the pond increased on addition of swine manure to the facility (Figure 4.37) but the sump Phosphorous levels have remained close to the detection limit (0.03µg/ml). The concentration levels of phosphorous in the pond are constantly higher than the levels in the sump. Very similar to Phosphorous, the concentration levels of *Phosphates* in the pond increased on addition of swine manure, while the concentration levels in the sump remained relatively unchanged (Figure 4.38) at the detection limit (0.10µg/ml).

It can be observed from Figure 4.39 that the *pH* of the well sample has been decreasing slightly according to seasonal groundwater variations. The pH of the pond sample was within the Ohio Secondary Maximum Contaminant Level (OSMCL). The pH of the sump water rose sharply to 12 on filling the facility with water and has been dropping since then. The last pH level reading for the sump was 8.4, which is within the OSMCL range of 7.0 to 10.5 and slightly lower than the National Secondary Drinking Water Regulations (NSDWR) upper limit of 8.5. Figures 4.40 to 4.43 show the monitoring results of *Alkalinity*, *Acidity*, *Conductivity*, and *Residual of Evaporation*, respectively. Before swine manure was added into the facility, the alkalinities in the sump were higher than the alkalinities in the pond. After swine manure was added into the facility, the alkalinities in the pond were found very high, while the alkalinities in the sump remained constant. High alkalinity in swine manure has also been observed by other researches (Morris et al., 2003; Masse et al., 2003)

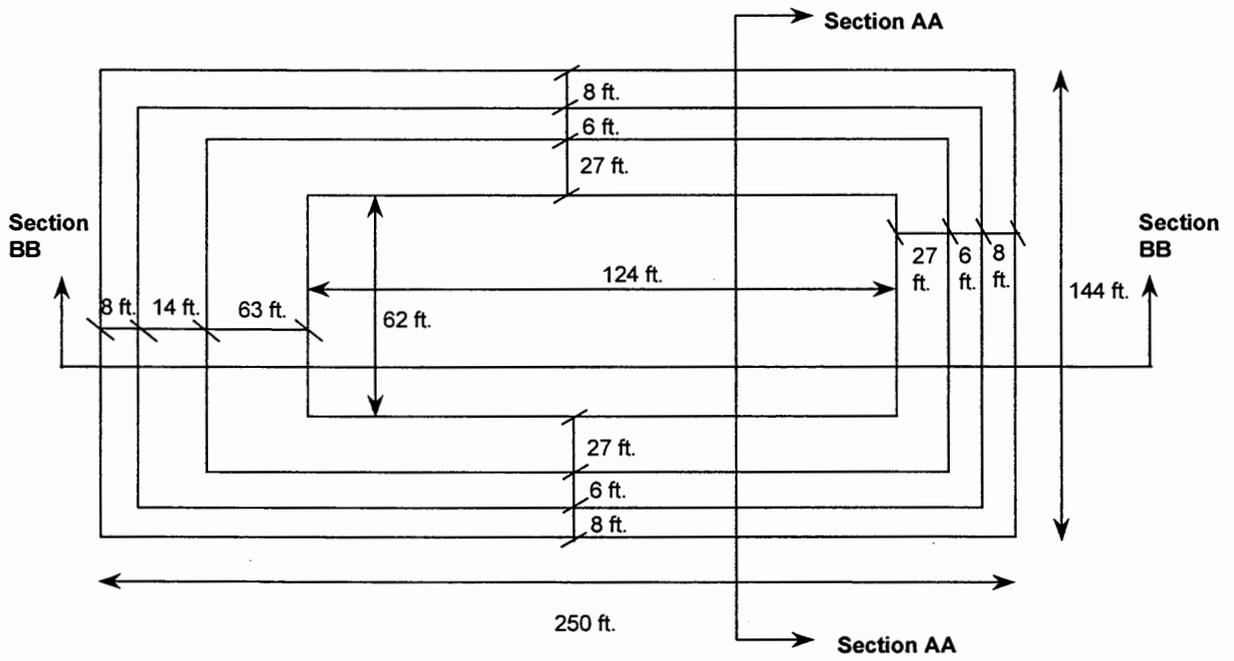


Figure 4.1 Plan View of Facility (not to scale)

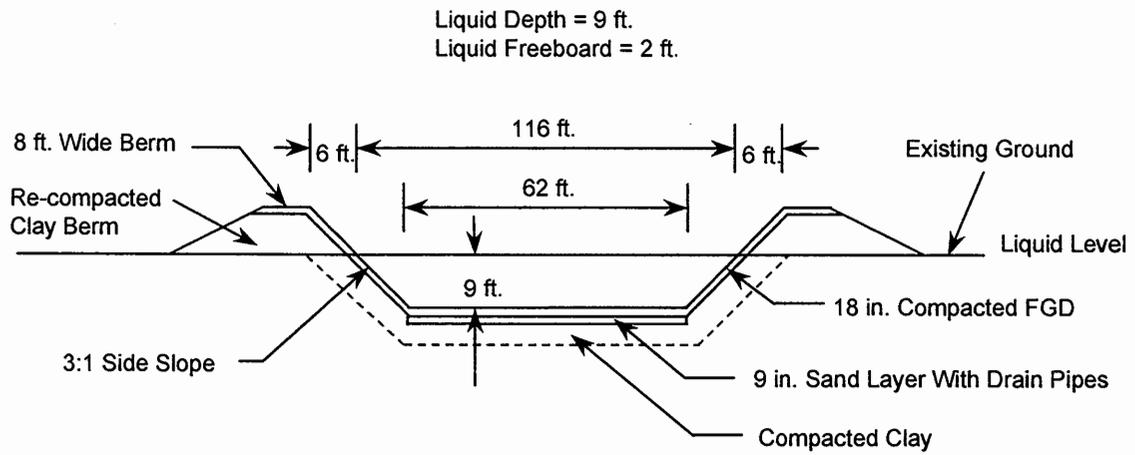


Figure 4.2 Section AA of Facility (not to scale)

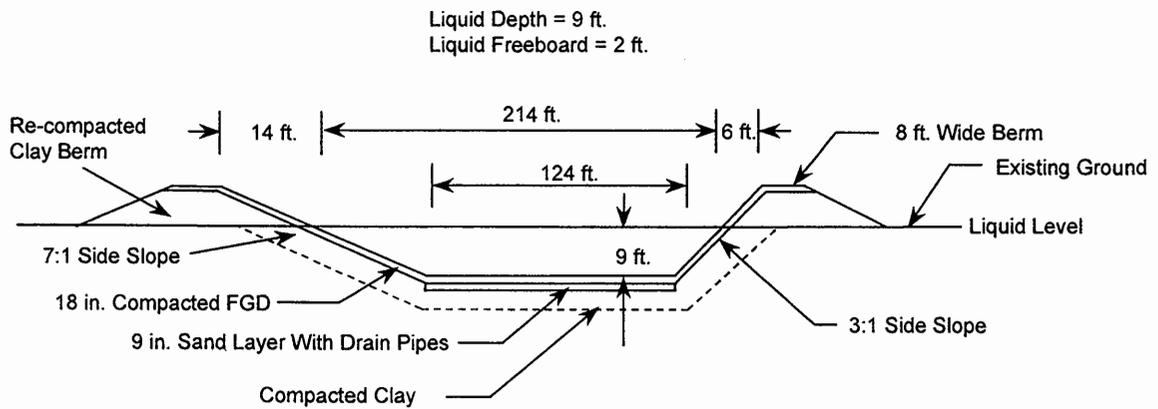


Figure 4.3 Section BB of Facility (not to scale)

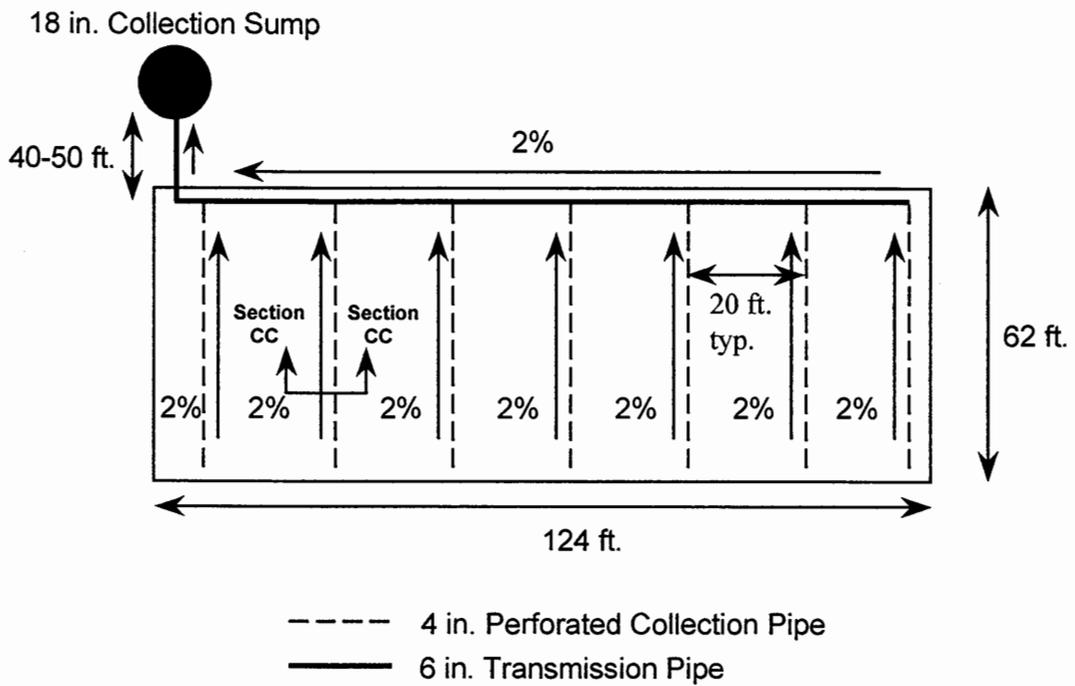


Figure 4.4 Leachate Collection System Layout (not to scale)

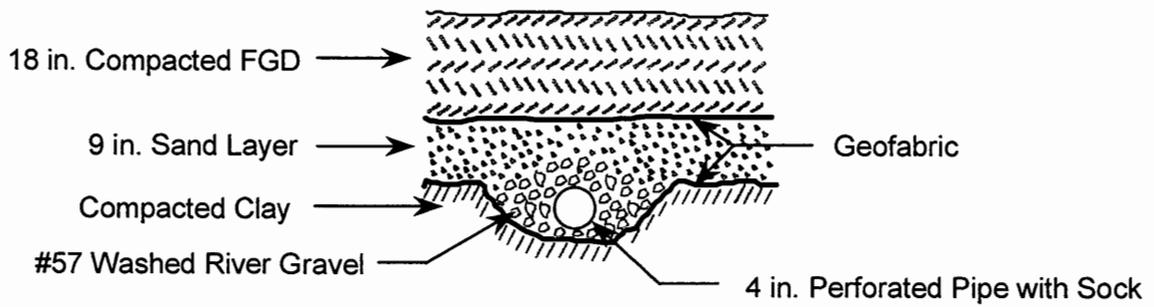


Figure 4.5 Section CC of Facility (not to scale)

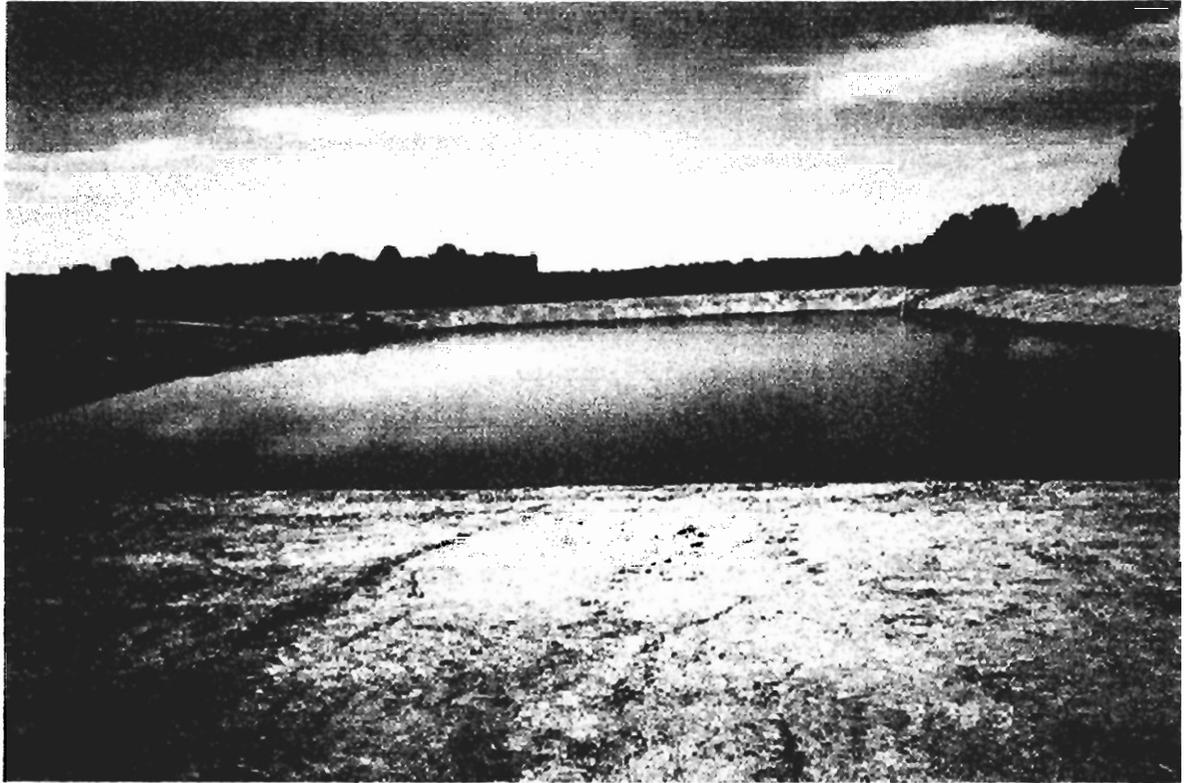
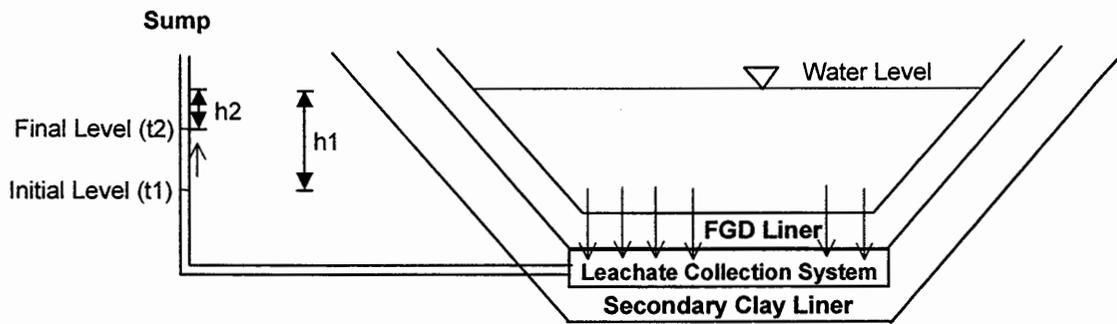


Figure 4.6 Facility Filled With Water

Table 4.1 FGD Test Pads Constructed

Pad Number	Thickness of Sand (inches)	Stabilized FGD Material			
		Thickness (inches)	Approx. FA:FC ratio	Approx. Lime content (%)	Moisture content (%)
TP1	6	27	1.25:1	8	62
TP2	6	36	1.25:1	8	69
TP3	6	30	1.25:1	8	58
TP4	6	36	0.8:1	4	84



$$k = \frac{L}{(t_2 - t_1)} \frac{a}{A} \ln\left(\frac{h_1}{h_2}\right)$$

L = Thickness of FGD liner
 a = Area of sump
 A = Effective area of FGD liner

Figure 4.7 Full Scale Permeability Test (not to scale)

Table 4.2 Full Scale Permeability Test Results

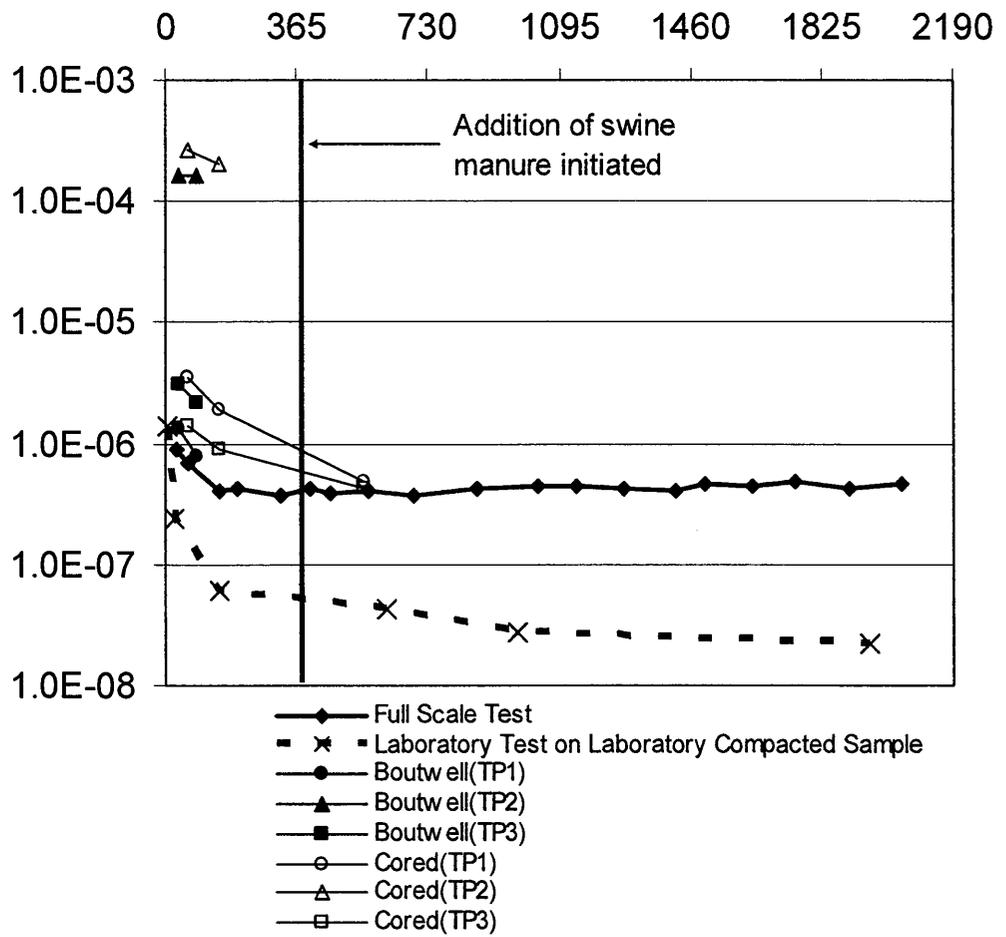
Curing Time (days)	Coefficient of permeability * (cm/sec)
31	9.1×10^{-7}
63	6.8×10^{-7}
153	4.1×10^{-7}
202	4.3×10^{-7}
317	3.8×10^{-7}
402	4.2×10^{-7}
456	3.9×10^{-7}
567	4.0×10^{-7}
693	3.8×10^{-7}
869	4.3×10^{-7}
1035	4.4×10^{-7}
1141	4.5×10^{-7}
1274	4.2×10^{-7}
1416	4.1×10^{-7}
1501	4.7×10^{-7}
1634	4.4×10^{-7}
1750	4.8×10^{-7}
1900	4.3×10^{-7}
2045	4.6×10^{-7}

1 cm/sec = 0.0328 ft/sec

* Effective area of FGD liner = Bottom area of pond

Coefficient of Permeability (cm/sec)

Curing Time (days)



