Demonstration of Innovative Applications of Technology for Cost Reductions to the CT-121 FGD Process

DOE ICCT PROJECT DE-FC22-90PC89650

Volume 4 of 6: Gypsum Stacking and Byproduct Evaluation

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Principal Investigators

C. Lamar Larrimore
Southern Company
Southern Company Services, Inc.
William Miller Ph.D.
University of Georgia

Project Manager

David P. Burford
Southern Company
Southern Company Services, Inc.
44 Inverness Center Parkway
Suite 230
Birmingham, Alabama 35242

Project Sponsors

Southern Company
US Department of Energy
Electric Power Research Institute

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LIST OF ABBREVIATIONS

AEC	anion exchange capacities
Al	Aluminum
ANC	acid neutralizing capacity
As	Arsenic
ASAE	American Society of Agricultural Engineers
B	Boron
BET	Brunnauer-Emmett-Teller
CCB	coal combustion byproducts
CCE	calcium carbonate equivalent
CEC	cation exchange capacities
CI	cone index
CT-121	Chiyoda Thoroughbred-121
D & O Plan	Design and Operating Plan
EC	electrical conductivities
EDAX	energy dispersive analyses by x-ray
FA	fly ash
Fe	Iron
FGD	flue gas desulfurization
GFAAS	graphite furnace atomic absorption spectrophotometer
ha	hectare
HDPE	high density polyethylene
HIV	hydroxy-interlayer vermiculite
HWSB	hot-water-soluble boron
ICP	inductively coupled plasma
K	Potassium
LOI	Loss of ignition
Mo	Molybdenum
MSL	Mean Sea Level

LIST OF ABBREVIATIONS (Continued)

Pb	Lead
PVC	Polyvinyl chloride
RMSE	root mean squared error
Se	Selenium
SEM	Scanning Electron Microscopy
SG	specific gravity
Si	Silicon
SO_4	Sulfate
SPT	Standard Penetration Test
WHC	water holding capacity
XRD	x-ray diffraction

VOLUME SUMMARY

The Chiyoda Thoroughbred-121 (CT-121) flue gas desulfurization (FGD) process was selected for demonstration at Georgia Power Company's Plant Yates near Newnan, Georgia by the Department of Energy under its Clean Coal Technology Program. During the approximately two-year operating period for the demonstration project, the FGD equipment installed on Unit 1 produced gypsum and a gypsum/ash mix as byproduct materials.

The scope of work included tasks designed to investigate storage/disposal and utilization options for the byproducts. Project objectives in this area included demonstration of the "stacking" technology to construct separate stacks for FGD gypsum and ash/gypsum which are larger than previously attempted; use of FGD gypsum as an agricultural soil amendment; and use of processed gypsum as a replacement for mined gypsum in wallboard and cement manufacturing processes.

The wet stacking disposal facility was designed to provide adequate storage for the projected byproduct volumes and, where possible, allow use of full-scale procedures and field evaluation of stackability. Although the ash/gypsum facility is still in operation, results clearly indicate that FGD gypsum and gypsum/ash can be successfully stored by wet stacking using upstream construction methods. Field evaluations have provided a number of recommendations to improve stackability and operational efficiency for future projects, and for modifying and implementing design elements of the demonstration facility to future large-scale projects.

Extensive greenhouse and field agronomic evaluations have concluded that the Yates gypsum is a high-quality material, similar to or better than most gypsum materials currently marketed. It should be suitable as a soil amendment on peanuts and other crops, and poses minimal, if any, environmental concerns. In fact, a plant food license has been obtained from the Georgia Department of Agriculture for food crop soil amendments. Benefits include amendments of acidic soils which limit root growth and crop yields, plus improvement of water infiltration and other properties of weathered soils. Other field work has determined that some grasses, particularly weeping lovegrass, can be established, for revegetation purposes, directly on the gypsum stack slopes.

Due to funding limitations, other manufacturing demonstrations for wallboard and cement industries were not undertaken. These tasks were actually proposed additions to the original scope of work. However, it appears that these potential end-users of CT-121 FGD gypsum are still clearly interested in this application.

1.0 INTRODUCTION

Earlier projects have been beneficial in indicating that FGD gypsum and gypsum-ash mixtures can be stacked. Stacking has proven to be superior to ponds (smaller land area) or landfills (lower cost, less equipment) for handling gypsum materials. However, the relatively small size of existing facilities has limited the direct transfer of operating and construction experience to much larger full-scale facilities. When compared to the calcium sulfite sludge generated by conventional inhibited or natural oxidation FGD processes, advantages of byproduct gypsum include a significantly larger market potential as well as the superior handling/storage method available (stacking). Possible uses for FGD gypsum are essentially the same as those for natural gypsum -- wallboard, cement, and agriculture. Objectives and scope of work were designed to fully investigate storage/disposal and utilization options for gypsum and gypsum/ash.

1.1 Overall Objectives

Project objectives pertaining to byproduct disposal and utilization included demonstration of the following:

1. Use of the "stacking" technology to construct separate stacks for FGD gypsum and ash/gypsum which are larger than previously attempted;
2. Use of FGD gypsum as an agricultural soil amendment;
3. Horizontal belt vacuum filter to lower chloride and moisture levels in gypsum; and
4. Use of processed gypsum as a replacement for mined gypsum in wallboard and cement manufacturing processes.

1.2 Specific Objectives

Detailed objectives of the stacking evaluation included:

1. Determine field handling, stackability, and trafficability characteristics of the FGD gypsum and FGD gypsum-fly ash;

2. Develop construction and operation procedures for implementation on a full-scale facility;

3. Evaluate engineering properties of FGD gypsum and FGD gypsum-fly ash from laboratory and field testing; and

4. Recommend design properties for use in design of a full-scale wet stacking facility.

Evaluation of gypsum and gypsum-fly ash in agricultural applications had the following objectives:

1. Determine yield response of important forage and grain crops to various rates and application methods on southeastern soils, and identify accessory management techniques to enhance the effect of such applications;

2. Assess food chain and environmental effects, if any, of cropland amended with gypsum or gypsum-ash, with particular emphasis on forage uptake and leaching of arsenic, boron, molybdenum, and selenium;

3. Quantify the effects and longevity of surface-applied gypsum on soil physical properties such as clay dispersion, infiltration, and soil loss;

4. Evaluate use of annuals in crop rotation after perennials, in terms of yield and rooting depth, as a step toward long-term improvement of southeastern soil productivity; and

5. Determine plant species and management practices useful in temporary or permanent revegetation of FGD gypsum stacks.

Activities proposed for gypsum processing and manufacturing applications have been intended to accomplish the following:

1. Procure and install a horizontal belt vacuum filter to wash and dewater approximately 5,000 tons of FGD gypsum to a quality suitable for manufacturers' raw material specifications (primarily free moisture less than 10% and chlorides less than 100 ppm associated with solids);

2. Perform a series of parametric tests to define the difficulty and cost of achieving a range of filter product qualities, when operated with gypsum slurry derived from several limestone sources; and

3. Transport necessary quantities of gypsum to selected wallboard and cement plants for trial production runs and extensive testing on raw materials and finished products.

2.0 TECHNICAL APPROACH

This section contains the basic approach for design, construction, and testing associated with byproduct evaluation, including storage/disposal and utilization options for these materials.

The Chiyoda Thoroughbred-121 (CT-121) flue gas desulfurization (FGD) process has been selected for demonstration at Georgia Power Company's Plant Yates near Newnan, Georgia by the Department of Energy under its Clean Coal Technology Program. The CT-121 technology is a wet FGD process that removes SO_2, can achieve simultaneous particulate control, and produces gypsum as a byproduct. In the Jet Bubbling Reactor (JBR), flue gas bubbles beneath the slurry, SO_2 is absorbed, and particulate matter is removed from the gas. The agitator circulates slurry to ensure that fresh slurry is always available in the froth or bubbling zone so that SO_2 removal can proceed at a rapid rate. Air is introduced into the bottom of the JBR to oxidize the absorbed SO_2 to sulfate, and limestone is added to neutralize the acid slurry and form gypsum.

The JBR is designed to allow time for complete reaction of the limestone, and for growth of large gypsum crystals. Gypsum or gypsum-fly ash slurry is continuously withdrawn from the JBR and pumped to a stacking area for disposal. The stacking technique of disposal involves filling a containment area with the gypsum or gypsum-fly ash slurry, allowing the solids to settle, removing clear liquid from the top of the stack for recirculation to the process, and stacking the gypsum or gypsum-fly ash using the upstream method of construction.

Previous demonstration projects on Plant Scholz CT-101 FGD gypsum (Garlanger and Ingra, 1980) and TVA Widows Creek FGD gypsum-fly ash (Garlanger and Ingra, 1984) have shown that wet stacking of utility byproduct gypsum and gypsum-fly ash is possible. These previous projects, however, were of limited operating duration and produced relatively small quantities of material. As a result, relatively small stacks were constructed which limited the transfer of construction and operational experience to larger full-scale facilities. Accordingly, the objective of the Plant Yates project was to demonstrate the use of the wet stacking method for both FGD gypsum and FGD gypsum-fly ash using stack heights and areas which will provide construction and operational experience similar to that expected for a full-scale facility. Further, characterization studies have only been performed on FGD gypsum and FGD gypsum-fly ash produced at Plant Scholz and Widows Creek. Little other information is available for utility byproduct gypsum produced at other facilities. Accordingly, a second objective of the project was to evaluate the engineering properties of the gypsum and gypsum-fly ash produced at Plant Yates to expand the data base of engineering properties available to the utility industry for designing FGD gypsum and FGD gypsum-fly ash wet stacking disposal facilities. Specifically, the objectives of the project are to:

- Demonstrate the construction and operation of a wet stacking disposal facility for FGD gypsum and FGD gypsum-fly ash larger than the previous Plant Scholz CT-101 and TVA Widows Creek projects;
- Determine the field handling, stackability and trafficability characteristics of FGD gypsum and FGD gypsum-fly ash and develop construction and operational procedures for implementation on full-scale facilities; and
- Evaluate the engineering properties of FGD gypsum and FGD gypsum-fly ash from laboratory and field testing and recommend design properties for use in the design of full-scale wet stacking disposal facilities.