1 cm/sec = 0.0328 ft/sec

Figure 4.8 Comparison of Permeability Test Methods

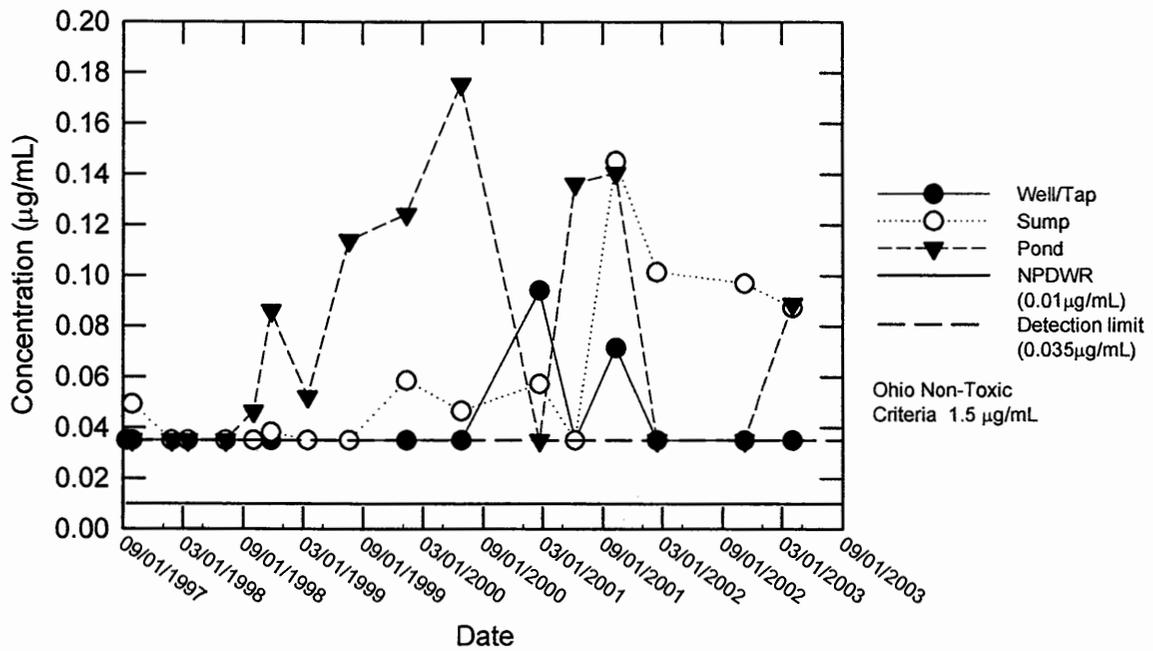


Figure 4.9 Concentration of Arsenic for Sump, Pond, and Well Samples

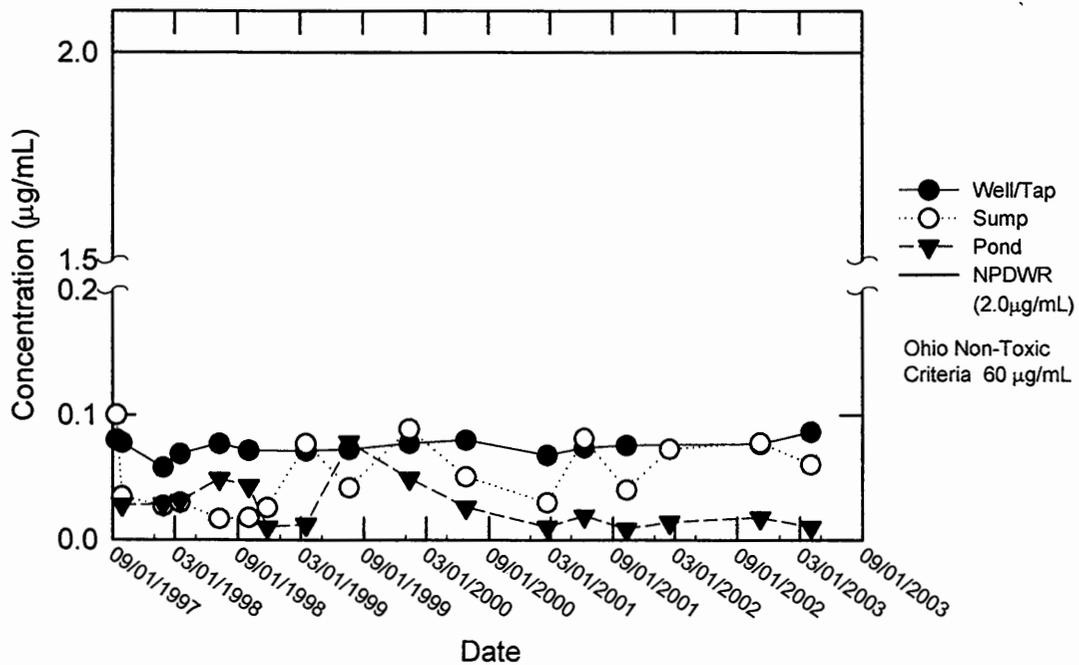


Figure 4.10 Concentration of Barium for Sump, Pond, and Well Samples

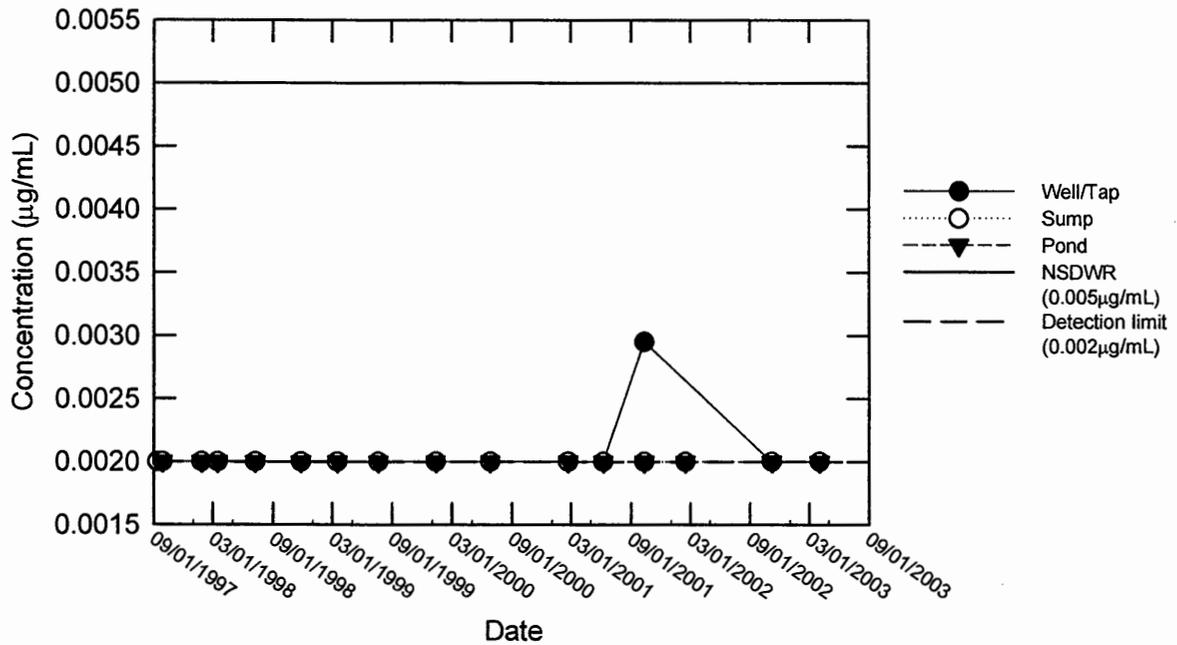


Figure 4.11 Concentration of Cadmium for Sump, Pond, and Well Samples

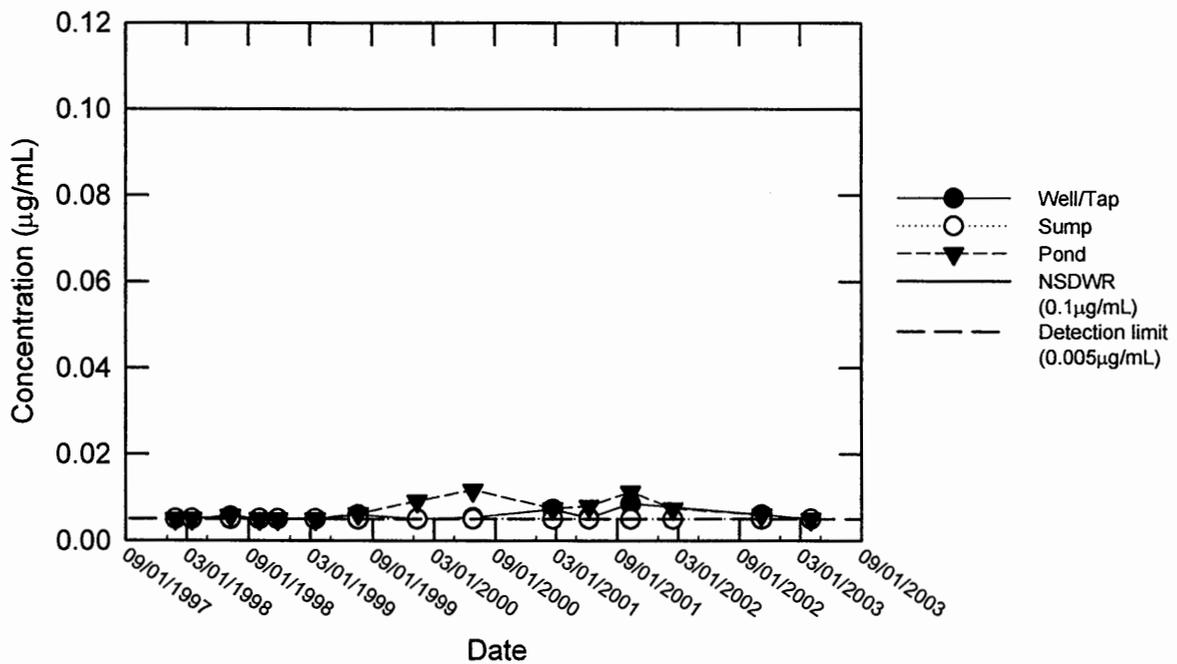


Figure 4.12 Concentration of Chromium for Sump, Pond, and Well Samples

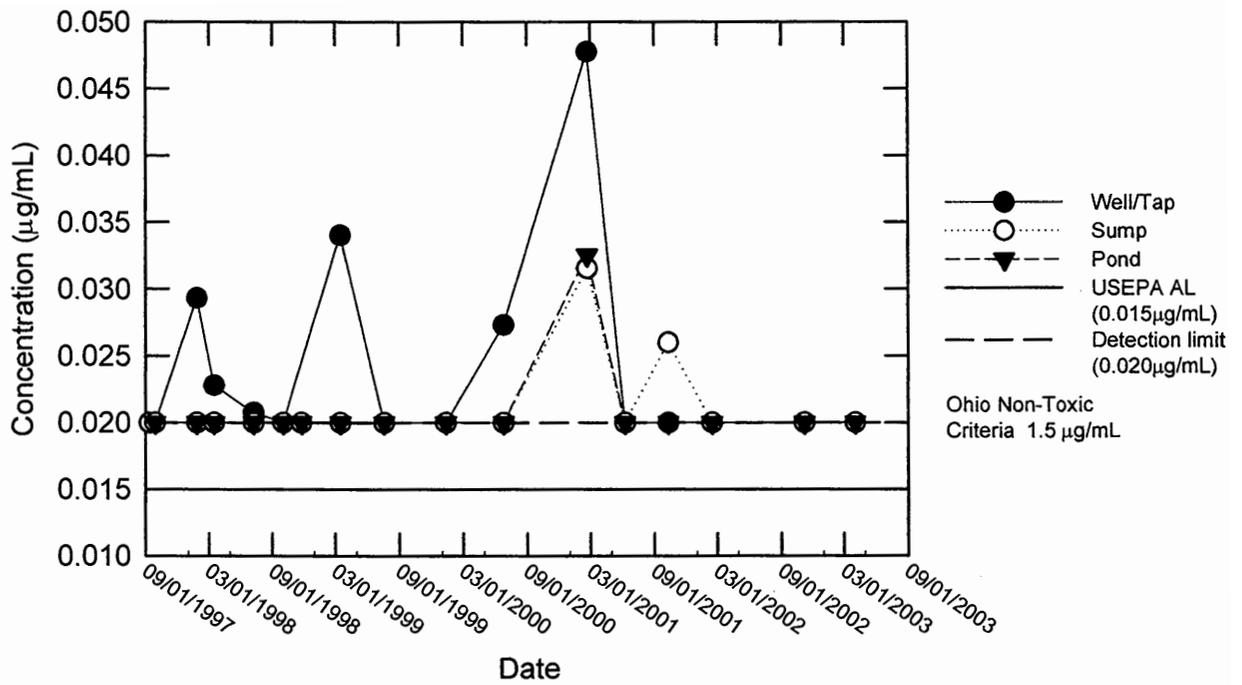


Figure 4.13 Concentration of Lead for Sump, Pond, and Well Samples

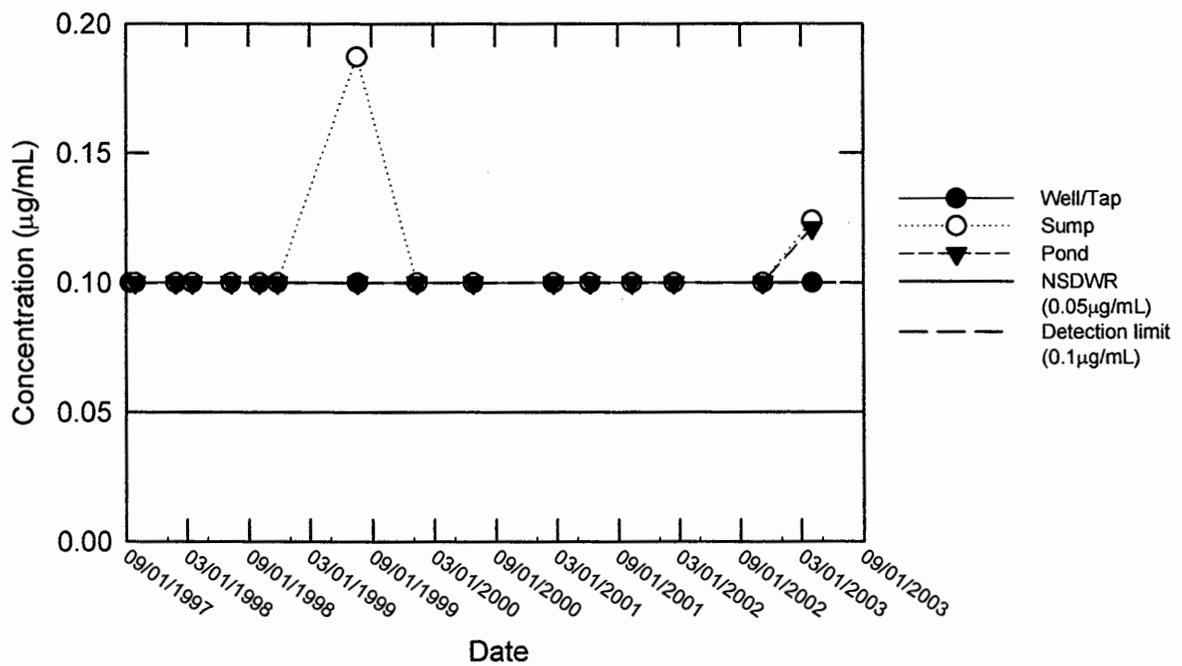


Figure 4.14 Concentration of Selenium for Sump, Pond, and Well Samples

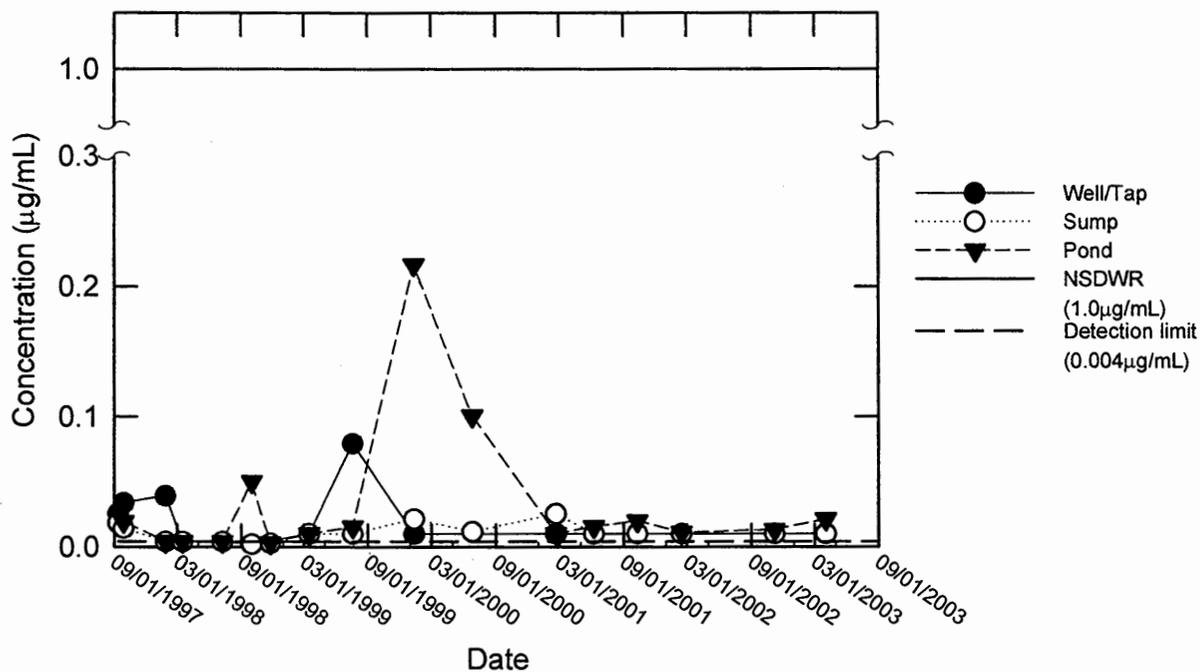


Figure 4.15 Concentration of Copper for Sump, Pond, and Well Samples

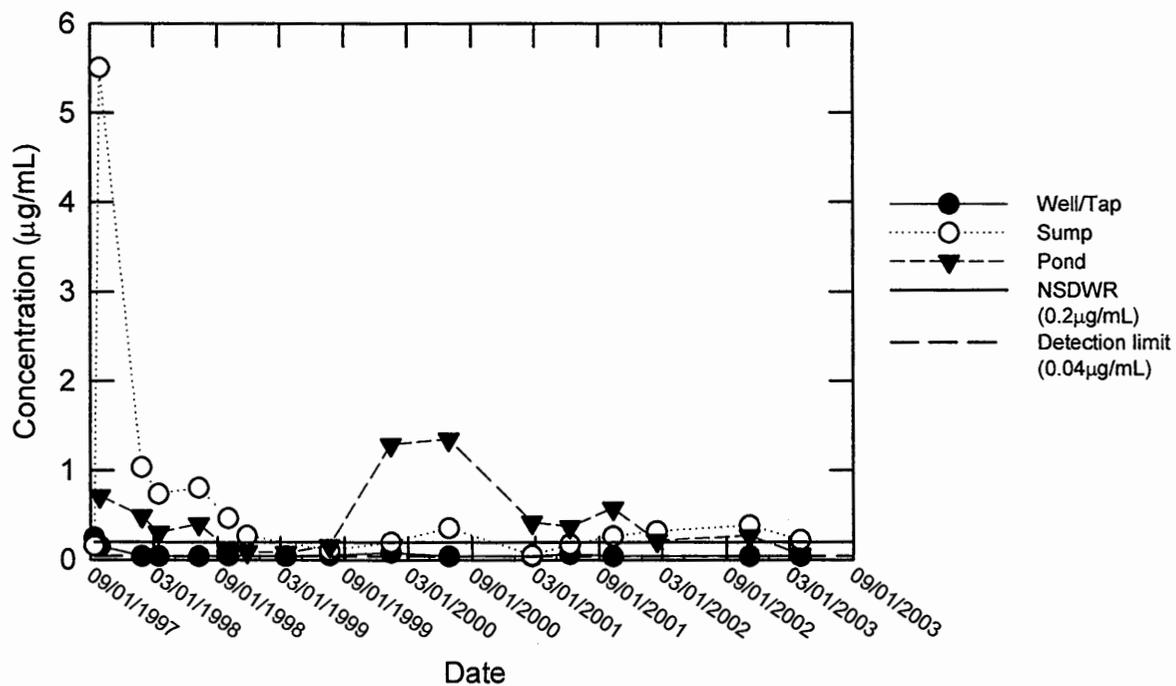


Figure 4.16 Concentration of Aluminum for Sump, Pond, and Well Samples

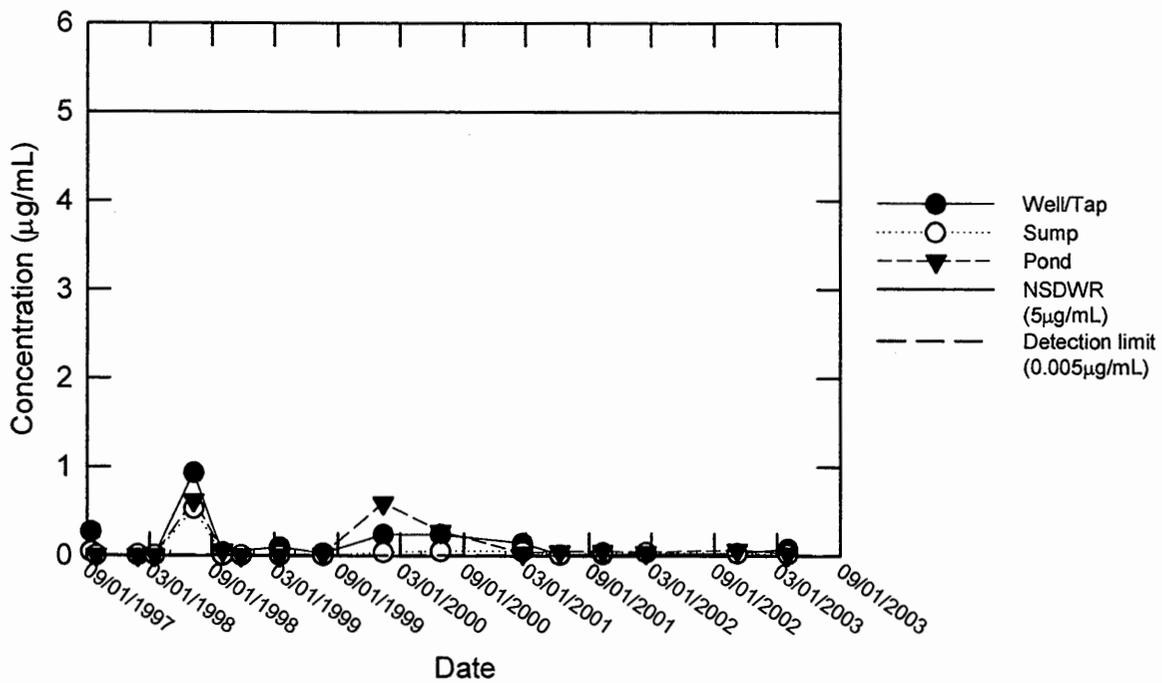


Figure 4.17 Concentration of Zinc for Sump, Pond, and Well Samples

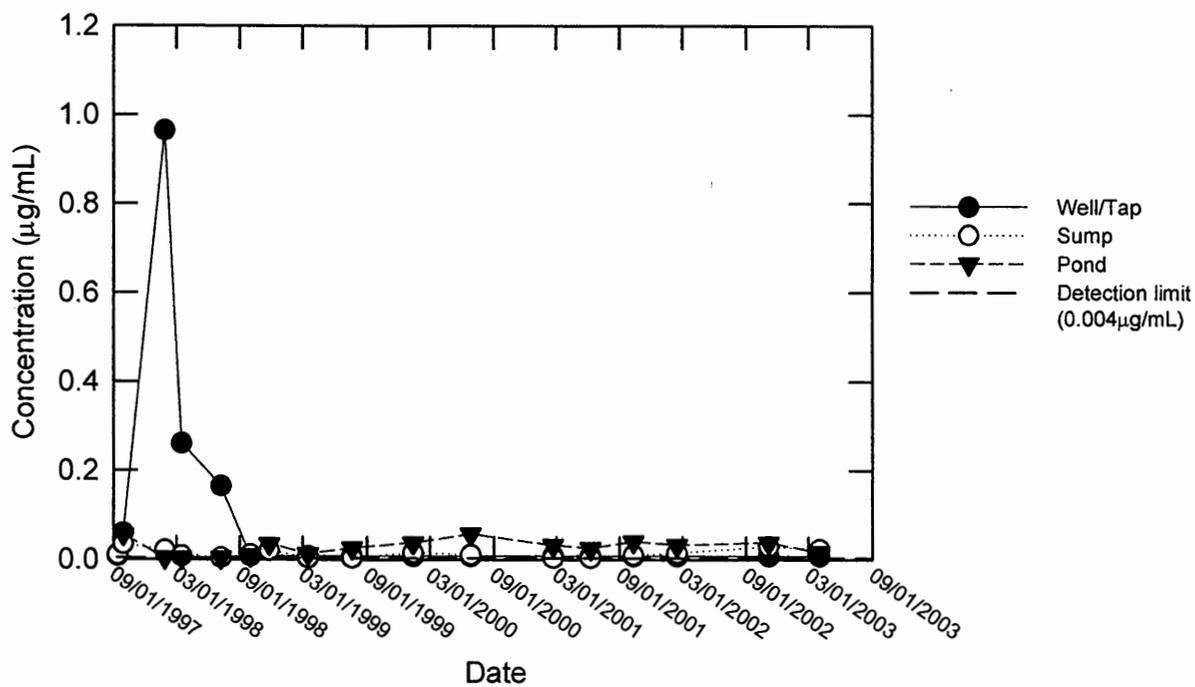


Figure 4.18 Concentration of Vanadium for Sump, Pond, and Well Samples

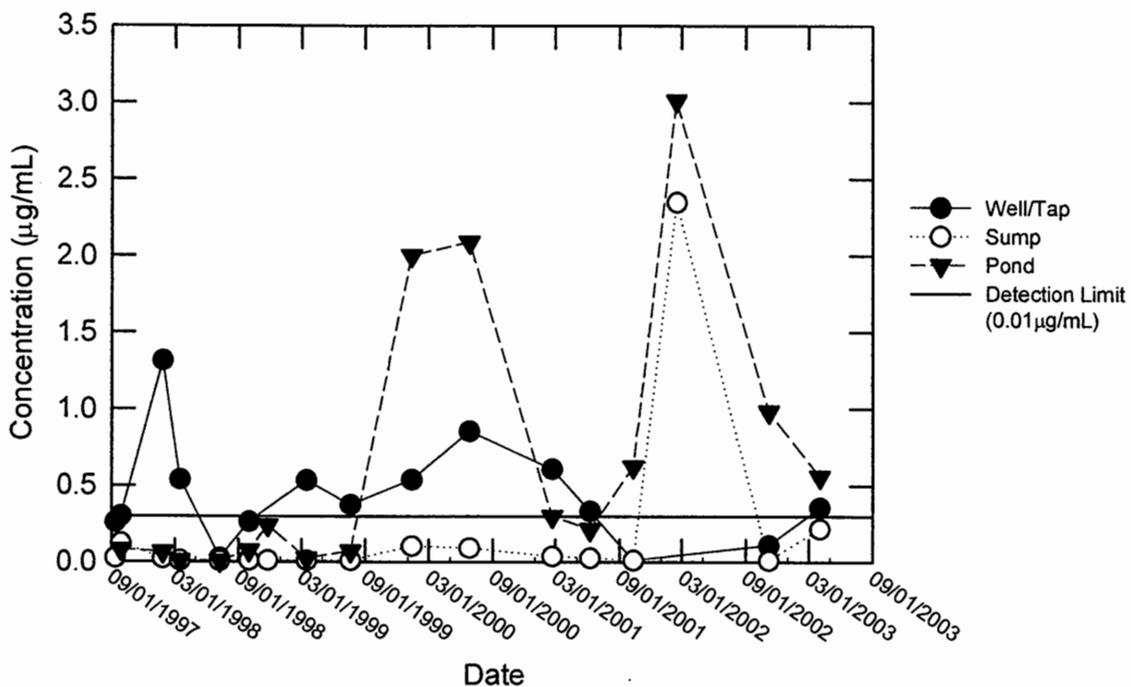


Figure 4.19 Concentration of Dissolved Iron for Sump, Pond, and Well Samples

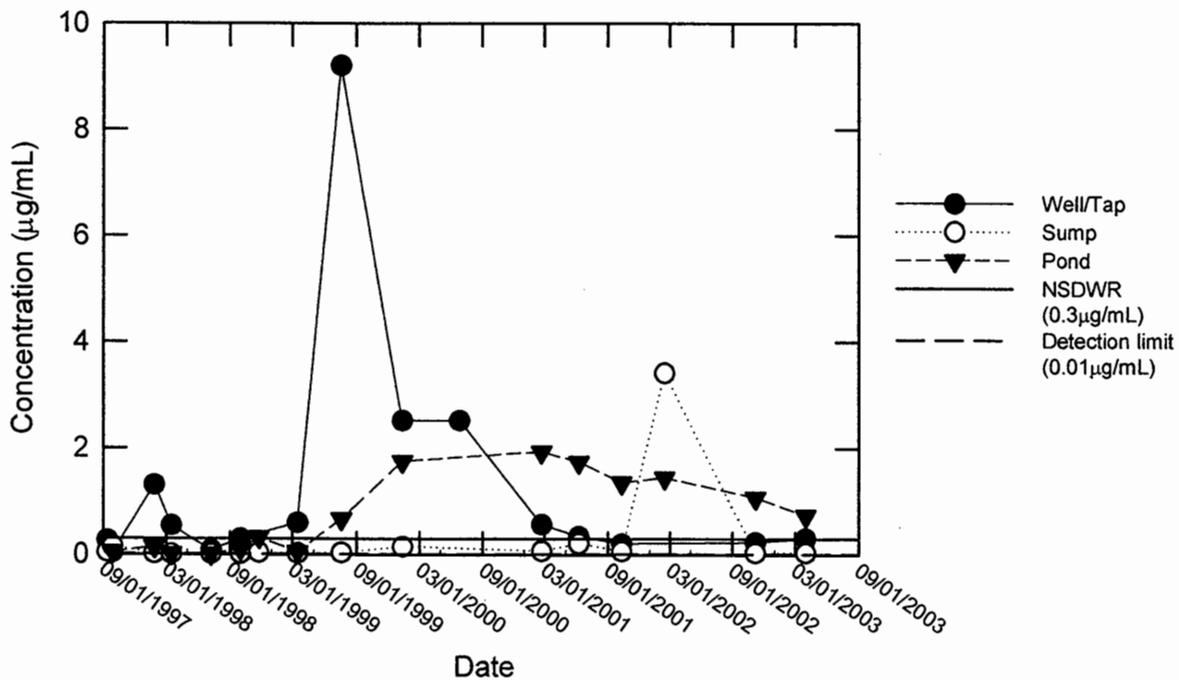


Figure 4.20 Concentration of Total Iron for Sump, Pond, and Well Samples

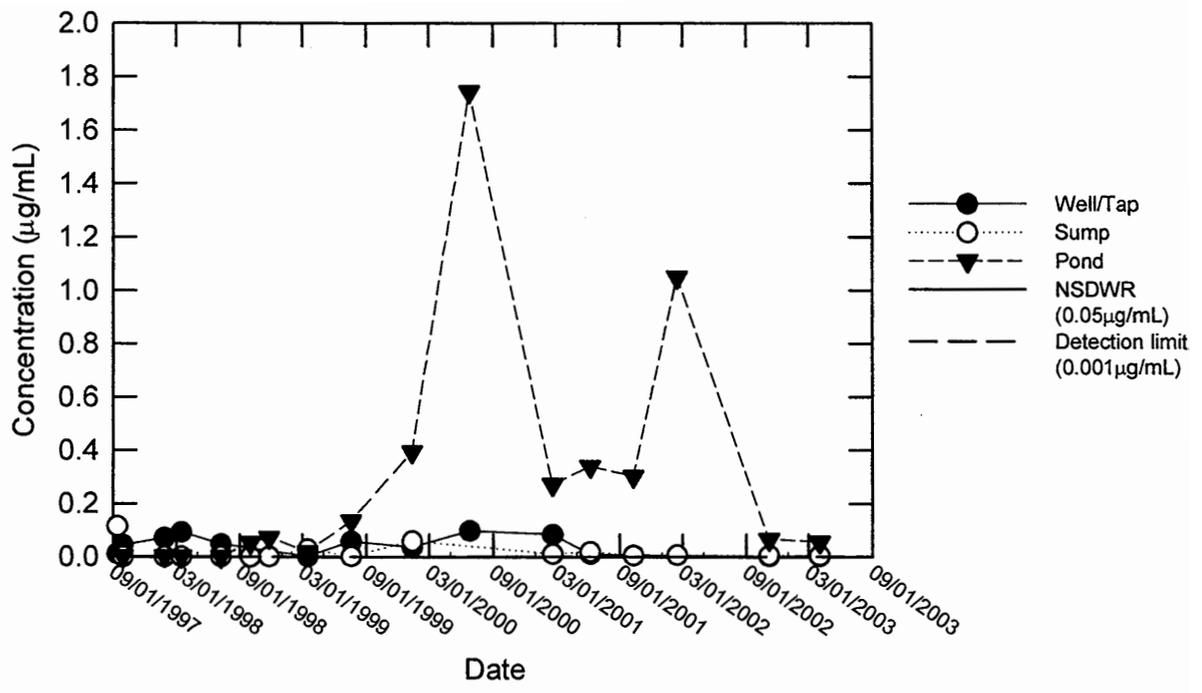


Figure 4.21 Concentration of Total Manganese for Sump, Pond, and Well Samples

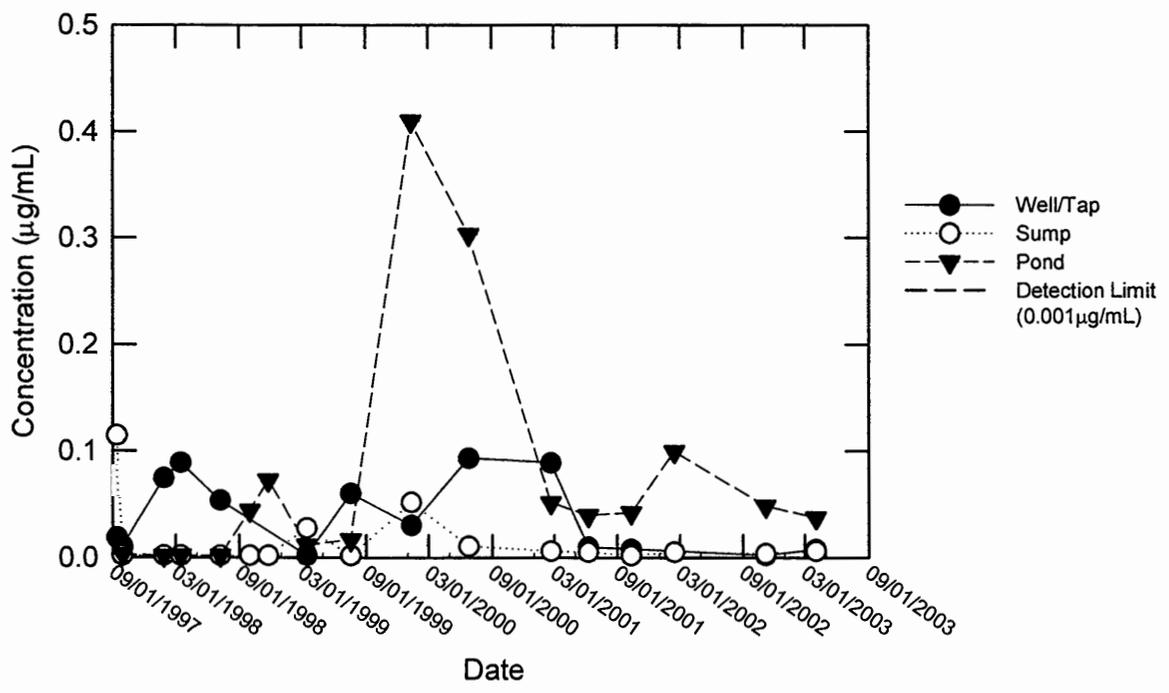


Figure 4.22 Concentration of Dissolved Manganese for Sump, Pond, and Well Samples