2.1 Design of Storage/Disposal Area

The disposal facility was designed to provide storage for the byproduct gypsum and gypsum-fly ash generated during a 24-month test period of the CT-121 FGD process at Plant Yates. It was projected that 28,600 tons of FGD gypsum (dry weight basis) would be produced during the first nine months of operation, and 92,600 tons of FGD gypsum-fly ash, comprised of 50 percent gypsum and 50 percent fly ash, would be produced during the remaining 15 months. The site of the Plant Yates byproduct disposal facility encompasses an area of approximately 10 acres located north of the power plant.

The proposed method of byproduct disposal/storage within the test facility incorporate slurry deposition with rim-ditch techniques and wet-stacking using the upstream method of construction.

These techniques are commonly used for large-scale disposal of byproduct phosphogypsum from the production of phosphoric acid used in fertilizer manufacturing.

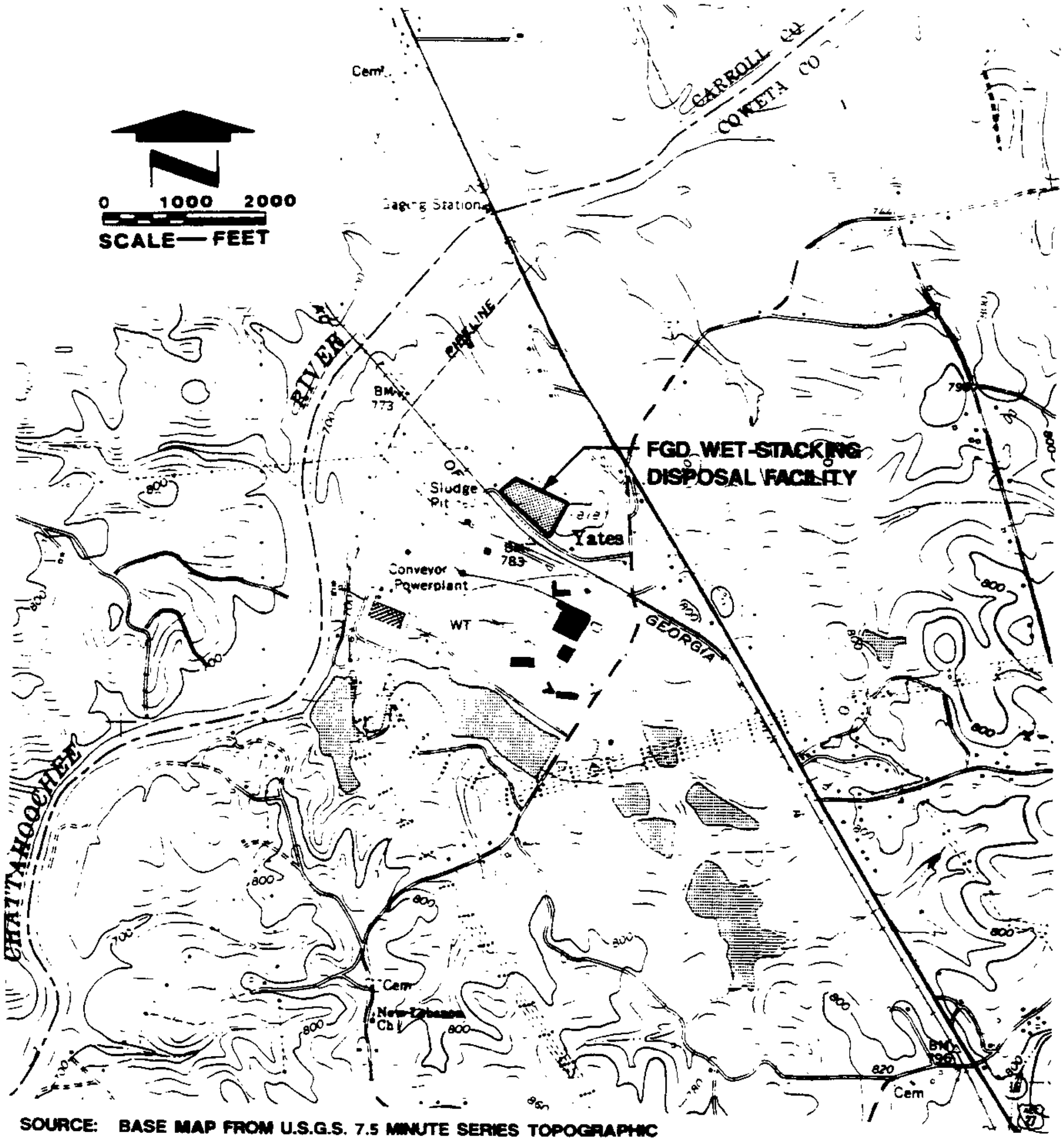
Site conditions pertinent to construction and operation of the FGD wet-stacking disposal facility, based on results of field exploration and laboratory testing programs undertaken by Ardaman & Associates, Inc. during the basic design phase, are described in the following section.

2.1.1 Site Evaluation

Plant Yates is located in Coweta County, Georgia on U.S. Alternate 27 between the towns of Newnan and Carrollton, on the east bank of the Chattahoochee River. The approximately 10-acre area available for construction of the FGD wet-stacking disposal facility is located on the north side of the power plant, about 1000 feet southwest of U.S. Alternate 27 and 2500 feet southeast of the Chattahoochee River (Figure 2-1). The area is bordered on the north by an existing powerline easement and on the south by an existing dirt roadway, powerline, and railroad track.

As shown on Figure 2-2, the general topography of the area slopes northwesterly toward the river with the disposal area located on the side of a topographic high. The total relief across the site is about 60 feet. The maximum elevation on the site is 814 feet (MSL) on the eastern edge, and the minimum elevation is 754 feet (MSL) on the western edge. A drainage feature exists just to the north of the eastern edge of the site which drains to the Chattahoochee River. Surface water runoff from the site presently flows northwestward from the drainage divide on the eastern side of the site to this drainage feature by both overland flow and via a drainage ditch along the roadway on the south side of the site.

A subsurface exploration program was undertaken by Ardaman & Associates, Inc., in cooperation with geologists from the Earth Sciences and Technology Group of Southern Company Services, Inc. at the proposed site in April and June 1990. The objectives of the subsurface exploration program were to:



SOURCE: BASE MAP FROM U.S.G.S. 7.5 MINUTE SERIES TOPOGRAPHIC MAP, WHITESBURG, GEORGIA. (PHOTOREVISED 1982 VERSION)

Figure 2-1. Site Location Map

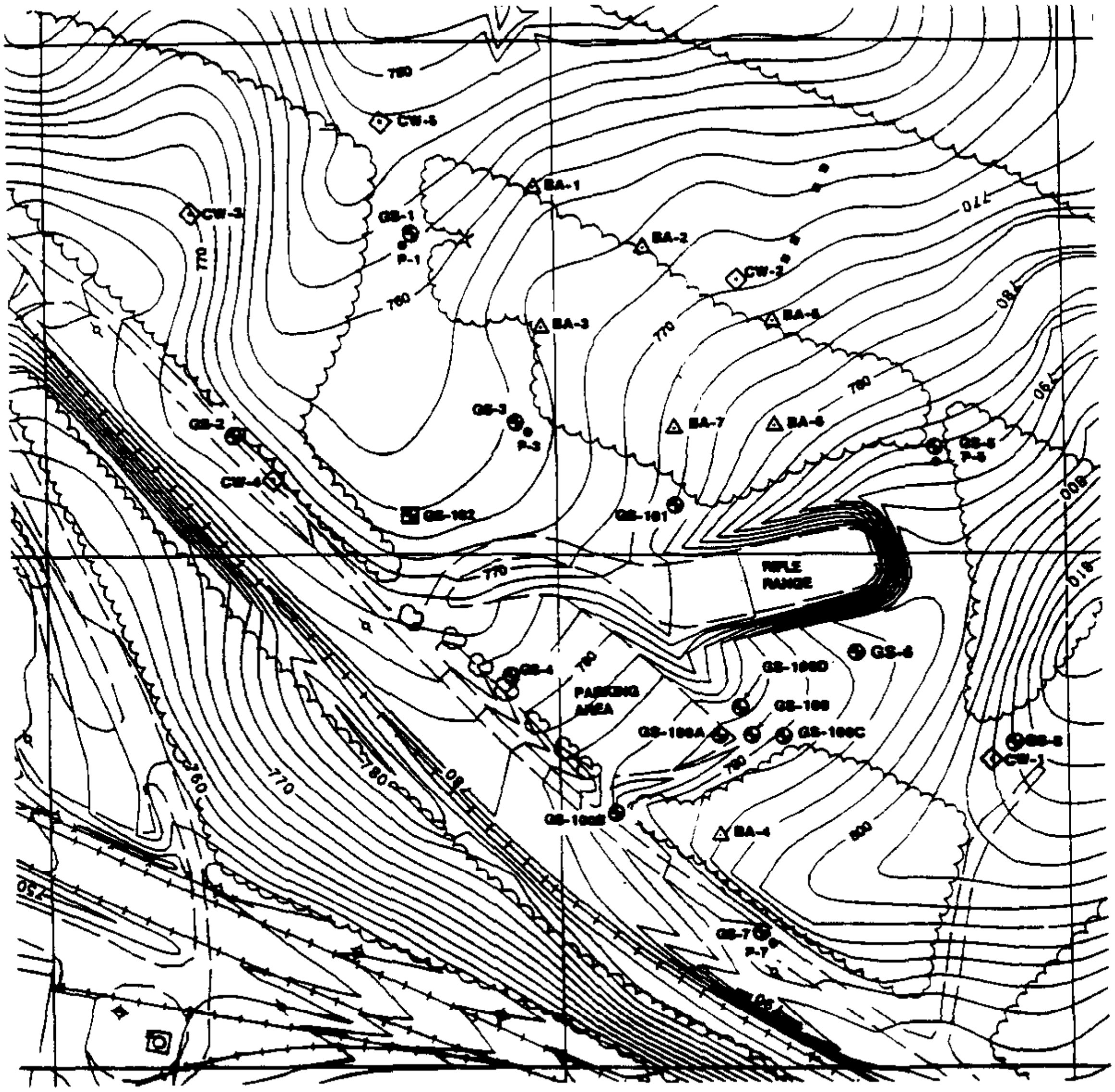


Figure 2-2. Site Location and Field Exploration Plan

1. Define the nature, extent, thickness and consistency of soils underlying the disposal area relevant to defining the near-surface hydrogeology and relevant to design and construction of the disposal facility;