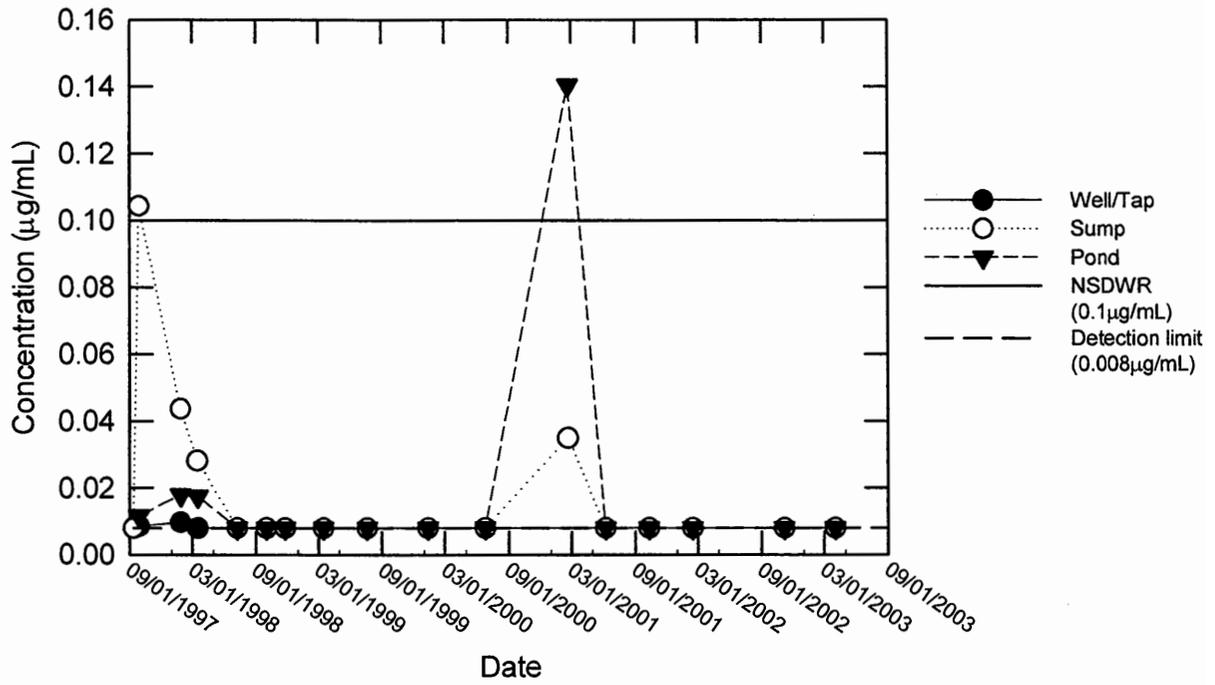


Figure 4.23 Concentration of Silver for Sump, Pond, and Well Samples

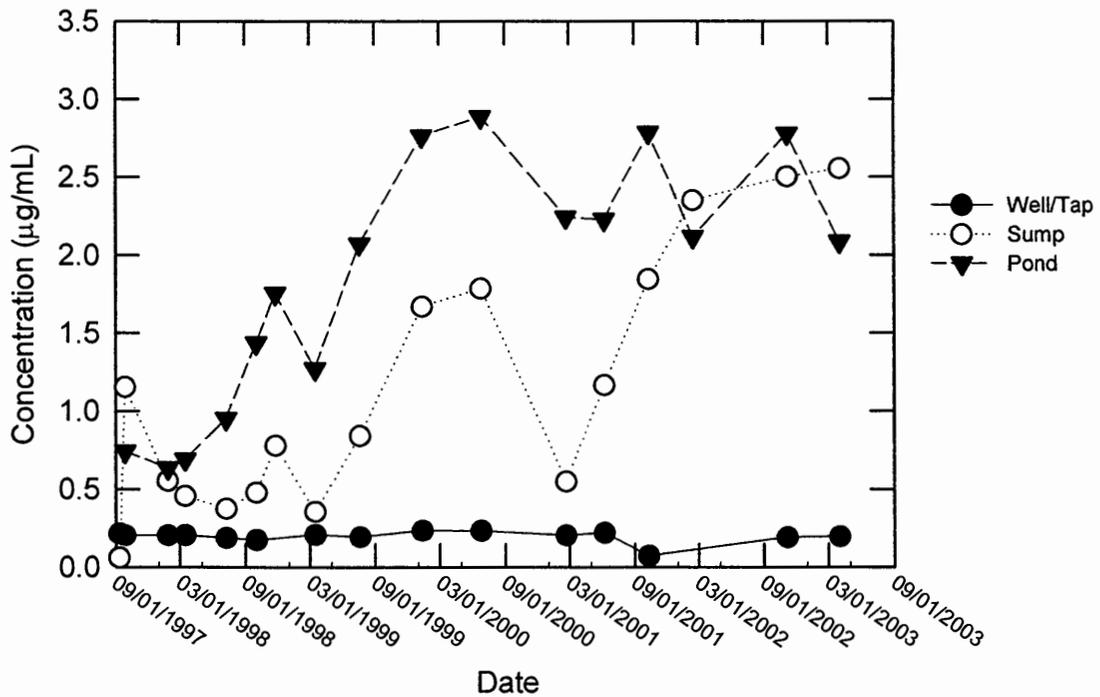


Figure 4.24 Concentration of Boron for Sump, Pond, and Well Samples

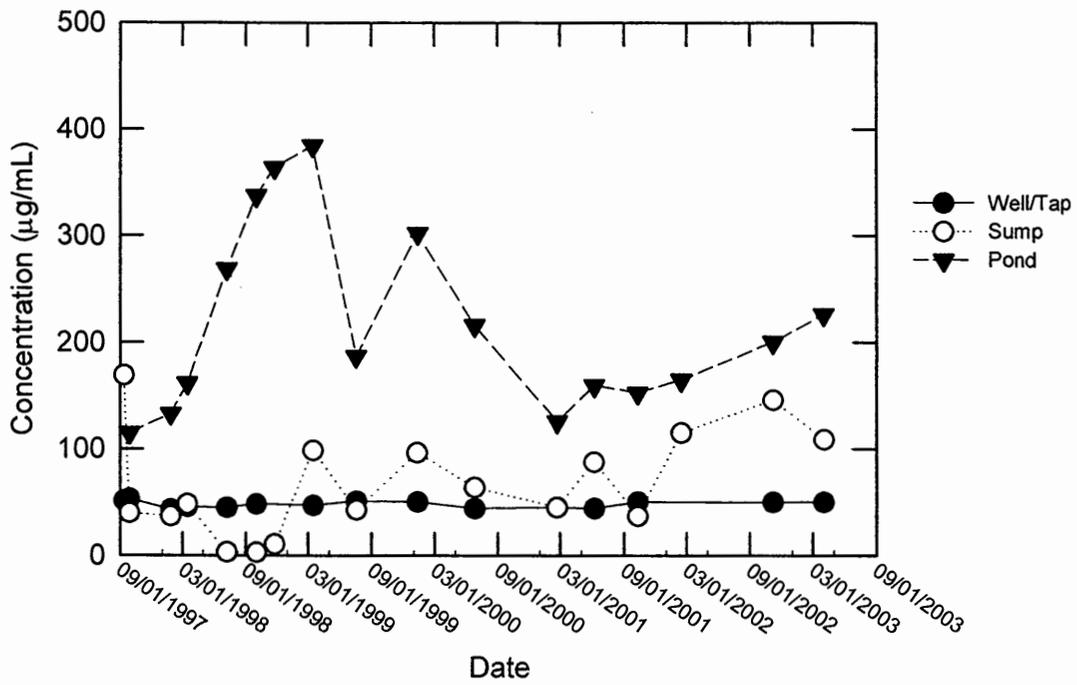


Figure 4.25 Concentration of Calcium for Sump, Pond, and Well Samples

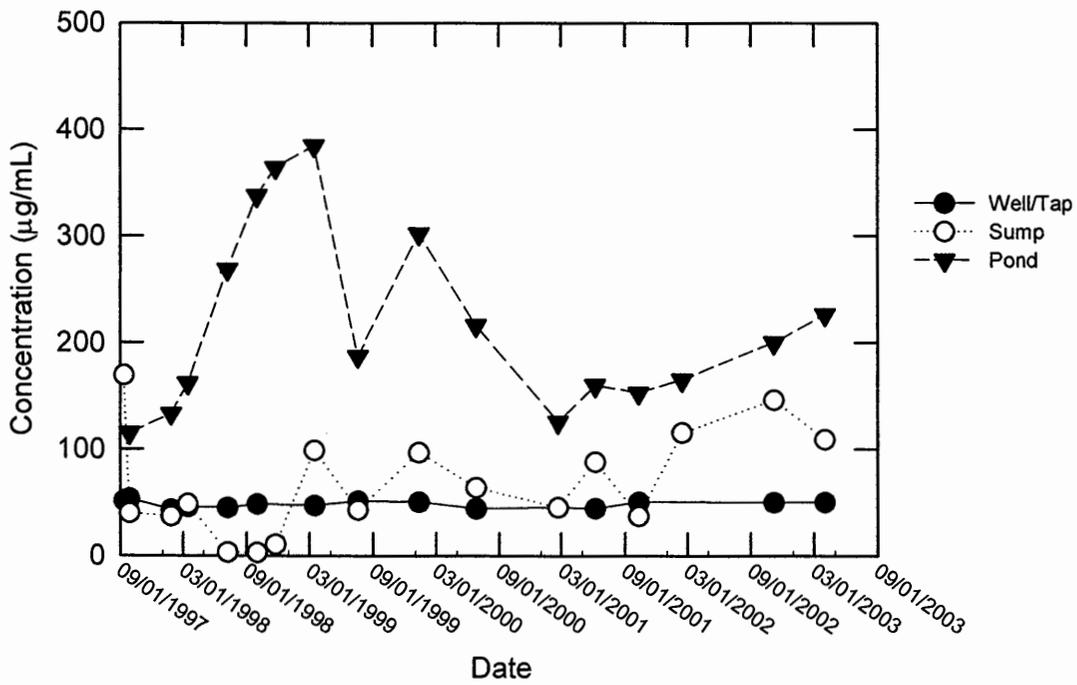


Figure 4.26 Concentration of Magnesium for Sump, Pond, and Well Samples

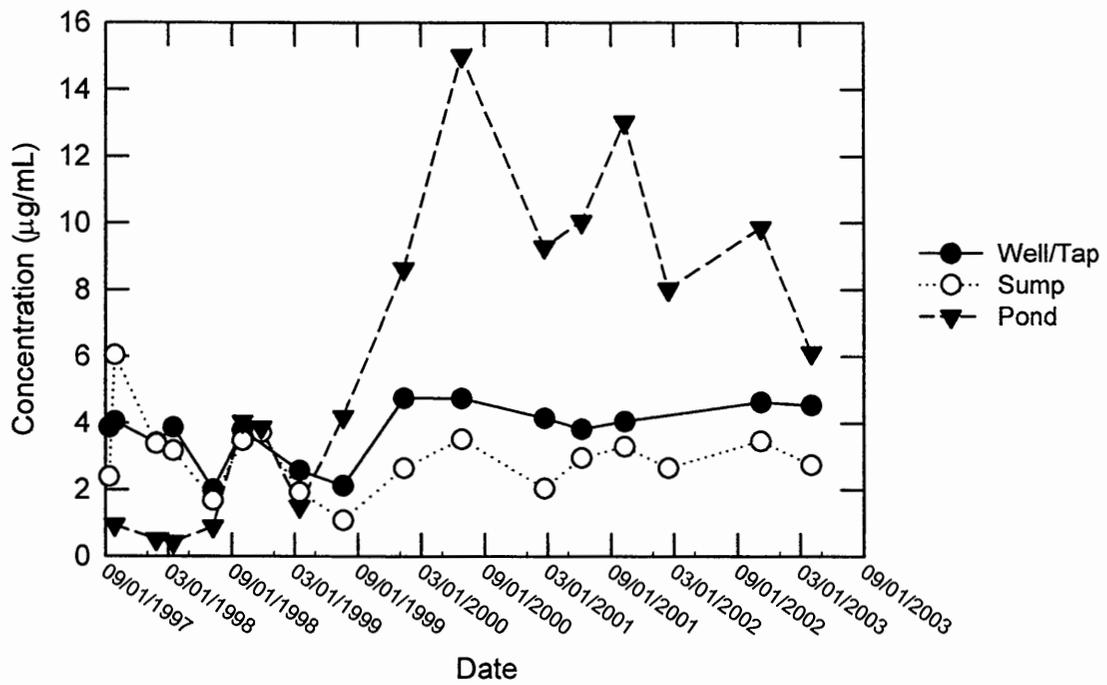


Figure 4.27 Concentration of Silica for Sump, Pond, and Well Samples

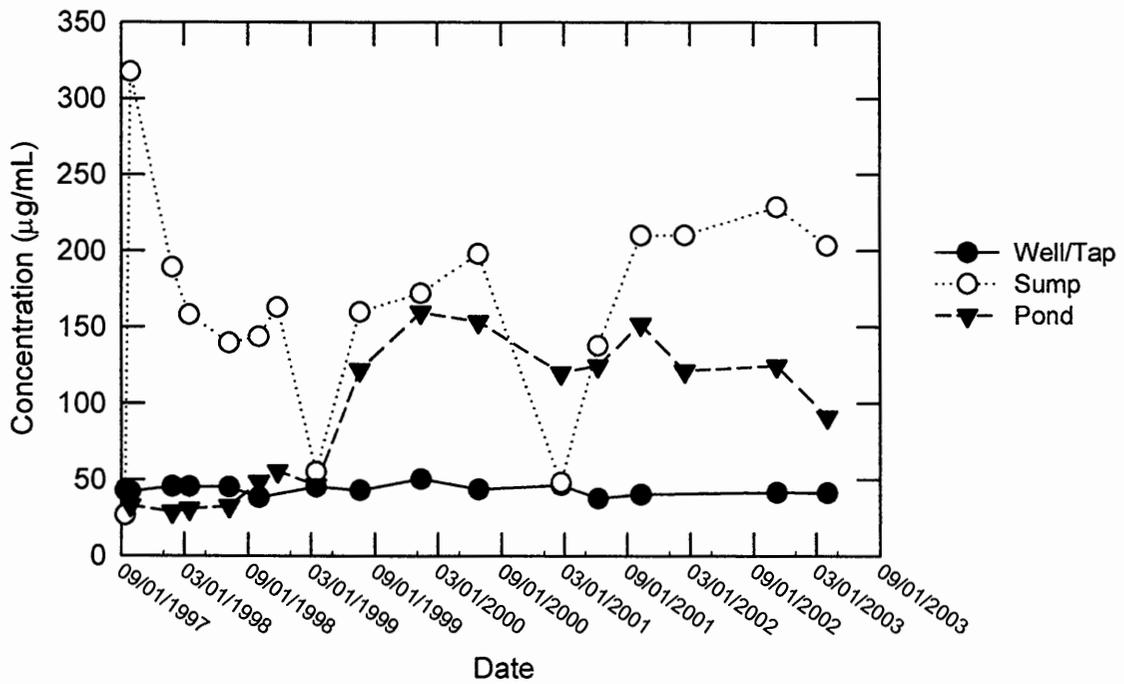


Figure 4.28 Concentration of Sodium for Sump, Pond, and Well Samples

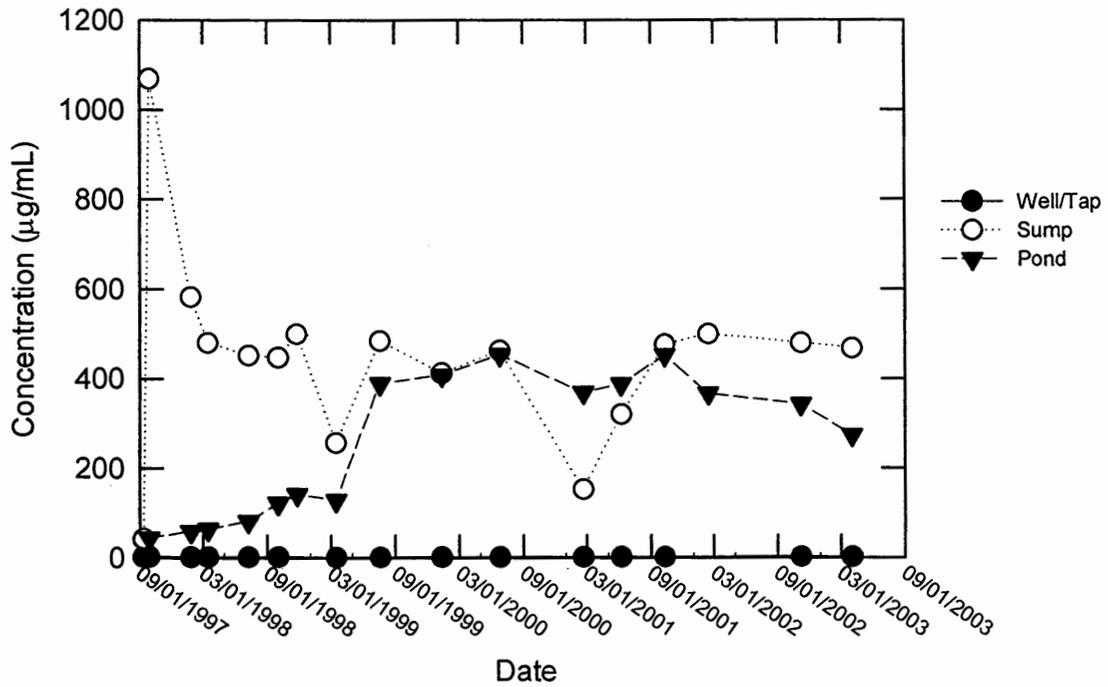


Figure 4.29 Concentration of Potassium for Sump, Pond, and Well Samples

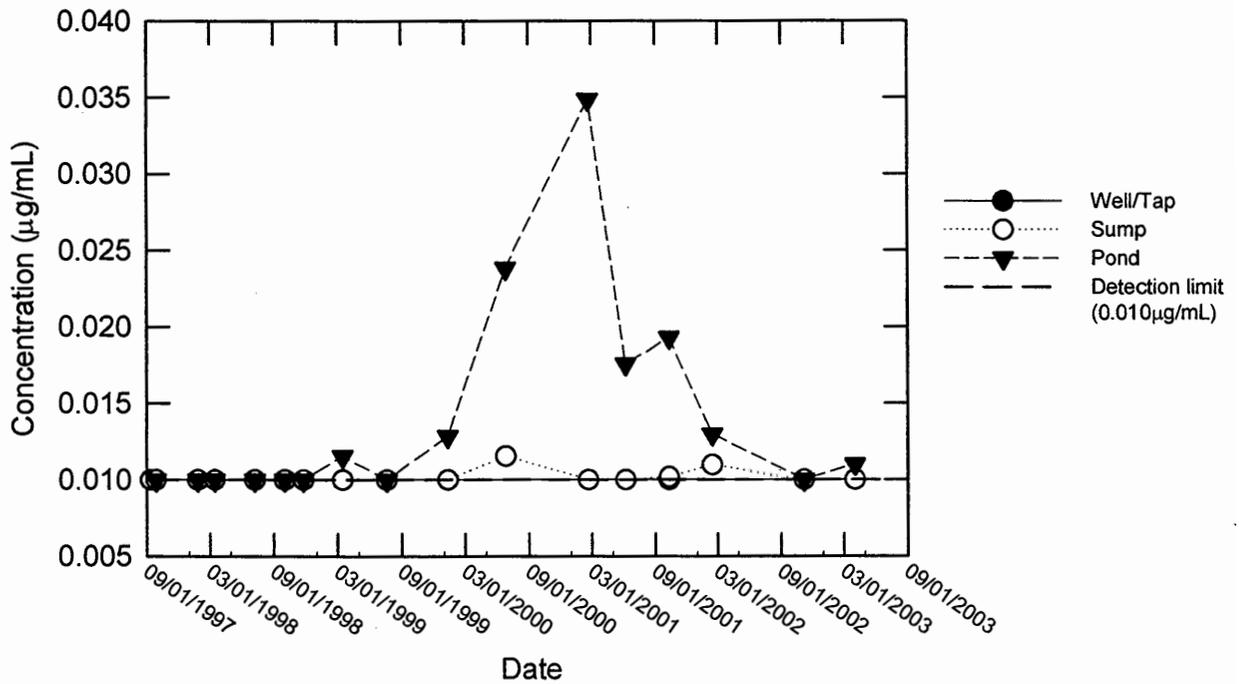


Figure 4.30 Concentration of Nickel for Sump, Pond, and Well Samples

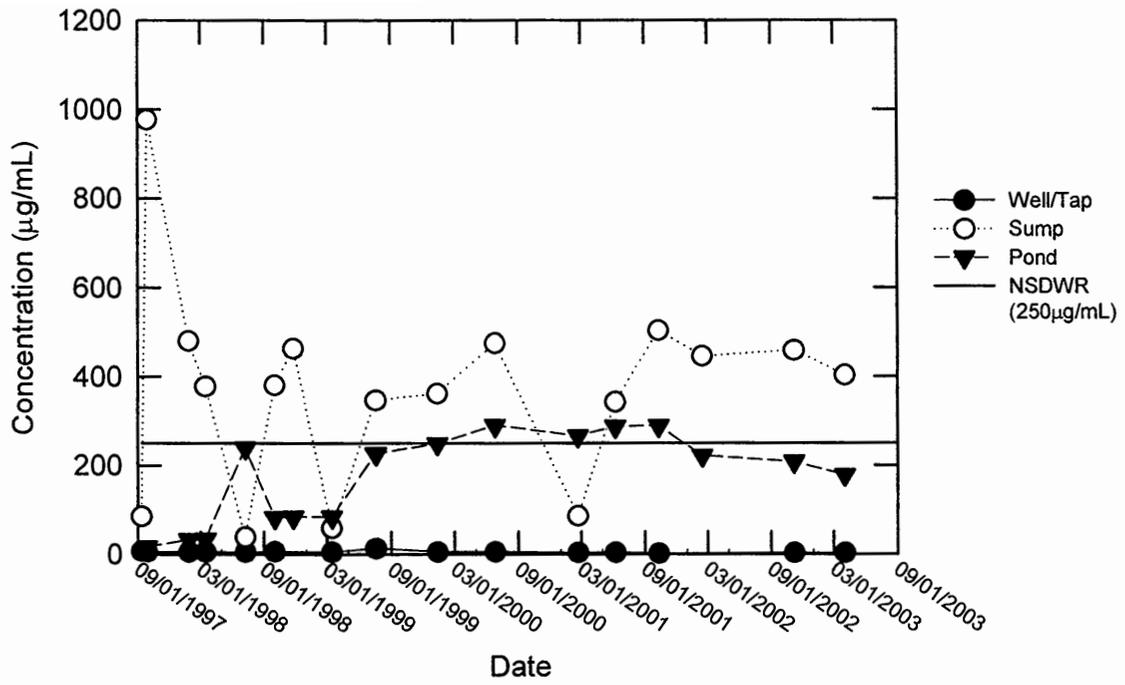


Figure 4.31 Concentration of Chloride for Sump, Pond, and Well Samples

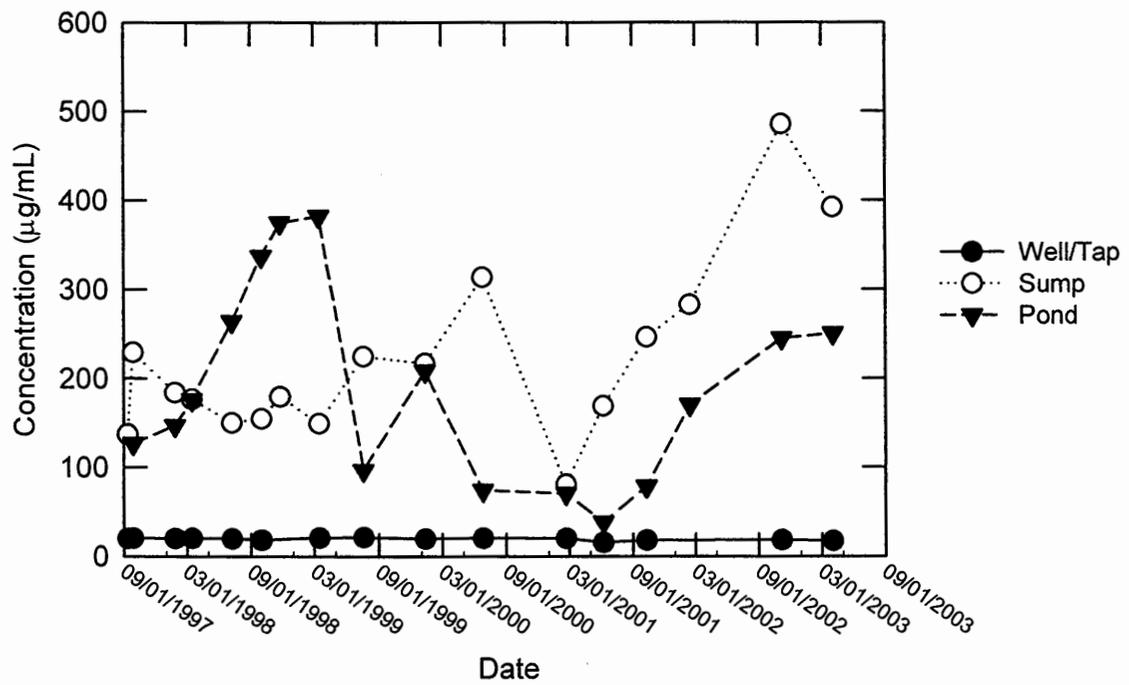


Figure 4.32 Concentration of Sulfur for Sump, Pond, and Well Samples

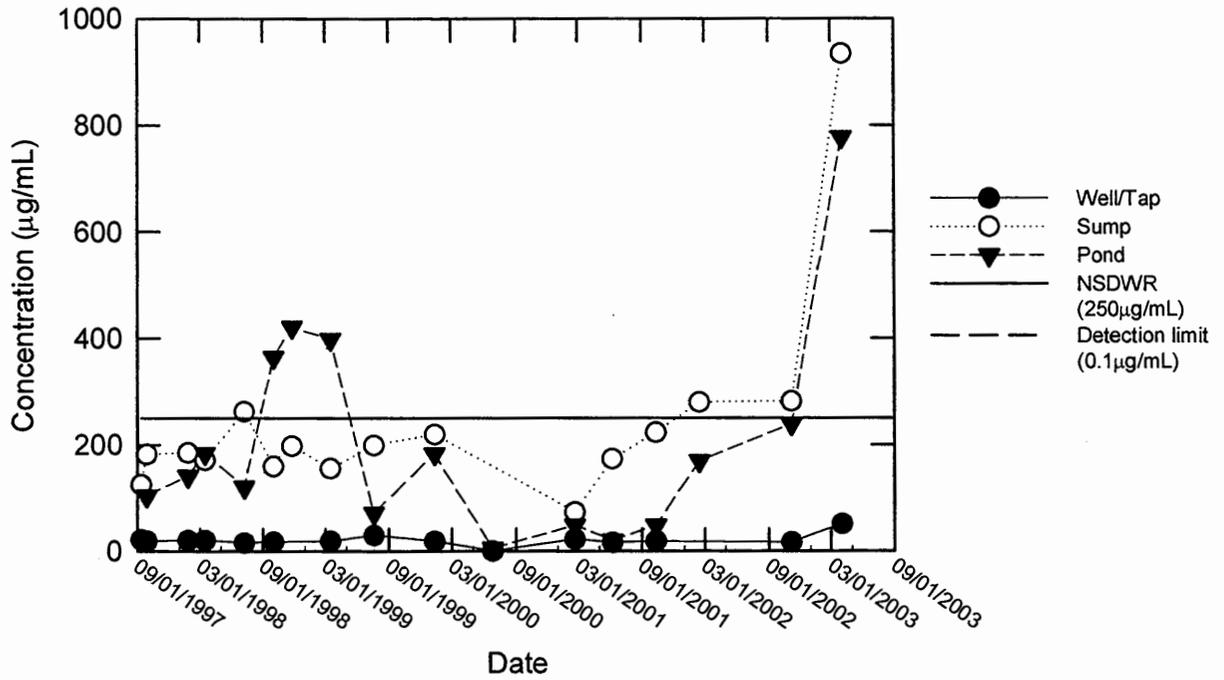


Figure 4.33 Concentration of Sulfate for Sump, Pond, and Well Samples

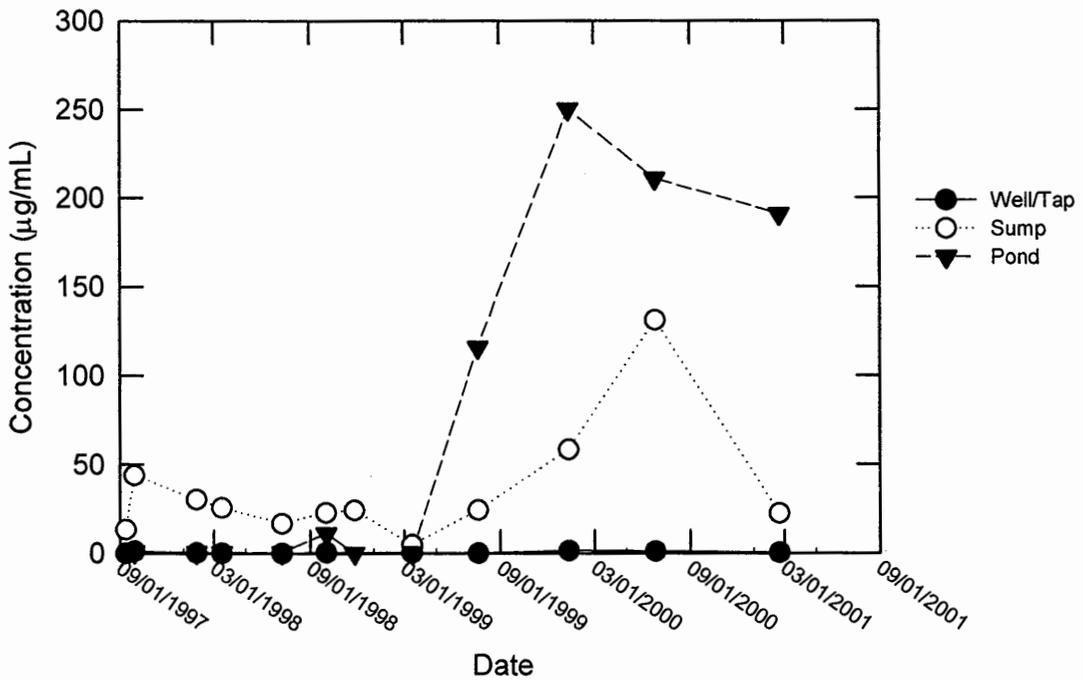


Figure 4.34 Concentration of Nitrogen for Sump, Pond, and Well Samples

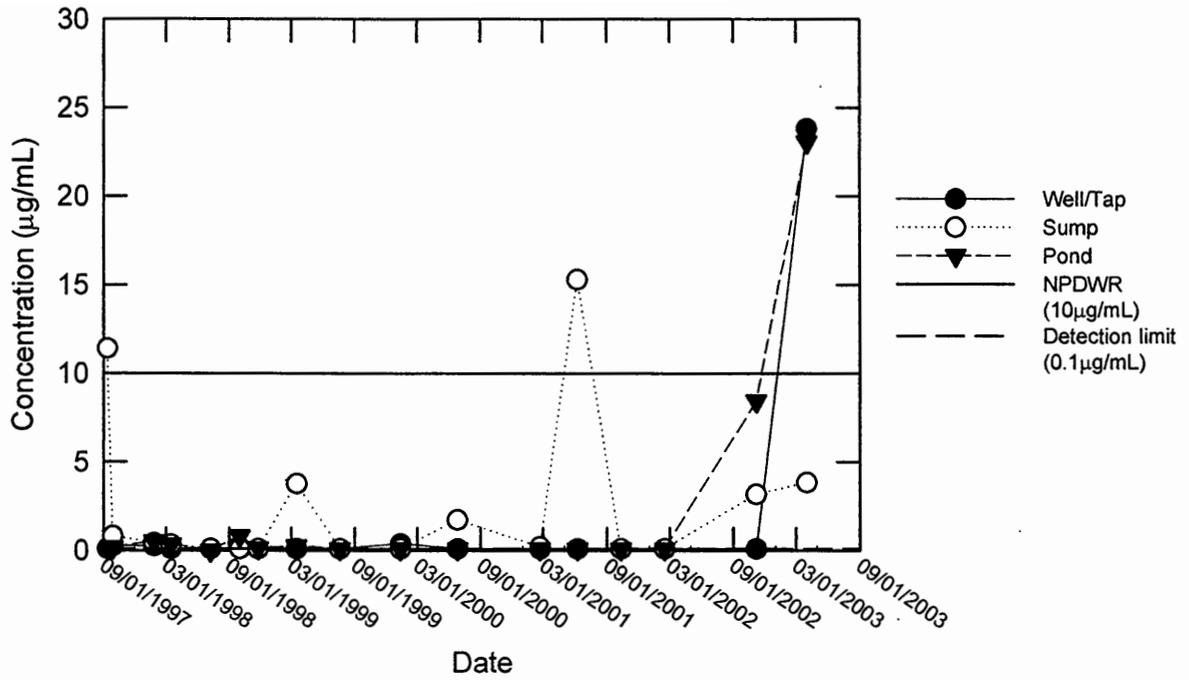


Figure 4.35 Concentration of Nitrate for Sump, Pond, and Well Samples

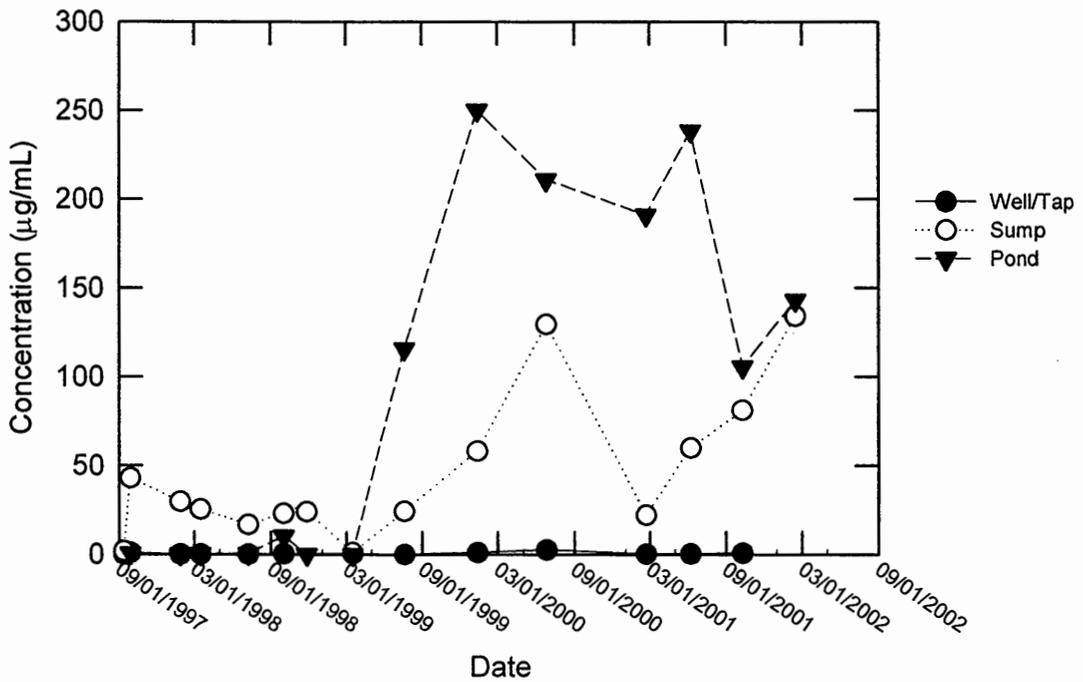


Figure 4.36 Concentration of Ammonia for Sump, Pond, and Well Samples

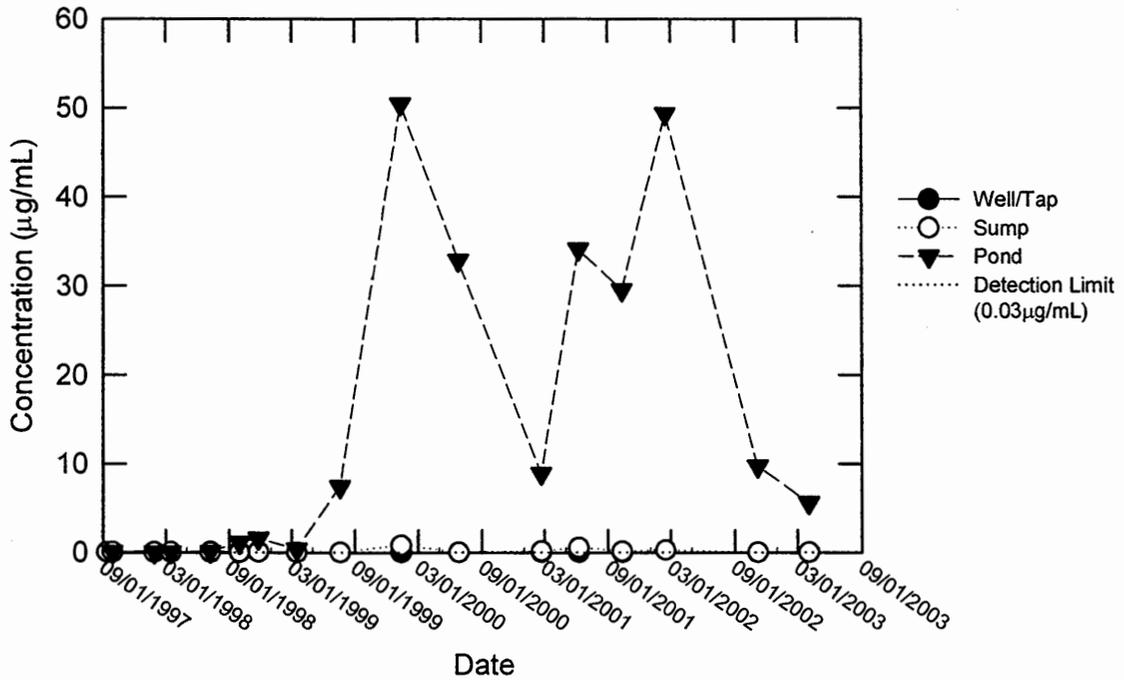


Figure 4.37 Concentration of Phosphorus for Sump, Pond, and Well Samples

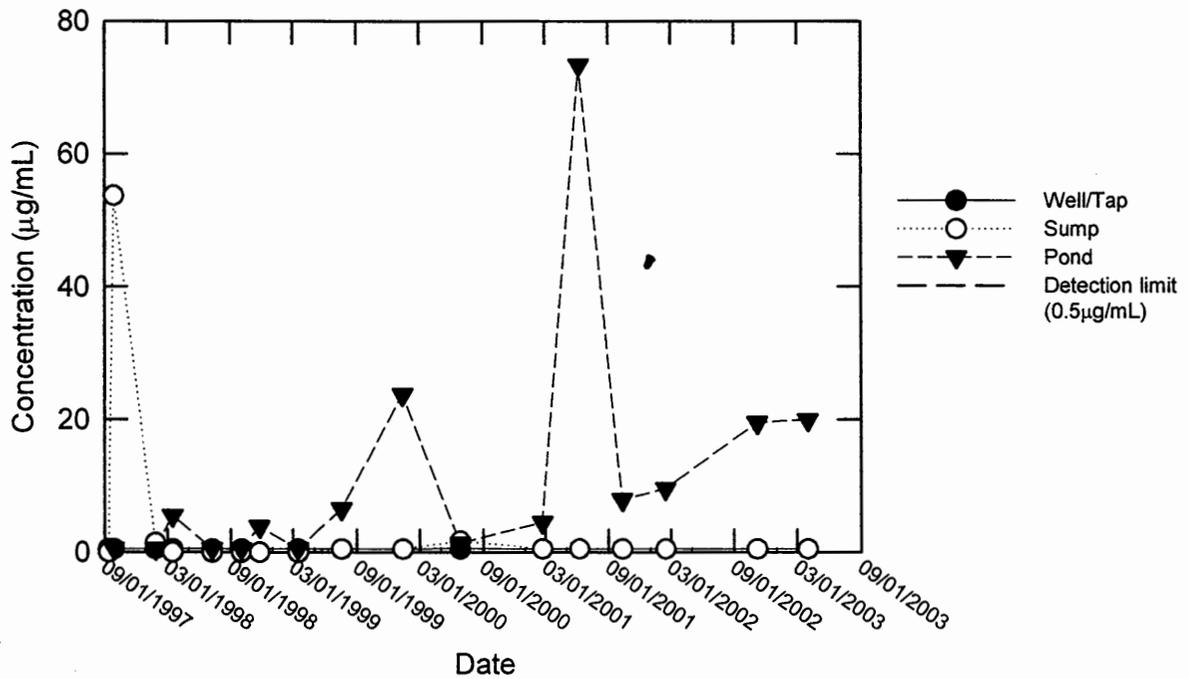


Figure 4.38 Concentration of Phosphates for Sump, Pond, and Well Samples

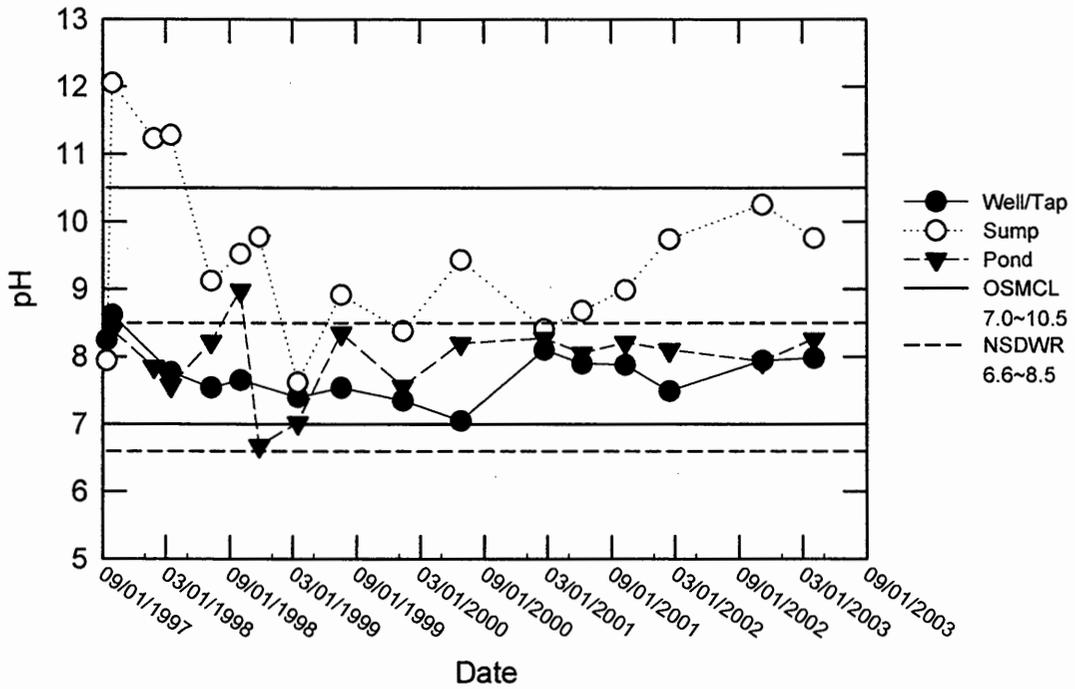


Figure 4.39 pH of Sump, Pond, and Well Samples

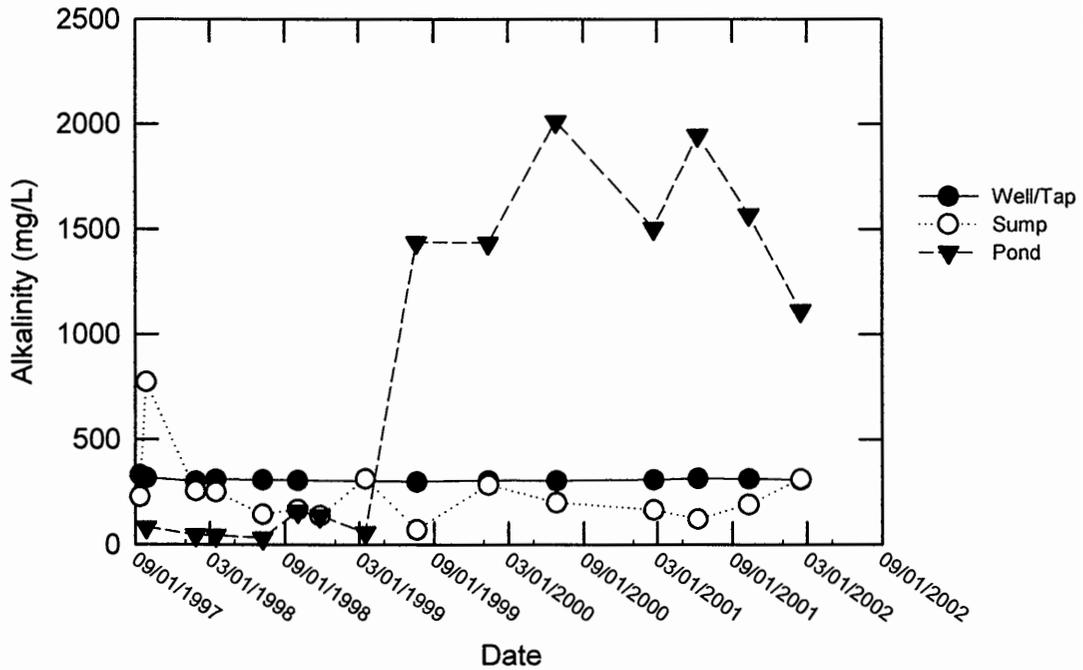


Figure 4.40 Alkalinity of Sump, Pond, and Well Samples

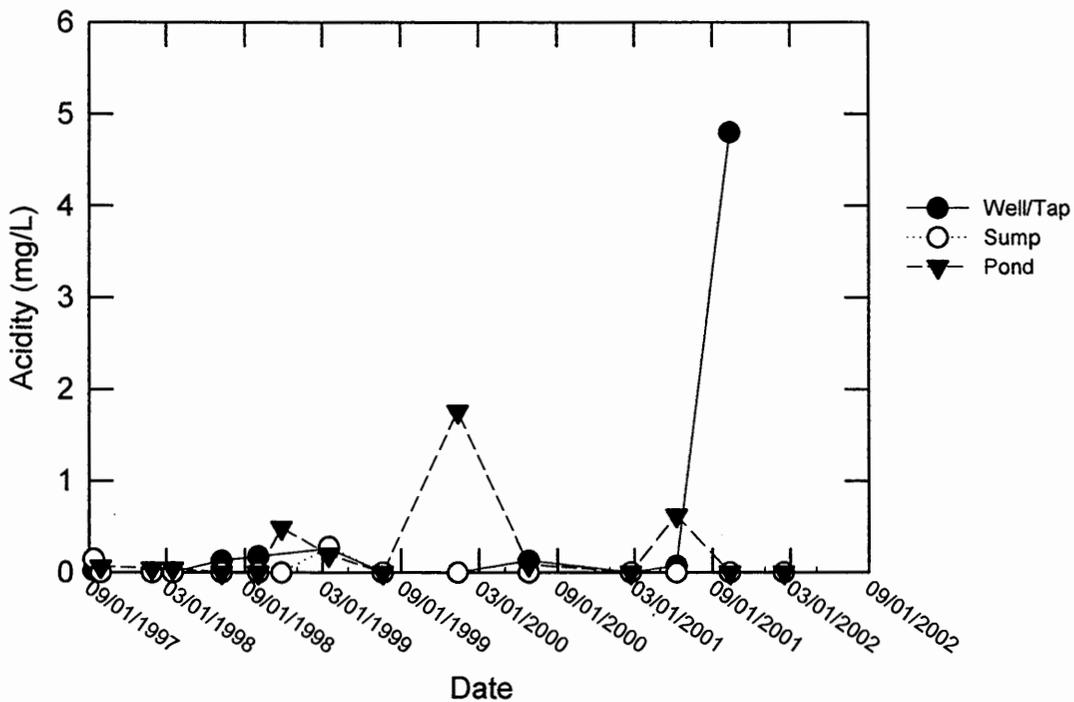


Figure 4.41 Acidity of Sump, Pond, and Well Samples

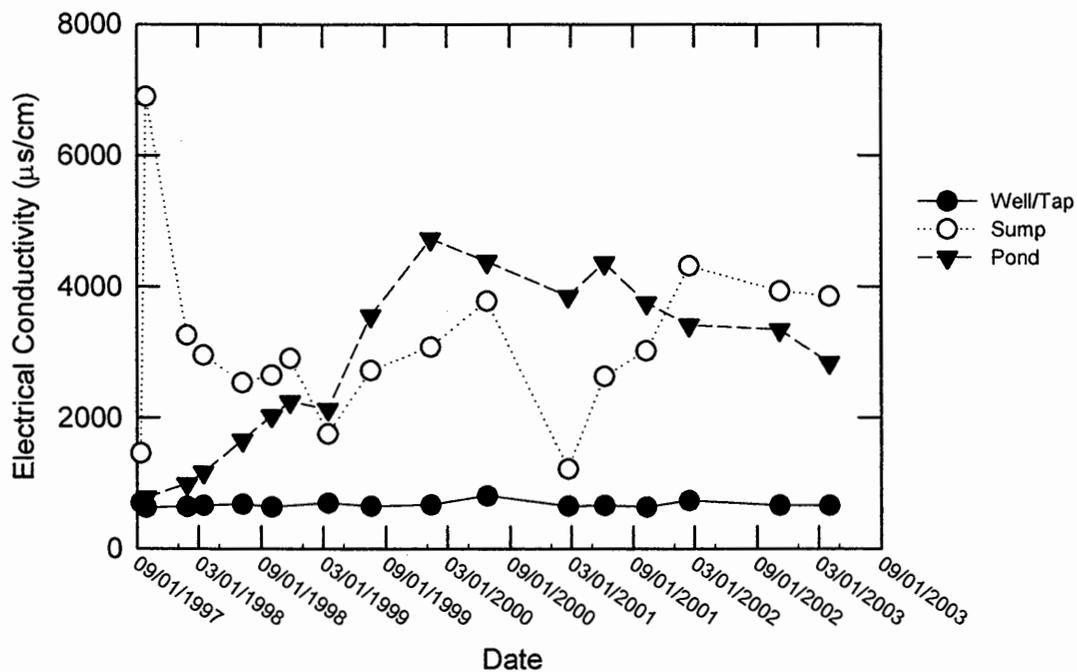


Figure 4.42 Conductivity of Sump, Pond, and Well Samples

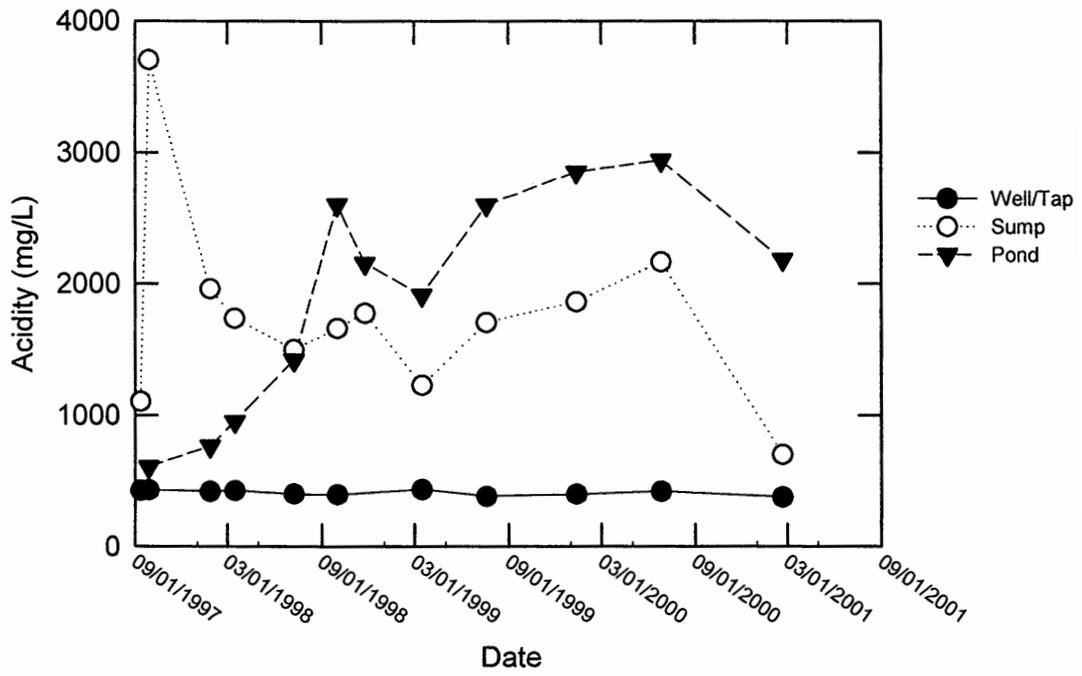


Figure 4.43 Residual of Evaporation of Sump, Pond, and Well Samples

Table 4.3 Water Quality Monitoring

Date Sample Collected	Location of Sample	pH	Electrical Conductivity ($\mu\text{S}/\text{cm}$)	Alkalinity (mg/L)	Acidity (meq/L)	Residue of Evaporation at 180°C (mg/L)
9/12/1997	Sump	7.94	1460.15	227.83	0.14	1102.86
	Well	8.25	702.43	331.06	0.02	427.14
9/28/1997	Sump	12.05	6894.24	772.64	0.00	3702.86
	Pond	8.39	780.48	82.24	0.06	607.50
	Well	8.62	628.72	317.50	0.00	430.00
1/26/1998	Sump	11.23	3260.40	254.76	0.00	1962.00
	Pond	7.85	988.00	44.97	0.04	764.00
	Well (Tap)	7.96	642.20	301.36	0.00	420.00