2. Determine the depth to the water table and direction of groundwater flow;

3. Determine the *in situ* horizontal coefficient of permeability of soils underlying the site via slug tests in piezometers; and

4. Identify potential borrow soils for use in construction of an earthen liner for the disposal facility.

The field exploration program consisted mainly of soil and rock borings; Standard Penetration Tests (SPT); soil, rock and water sampling; and piezometer and compliance monitor well installation. Details of the field exploration programs and a complete presentation of the results are included in a Yates Project interim report (Ardaman, 1990). The results are summarized below, in terms of the general stratigraphy and properties of the site soils.

The rock units underlying the disposal area were identified by the Earth Sciences and Technology Group in 1990 as the Franklin Gneiss, a granitic gneiss, and the Waresville Schist, a sequence of amphibolite interlayered with chlorite schist. The Franklin Gneiss occurs in the western portion of the site and the Waresville Schist in the eastern portion of the site. The Waresville Schist is intruded by a body of Franklin Gneiss, a sillimanite mylonitic gneiss, along a narrow area on the eastern edge of the site. Portions of this body also outcrop at the top of the hill on the eastern edge of the site. Measurements of the strike and dip of this unit at the contact with the Waresville Schist made by the Earth Sciences and Technology Group indicate a strike of N30°E and a relatively steep dip of 80°SE.

The soils at the disposal facility are primarily residual, having developed in place from the weathering of underlying rock. The site stratigraphy is depicted in a generalized subsurface profile in Figure 2-3. The soils have been described geologically by the type of rock from which they weathered (i.e., metamorphic rocks generally comprised of quartzofeldspathic gneiss, or hornblende gneiss/amphibolite), by an engineering classification in accordance with ASTM

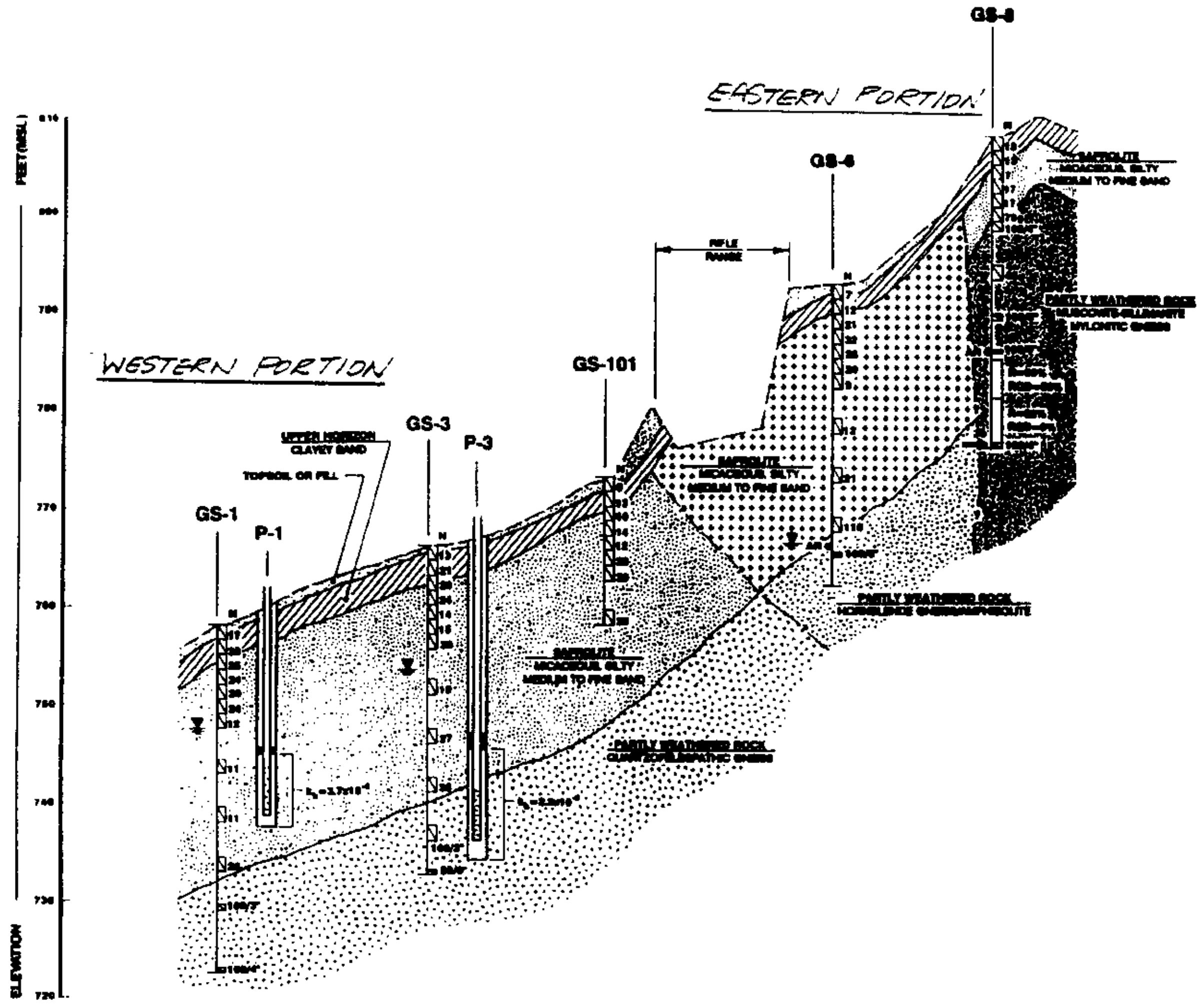


Figure 2-3. Generalized Site Soil Profile

standard D 2487 after remolding the samples to produce a homogeneous soil (i.e., without any relict structure or mineral segregation), and by the location of the sample in the weathering profile in general accordance with the classification by Sowers and Richardson (Sowers, 1983). This weathering profile classification was used to describe soil samples as either in the upper horizon (residual soil without relict structure), as saprolite (residual soil containing relict structure), or partly weathered rock (generally defined when the Standard Penetration Test resistance exceeded 50 blows/foot).

The top of the partly weathered rock, generally varied from 19.5 to 26 feet below land surface in the Franklin Gneiss (western portion of the site) and from 19 to 38.5 feet below land surface in the Waresville Schist (eastern portion of the site). The top of the partly weathered rock follows a trend similar to land surface, sloping to the northwest. Upon remolding of the samples to remove the relict structure and mineral segregation, the partly weathered rock classified as slightly micaceous to micaceous, silty, medium to fine sands, generally light grayish-brown to grayish-brown in color in the Franklin Gneiss, and dark gray to dark greenish-gray in color in the Waresville Schist.

Saprolite, weathered from the underlying metamorphic rocks, overlies the partly weathered rock and occurs within 3.0 to 8.0 feet of the surface. Thicknesses varied from 12.5 to 22.0 feet in the Franklin Gneiss (western portion of the site) and 15.5 to 32.0 feet in the Waresville Schist (eastern portion of the site). Upon remolding of the samples to remove the relict structure and mineral segregation, the saprolite was comprised of: (i) white, light yellowish-brown, light orangish-brown, grayish-brown or brown, slightly micaceous to micaceous, silty, fine to medium sand in the Franklin gneiss, occasionally becoming a brown micaceous sandy silt; and (ii) brown, gray, dark gray or grayish brown, slightly micaceous to micaceous, silty, fine to medium sand in the Waresville Schist, occasionally becoming a micaceous, sandy silt. Saprolite weathered from the Franklin Gneiss contained (in order of abundance) quartz, feldspar and biotite minerals, and saprolite weathered from the Waresville Schist contained feldspar, hornblende, quartz and biotite minerals.

Upper horizon soils overlie the saprolite and consist of: (i) brown, orangish-brown and reddish-brown sandy clay to slightly micaceous sandy clay; (ii) orangish-brown and reddish-brown clayey medium to fine sand to slightly micaceous clayey medium to fine sand; and (iii) occasionally a reddish-brown to orangish-brown slightly micaceous sandy silt. The upper horizon soils are overlain by a 0.5- to 1.0-foot thick top soil layer generally comprised of brown to dark brown slightly clayey to clayey fine sand with roots. The upper horizon soils vary in thickness from 0.5 to 7.5 feet with an average of about 4 feet. The Standard Penetration Test resistance varies widely from 4 to 38 blows/foot with an overall average of 14 blows/foot, characteristic of stiff clayey soils.