3/16/1998	Sump	11.28	2954.12	251.24	0.00	1736.00
	Pond	7.57	1165.84	42.99	0.04	952.00
	Well	7.77	661.96	310.60	0.00	426.00
7/9/1998	Sump	9.12	2536.56	143.69	0.00	1498.57
	Pond	8.22	1658.52	31.06	0.00	1420.00
	Well	7.54	682.92	308.19	0.13	400.00
10/2/1998	Sump	9.52	2650.00	167.28	0.00	1661.43
	Pond	8.98	2030.00	158.59	0.00	2604.00
	Well	7.65	640.00	305.06	0.18	395.71
11/25/1998	Sump	9.77	2905.12	138.41	0.00	1777.14
	Pond	6.68	2243.88	137.74	0.49	2156.00
	Well	7.64	672.08	310.39	0.13	404.29
3/16/1999	Sump	7.62	1756.08	312.44	0.28	1227.14
	Pond	7.02	2134.40	57.77	0.20	1913.33
	Well	7.40	701.35	299.02	0.26	434.29
7/20/1999	Sump	8.92	2720.84	71.24	0.00	1707.14
	Pond (Center)	8.24	3555.52	1436.48	0.00	2600.00
	Pond (Edge)	8.35	3295.36	1363.44	0.00	2511.43
	Well	7.54	650.40	304.88	0.00	382.86
1/12/2000	Sump	8.38	3078.56	283.80	0.00	1862.86
	Pond	7.56	4726.24	1433.79	1.76	2850.00
	Well	7.35	672.08	303.90	0.00	398.57
Regulatory Standards		6.6 - 8.5**				
		7.0 - 10.5§				

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- § Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	pH	Electrical Conductivity (mS/cm)	Alkalinity (mg/L)	Acidity (meq/L)	Residue of Evaporation at 180oC (mg/L)
6/26/2000	Sump	9.43	3780	199.6	0.0	2166
	Pond	8.20	4380	2012.0	0.1	2939
	Well	7.05	810	308.9	0.1	420
2/20/2001	Sump	8.41	1220	164.9	0.0	700
	Pond	8.27	3850	1502.3	0.0	2183
	Well	8.10	650	315.4	0.0	377
6/8/2001	Sump	8.68	2630	121.7	0.0	-
	Pond	8.05	4360	1947.5	0.6	-
	Well (Tap)	7.90	662	313.3	0.1	-
10/11/2001	Sump	8.99	3020	191.351	0.0	-
	Pond	8.21	3750	1568.935	0.0	-
	Well	7.88	640	307.343	4.8	-
2/14/2002	Sump	9.74	4310	311.3	0.0	-
	Pond	8.1	3410	1111.4	0.0	-
	Well	7.49	735	-	-	-
11/7/2002	Sump	10.25	3930	-	-	-
	Pond	7.93	3340	-	-	-
	Well	7.94	664	-	-	-
4/2/2003	Sump	9.76	3850	-	-	-
	Pond	8.26	2840	-	-	-
	Well	7.98	662	-	-	-
Regulatory Standards		6.6 - 8.5**				
		7.0 - 10.5\$				

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Al (Dissolved)	As	B	Ba	Ca
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
9/12/97	Sump	0.157	<0.035	0.059	0.100	169.111
	Well	0.248	<0.035	0.214	0.080	51.304
9/28/97	Sump	5.505	0.049	1.154	0.035	39.844
	Pond	0.713	<0.035	0.742	0.028	114.766
	Well	0.151	<0.035	0.204	0.078	53.127
1/26/98	Sump	1.033	<0.035	0.552	0.027	36.849
	Pond	0.489	<0.035	0.635	0.028	132.885
	Well (Tap)	<0.040	<0.035	0.203	0.058	43.053
3/16/98	Sump	0.737	<0.035	0.455	0.030	48.298
	Pond	0.305	<0.035	0.692	0.031	161.677
	Well	<0.040	<0.035	0.205	0.069	45.429
7/9/98	Sump	0.809	<0.035	0.374	0.017	2.871
	Pond	0.403	<0.035	0.952	0.049	268.391
	Well	<0.040	<0.035	0.187	0.077	44.950
10/2/98	Sump	0.465	<0.035	0.478	0.018	2.600
	Pond	0.118	0.046	1.435	0.043	337.534
	Well	0.048	<0.035	0.173	0.072	48.217
11/25/98	Sump	0.270	0.038	0.779	0.026	10.568
	Pond	0.090	0.086	1.753	0.010	363.885
	Well	<0.027	<0.035	0.194	0.079	50.254
3/16/99	Sump	<0.040	<0.045	0.354	0.077	98.625