Piezometer groundwater levels measured in April, June and November 1990, and compliance monitor well water levels measured in August and November 1990 indicated that the direction of groundwater flow is generally northwest across the site, consistent with the slope of the topography. The hydraulic gradient of the water table surface in November 1990 varied from about 5% in the eastern portion of site to about 2% in the western portion of the site, with an overall average of about 3%, as shown in Figure 2-4. A similar hydraulic gradient also was calculated for the August 1990 water level readings.

The change in water table elevation across the site in November 1990 was about 30 feet, varying from 771 feet (MSL) on the east side of the site at compliance monitor well CW-1 to 741 feet (MSL) on the west side. The measured depth to the water table in the western portion of the site varied from 8.7 to 13.6 feet below land surface. In the topographically higher east side of the site the water table is deeper, exceeding 30 feet below land surface.

Based upon *in situ* horizontal coefficients of permeability measured by rising-head and falling-head tests in four piezometers, and the hydraulic gradient of the water table across the site, the groundwater seepage velocity in the saprolite was estimated to be in the range of 4 to 14 feet/year. The greater seepage velocity was estimated for the western portion of the site for saprolite weathered from quartzofeldspathic gneiss, and the slower seepage velocity was estimated for the eastern portion of the site for saprolite and partly weathered rock weathered

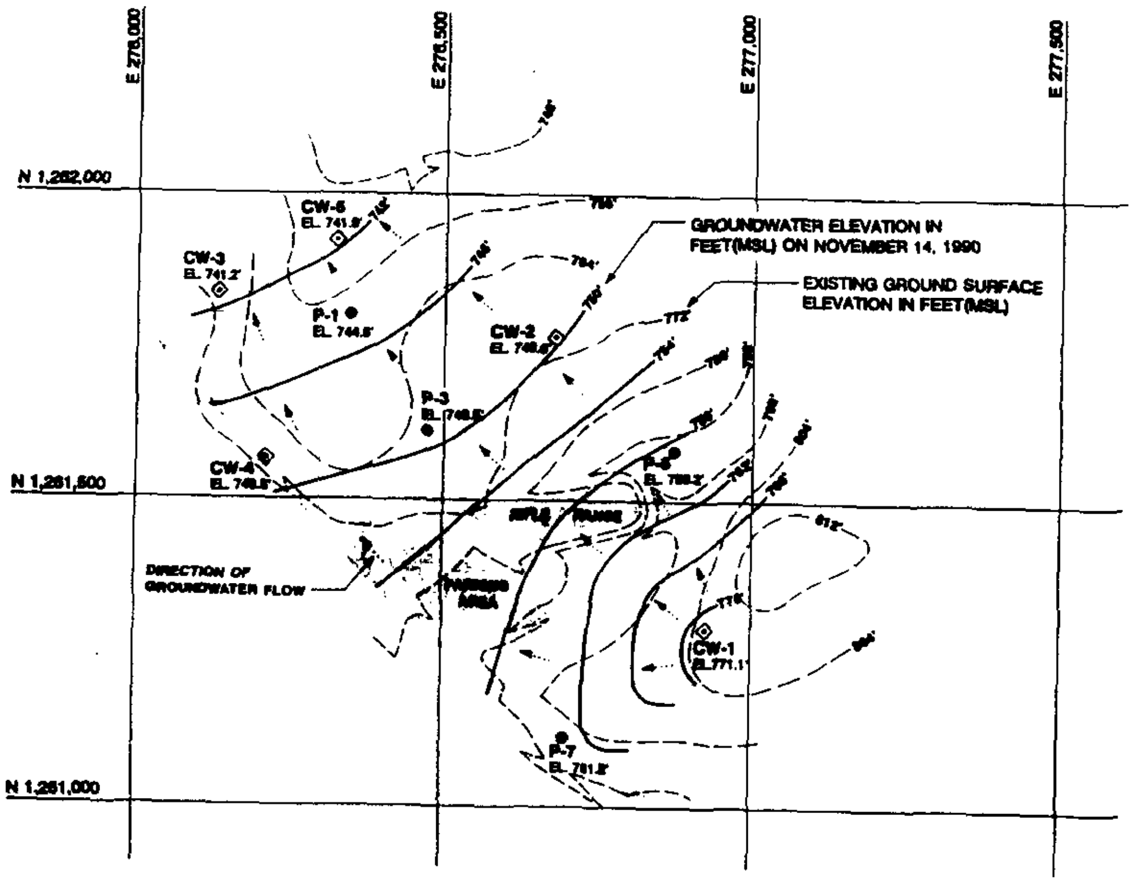


Figure 2-4. Site Groundwater Elevation Contours (November 1990)

from hornblende gneiss/amphibolite. The estimated seepage velocities are relatively slow, indicating that the time for groundwater to migrate across the site will be relatively long.

2.1.2 Properties of Site Soils and Earthen Construction Materials

This section summarizes the results of a laboratory testing program conducted by Ardaman & Associates, Inc. to assess the engineering properties of *in situ* upper horizon soils and saprolite, and the compaction and permeability characteristics of upper horizon soils when reworked and compacted into an earthen liner. Details of the laboratory testing program and a complete presentation of the results are included in a report by Ardaman & Associates, Inc. (Ardaman, 1990).

The upper horizon soils consist of: (i) brown, orangish-brown and reddish-brown sandy clay to slightly micaceous sandy clay; (ii) orangish-brown and reddish-brown clayey medium to fine sand to slightly micaceous clayey medium to fine sand; and (iii) occasionally a reddish-brown to orangish-brown slightly micaceous sandy silt. Index tests consisting of moisture content determinations, particle size analyses, fines content determinations and Atterberg limits were performed on selected samples to aid in the classification and characterization of the upper horizon soils. The *in situ* density was also determined on three undisturbed Shelby tube soil samples.

The particle size distributions of the upper horizon soils determined on nine samples from the disposal facility site in accordance with ASTM Standards D 421 and D 422 indicate that the soils are comprised of clayey medium to fine sands, sandy clays and sandy silts. The fines contents (i.e., soil fraction by dry weight finer than the U.S. Standard No. 200 sieve) varied from 36 to 84%, with an overall average of 58. The natural moisture content of the upper horizon soils determined on 26 samples in accordance with ASTM Standard D 2216 varied from 19 to 41% with an overall average of 28%. The natural moisture content generally increased with increasing fines content. Three undisturbed samples representing the range in types of upper horizon soils encountered at the site (i.e., SC, CL and CH type soils) displayed similar total unit weights of

109.1 to 110.4 lb/ft^3. Based upon the measured natural moisture contents, the *in situ* dry densities varied from 82.8 to 90.0 lb/ft^3, and the degree of saturation equaled 69 to 87%.

The Atterberg limits determinations performed for ten samples of the upper horizon soils from the disposal area indicated liquid limits varying from 35 to 82% and plasticity indices varying from 8 to 44%. Based on these Atterberg limits and considering the fines contents presented above, the upper horizon soils classify as SC-type clayey sands, CL- and CH-type lean and plastic clays, respectively, and MH-type silts when classified in accordance with ASTM Standard D 2487, "Classification of Soils for Engineering Purposes".

Based upon the range of index characteristics identified for the upper horizon soils, six soil samples were selected for performance of compaction and permeability tests to determine the coefficient of permeability obtainable by an earthen liner.

Standard Proctor compaction tests (ASTM Standard D 698) were performed on the six selected samples of the upper horizon soils. The standard Proctor optimum moisture content, w_{opt}, and maximum dry density, γ_{dmax}, vary widely from 16.6 to 31.0% and 86.9 to 115.4 lb/ft^3. As expected, the two slightly micaceous sandy silts display the lower maximum dry densities, and the clayey sands to sandy lean clays display the higher maximum dry densities. Unconfined compressive strengths measured with a hand-held penetrometer on the standard Proctor compacted samples varied from 4.5 to 5.0 tons/ft^2 on specimens compacted dry and at the optimum moisture content, to 2.5 tons/ft^2 on specimens compacted 3 to 5% wet of the optimum moisture content. These unconfined compressive strengths are characteristic of very stiff to hard clayey soils.

The results of permeability tests performed on laboratory compacted samples of the upper horizon soils are presented in Figure 2-5. The test specimens were prepared at molding moisture contents from 2.3% dry to 7.2% wet of the standard Proctor optimum molding moisture content and compacted to dry densities approximately equal to 95% of the standard Proctor maximum dry

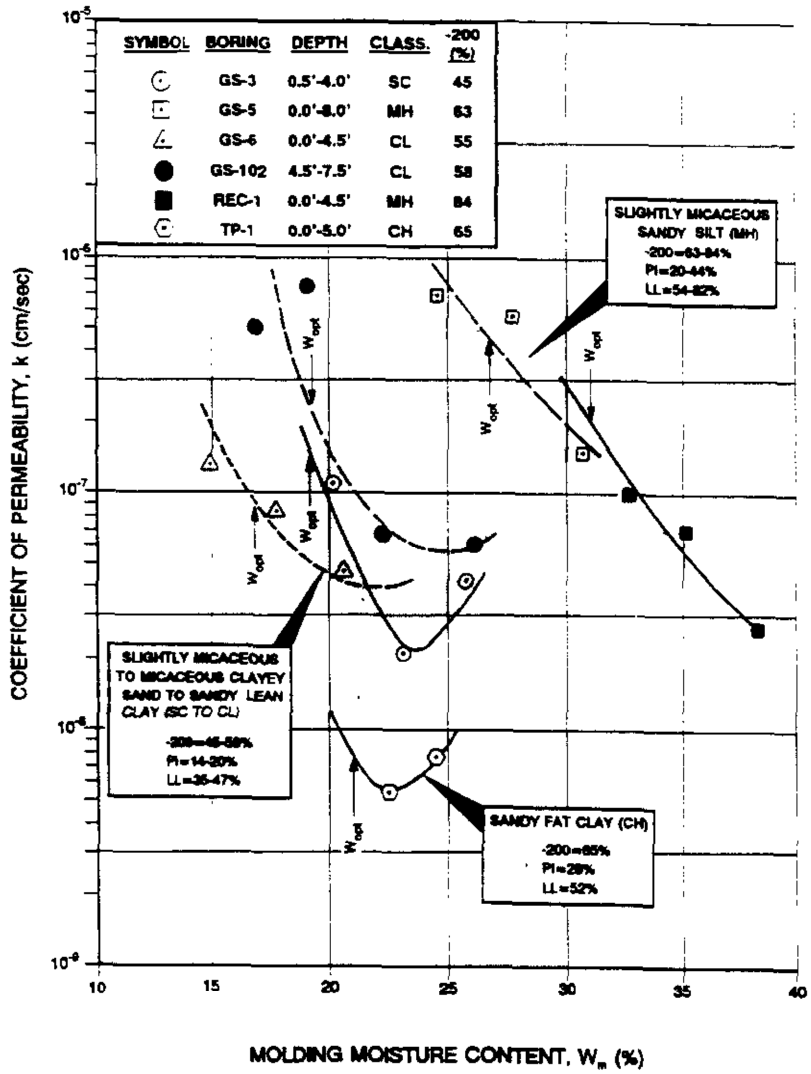


Figure 2-5. Coefficient of Permeability versus Molding Moisture Content for Compacted Upper Horizon Soils

density when compacted on the dry side of the optimum moisture content and 98% of the standard Proctor dry density at the corresponding molding moisture content when compacted on the wet side of the optimum moisture content. As shown in Figure 2-5, the following coefficients of permeability were achieved on compacted test specimens of the upper horizon soils.

- The slightly micaceous to micaceous clayey sands to sandy lean clays displayed coefficients of permeability varying from $7x10^{-7}$ cm/sec when compacted at moisture contents slightly less than the standard Proctor optimum moisture content to minimum values of between $2x10^{-8}$ and $5x10^{-8}$ cm/sec when compacted at moisture contents about 4 to 5% wet of the standard Proctor optimum moisture content.

- The sandy fat clay displayed coefficients of permeability of $6x10^{-9}$ to $8x10^{-9}$ cm/sec when compacted at molding moisture contents 0.5 to 2.5% wet of the standard Proctor optimum moisture content.

- The slightly micaceous sandy silts displayed coefficients of permeability varying from $7x10^{-7}$ cm/sec when compacted at moisture contents slightly less than the standard Proctor optimum moisture content to minimum values of less than $1x10^{-7}$ cm/sec when compacted at moisture contents about 4 to 7% wet of the standard Proctor optimum moisture content.

Based upon these laboratory test results, the upper horizon soils at the disposal facility were considered to be suitable for use in construction of an earthen liner provided they could be homogenized and compacted at molding moisture contents wet of the standard Proctor optimum moisture content. The natural moisture contents of the clayey sands to sandy clays were 3 to 7% wet of the standard Proctor optimum moisture content, and accordingly occur *in situ* at moisture contents that were acceptable to somewhat high for compaction without drying. The sandy silts occur at moisture contents 6 to 10% wet of the standard Proctor optimum moisture content, and accordingly occur *in situ* at moisture contents somewhat high for compaction without drying.

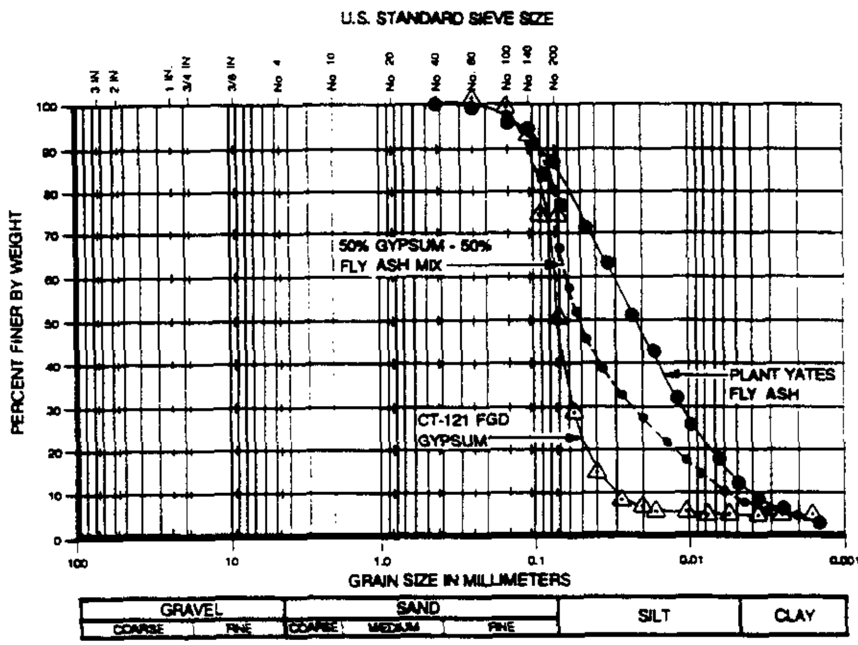
2.1.3 Design Properties of Gypsum and Gypsum-Fly Ash

Gypsum was not available from Plant Yates for laboratory testing to determine engineering properties for design of the CT-121 FGD gypsum and gypsum-fly ash disposal facility. Instead, engineering properties for design were selected based upon the results of laboratory and field testing previously undertaken for the Plant Scholz demonstration project (Garlanger and Ingra, 1980). Since the Plant Yates demonstration project will use the CT-121 process, it was anticipated that the engineering properties determined for the Plant Scholz materials would be, for the most part, applicable for the engineering evaluation and design.

The particle size distribution of CT-121 FGD gypsum from a Chiyoda Thoroughbred-121 FGD scrubber at the Abbott Power Plant at the University of Illinois, and of gypsum-fly ash made by combining this FGD gypsum with Plant Yates fly ash, was determined, however, to allow a general description of the materials expected to be produced at Plant Yates.

The particle size distribution determined from sieve and hydrometer analyses on a sample of CT-121 FGD gypsum from a CT-121 scrubber operating at the Abbott Power Plant at the University of Illinois is presented in Figure 2-6. As shown, the gypsum consists largely of fine sand-size to coarse silt-size particles, with 35% fine sand-size particles (>0.074 mm in size), 61% silt-size particles (between 0.074 and 0.005 mm in size) and 4% clay size particles (<0.005 mm in size). This particle size distribution is similar to that previously found for the Plant Scholz CT-101 FGD gypsum.

The particle size distribution determined from sieve and hydrometer analyses on a sample of fly ash from Plant Yates provided by Georgia Power Company is depicted in Figure 2-6. The fly ash sample was a composite sample obtained by combining fly ash from several of the hoppers in Unit 1. As shown, the fly ash is finer than the CT-121 FGD gypsum and is comprised largely of coarse to fine silt-size particles, with 15% fine sand-size particles, 73% silt-size particles, and 12% clay-size particles.



SYMBOL	DESCRIPTION
△	CT-121 FGD GYPSUM (ABBOTT POWER PLANT, UNIVERSITY OF ILLINOIS)
●	PLANT YATES FLY ASH (UNIT 1)
•	GYPSUM-FLY ASH MIX OF 50% GYPSUM AND 50% FLY ASH BY DRY WEIGHT BASIS

Figure 2-6. Particle Size Distribution of CT-121 FGD Gypsum, Plant Yates Fly Ash and Gypsum-Fly Ash

The particle size distribution of gypsum-fly ash comprised of 50% CT-121 FGD gypsum and 50% fly ash on a dry weight basis, similar to that projected for Plant Yates, calculated from the two measured particle size distributions is presented in Figure 2-6. The particle size distribution of the gypsum-fly ash occurs between the particle size distributions for the two components (i.e., the gypsum and fly ash), and indicates that the gypsum-fly ash will be comprised of about 25% fine sand-size particles, 67% silt-size particles and 8% clay-size particles.

Based on previous test results obtained on the Plant Scholz CT-101 FGD gypsum and gypsum-fly ash, the typical physical properties in Table 2-1 were selected for seepage and stability analyses for the Plant Yates gypsum and gypsum-fly ash stacks.

TABLE 2-1
TYPICAL PHYSICAL PROPERTIES FOR FGD BYPRODUCTS

Parameter	Gypsum	Gypsum/Fly Ash
γ_{SAT} (lb/ft^3)	105	101
γ_d (lb/ft^3)	75	65
γ_t (lb/ft^3)	91	83
S (%)	71.3	64.1
w_c (%)	40.3	56.0
$\bar{\phi}$ (degrees)	40	40
$\bar{c}$ (lb/ft^3)	0	0
k (cm/sec)	2×10^{-3}	5×10^{-4}

γ_{SAT} = saturated unit weight
γ_t = total unit wt. above phreatic surface for 50% saturation
S = solids content
$\bar{\phi}$ = effective friction angle
k = coefficient of permeability
γ_d = dry density
w_c = saturated moisture content
$\bar{c}$ = effective cohesion

Field and laboratory testing on CT-121 FGD gypsum from the Plant Scholz demonstration project indicated that sedimented gypsum *in situ* dry densities within the range of 75 to 80 lb/ft^3 (solids contents of 71.3 to 74.0%) can be expected. Because the specific characteristics of the Plant Yates CT-121 FGD gypsum were not yet known, the lower bound of this range was selected for design of the gypsum stack. The coefficient of permeability and effective friction angle for the gypsum were then selected for this dry density.