	Pond	0.080	0.052	1.271	0.046	384.444
	Well	<0.040	<0.045	0.208	0.071	47.097
7/20/99	Sump	0.106	<0.045	0.840	0.042	42.746
	Pond (Center)	0.158	0.114	2.071	0.008	187.015
	Pond (Edge)	0.147	0.074	2.035	0.012	174.951
	Well	0.050	<0.045	0.194	0.073	51.005
1/12/00	Sump	0.197	0.059	1.670	0.089	96.484
	Pond	1.291	0.124	2.762	0.049	301.880
	Well	0.081	<0.045	0.233	0.078	50.182
Regulatory Standards		0.05 - 0.2**	0.05* 1.5#		2.0* 60.0#	

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Al (Dissolved)	As	B	Ba	Ca
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
6/26/00	Sump	0.355	0.047	1.783	0.051	63.855
		1.350	0.176	2.886	0.026	215.858
	Well	<0.040	<0.045	0.233	0.080	44.055
2/20/01	Sump	0.052	0.057	0.547	0.030	45.066
	Pond	0.423	<0.045	2.241	0.010	125.332
	Well	<0.040	0.094	0.214	0.068	45.205
6/8/01	Sump	0.172	<0.045	1.166	0.081	87.919
	Pond	0.371	0.136	2.225	0.019	159.587
	Well (Tap)	0.065	<0.045	0.203	0.074	44.160
10/11/01	Sump	0.264	0.145	1.843	0.040	36.920
	Pond	0.577	0.140	2.786	0.009	152.833
	Well	0.041	0.071	0.219	0.076	50.148
2/14/02	Sump	0.321	0.101	2.349	0.073	115.130
	Pond	0.216	<0.045	2.115	0.014	164.936
	Well					
11/7/02	Sump	0.386	0.097	2.500	0.078	145.932
	Pond	0.268	<0.045	2.778	0.018	199.994
	Well	0.040	<0.045	0.191	0.077	49.991
4/2/03	Sump	0.219	0.087	2.552	0.061	108.730
	Pond	0.058	0.089	2.084	0.010	226.117
	Well	<0.040	<0.045	0.195	0.087	50.045
Regulatory Standards		0.05 - 0.2**	0.05* 1.5#		2.0* 60.0#	

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Cd	Cr	Cu	Fe (Dissolved)	Fe (Total)
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
9/12/1997	Sump	<0.001	0.080	0.018	0.026	0.043
	Well	<0.001	0.125	0.026	0.260	0.267
9/28/1997	Sump	<0.001	-	0.014	0.120	0.150
	Pond	<0.001	-	0.019	0.081	0.048
	Well	<0.001	-	0.034	0.301	0.039
1/26/1998	Sump	0.001	<0.005	<0.004	0.022	0.019
	Pond	<0.001	<0.005	<0.004	0.065	0.142
	Well (Tap)	0.001	<0.005	0.039	1.315	1.313
3/16/1998	Sump	0.001	<0.005	<0.004	0.008	<0.006
	Pond	<0.001	<0.005	<0.004	0.008	0.016
	Well	<0.001	<0.005	<0.004	0.539	0.546
7/9/1998	Sump	<0.001	<0.005	<0.004	<0.006	<0.006
	Pond	<0.001	0.006	<0.004	<0.006	<0.006
	Well	<0.001	0.006	<0.004	0.026	0.083
10/2/1998	Sump	-	<0.002	<0.002	<0.010	<0.010
	Pond	-	<0.002	0.050	0.074	0.097
	Well	-	<0.002	<0.002	0.263	0.302
11/25/1998	Sump	<0.001	<0.002	0.003	<0.010	0.037
	Pond	<0.001	<0.002	0.003	0.242	0.323
	Well	0.001	0.002	<0.002	0.183	0.187
3/16/1999	Sump	<0.002	<0.005	<0.010	<0.010	0.024
	Pond	<0.002	<0.005	<0.010	0.024	0.048
	Well	<0.002	<0.005	<0.010	0.534	0.603
7/20/1999	Sump	<0.002	<0.005	<0.010	<0.010	0.034
	Pond (Center)	<0.002	0.006	0.015	0.072	0.675
	Pond (Edge)	<0.002	0.007	0.026	0.080	0.947
	Well	<0.002	0.006	0.080	0.374	9.205
1/12/2000	Sump	<0.002	<0.005	0.021	0.104	0.153
	Pond	<0.002	0.009	0.217	2.000	1.757
	Well	<0.002	<0.005	<0.010	0.539	2.524
Regulatory Standards		0.005*	0.1*	1.0**		
		0.15#	3.0#	1.3***		