Limited laboratory testing was undertaken on gypsum-fly ash produced during the Plant Scholz demonstration project. Laboratory consolidation testing performed on a sample comprised of about 75% fly ash and 25% gypsum indicated that gypsum-fly ash sediments to a lower dry density than gypsum. Based upon these limited laboratory test results, an estimated *in situ* dry density for sedimented gypsum-fly ash in the range of 55 to 65 lb/ft^3 appears reasonable.

Extensive laboratory and field testing on gypsum-fly ash produced at TVA's Widows Creek Steam Plant in Stevenson, Alabama indicated *in situ* dry densities of sedimented gypsum-fly ash ranging from about 65 to 80 lb/ft^3. Considering the available data from both demonstration projects, an *in situ* dry density for sedimented gypsum-fly ash of 65 lb/ft^3 was selected for use in stability and seepage analyses of the gypsum-fly ash stack, corresponding to the upper bound expected from the Plant Scholz data and lower bound found at Widows Creek. The coefficient of permeability and effective friction angle for the gypsum-fly ash were then selected for this dry density based upon available laboratory test results.

2.1.4 Design and Construction Recommendations

An engineering evaluation was performed by Ardaman & Associates, Inc. to provide the basis for basic design and operating recommendations for the Plant Yates FGD gypsum and gypsum-fly ash disposal facility. Results of the evaluation were presented in an interim project report by Ardaman & Associates, Inc. (Ardaman, 1990). The detailed design and construction drawings presented in Appendix A were subsequently prepared by Ardaman & Associates.
The engineering evaluation and basic design of the facility primarily considered regulatory requirements, operating constraints, stack stability and seepage patterns, slurry distribution, clarification and decant requirements and storm water management. The layout and design features of the disposal facility, comprised of a gypsum stacking area, gypsum-fly ash stacking area, and surge pond, are described in this section.

The surge pond was incorporated in the wet-stacking disposal facility to impound storm water runoff from the 7.1 acre site (i.e., the area within the outside edge of the containment dikes), and to accommodate system surges in water use. The surge pond was sized to have adequate capacity to accommodate an operating volume of 1,000,000 gallons of process water, 250,000 gallons of process water from drainage of the scrubber equipment, and the runoff from a 10 year, 24 hour rainfall event. A minimum freeboard of 3 feet was provided between the maximum operating level resulting from these design criteria and the dike crest.

The surge pond is located on the west end of the disposal facility as shown on Figure 2-7. The base of the pond encompasses an area of 0.43 acres with a uniform bottom elevation of 756.0 feet (MSL). The exterior containment dikes have an inboard slope of 3.0 horizontal to 1.0 vertical (3H:1V), a 15-foot crest width, an inboard crest elevation of 770.0 feet (MSL) and outboard crest elevation of 770.3 feet (MSL; see Figure A-4 in Appendix A). The internal containment dike between the surge pond and gypsum stacking area has a wider dike crest of 20 feet to allow access to the gypsum stacking area, an inboard slope of 3H:1V and an inboard crest elevation of 770.0 (MSL; see Figure A-4 in Appendix A).

The composite liner system consists of 12 inches of compacted clayey soils overlain by a smooth, 60 mil thick, high density polyethylene (HDPE) synthetic liner on the bottom and inside slopes of the surge pond. The top of the liner extends up to elevation 768.0 feet (MSL) and is held in place by a soil-backfilled anchor trench.

An outside dike slope of 3H:1V was used for the surge pond, except for a steeper slope of 2.5H:1V in the highest portion of the dike to minimize the fill volume and to avoid placing fill around an existing compliance monitor well. The 2.5H:1V side slope is structurally adequate for the approximately 18-foot high dike (see Figure A-4 in Appendix A). (Note that the flatter 3.0H:1.0V inboard slope was selected primarily to facilitate installation of the HDPE liner within the surge pond.)

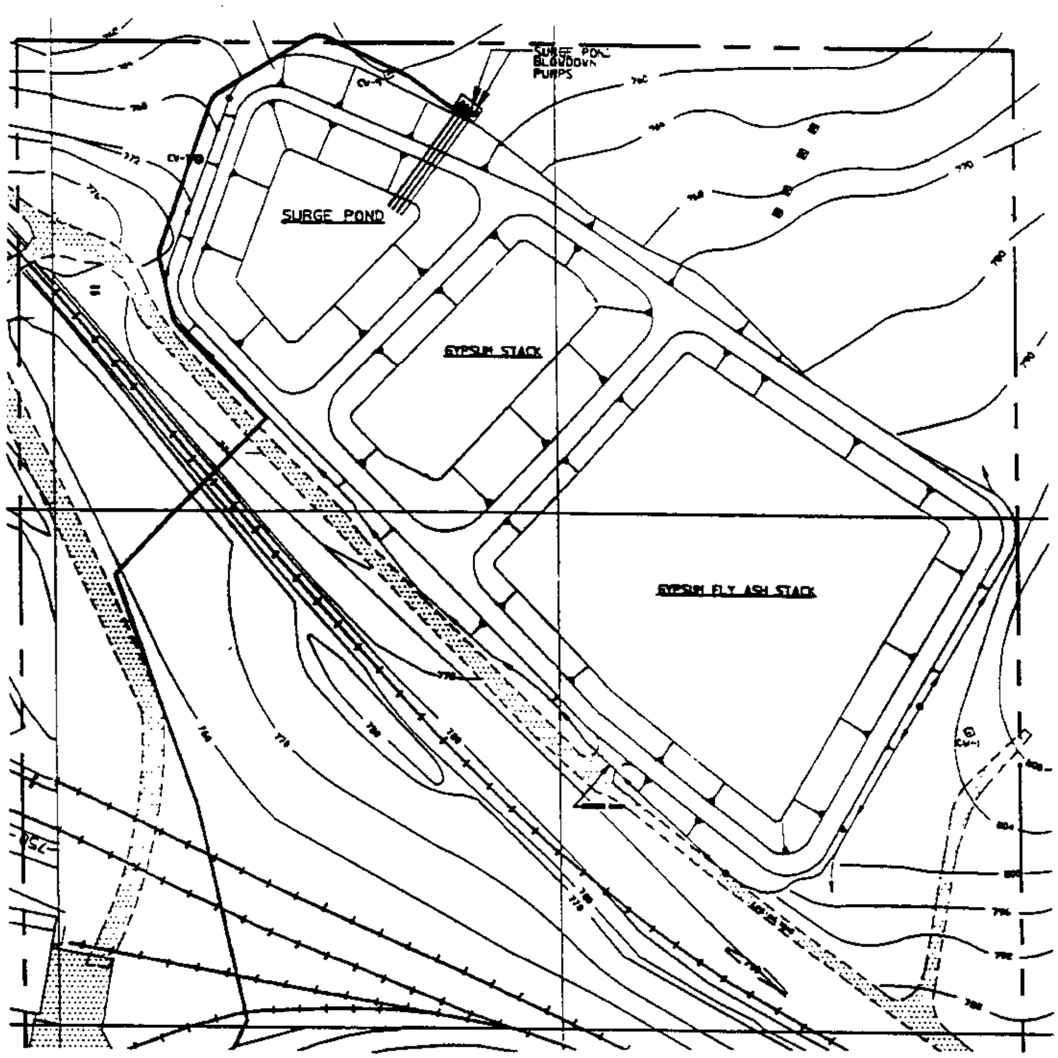


Figure 2-7. Layout of Disposal Area

The normal operating water level elevation for the surge pond equals 761.5 feet (MSL) for the 3.1 acre-feet (1,000,000 gallons) of operating water volume, resulting in a normal operating water depth of 5.5 feet. Including the 0.77 acre-feet (250,000 gallons) of process water drainage from the scrubber equipment and 3.55 acre-feet (1,156,700 gallons) of rainfall runoff from the required design 10-year 24-hour storm event, the water level rises to a maximum operating water level elevation of 767.0 feet (MSL). At this maximum operating water level, the impounded depth of water equals 11.0 feet while providing 3.0 feet of freeboard.

[NOTE: The 10-year, 24-hour storm event for the site was selected as 6 inches based upon the "Rainfall Frequency Atlas of Alabama, Florida, Georgia, and South Carolina for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years" published by the U.S. Department of Agriculture, Soil Conservation Services, Gainesville, Florida. The runoff volume of 3.55 acre-feet is conservatively based upon 100% runoff from the 7.1 acre surge pond watershed.]

Because 3 feet of freeboard was provided in the surge pond at the design 10 year, 24 hour storm event, some additional stormwater could be impounded within the surge pond by encroaching on the 3 feet of freeboard. For instance, the surge pond could accommodate runoff from a 100 year, 24 hour storm event with a reduced freeboard of approximately 1.8 feet. The relationship between the water surface elevation and storage capacity for the surge pond is presented in Figure 2-8.

Although it is unlikely that an emergency release of water from the surge pond or overtopping of the containment dike would occur, the surge pond design incorporated an emergency outfall, in accordance with common engineering practice, to provide for the controlled release of excess water and to prevent the dike from being overtopped. Without an emergency outfall, an extreme rainfall event could result in overtopping of the dike and potentially the failure of the dike and complete release of the impounded process water. An unlikely discharge from the surge pond would be initiated at a low point in the containment dike crest causing the sandy soil cover above the liner to be eroded down to the full depth and width of the lined overflow weir. This type of

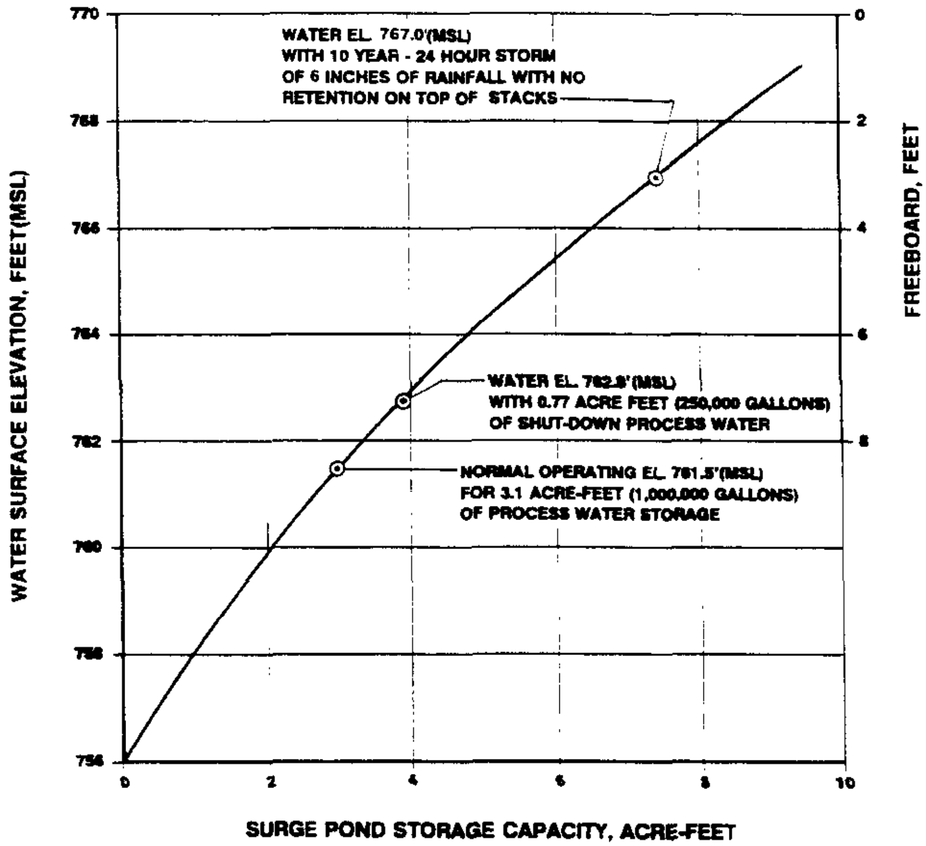


Figure 2-8. Stage-Storage Relationship for Surge Pond

emergency overflow is only intended for use to prevent the containment dike from being overtopped during an extreme rainfall event.

The gypsum stacking area was designed to accommodate the disposal of 28,600 tons (dry weight basis) of FGD gypsum over a test period of 9 months. The FGD gypsum will be pumped to the stacking area at a rate of 900 gal/min at a solids content of about 2.9%. After deposition in the stacking area, the settled gypsum will be partially excavated around the perimeter of the area and stacked using the upstream method of construction. The stacking area has been sized to provide a final stack height of about 15 feet above the crest of the containment dike at the end of the 9 month test period in order to provide a reasonable height over which to demonstrate the stackability of the gypsum.

[NOTE: Solids content, S, is based upon a gypsum production rate, W_g = 223 lb/min (i.e. 28,600 tons over a test period of 274 days with gypsum production actually occurring on 178 days or 65% of the time) and a process water flow rate, W_w = 900 gal/min (7497 lb/min), with the solids content defined as the ratio $W_g / W_g + W_w$.]

The gypsum stacking area is located between the surge pond and gypsum-fly ash stacking area. The base of the stack encompasses an area of 0.61 acres with a uniform bottom elevation of 762.0 feet (MSL). The surrounding containment dikes have 20-foot wide crest widths and 3H:1V inboard and outboard slopes. The inboard crest elevation of the containment dike varies from 770.0 feet (MSL) along the western side of the stacking area, 8 feet above the bottom, to 780.0 feet (MSL) along the eastern side of the area, 18 feet above the bottom (Figure A-4, Appendix A). The crest of the dike is sloped inward at 2% so that rainfall runoff on the dike crest is directed into the stacking area. A composite liner, consisting of 12 inches of compacted clayey soils overlain by a 60 mil HDPE synthetic liner, was used in the bottom and on inboard slopes of the gypsum stacking area. Textured liner sheets were used on the inside slopes and a portion of the bottom to improve the stability of the gypsum stack slopes. Smooth liner sheets were used on the remainder of the bottom area. The top of the liner extended to within 1.5 feet of the inside dike crest, and was held in place with a soil-backfilled anchor trench.

An underdrain system, installed within lined trenches a the base of the gypsum disposal area, was included as a positive seepage control feature to prevent seepage from exiting on the slopes of the gypsum stack, and allow stacking of the gypsum at a 2H:1V slope with a factor of safety against sliding on the liner of at least 1.5. The underdrain consisted of a filter fabric wrapped gravel drain containing a 6-inch diameter perforated corrugated HDPE collection pipe (see Detail A on Figure A-4, Appendix A). Two 6-inch diameter HDPE outlet pipes from the underdrain discharge into the surge pond.

The gypsum stack could be raised with side slopes of 2H:1V, with the final top elevation of the stack depending upon the actual quantity of gypsum produced during the test period, and the *in situ* dry density achieved by the sedimented gypsum. For a potential range of gypsum *in situ* dry density of 70 to 80 lb/ft^3 (solids contents of 68.4 to 74.0%) and projected test period gypsum production of 28,600 tons, a gypsum storage volume of 18.7 to 16.4 acre-feet is required, respectively. For this range in storage volume, average top of stack elevations of 787 to 783 feet (MSL), respectively, would be achieved. Based upon field and laboratory testing on CT-101 FGD gypsum from the Plant Scholz demonstration project, a sedimented gypsum *in situ* dry density within the upper portion of this potential range between 75 and 80 lb/ft^3 (solids contents of 71.3 to 74.0%) is likely to be achieved. A final average stack elevation, therefore, of about 783 to 784 feet (MSL) was projected, about 13 to 14 feet above the crest of the containment dike. The gypsum stacking area, however, was sized to accommodate the projected test period gypsum production at an average *in situ* dry density as low as 70 lb/ft^3. The average projected gypsum stack height versus time relationship over the 9-month period is presented in Figure 2-9.

The gypsum-fly ash stacking area was designed to accommodate the disposal of 92,600 tons (dry weight basis) of FGD gypsum-fly ash over a test period of 15 months. The gypsum-fly ash will be comprised of approximately 50% CT-121 FGD gypsum and 50% fly ash, and will be pumped to the stacking area at a rate of 900 gal/min at a solids content of 5.5%. After deposition in the stacking area, the settled gypsum-fly ash excavated around the perimeter of the area and stacked

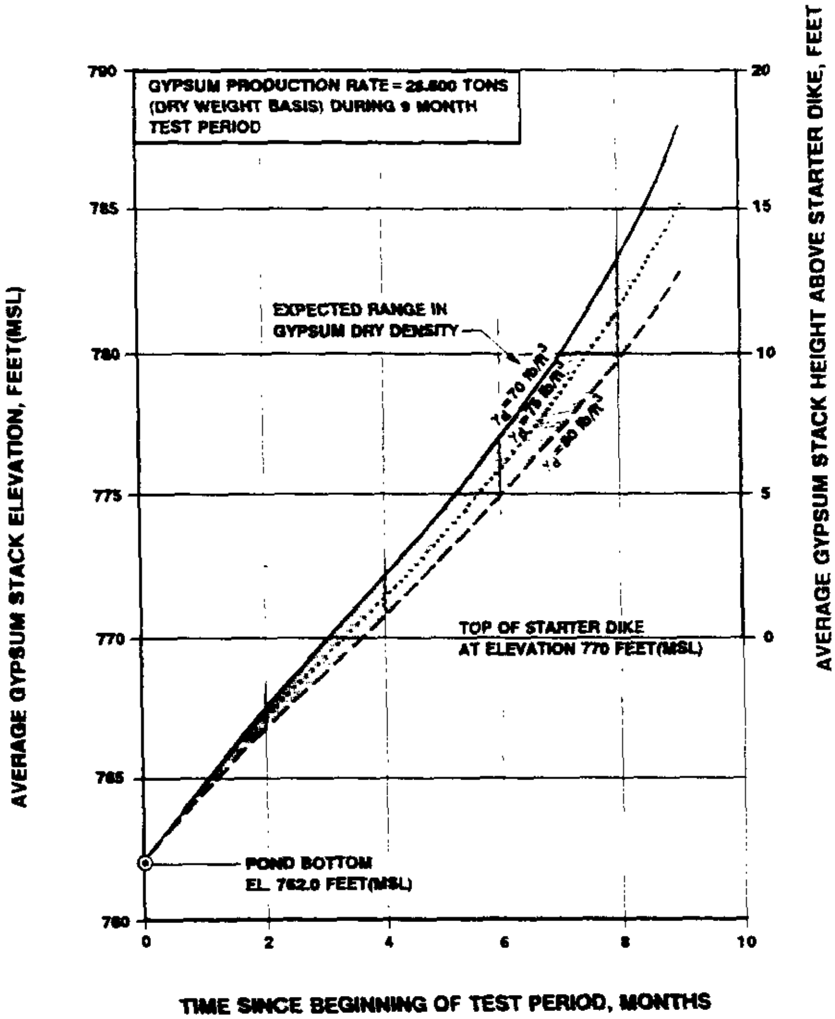


Figure 2-9. Projected Gypsum Stack Growth Rate

using the upstream method of construction. The stacking area has been sized to provide a final stack height of about 30 feet above the crest of the containment dike at the end of the 15-month test period.

[NOTE: The solids content is based upon a gypsum-fly ash production rate = 433 lb/min (i.e. 92,600 tons over a test period of 456 days with gypsum-fly ash production actually occurring on 297 days or 65% of the time) and a process water flow rate = 900 gal/min. (7497 lb/min).]