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Cd	Cr	Cu	Fe (Dissolved)	Fe (Total)
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
6/26/2000	Sump	<0.002	<0.005	0.012	0.090	
	Pond	<0.002	0.012	0.101	2.088	
	Well	<0.002	0.005	0.418	0.855	
2/20/2001	Sump	<0.002	<0.005	0.026	0.036	0.067
	Pond	<0.002	0.007	0.010	0.299	1.937
	Well	<0.002	0.007	<0.010	0.607	0.571
6/8/2001	Sump	<0.002	<0.005	<0.010	0.026	0.210
	Pond	<0.002	0.008	0.016	0.213	1.743
	Well (Tap)	<0.002	0.005	<0.010	0.332	0.344
10/11/2001	Sump	<0.002	<0.010	<0.010	0.010	0.063
	Pond	<0.002	0.011	0.020	0.624	1.355
	Well	0.003	0.009	<0.010	<0.010	0.207
2/14/2002	Sump	<0.002	<0.005	<0.010	2.348	3.415
	Pond	<0.002	0.007	0.011	3.011	10.460
	Well					
11/7/2002	Sump	<0.002	<0.005	<0.010	<0.010	0.039
	Pond	<0.002	0.006	0.013	0.984	1.077
	Well	<0.002	0.006	<0.010	0.110	0.235
4/2/2003	Sump	<0.002	<0.005	<0.010	0.216	0.038
	Pond	<0.002	<0.005	0.021	0.558	0.739
	Well	0.002	<0.005	<0.010	0.355	0.308
Regulatory Standards		0.005*	0.1*	1.0**		
		0.15#	3.0#	1.3***		

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	K (µg/ml)	Mg (µg/ml)	Mn (Dissolved) (µg/ml)	Mn (Total) (µg/ml)	Na (µg/ml)
9/12/1997	Sump	42.53	68.42	0.114	0.115	26.79
	Well	2.26	31.74	0.019	0.012	43.08
9/28/1997	Sump	1069.29	0.34	<0.002	<0.002	317.55
	Pond	44.28	18.33	0.003	0.002	32.94
	Well	2.80	32.98	0.011	0.044	42.17
1/26/1998	Sump	581.90	0.53	<0.002	<0.002	189.08
	Pond	59.33	10.87	0.002	0.002	28.75
	Well (Tap)	2.00	35.77	0.075	0.072	45.58
3/16/1998	Sump	480.11	0.43	<0.002	<0.002	158.07
	Pond	64.35	11.27	<0.002	0.002	30.71
	Well	1.75	35.05	0.089	0.094	45.46
7/9/1998	Sump	451.83	0.06	<0.002	<0.002	139.55
	Pond	81.97	8.14	<0.002	<0.002	32.65
	Well	1.74	33.27	0.054	0.048	45.15
10/2/1998	Sump	447.32	0.17	<0.001	<0.001	143.53
	Pond	122.06	17.90	0.044	0.054	48.41
	Well	2.56	30.08	0.002	0.002	38.29
11/25/1998	Sump	499.17	0.19	<0.001	0.001	163.07
	Pond	141.70	18.88	0.073	0.074	55.44
	Well	2.19	30.69	0.002	0.002	41.22
3/16/1999	Sump	256.82	37.46	0.028	0.028	55.10
	Pond	128.71	13.05	0.012	0.020	46.31
	Well	1.47	34.99	0.060	0.058	45.34
7/20/1999	Sump	484.12	4.68	<0.002	0.002	159.76
	Pond (Center)	389.20	61.22	0.017	0.136	121.93
	Pond (Edge)	366.22	57.73	0.015	0.175	136.73
	Well	1.54	33.27	0.030	0.036	43.14
1/12/2000	Sump	412.23	26.87	0.052	0.060	172.05
	Pond	407.73	68.28	0.410	0.395	159.53
	Well	2.03	36.77	0.093	0.098	50.58
Regulatory Standards					0.05**	

* Primary Drinking Water Standard
 ** Secondary (Non-health related) Drinking Water Standard
 *** Action Level
 \$ Ohio Secondary Maximum Contaminant Level
 # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	K	Mg	Mn (Dissolved)	Mn (Total)	Na
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
6/26/2000	Sump	462.423	6.352	0.011		197.837
	Pond	453.483	89.988	0.303		153.471
	Well	1.906	32.606	0.067		43.653
2/20/2001	Sump	152.748	10.389	0.006	0.011	48.258
	Pond	368.893	61.049	0.052	0.272	120.000
	Well	1.768	34.621	0.089	0.084	46.491
6/8/2001	Sump	320.353	7.722	0.005	0.020	137.795
	Pond	388.083	71.091	0.040	0.340	124.599
	Well (Tap)	1.995	26.146	0.010	0.011	37.738
10/11/2001	Sump	476.087	4.452	<0.002	0.005	209.855
	Pond	452.029	86.342	0.042	0.303	151.898
	Well	1.982	28.990	0.008	0.006	40.400
2/14/2002	Sump	499.709	6.838	0.005	0.007	210.102
	Pond	366.659	69.466	0.100	1.050	121.100
	Well					
11/7/2002	Sump	479.400	4.231	0.004	0.006	228.689
	Pond	342.785	85.969	0.048	0.067	124.542
	Well	2.417	29.720	0.002	0.002	41.569
4/2/2003	Sump	468.332	10.616	0.006	0.005	203.282
	Pond	273.669	64.225	0.038	0.055	91.181
	Well	2.287	28.374	0.008	0.003	41.344
Regulatory Standards					0.05**	

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Ni	P (Total)	Pb	S (Total)	Se
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
9/12/1997	Sump	0.006	0.044	<0.020	137.26	<0.100
	Well	0.008	0.043	<0.020	20.18	<0.100
9/28/1997	Sump	0.007	0.075	<0.020	228.92	<0.100
	Pond	0.007	0.054	<0.020	126.76	<0.100
	Well	0.003	0.054	<0.020	20.45	<0.100
1/26/1998	Sump	<0.009	<0.030	<0.020	183.96	<0.100
	Pond	<0.009	<0.030	<0.020	146.95	<0.100
	Well (Tap)	<0.009	0.083	0.029	20.16	<0.100
3/16/1998	Sump	<0.009	0.042	<0.020	176.41	<0.100
	Pond	<0.009	<0.030	<0.020	175.99	<0.100
	Well	<0.009	0.034	0.023	20.40	<0.100
7/9/1998	Sump	<0.009	<0.030	<0.020	149.93	<0.100
	Pond	<0.009	0.098	<0.020	263.87	<0.100
	Well	<0.009	0.118	0.021	19.65	<0.100
10/2/1998	Sump	<0.005	<0.020	<0.020	154.37	<0.100
	Pond	0.009	1.131	<0.020	337.15	<0.100
	Well	<0.005	0.030	<0.020	18.32	<0.100
11/25/1998	Sump	<0.005	0.073	<0.020	179.26	<0.100
	Pond	<0.005	1.600	<0.020	374.67	<0.100
	Well	<0.005	0.029	0.029	19.44	<0.100
3/16/1999	Sump	<0.010	<0.100	<0.020	149.31	-
	Pond	0.012	0.370	<0.020	382.24	-
	Well	<0.010	<0.100	0.034	20.58	-
7/20/1999	Sump	<0.010	<0.100	<0.020	224.45	<0.100
	Pond (Center)	<0.010	7.448	<0.020	96.81	<0.100
	Pond (Edge)	0.011	6.024	<0.020	92.45	<0.100
	Well	<0.010	<0.100	<0.020	21.39	<0.100
1/12/2000	Sump	<0.010	0.812	<0.020	216.48	<0.100
	Pond	0.013	50.453	<0.020	208.23	<0.100
	Well	<0.010	<0.100	<0.020	19.70	<0.100
Regulatory Standards				0.015***		0.05*
				1.5#		1.0#

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Ni	P (Total)	Pb	S (Total)	Se
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
6/26/2000	Sump	0.012	<0.100	<0.020	313.699	<0.100
	Pond	0.024	32.876	<0.020	74.091	<0.100
	Well	<0.010	<0.100	0.027	20.308	<0.100
2/20/2001	Sump	<0.010	0.157	0.032	80.678	<0.100
	Pond	0.035	8.929	0.033	70.328	<0.100
	Well	<0.010	<0.100	0.048	20.189	-
6/8/2001	Sump	<0.010	0.567	<0.020	168.837	<0.100
	Pond	0.018	34.122	<0.020	38.129	<0.100
	Well (Tap)	<0.010	<0.100	<0.020	15.283	<0.100
10/11/2001	Sump	0.010	0.152	0.026	245.848	<0.100
	Pond	0.019	29.557	<0.020	78.311	<0.100
	Well	<0.010	<0.100	<0.020	17.856	<0.100
2/14/2002	Sump	0.011	0.286	<0.020	282.666	<0.100
	Pond	0.013	49.342	<0.020	170.360	<0.100
	Well					
11/7/2002	Sump	<0.010	<0.100	<0.020	485.532	0.124
	Pond	<0.010	9.729	<0.020	244.852	0.121
	Well	<0.010	<0.100	<0.020	18.241	<0.100
4/2/2003	Sump	<0.010	<0.100	<0.020	392.099	<0.100
	Pond	0.011	5.609	<0.020	249.897	<0.100
	Well	<0.010	<0.100	<0.020	17.154	<0.100
Regulatory Standards				0.015***		0.05*
				1.5#		1.0#

- * Primary Drinking Water Standard
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- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Si	Ag	V	Zn
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
9/12/97	Sump	2.383	<0.008	0.010	0.043
	Well	3.872	<0.008	<0.005	0.271
9/28/97	Sump	6.037	0.104	0.035	<0.005
	Pond	0.935	0.012	0.056	<0.005
	Well	4.052	0.008	0.059	<0.005
1/26/98	Sump	3.374	0.044	0.021	0.009
	Pond	0.508	0.018	0.004	<0.005
	Well (Tap)	3.405	0.010	0.965	<0.005
3/16/98	Sump	3.169	0.028	0.008	<0.005
	Pond	0.426	0.018	<0.004	<0.005
	Well	3.869	0.008	0.261	<0.005
7/9/98	Sump	1.675	<0.008	<0.004	0.531
	Pond	0.893	<0.008	<0.004	0.623
	Well	1.998	<0.008	0.165	0.933
10/2/98	Sump	3.476	<0.003	0.011	<0.001
	Pond	4.039	0.008	0.010	0.055
	Well	3.787	0.006	<0.005	0.035
11/25/98	Sump	3.715	0.004	0.020	<0.001
	Pond	3.863	<0.001	0.035	<0.001
	Well	3.881	0.004	0.016	<0.001
3/16/99	Sump	1.929	<0.005	<0.010	<0.005
	Pond	1.495	<0.005	0.013	<0.005
	Well	2.569	<0.005	<0.010	0.095
7/20/99	Sump	1.091	<0.050	<0.010	<0.005
	Pond (Center)	4.196	<0.050	0.026	0.019
	Pond (Edge)	4.093	<0.050	0.034	0.037
	Well	2.121	<0.050	<0.010	0.029
1/12/00	Sump	2.646	<0.050	0.016	0.039
	Pond	8.633	<0.050	0.038	0.598
	Well	4.751	<0.050	<0.010	0.239
Regulatory Standards			0.10**		5.0**

- * Primary Drinking Water Standard
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- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Si	Ag	V	Zn
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
6/26/2000	Sump	3.520	<0.050	0.011	0.051
	Pond	15.015	<0.050	0.058	0.275
	Well	4.741	<0.050	<0.010	0.239
2/20/2001	Sump	2.037		<0.010	0.050
	Pond	9.283		0.033	0.030
	Well	4.147		<0.010	0.139
6/8/2001	Sump	2.950	<0.005	<0.010	0.009
	Pond	10.042	<0.005	0.025	0.045
	Well (Tap)	3.822	<0.005	<0.010	0.012
10/11/2001	Sump	3.294	<0.005	0.010	0.038
	Pond	13.028	<0.005	0.041	0.050
	Well	4.049	<0.005	<0.010	0.018
2/14/2002	Sump	2.648	<0.005	0.015	0.038
	Pond	8.014	<0.005	0.032	0.038
	Well				
11/7/2002	Sump	3.456	<0.005	0.030	0.028
	Pond	9.864	<0.005	0.038	0.066
	Well	4.629	<0.005	<0.010	0.026
4/2/2003	Sump	2.742	<0.005	0.024	0.018
	Pond	6.113	<0.005	0.016	0.024
	Well	4.536	<0.005	<0.010	0.078
Regulatory Standards			0.10**		5.0**

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
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- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Cl ⁻	PO ₄ ⁻	SO ₄ ⁻	NO ₃ ⁻
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
9/12/97	Sump	85.38	0.00	125.25	11.41
	Well	6.91	0.00	21.82	0.00
9/28/97	Sump	976.92	53.71	182.11	0.81
	Pond	16.80	0.00	104.46	0.17
	Well	5.77	0.00	18.95	0.26
1/26/98	Sump	480.08	1.36	185.05	0.41
	Pond	32.69	0.00	141.25	0.51
	Well (Tap)	5.46	0.00	20.45	0.25
3/16/98	Sump	377.50	0.00	171.19	0.33
	Pond	34.33	5.51	183.79	0.35
	Well	5.18	0.00	20.63	0.00
7/9/98	Sump	38.93	0.00	262.31	0.00
	Pond	239.67	0.00	120.82	0.00
	Well	4.83	0.00	16.00	0.00
10/2/98	Sump	381.08	0.00	159.67	0.00
	Pond	82.71	0.00	364.31	0.82
	Well	5.80	0.00	17.48	0.14
11/25/98	Sump	462.53	0.00	197.75	0.00
	Pond	83.85	3.86	421.48	0.14
	Well	5.25	0.43	18.63	0.00
3/16/99	Sump	59.28	0.00	155.68	3.78
	Pond	84.88	0.18	397.69	0.25
	Well	5.08	0.00	19.01	0.00
7/20/99	Sump	346.77	<0.10	199.19	<0.10
	Pond (Center)	226.34	6.58	71.71	<0.10
	Pond (Edge)	219.00	3.94	69.16	<0.10
	Well	13.30	<0.10	29.95	<0.10
1/12/00	Sump	362.14	<0.10	219.16	<0.10
	Pond	249.30	23.78	183.35	<0.10
	Well	5.36	<0.10	18.69	0.39
Regulatory Standards		250**		250**	10*

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 ** Secondary (Non-health related) Drinking Water Standard
 *** Action Level
 \$ Ohio Secondary Maximum Contaminant Level
 # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Cl-	PO ₄ -	SO ₄ -	NO ₃ -
		(µg/ml)	(µg/ml)	(µg/ml)	(µg/ml)
6/26/2000	Sump	474.64	1.66	<0.10	1.73
	Pond	289.97	1.35	5.09	<0.10
	Well	5.28	0.51	<0.10	<0.10
2/20/2001	Sump	86.38	<0.10	73.20	0.21
	Pond	266.47	4.48	48.56	<0.10
	Well	3.43	<0.10	22.05	<0.10
6/8/2001	Sump	342.55	<0.50	172.99	15.29
	Pond	287.76	73.38	19.73	<0.50
	Well (Tap)	3.9	<0.50	16.23	<0.50
10/11/2001	Sump	503.59	<0.50	222.82	<0.50
	Pond	289.05	7.94	48.39	<0.50
	Well	1.53	<0.50	18.29	<0.50
2/14/2002	Sump	445.51	<0.50	279.95	<0.50
	Pond	222.16	9.57	169.38	<0.50
	Well				
11/7/2002	Sump	459.07	<0.10	281.62	3.18
	Pond	207.91	19.54	238.77	8.45
	Well	2.79	<0.10	16.63	<0.10
4/2/2003	Sump	403.11	<0.10	934.52	3.85
	Pond	177.98	19.94	777.23	23.06
	Well	2.88	<0.10	51.18	238.15
Regulatory Standards		250**		250**	10*

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Ammonia (NH ₄ as µg N / ml)	Total Nitrogen (µg N / ml)
9/12/97	Sump	1.80	13.21
	Well	0.00	0.00
9/28/97	Sump	43.02	43.83
	Pond	0.57	0.74
	Well	0.87	1.13
1/26/98	Sump	29.68	30.09
	Pond	0.08	0.59
	Well (Tap)	0.00	0.25
3/16/98	Sump	25.28	25.61
	Pond	0.08	0.43
	Well	0.08	0.08
7/9/98	Sump	16.80	16.80
	Pond	0.40	0.40
	Well	0.00	0.00
10/2/98	Sump	23.00	23.00
	Pond	10.25	11.07
	Well	0.30	0.44
11/25/98	Sump	24.20	24.20
	Pond	0.00	0.14
	Well	0.50	0.50
3/16/99	Sump	1.00	4.78
	Pond	0.00	0.25
	Well	0.40	0.40
7/20/99	Sump	24.21	24.21
	Pond (Center)	115.71	115.71
	Pond (Edge)	109.53	109.53
	Well	0.00	0.00
1/12/00	Sump	58.25	58.25
	Pond	250.04	250.04
	Well	1.06	1.45

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
- *** Action Level
- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Ammonia (NH ₄ as µg N / ml)	Total Nitrogen (µg N / ml)
6/26/2000	Sump	129.35	131.08
	Pond	210.80	210.8
	Well	2.55	2.55
2/20/2001	Sump	22.10	22.31
	Pond	190.90	190.9
	Well	0.21	0.21
6/8/2001	Sump	59.940	-
	Pond	238.390	-
	Well (Tap)	0.300	-
10/11/2001	Sump	81.13	-
	Pond	105.53	-
	Well	0.76	-
2/14/2002	Sump	134.1	-
	Pond	143.1	-
	Well	-	-
11/7/2002	Sump	-	-
	Pond	-	-
	Well	-	-
4/2/2003	Sump	-	-
	Pond	-	-
	Well	-	-

- * Primary Drinking Water Standard
- ** Secondary (Non-health related) Drinking Water Standard
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- \$ Ohio Secondary Maximum Contaminant Level
- # Ohio Non-Toxic Criteria

5 SUMMARY AND CONCLUSIONS

5.1 Summary

This project report presents the results of a research program co-funded by OCDO and CBRC and conducted at The Ohio State University from January 1, 2000 to June 30, 2005, to investigate the long-term characteristics of stabilized flue gas desulfurization (FGD) materials in the construction of low permeability liners. Phase I work (OCDO Project CDO/D-95-19) earlier had shown that FGD material liners exhibit short-term characteristics that are suitable for liner applications (Wolfe et al., 2000).

The objective of the research program presented in this report was to establish long-term field-verified time-dependent relationships for the performance of liners constructed from stabilized FGD by-products generated in Ohio. The project objective was accomplished with a coordinated program of testing and analyzing small-scale laboratory specimens under controlled conditions, medium-scale wetland experiments, and monitoring of a full-scale FGD-lined pond facility. Although the specific uses directly addressed by this report include liners for surface impoundments, the results presented in this study will also be useful in other applications, especially in the design of daily covers and liners for landfills, seepage cutoff walls and trenches, and for nutrient retention and pollution mitigation wetlands. The results obtained from this study are being incorporated into a revised draft ASTM standard guide for the use of FGD materials in the construction of liners and encapsulations.

5.1.1 Laboratory Testing Program

The small-scale laboratory testing program consisted of long-term permeability characterization, comparison of laboratory and field (Boutwell) permeability procedures, permeability and strength development of FGD-clay mixtures, evaluation of leaching potential, and the implications of leaching tests for stabilized FGD pond liners.

The stabilized FGD material generated by the Conesville power plant of AEP was used in this study. At this plant, a lime-enriched wet scrubbing process is used to remove the SO₂ from the flue gases. The filter cake (FC) obtained in this process is mixed with Class F fly ash (FA) and lime (L) to produce the stabilized FGD. The FGD material is stored on a temporary curing pad for 3-4 days to reduce the moisture content and allow for some curing. This permits the material to be handled more easily and subsequently it can be hauled to the plant landfill.

In order to characterize the long-term permeability of stabilized FGD materials, a set of experiments were conducted to evaluate the effect of more than 5 years of curing time on the laboratory permeability of the FGD material used in the construction of the full-scale FGD-lined pond facility. The FGD material tested had a target FA:FC ratio of 1.8:1 and lime content of 8% as per power plant control operations. Four permeability samples were prepared using standard proctor test guidelines (ASTM D698, 1997) at as received moisture contents. The coefficient of permeability was measured in the laboratory using a falling head test (ASTM D5084, 1996; ASTM D5856, 1996) for short curing times (7, 28, 60 days) and long curing times (150, 580, 980, 1960 days). It was observed that the coefficient of permeability for all the four samples

tested in the laboratory decreased with curing time. The rate of decrease in permeability of the samples was much greater at shorter curing times as compared to longer curing times. At 60 days of curing, all the samples exhibited permeability values in the 10^{-7} to 10^{-8} cm/sec range. At 1960 days (5 years and 4 ½ months) of curing, the permeability values were in the 10^{-8} to 10^{-9} cm/sec range. It was shown that lime and fly ash enriched stabilized FGD materials can be compacted in the laboratory using standard soil testing procedures to obtain long-term permeability coefficients that are in the 10^{-8} to 10^{-9} cm/sec range, which is lower than the 1×10^{-7} cm/sec value typically recommended by USEPA for constructing liners for waste containment facilities (Goldman, et al., 1988).

Four FGD test pads (approximately 60 feet long, 15 feet wide, and 5 feet high) were constructed at the Conesville landfill of AEP in August and September of 2002. Each test pad used a different stabilized FGD material recipe. The lime content ranged from 4.5 to 10% and the fly ash to filter cake ratio (FA:FC) ranged from 1:1 to 1.5:1. The as received moisture contents ranged from about 50 to 72%. Each FGD material recipe was used to construct a test pad. Compaction of each pad was achieved by using a compaction roller that is routinely used at the landfill. Each test pad was instrumented at its center with a Boutwell apparatus (Boutwell, 1992) immediately after the construction of the test pad. Samples of the FGD material used in the construction of the test pads were prepared in the laboratory for permeability testing and compacted using Standard Proctor compactive effort. The Boutwell apparatuses installed in the field test pads were used to measure the field permeability of the compacted test pads, while falling-head permeability tests carried out on laboratory compacted samples measured the laboratory controlled values. All measurements were done for curing times of 7, 28, and 60 days.

Samples with higher moisture contents (Test Pads 1 and 2) showed good agreement between laboratory and field (Boutwell) permeability values at longer curing times, while samples with lower moisture contents (Test Pads 3 and 4) showed poor correlation of the Boutwell permeability with the laboratory measured values for all curing times. As expected, the laboratory permeability values were the lowest for Test Pad 3 (since this sample had the highest lime and FA:FC content). However, this Test Pad gave the highest field (Boutwell) permeability values. Test Pad 4 standpipe for Boutwell test did not hold water for long so no significant test measurements could be made. However, the laboratory samples for Test Pad 4 exhibited permeability values in the 10^{-5} to 10^{-6} cm/sec range. As in the previous study (Wolfe et al., 2000), we found that the Boutwell tests carried out in this project on field constructed FGD material test pads did not provide a satisfactory correlation with control laboratory permeability values.

The permeability and strength development of low fly ash content FGD and clay mixtures were studied to obtain mixture permeability values in the 10^{-7} cm/sec range. All samples were compacted using Standard Proctor compactive effort. Permeability and unconfined compressive strength measurements were made for the four FGD:clay ratios (100:0, 75:25, 50:50, 25:75, and 0:100), and the four types of FGD recipes (FA:FC=1.04:1 with 4.54%L, FA:FC=1.07:1 with 6.82%L, FA:FC=1.46:1 with 10%L, and FA:FC=1.45:1 with 6.79%L) for curing times of 7, 28, 60, and 90 days. It was found that as the FGD:clay ratio decreased, the permeability reduced. The permeability of the clay only samples remain the same with curing time, while the permeability of the FGD material reduces significantly with curing time. The mixtures of clay and FGD exhibit reduction in permeability values with curing time. As the FGD:clay ratio

decreases, the rate of decrease of permeability with curing time increases. FGD:clay mixtures of 25:75 achieve 10^{-7} cm/sec range permeabilities within 7 to 28 days of curing. FGD:clay mixtures of 50:50 exhibit 10^{-7} cm/sec range permeabilities within 60 to 90 days of curing. The unconfined compressive strength of the clay samples is very low (25-35 psi) and is unaffected by curing time. The FGD material containing samples exhibit significant strength gains with curing time, and the amount of strength gain with curing time increases as the FGD:clay ratio increases.

The leaching potential of stabilized FGD material was evaluated using TCLP and modified TCLP testing procedures. A total of five stabilized FGD material samples from Conesville power plant were collected over a four-week period, and analyzed according to USEPA TCLP Method 1311. The FGD leachate data for various constituents studied did not vary over a wide range and are bracketed within a reasonably small range of values. The mean values calculated for the potential contaminants are very low. A comparison of the FGD leachate data with Ohio EPA non-toxic criteria shows that for the contaminants studied, the FGD material meets all the criteria specified by the Ohio EPA by a large factor of safety and hence the stabilized FGD material used in the study can be characterized to be non-toxic. The range and mean values for all constituents are lower than the primary standards (NPDWR). As an example, for Arsenic, the concentration values ranged from 0.004 to 0.008 mg/l with a mean value of 0.006 mg/l, which is less than one-eighth the primary standard value of 0.05 mg/l. Hence, the leachate from stabilized FGD material studied in this investigation meets all the National Primary Drinking Water Regulations. In general, the FGD leachate concentration levels are also lower than the secondary (non-health and unenforceable) standards. The exceptions being pH (mean value of 11.08) and Aluminum (mean value of 5.114 mg/l). The TCLP testing program conducted on the stabilized FGD material

indicates that the stabilized FGD material tested in the laboratory is a relatively clean material, non-toxic and poses very minimal risks, if any, for groundwater contamination. Other leaching solutions (acetic citric acid, ammonium citrate, oxalic acid, ammonium oxalate, and pond water) were also applied to study the leaching potential of the stabilized FGD material. Leaching tests were carried out by following the standard USEPA Toxicity Characteristic Leaching Procedure (TCLP), method 1311; with the exception of the leaching solution. Leaching results vary considerably depending on the leaching solution. In general, citric acid and ammonium citrate resulted in the largest leachate values for most elements. Ammonium oxalate generally resulted in the lowest leachate values. It should be emphasized, however, that none of the concentration of these elements exceeds the nontoxic criteria levels established by OEPA.

To develop a better understanding of the leaching behavior of fixated FGD material, a detailed and rigorous leaching kinetic study (using a flow-through-rotating disk apparatus) was conducted to (1) determine whether the leaching kinetics of specific elements are transport- or reaction-controlled, (2) elucidate the role of pH on controlling the leaching kinetics of stabilized FGD material, and (3) propose leaching models for specific elements that take into account the effect of pH. It was observed that a change of hydrodynamics of the system had no effect on the leaching kinetics of the stabilized FGD material for all selected elements, and hence a surface reaction mechanism controls the leaching kinetics. The effect of protons on leaching kinetics was further studied. The leaching rates of selected elements were constant at pH 6.8 and 5 indicating the overall leaching kinetics was controlled by intrinsic hydration mechanism at near neutral pH conditions. When pH was below 3.7 (5.0 for Mg and Fe), leaching rates started increasing indicating the proton-promoted leaching process was dominating. Mathematical modeling

indicates the leaching rates of divalent and trivalent cations increase 3.2 and 5.2 times, respectively, when pH decreases 1 unit. In summary, the leaching process of stabilized FGD material conducted in a flow-through-rotating disk shows an independent relationship of leaching kinetics on hydrodynamic condition suggesting the leaching process is controlled largely by surface reaction.

Implications of the above-described leaching tests for the full-scale FGD-lined pond facility were investigated. The leaching concentrations of selected elements from the standard TCLP test were compared with the maximum concentrations observed in the sump leachates from the water quality monitoring of the full-scale facility. We found the leaching potentials of As, Cd, Cr, and Se, obtained from the standard TCLP test do not represent the maximum limits for the concentrations observed in the sump leachates. In fact, most of the TCLP results were lower than the observed maximum concentrations at the facility. The observation suggests the standard TCLP test may underestimate the leaching potentials of some elements under the field condition at the site. Results obtained from modified TCLP tests suggest a higher leaching potential of stabilized FGD material could be established by using oxalic and citric acids as the leaching solutions when evaluating the environmental impact. However, these leaching solutions overestimated the extent of leaching for a number of elements. Modified TCLP leaching tests with pond water appeared to provide the closest representation of leaching in the field. However, leaching tests carried out with pond water significantly under predicted the concentrations of Al, Fe, Mg, Mn, Ni, and V. Both batch leaching studies and field data demonstrated that the extent of leaching is time dependent. Many of the maximum concentrations in the sump leachates occurred right after filling the facility with water; e.g., As, Al, Cr, Ba, dissolved and total Fe, Cu,

dissolved and total Mn, K, and Mg. The leaching kinetic study found that high leaching rates can be observed during the initial stages of the leaching process. A comparison of results obtained from the modified TCLP test carried out with pond water and water quality monitoring conducted at the facility on 2/14/2004 showed that the leaching results varied somewhat compared to the observed concentration levels in the sump. However, the leaching results suggest the stabilized FGD material is not a source for many elements. In fact, the lag of the concentration profiles in the sump (when compared to the profile of the pond) suggest the stabilized FGD liner could be a sink for As, V, Mn, B, Mg, and Ni. The surface-controlled mechanism determined by the leaching kinetic study suggests the hydrodynamic conditions in the field (e.g., flow rate through the liner) should not greatly affect the leaching rate of elements from the full-scale stabilized FGD material pond liner.

5.1.2 Medium-Scale Wetland Experiments

Pilot-scale wetland experiments were carried out in four created 12-m² wetland basins at the Olentangy River Wetland Research Park. in Columbus, Ohio, USA (Figures 3.1, 3.2, and 3.3). Stabilized FGD material, received from the Conesville power plant of America Electric Power, was used as the liner for FGD basins, while local clay soil was used as a liner for the two control basins. The FGD material was notably more alkaline than the clay because it is treated with lime as a part of the stabilization process. The FGD material was relatively high in concentrations of S as well as Ca from the unreacted lime. Higher concentrations of metals Mg, Ca, and metalloids Al and B were detected in the FGD material than in the clay liner material.

Water levels in the FGD-lined basins were consistently lower than clay-lined basins in 2001, and were statistically lower in 2002 and 2003. This trend is because the permeability of the FGD-liner was higher than the permeability of the clay-liner. A field infiltration study was conducted in the four wetland basins in July 2003 to verify the different hydrology in the FGD basins. The study showed that while the water level dropped at $4-6 \times 10^{-6}$ cm/sec in the clay-lined basins, it dropped 100 times faster (10^{-4} cm/sec) in the FGD lined basins. There were no significant differences in surface water outflows for clay-lined and FGD-lined basins in any of the 3 years for temperature dissolved oxygen, conductivity, pH, redox potential, and turbidity. Leachate water from the FGD-lined basins showed significantly higher conductivity than did leachate water from the clay-lined basins for all three years of the study. Leachate water from FGD-lined basins was also consistently more alkaline than leachate in the clay-lined basins, but both systems were less in the last year of the study. Elemental analysis of leachate water shows significantly higher concentrations of K, Na, and Mo in the first year in leachate water from FGD-lined basins than clay-lined basins. In the second year of sampling, K and Na continued to be higher in the leachate of the FGD basins but were joined by significantly higher concentrations of Ca, S, and B. The higher Ca, Na, and K are consistent with the significantly higher conductivity seen in the leachate. There were no significant differences between the clay-lined and FGD-lined basins on retaining phosphorus when very high concentrations of phosphorus were added to all basins in the 2003 experiment. The only significant difference seen in nutrient retention was before the increased concentrations of phosphorus were added. During that period, the clay-lined wetlands discharged significantly lower concentrations of soluble reactive phosphorus than did the FGD-lined basins. Plant biomass in the FGD-lined basins was consistently lower than wetland plant biomass in clay-lined basins for all three growing season.

The FGD basins, while lower in productivity, had 5 species dominating while the clay basins had only 3 species dominating in 2003. Fewer stems were counted in the FGD-lined basins than the clay-lined basins, but greater richness of species was found in the FGD basins. There was substantially greater presence of the common marsh herbs *Eleocharis obtuse* and *Leersia oryzoides* in the FGD-lined basins implying that more species may have greater success in FGD-lined wetlands than in the clay basins during periods of high nutrients. But this conclusion is tempered by the point that the “stress” that caused lower productivity in the FGD basins is more likely low water levels than any chemical effects of the FGD material. Some indicators of plant morphology illustrate differences between the clay and FGD basins. There were significantly more plant stems in the clay basins in both 2001 and 2002. Greater concentrations of Al and Fe were detected in three-square rush (*Scirpus americanus*) plant tissue samples from FGD-lined basins in year 2003. These elements were present in higher concentrations in the FGD liner material than in the clay liner supporting the idea that some plant roots were able to reach through 2 feet (60 cm) of top soil and enter the liner material. This would be particularly the case if there were low water levels that would cause the plants to extend their roots deeper into the basins as was the case in the FGD basins. On the other hand, plants in the FGD basins did not have higher concentrations of Ca and B, two elements that are much higher in the FGD leachate. *Scirpus* had higher concentrations of Na, Mn and P in the clay-lined basins. Topsoil analysis after both full growing seasons (2002 and 2003) showed comparable concentrations of B between FGD-lined and clay lined basins. The concentrations of Ca and Mg were similar for topsoil in both treatment types. Topsoils from FGD-lined basins contained slightly greater concentrations of Fe and Mn during both years. There were statistically higher concentrations of S both years in the clay basins but the concentrations may not be ecologically different. After

both full growing seasons (2002 and 2003), higher Mo was detected in the clay-lined basins than the FGD-lined basins.

In summary, higher concentrations of elements common in FGD-liner material were found in leachate water in the FGD basins, suggesting that introduced river water was transported through the liners in these basins to the leachate collection system. The FGD mixture as implemented in this project did not serve as an effective aquiclude to water movement. It was about 20 times more permeable than the clay liner material. Basins lined with the FGD material (vertical infiltration of 10^{-4} cm/sec) consistently showed lower water levels than basins lined with clay material (vertical infiltration of 5×10^{-6} cm/sec). These marked differences in hydrologic regime probably affected vegetative growth and nutrient removal. Experiments with more impermeable FGD liners are needed to isolate the effects of the liner from the hydrologic effects observed in this study, some of which were due to different water levels. There were no significant differences in phosphorus retention between the clay and FGD-lined basins during the high-phosphorus pulsing period, refuting the hypotheses generated by earlier small-scale mesocosm wetland studies. Plant productivity was lower in the FGD-lined wetland basins than in the clay-lined basins but we believe that this difference was caused more by difference in hydrology than by any effect of FGD material on plant growth. This conclusion is supported by the lack of substantial differences in elemental concentrations in plant tissue and topsoil between the FGD-lined and clay-lined basins. Tradeoffs exist between productivity and diversity in most ecosystems. Plant data comparing FGD and clay-lined basins support this theory. The FGD-lined basins, which were stressed by low water levels, had a greater richness of plant species than

did the clay-lined basins that had higher water levels. The clay-lined basins showed greater total plant productivity but with fewer plant species.

Additional studies are needed with FGD material designed to achieve low permeabilities similar to the clay material. We also propose additional studies that mix the FGD material in the topsoil so as to investigate the effectiveness of a topsoil/FGD mix on water quality and the effect of the mixture on plant productivity and wetland ecosystem health.

5.1.3 Full-Scale FGD-Lined Facility

Permeability of a field compacted FGD structure is a function of the construction process, and hence the field validation of properties obtained in the laboratory is an important part of the documentation process. The million-gallon FGD-lined pond facility constructed in 1997 at South Charleston was monitored for a total period of about 5 ½ years. The facility was constructed to address two critical questions about the behavior of stabilized FGD products constructed in the field, i.e. what is the permeability of a compacted engineered liner of known thickness and density, and what is the quality of the water that flows through the FGD liner.

The detailed design and construction of the facility is documented in Wolfe et al., 2000. The FGD lined facility was used to store water for the first year. In early September of 1998, some of the water was replaced with swine manure. Since then swine manure has continued to be added and removed from the facility on a regular basis depending on the manure storage vs. field spreading needs of the research farm. Monitoring of the site for field permeability and water

quality was carried out for a period of about 5 ½ years. The average monitoring frequency was about three months. The monitoring program consisted of field permeability and water quality monitoring. Field permeability monitoring involved a full-scale falling head permeability test on the pond facility by lowering the water level in the sump to create a head difference across the FGD liner. The amount of time taken to increase the water in the sump to specific levels was observed. Knowing the thickness of the FGD liner and its plan view area, the effective permeability of the field compacted FGD-lined facility was calculated. The water quality monitoring of the site was conducted by collecting water samples from the pond, sump (leachate) and a vicinity well (or a vicinity tap). All water samples were tested for several constituents and properties including pH, electrical conductivity, alkalinity, acidity, total dissolved solids, aluminum, arsenic, boron, barium, calcium, cadmium, chromium, copper, iron, potassium, magnesium, manganese, sodium, nickel, phosphorous, lead, sulfur, selenium, silica, silver, vanadium, zinc, chloride, phosphate, sulfate, nitrate, ammonia and nitrogen. Although the vicinity well (or tap) was about 1,000 feet from the site and not necessarily hydrologically connected to the site, the well (or tap) samples were investigated so that potential contamination of the farm water supply from the FGD lined facility, if any, could be detected.

The full-scale permeability of the facility was evaluated to be 9.1×10^{-7} cm/sec at a curing time of one month. The permeability coefficient continued to reduce over time (due to curing of FGD) and stabilized at approximately 4×10^{-7} cm/sec at about 150 days of curing. Beyond 150 days, the permeability of the FGD material liner has been maintained at around 4×10^{-7} cm/sec till 5 ½ years of monitoring of the facility. The FGD permeability coefficient data range obtained from the full-scale tests is comparable to typical clays used in the construction of compacted liners.

This includes the effect of freeze-thaw cycling on the actual permeability of the full-scale field compacted FGD liner. The actual area over which water flows through the FGD liner is greater than the bottom area of the pond (i.e., a significant amount of water may flow through the sides of the pond). Hence the full-scale permeability values presented in this study should be taken to be an upper bound to the actual permeability of the field-compacted FGD liner. The addition of swine manure to the facility did not significantly affect the actual permeability of the liner. The specific seepage rate for the full-scale facility was very low ($0.095 \text{ in}^3/\text{in}^2/\text{day}$). Hence, it can be concluded that if there was no secondary clay liner constructed for the facility (as would be the norm for typical FGD-lined pond and manure storage facilities), the seepage rate loss from such FGD facilities would be very low. The actual field permeability data obtained from the full-scale pond tests was compared with a) laboratory tests conducted on several laboratory compacted samples collected during pond construction, b) laboratory tests conducted on field compacted samples cored from test pads installed at the site, and c) field permeability tests (Boutwell) conducted on the test pads. All the test procedures showed decreasing permeability coefficient with increasing curing time. It was observed that the laboratory compacted samples had permeability coefficients which were an order of magnitude lower than the full-scale testing values. Permeability values obtained from Boutwell tests and cored samples tested in the laboratory were in close agreement with each other but were one to three orders of magnitude higher than the full-scale tests. The test pad sample permeability values (Boutwell tests and cored sample testing) indicated a large scatter in the data. The permeability coefficients varied from 10^{-4} cm/sec ($3 \times 10^{-6} \text{ ft/sec}$) to 10^{-7} cm/sec ($3 \times 10^{-9} \text{ ft/sec}$) with average permeability value in range of 10^{-5} cm/sec ($3 \times 10^{-7} \text{ ft/sec}$). This may be due to the unsuitable compaction achieved for the test pads. Furthermore, the Boutwell test procedure relates infiltration rate with permeability

coefficient by assuming certain direction and boundary conditions of flow, which are nearly impossible to control in the field. However, it is important to note that the actual measured field permeability values of the full-scale FGD liner are an order of magnitude higher than laboratory measured values.

The water quality monitoring program showed that the concentration level of various analytes (pH, electrical conductivity, alkalinity, Ag, Al, Ca, Cl, PO_4^{-3} , Cr, K, Mg, Na, and Si) in the sump (leachate) increased suddenly following the filling of the facility with water. Thereafter, the concentration levels reduced rapidly. The leachate from the FGD lined facility needs to meet OEPA's non-toxic criteria. All the non-toxic parameters (Arsenic, Barium, Cadmium, Chromium, Lead, Selenium) measured for the FGD facility while holding water and swine manure were much lower than OEPA's non-toxic criteria. It should be noted that the leachate from the full-scale FGD-lined facility meets most of the National Primary Drinking Water Regulations (NPDWR) limits. NSDWR limits are non-enforceable non-health related guidelines regulating potential contaminants that may cause cosmetic or aesthetic effects in drinking water. From a regulatory perspective, the leachate from the FGD material is not required to meet any of the NSDWR limit values, yet the leachate concentration levels measured from the FGD lined facility are generally lower or comparable to the NSDWR limits for most potential contaminants of concern. In particular, Arsenic concentration levels of the pond and sump samples were very low in the first year of monitoring. Upon addition of swine manure to the facility (in early September, 1998), the concentration level of Arsenic in the pond increased gradually to a maximum value of $0.18\mu\text{g/mL}$ over a two-year period and then reduced. The Arsenic concentrations in sump samples were close to the detection limit for the first four years of

sampling (from September 1997 to February 2001), but a noticeable increase was found in the recent sampling events (October 2001~April 2003). It should be noted, however, arsenic levels in the sump and pond have remained lower than Ohio EPA's non-toxic regulatory value of 1.5 µg/ml for the duration of the project.

5.1.4 Permeability Measurements

An important objective of this research project was to measure the actual permeability of a field-compacted FGD liner. The full-scale FGD lined pond facility (capacity of one million gallons), constructed in 1997 using 2,700 tons of lime and fly ash enriched fixated FGD material, was monitored for a period of nearly 6 years. The long-term permeability of the full-scale field compacted FGD liner was in the 10^{-7} cm/sec range. Hence, lime and fly ash enriched FGD materials can be compacted in the field to give a coefficient of permeability in the range of 10^{-7} cm/sec (3×10^{-9} ft/sec).

An important question to address is how the actual permeability of the lime-fly ash enriched FGD material compares with permeability results from laboratory testing and field test pad (Boutwell) procedures. A summary of the permeability results from Phase I and II of the project are presented in Table 5.1. In addition to the full-scale FGD liner measurements, five different sets of laboratory tests and two distinct field test pad programs (using Boutwell procedure) implemented in the project are summarized in the Table 5.1. It can be observed from the Table that to obtain a laboratory permeability value in the 10^{-8} cm/sec range or lower, a minimum of FA:FC ratio of 1.7:1 and lime content of 8% is needed. For the full-scale facility (with average

FA:FC ratio was 1.8:1 and lime content of 8%), permeability values in the range of 10^{-7} cm/sec were obtained. This observation that the actual full-scale field permeability values for the FGD material are an order of magnitude higher than those obtained in the laboratory is similar to that for clay materials.

However, it can be observed from Table 5.1, that while the Test Pad 1 testing program had enough lime, it was lacking in fly ash. Furthermore, the small size of the test pads resulted in inadequate compaction of the FGD material. In the Test Pad 2 testing program, the FGD material provided by the power plant was lacking in fly ash and lime (due to power plant operating limitations) and hence permeability values achieved were much higher. Furthermore, it needs to be noted that the first three mixes of Test Pad 1 program were similar in composition and were compacted similarly, yet their permeability values differ by three orders of magnitude. The results from the Boutwell tests on the tests pads carried out in this program seem unreliable for two main reasons. One is that the Boutwell apparatuses require special and careful installation. Although the installation of the Boutwell apparatuses for both the test pads was done by a certified engineering company, yet the results varied significantly even for similar material mixes. This is particularly problematic for the FGD material since it gains strength with curing time (unlike clay) and digging a hole for the installation of the Boutwell apparatus can cause significant cracking and damage in the test material surrounding the hole. Secondly, for the test pad tests, the boundary conditions of flow are unknown. Boutwell tests conducted on test pads can predict accurate infiltration rates but to relate the infiltration rate with coefficient of permeability, the boundary conditions, which are typically not well known, need to be accurately specified. Hence, the Boutwell test is not recommended for estimating the field permeability of

FGD material. Instead, it is recommended that falling-head laboratory tests be conducted on laboratory compacted FGD material samples and that the field permeability values (for properly compacted field liners) for FGD material be considered to be an order of magnitude higher than the laboratory measured values.

Table 5.1: Summary of Permeability Measurement Tests

Testing Procedure	FGD Material Composition			γ_d (kN/m ³)	k (cm/sec) [curing time (days)]		Comments
	FA:FC	Lime (%)	w (%)				
Lab Tests 1: 1997 mixes prepared in the laboratory and tested using Falling Head Test in the laboratory	1:1	4	32	11.9	2.3×10^{-6}	[90 days]	Fly ash and filter cake from Conesville powerplant were mixed in the laboratory with lime and water
	1:1	8	35	11.3	1.8×10^{-7}	[90 days]	
	2:1	5	27	12.4	1.4×10^{-6}	[90 days]	
	2:1	8	32	12.2	4.8×10^{-8}	[90 days]	
Lab Tests 2: 1997 plant mixes tested using Falling Head Test in the laboratory	1.7:1	5	48	11.1	2.6×10^{-7}	[90 days]	Conesville Fixated FGD material
	1.7:1	8	42	11.9	3.0×10^{-8}	[90 days]	Gavin Fixated FGD material
	1.7:1	4	51	10.8	1.7×10^{-7}	[90 days]	
	1.7:1	8	39	12.5	1.0×10^{-8}	[90 days]	
Lab Tests 3: 1998 plant mixes tested using Falling Head Test in the laboratory	0.8:1	4	60	9.1	5.3×10^{-6}	[90 days]	Conesville Fixated FGD material
	0.8:1	10	60	9.5	3.4×10^{-6}	[90 days]	
Lab Tests 4: Plant mixes from 1997 construction of full-scale FGD lined facility at OARDC. Samples compacted in laboratory and tested using Falling Head Test in the laboratory	1.8:1	8	49	11	2.1×10^{-7}	[60 days]	Conesville Fixated FGD material
					2.8×10^{-8}	[1960 days]	
	1.8:1	8	62	11.6	1.2×10^{-7}	[60 days]	
					1.6×10^{-8}	[1960 days]	
Lab Tests 5: 2002 plant mixes for 2nd set of test pads compacted in the laboratory and tested using Falling Head Test in the laboratory	1.8:1	8	52	10.5	4.2×10^{-8}	[60 days]	Conesville Fixated FGD material
					3.5×10^{-8}	[1960 days]	
	1.8:1	8	62	9.6	2.7×10^{-8}	[60 days]	
					4.7×10^{-9}	[1960 days]	
Lab Tests 5: 2002 plant mixes for 2nd set of test pads compacted in the laboratory and tested using Falling Head Test in the laboratory	1:1	4.5	72	8.4	1.4×10^{-5}	[60 days]	Conesville Fixated FGD material
	1:1	6.8	63	8.8	5.4×10^{-6}	[60 days]	
	1.5:1	10	53	9.3	2.3×10^{-6}	[60 days]	
	1.5:1	6.8	50	9.6	7.2×10^{-6}	[60 days]	
Full Scale FGD Lined Facility Tests: Facility constructed in 1997 with 2,700 tons of FGD material and designed to test the actual permeability of the field-compacted FGD liner	1.8:1 (ranged from 1.5:1 to 2.4:1)	8 (ranged from 6.8 to 8.5)	49 to 52	9.6 to 11.6	6.87×10^{-7}	[60 days]	Conesville Fixated FGD material
				4.2×10^{-7}	[1275 days]		
				4.6×10^{-7}	[2050 days]		
Test Pads 1: Test pads constructed in the field using FGD material from the 1997 construction of the full-scale FGD lined facility and tested using field Boutwell test procedure	1.25:1	8	62	< 8	8.0×10^{-7}	[90 days]	Conesville Fixated FGD material; inadequate compaction due to small size of test pads
	1.25:1	8	69	< 8	1.6×10^{-4}	[75 days]	
	1.25:1	8	58	< 8	2.3×10^{-6}	[75 days]	
	0.8:1	4	84	< 8	1.2×10^{-4}	[75 days]	
Test Pads 2: Test pads constructed at Conesville landfill in 2002 and tested using field Boutwell test procedure	1:1	4.5	72	8.4	1.3×10^{-5}	[60 days]	Conesville Fixated FGD material; adequate compaction achieved
	1:1	6.8	63	8.8	1.9×10^{-6}	[60 days]	
	1.5:1	10	53	9.3	1.8×10^{-4}	[60 days]	
	1.5:1	6.8	50	9.6	-	-	

5.2 Conclusions

This research program consisted of coordinated small-scale laboratory, medium-scale wetland, and full-scale pond testing conducted at The Ohio State University for three years. Results from the overall 6 years research program for the laboratory testing and full-scale FGD liner pond monitoring show that stabilized FGD materials can be used as low permeability liners in the construction of water and manure holding ponds. Long-term actual permeability coefficients in the range of 10^{-7} cm/sec (3×10^{-9} ft/sec) can be obtained in the field by compacting lime and fly ash enriched stabilized FGD materials. Leachate from the FGD material meets Ohio's non-toxic criteria for coal combustion by-products, and for most potential contaminants the national primary and secondary drinking water standards are also met. The low permeability non-toxic FGD material investigated in this study poses very minimal risks, if any, for groundwater contamination. Medium-scale FGD wetland experiments indicated higher concentrations of elements common in FGD-liner material in the leachate water in the FGD basins. The FGD mixture as implemented in the wetland experiments did not serve as an effective aquiclude to water movement. There were no significant differences in phosphorus retention between the clay and FGD-lined basins during the high-phosphorus pulsing period. Plant productivity was lower in the FGD-lined wetland basins than in the clay-lined basins. The FGD-lined basins, which were stressed by low water levels, had a greater richness of plant species than did the clay-lined basins that had higher water levels. The clay-lined basins showed greater total plant productivity but with fewer plant species.

Future research work is recommended to extend the knowledge developed in this project to the use of FGD materials in the construction of landfill caps and liners, where the cost saving to the utility are significant and the clay borrow sources can be preserved.

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Appendix B

**Paper
02-CBRC-M12**

**Commercial Production of Fired Bricks with Illinois
Basin Class F Fly Ash**

Melissa Chou

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A. CONTRACTOR ACTION (CONTRACTOR COMPLETES PART A. 1-5)

1. Document Title: COMMERCIAL PRODUCTION OF FIRED BRICKS WITH ILLINOIS BASIN CLASS F FLY ASH

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<input type="checkbox"/>	<input checked="" type="checkbox"/>	is any patentable subject matter disclosed in the report?
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◆5. Signed Mei-In M. Chou (Contractor) Date 10-5-05

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Address 615 E. Peabody Dr. Champaign, IL 61820

B. DOE PATENT COUNSEL ACTION

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COMMERCIAL PRODUCTION OF FIRED BRICKS WITH ILLINOIS BASIN CLASS F FLY ASH

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KEYWORDS: Class F fly ash, fired paving and building bricks, coal combustion byproducts

Abstract

For the past several years, researchers at the Illinois State Geological Survey (ISGS)/University of Illinois (UIUC) have been working with several brick manufacturers in Illinois and Indiana to develop high quality, marketable brick products that will potentially use high-volumes of Class F fly ash. Scale-up production tests were conducted at commercial facilities to determine whether these fly ash-containing fired bricks could be commercially viable. This year, supported by the United States Department of Energy, National Energy Technology Laboratory - West Virginia University Research Corporation - Combustion Byproducts Recycling Consortium and the utility and brick industries, a total of about 4,000 full-size paving bricks and 6000 full-size three-hole building bricks have been produced at an Indiana brick plant for evaluation. The process uses fly ash to substitute for part of the clay and shale which are the two main ingredients used by the brick plant for their conventional brick making. The paving bricks produced contain 20% by volume of fly ash from a nearby source, and the building bricks produced contain 20%, 30%, or 40% by volume of fly ash from the same source. The extrusion and firing evaluations have been completed for making paving bricks, and their final products have met ASTM C902 standard specifications. The extrusion evaluation has been completed for making building bricks, and the firing evaluation is in progress. The brick plant currently produces sixteen million bricks per year. Successful results from this investigation could lead to the plant using between 8,000 and 16,000 tons of fly ash per year.

Background

More than six million tons of Class F fly ash is generated from burning about one hundred million tons of Illinois Basin coal each year. Most of this fly ash is ponded or landfilled, and is readily available for value-added applications. For the past three years, researchers at the Illinois State Geological Survey and the University of Illinois have been working with brick manufacturers to develop high quality and marketable brick products using large volumes of Class F fly ash generated from burning Illinois coals (Chou 2000; 2001; 2002). In this process of making fired building and face bricks, fly ash is used as a substitute raw material for part of the clay and shale used in conventional bricks. Under the right conditions, the production of building and face bricks containing Illinois coal fly ash can be commercially viable. The test bricks produced so far have met or exceeded ASTM C216 facing (building) brick specifications. Nevertheless, until the brick industry gains more confidence in using fly ash as a raw material for their brick production, evaluation and testing will be needed on a case-by-case basis. With support and cooperation from the United

States Department of Energy National Energy Technology Laboratory - West Virginia University Research Corporation - Combustion Byproducts Recycling Consortium (DOE-WVU-CBRC) and the utility and brick industries, this study has furthered the initial commercialization process and tested the ponded fly ash of an Indiana power plant as a viable raw material for fired brick production at a brick plant located less than five miles from the power plant.

Raw Materials

Approximately 20 tons of ponded fly ash was shipped to the brick plant for commercial-scale test runs making paving bricks. A 40-ton lot of ponded fly ash was later shipped to the same brick plant facility for commercial-scale production test runs making three-hole building bricks. Samples from the 20-ton lot (Ash II) and the 40-ton lot (Ash III) of fly ash were analyzed for their chemical composition in two successive trials.

The typical major and minor metal oxides and the unburned carbon content (measured as loss on ignition, LOI) of the fly ash, clay, and shale samples are shown in Table 1. The ash materials are comparable to the clay and shale materials in their major metal oxides content. The LOI for the fly ash samples ranged from 1.16% to 4.95% by weight, which is somewhat lower than the LOI of the shale and clay materials of conventional bricks which ranged from 6.93% to 9.06% by weight. The data obtained in earlier testing indicated that the unburned carbon content of all the fired brick products with and without fly ash was less than 1% by weight, suggesting that unburned carbon is consumed during firing.

Bench-Scale Production (Mold Pressing and Preliminary In-Plant Firing)

Paving bricks are solid with no bore holes and building bricks have three bore holes, thereby requiring that the formulation and firing conditions for the paving bricks and building bricks be examined by conducting as many pre-cursor tests as necessary. During pre-cursor testing, small batches of commercial-size green paving bricks and building bricks were made by mold-press at the ISGS bench-scale facility and were later fired as part of a commercial firing at the brick plant.

More than twenty-four commercial-size green paving bricks containing fly ash at 10, 20, 30, 40 and 50% by volume balanced with clay and shale samples were produced. These bricks then underwent preliminary in-plant firing tests producing high-quality, attractive, and strong paving bricks.

Similarly, to determine which fly ash containing building brick formulations would be best suited for scale-up tests, new sets of commercial-size mold-pressed three-hole building bricks were produced at the ISGS. These mold-pressed bricks were made with increased fly ash inputs of 40, 50, and 60% by volume. Each formulation contained a constant level of clay material with the balance made up with shale. These mold-pressed green building bricks were successfully fired as part of their commercial firing at the brick plant.

Commercial-Scale Production (Extrusion and Firing)

After preliminary in-plant firing tests, which produced high-quality, attractive, and strong paving and building bricks, commercial-scale extrusion and firing proceeded at the brick plant at a rate of about 2000 bricks per batch.

Two scale-up extrusion and firing tests were conducted for making paving bricks with the following formulations:

Run-1	20 vol% fly ash II	80 vol% shale	0 vol% clay
Run-2	20 vol% fly ash II	60 vol% shale	20 vol% clay

Four scale-up extrusion and firing tests were conducted for making building bricks with the following formulations: Run-3 was included as a standard run which adopted the building brick formulation currently using by the brick plant.

Run-3	0 vol% fly ash III	85.7 vol% shale	14.3 vol% clay
Run-4	20 vol% fly ash III	70 vol% shale	10 vol% clay
Run-5	30 vol% fly ash III	60 vol% shale	10 vol% clay
Run-6	40 vol% fly ash III	50 vol% shale	10 vol% clay

Final Paving Brick Products and Evaluation

To evaluate paving bricks produced for commercial quality, the ASTM C902 specification for pedestrian and light traffic bricks was used (ASTM 2004). For an average of five bricks, the ASTM C902 sets the minimum compressive strength at 8,000 psi for Grade SX (severe weather); maximum cold water absorption at 8% by weight; maximum saturation coefficient not greater than 0.78; and the maximum abrasion resistance index at 0.11 for Type I brick that is exposed to extensive abrasion, as typically found in driveways or entrances to a public building. The saturation coefficient is defined by the ratio of the cold water absorption to the boiling water absorption. The abrasion resistance index is defined by the ratio of the cold water absorption to the compressive strength in percent.

The engineering test results from the two commercial-scale paving brick production runs are shown in Table 2. The engineering properties of the final products met or exceeded ASTM C902 specifications. The data also indicated that the bricks containing 20% by volume of clay as a balance material reduced their cracking and chipping, thereby significantly increasing the production yield (Chou 2005).

Final Building Brick Products and Evaluation

A total of four scale-up extrusion test runs were conducted at the brick plant. These extrusion tests successfully produced green bricks (Figure 2) with fly ash inputs of 0, 20, 30, and 40% by volume for firing evaluation. The trial conducted without fly ash was used as a standard run.

The commercial scale-up firing tests have produced strong and attractive bricks with a desired red color, and they have exhibited no difference from the standard bricks

produced without fly ash input. Although these final building brick products (Figure 3) met the brick company's in-house specification for the commercial market, engineering tests are in progress at the ISGS to determine their engineering properties with respect to the ASTM C216 guidelines (ASTM 2004) for facing (building) bricks in the severe weather grade.

One of the concerns of brick producers with respect to the physical properties of the fly ash containing fired bricks is the shrinkage rate. Shrinkage occurs during both drying and firing processes. The shrinkage rate was calculated based on the measurement of the brick length. The length of the fired bricks from each batch shown in Figure 4 was determined by first measuring multiple brick samples selected randomly from the brick pile, then taking an average value from these measurements. The results indicated that the total shrinkage rate (dried plus fired) for the Run-3, Run-4, Run-5, and Run-6 was 9%, 8%, 8%, and 9%, respectively, meeting the specification of the brick plant. In addition, the production yield for all four batches was greater than 95%, which also met the brick plant specification.

Summary

This study indicated that paving bricks could be successfully produced with 20% by volume of Class F fly ash. The engineering properties of these paving bricks either met or exceeded ASTM C902 specifications. In addition, a low level of clay material (20% by volume) in the raw mix containing fly ash improved the extruding ability of the mixed raw material and greatly improved the final product yield. This study also indicated that building bricks can be produced with 40% by volume (about 37% by weight) of fly ash at a yield greater than 95%. Although these building brick products met the brick company's own specifications to be marketable, determining their engineering properties with respect to ASTM C216 guidelines for facing (building) bricks in the severe weather grade is in progress at the ISGS. The continued study includes evaluations of the economic and environmental impacts of commercial fly ash brick production. The results of these studies will help the brick plant to move one step closer to commercial production of bricks containing fly ash.

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Biography of Primary Author

Dr. Mei-In M. Chou earned her PhD in chemistry from Michigan State University, with Prof. R.H. Grubbs - 2005 Nobel price recipient. Dr. Chou joined the Survey in 1978.

Since then, she has been the principal investigator of many projects in coal and geochemical investigations. In addition, she has led multiple projects in process development to utilize high volumes of solid coal combustion byproducts in value added applications. In 2001, she was awarded an adjunct professorship by the University of Illinois. Currently, she is leading state and federally funded projects making high-quality construction products with fly ash and bottom ash.

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Table 1: Metal oxides composition (wt%) of fly ash, shale and clay samples used in fired brick making

Sample ID	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI
Ash II	59.13	26.32	5.04	0.85	0.05	1.38	1.06	0.60	3.52	0.09	1.16
Ash II (duplicate*)	54.78	24.36	5.48	1.22	0.06	1.04	3.00	1.11	2.75	0.23	4.95
Ash III	54.27	23.90	11.62	1.27	0.02	1.10	1.23	0.78	2.8	0.18	1.70
Ash III (duplicate*)	54.47	23.52	12.35	1.26	0.03	1.09	1.20	0.73	2.88	0.20	1.8
Shale/Clay Mix	59.64	18.29	6.49	1.10	0.12	1.91	0.61	0.85	3.08	0.16	7.46
Shale	60.15	17.88	6.67	1.07	0.10	1.96	0.70	0.94	3.09	0.16	6.93
Shale (duplicate*)	59.58	18.07	6.81	1.07	0.10	1.68	0.71	0.94	2.84	0.18	7.62
Clay	58.21	20.85	5.48	1.17	0.08	1.31	0.7	0.46	2.36	0.12	9.06

Ash II = the 20-ton lot fly ash sample; duplicate* = duplicated sampling of the sample indicated; Ash III = the 40-ton lot fly ash sample.

Table 2: Engineering properties of paving bricks with 20 vol% of fly ash from two commercial-scale production runs (Chou 2005)

		Run-1	Run-2
Max. water absorption	Cold water, wt% (Class SX <8 wt%)	1.75	6.81
	Boiling water, wt%	2.55	9.65
	Saturation coefficient* (Class SX <0.78)	0.69	0.71
Fired compressive strength, psi (Class SX >8,000 psi)		29,910	23,540
Suction rate, g (wt. gain/ minute)		2.50	20.8
Modulus of Rupture, psi (>1,000 psi)		1737	1959
Abrasion Resistance Index (Type I < 0.11)		0.006	0.029
ASTM C902 Classification		Class SX Type I	Class SX Type I
Production Yield		75%	100%

ASTM C902 - Standard specifications for Pedestrian and Light Traffic Paving Brick.
 Run-I = 20 vol% fly ash II and 80 vol% shale; Run-II = 20 vol% fly ash III, 60 vol% shale, and 20 vol% clay

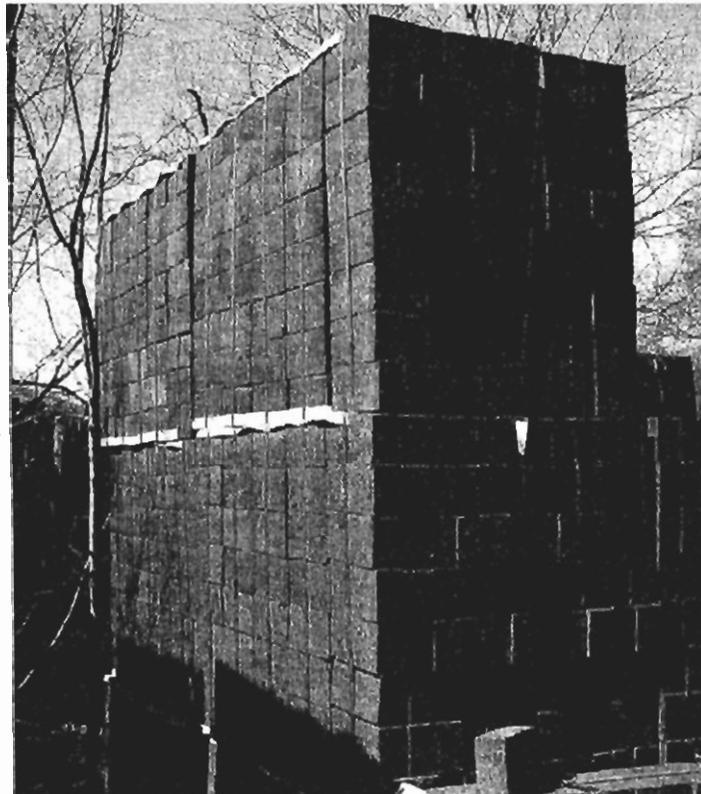


Figure 1: Fired paving bricks containing 20 vol% fly ash

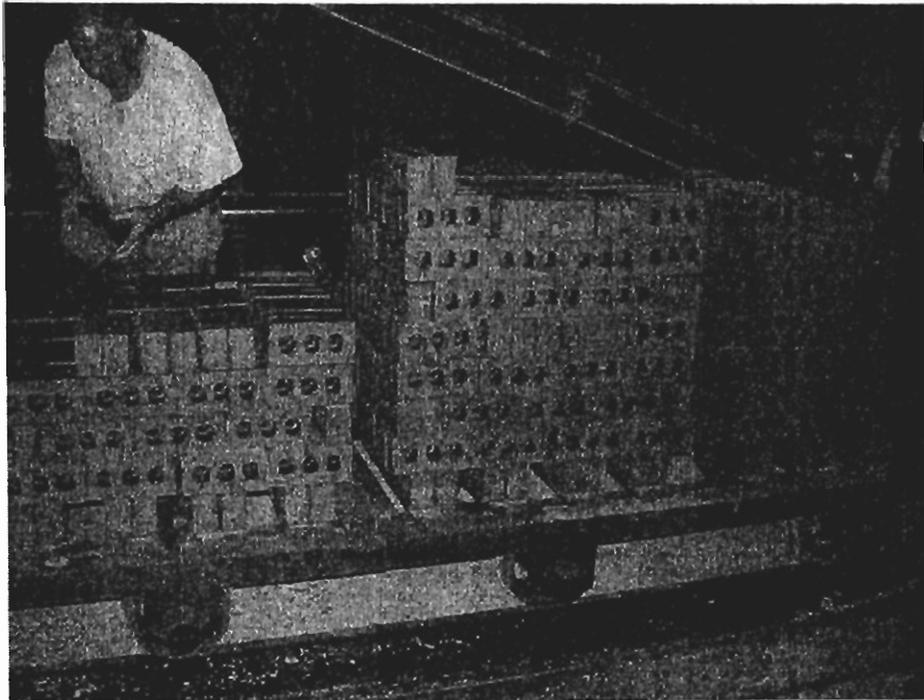


Figure 2: Scale-up extrusion at the brick plant produced three-hole green building bricks (700 bricks per car)

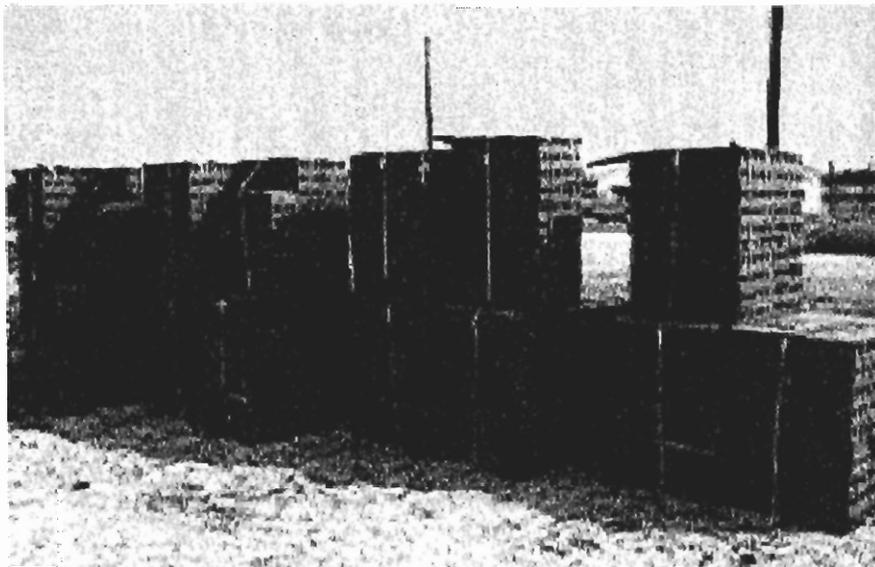


Figure 3: Four batches of fired building bricks produced from scale-up production test runs with fly ash inputs at 0, 20, 30, and 40 % by volume

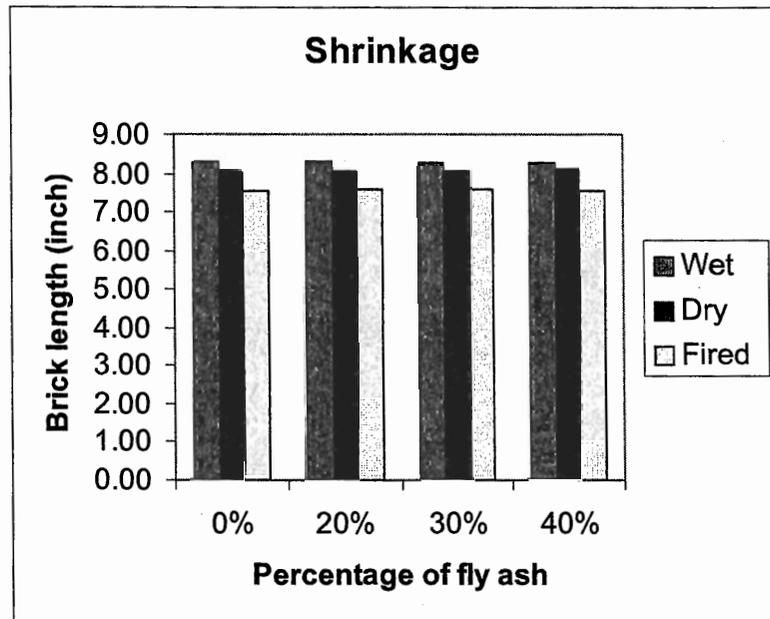


Figure 4: Changes in the brick length after drying and firing