The gypsum-fly ash stacking area is located on the east end of the disposal area. The base encompasses an area of about 2.6 acres. The western most 0.73 acres is level at an elevation of 772.0 feet (MSL), and the remaining 1.9 acres slopes uphill to the east at an overall average slope of about 7.4% (about 13.5H:1V) to Elevation 790.0 feet (MSL). The surrounding containment dikes have 20-foot wide crest widths and 3H:1V inboard and outboard slopes. The inside crest elevation of the containment dike varies from 780.0 feet (MSL) along the western side of the stacking area, 8 feet above the bottom, to 802.0 feet (MSL) along the eastern side of the stacking area, 12 feet above the bottom (Figures A-4 and A-5, Appendix A). The crest of the dike is sloped inboard at 2% so that rainfall runoff on the dike crest is directed into the stacking area.

As with the gypsum stack, a composite liner consisting of 12 inches of compacted clayey soils overlaid by a 60 mil HDPE synthetic liner was used on the bottom and inboard slopes of the gypsum-fly ash stacking area. Textured liner sheets were used on the inboard slopes and a portion of the bottom to improve the stability of the gypsum-fly ash stack slopes. Smooth liner sheets were used on the remainder of the bottom area. The top of the liner extended up to within 1.5 feet of the inside dike crest, and was held in place with a soil-backfilled anchor trench.

An underdrain system, consisting of two perimeter drains installed within lined trenches in the base of the stacking area, were included as a positive seepage control feature to prevent seepage from exiting on the slopes of the stack, and to allow stacking the gypsum-fly ash at a 2H:1V slope with a factor of safety against sliding on the liner of at least 1.5. Each underdrain will consist of a filter fabric wrapped gravel drain containing an 8-inch diameter perforated corrugated HDPE collection pipe (Detail B on Figure A-4, Appendix A). Outlet pipes from each underdrain will exit the stacking area to manholes near the west end of the stacking area. An 8-inch diameter HDPE pipe will be used to transport the underdrain flow from these manholes to the surge pond.

The gypsum-fly ash stacking area was not scheduled to be used during the first 9 months of the demonstration project while the gypsum stack was being constructed. Rainfall runoff collected in the gypsum-fly ash stacking area prior to activation was free of contamination and could be discharged off-site. Therefore, the drain outlet pipes were provided with control valves located near the upstream manholes to facility temporary water storage in the gypsum fly ash area. Alternatively, the downstream manhole was also provided with a control valve to allow clean rainfall accumulated prior to activation in the gypsum fly ash area to be released through a discharge pipe on the north side of the disposal facility.

The gypsum stack can be raised with side slopes of 2H:1V. The final top elevation of the stack will depend upon the actual quantity of gypsum-fly ash produced during the test period, and the *in situ* dry density achieved by the sedimented gypsum-fly ash. For a potential range of *in situ* dry density of 55 to 65 lb/ft^3 (solids contents of 57.7 to 64.1%) and projected test period gypsum-fly ash production of 92,600 tons, a storage volume of 77.3 to 65.4 acre-feet is required, respectively. For this range in storage volumes, average top of stack elevations of 804 to 811 feet (MSL), respectively, would be achieved. The average projected gypsum-fly ash stack height versus time relationship over the 15-month test period is presented in Figure 2-10.

2.2 Permits

Byproduct-related activities associated with construction and operation of the Chiyoda CT-121 FGD equipment required a solid waste permit for the new area used for gypsum stacking, as well as modification of the existing NPDES permit for liquid effluents.

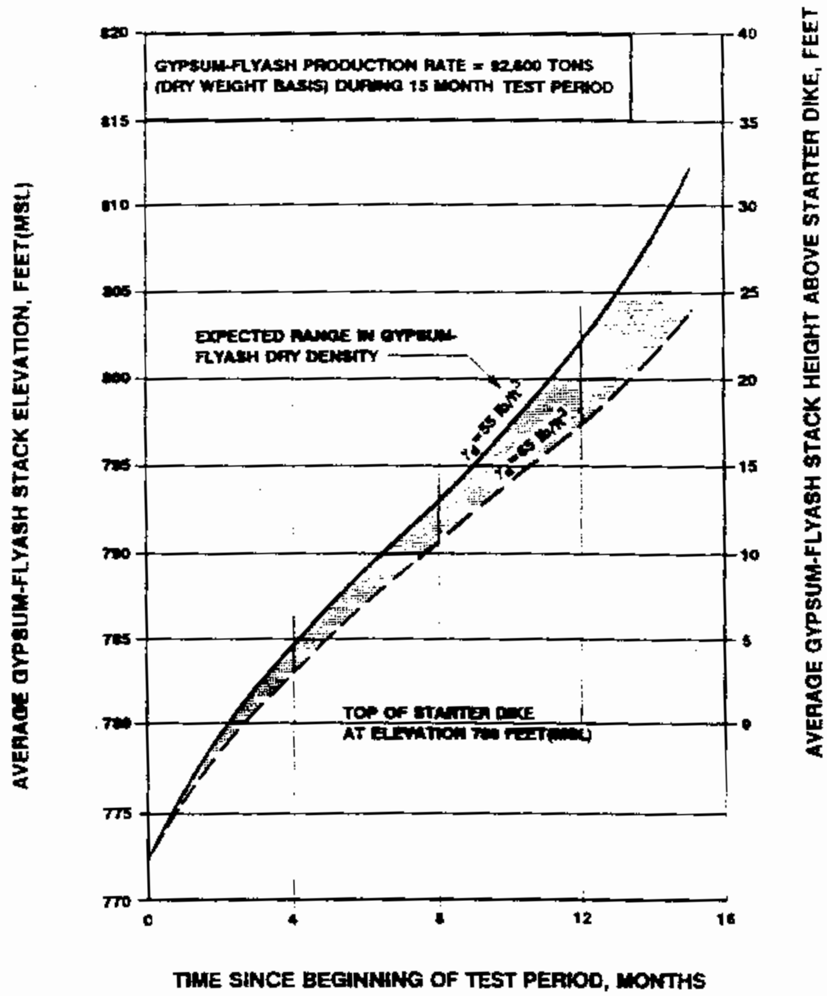


Figure 2-10. Projected Gypsum-Fly Ash Stack Growth Rate

2.2.1 Emergency Discharge

Prior to operation of the scrubber, approval was obtained from the Georgia Department of Natural Resources, Environmental Protection Division (EPD) on November 29, 1989 to pump surge pond effluent to the Plant Yates active ash pond during unusual or emergency

Situations (Shelnutt, 1995). The present NPDES permit # GA0001473 does not specifically address this discharge. However, this outfall was included in the Form 2C application for the NPDES permit renewal as OSN01P ("scrubber pond emergency"). Mr. Drew Zurow, EPD North Unit Coordinator for the Industrial Wastewater Section, has indicated that EPD approval is not required for operation of the emergency pumps during routine testing.

2.2.2 Solid Waste Disposal

Several steps were required prior to initiating operation of the gypsum stack area. The first two activities involved zoning approval from Coweta County and site approval by the Georgia Geological Survey. Following these initial steps, design information from Ardaman & Associates was used by Tribble and Richardson to develop a Design & Operating Plan for submittal to the Georgia EPD (Tribble & Richardson, 1991). The D & O Plan was approved and permit number 038-014D(I) issued on February 14, 1992 (including 30-day appeal), allowing construction to be completed. Ardaman provided quality control inspection and testing during the construction period, as well as certification that containment dikes, composite liner, and underdrain system are constructed in accordance with the D & O specifications. The Georgia EPD issued notification on October 14, 1992 that operation of the stack could begin.

Georgia Power has requested a Major Modification to the existing permit for the gypsum stack (Jackson, 1995). Although the facility as designed is more than adequate for gypsum and ash/gypsum produced during the ICCT project period. However, the Georgia Power decision to run the scrubber commercially (beginning January 1, 1995) after the demonstration project increases the possibility that additional gypsum storage/disposal capacity may be needed in future

The construction drawings prepared by Ardaman and Associates, Inc. are presented in Appendix A. An overview of the general construction sequence, procedures and materials used, along with a summary of the quality control inspection and testing program, is presented in the following sections.

2.3.1 General Earthwork and Drainage

The initial site preparation phase of construction included clearing and grubbing, surface dewatering and general site grading. All vegetation was removed from the construction limits with all roots grubbed to a minimum depth of 12 inches below the proposed subgrade surface. Due to the relatively deep groundwater levels across the site, only surface dewatering was required during construction. The existing service road was relocated and pipe culverts within the graded area were removed.

The subgrade on which the composite liner was installed and on which the earthen containment dikes were constructed was graded through excavation and fill placement to alter the fundamental contours of the site to the design lines and grades of the proposed facility (Figure A-1, Appendix A). Existing surfaces and those exposed as a result of excavation were compacted to a depth of at least 6 inches before placement of any fill. Earthen fill materials were obtained from on-site borrow sources and consisted mainly of silty and clayey fine to coarse sands, sandy clays, and sandy silts. The fixed decant structures in the gypsum and gypsum-fly ash stacking areas, and the associated buried piping, were installed during the site grading phase.

The earthen containment dikes were then constructed upon the subgrade using fill materials obtained from on-site borrow sources (made available as a result of mandatory excavation related to site grading), and consisting mainly of silty and clayey fine to coarse sands and sandy silts. Clayey soils encountered within potential borrow areas which met the clay liner material requirements were generally not used for dike construction, but were stockpiled for later use as earthen liner borrow material.

The dike fill materials were wetted or dried, as needed, and homogenized, placed and compacted in successive horizontal layers having a loose thickness of 12 inches. Compaction was achieved using a tamping roller and steel wheel (sheeps-foot) power roller. After a lift was placed and compacted, its surface was scarified just prior to placement of the next layer to permit proper bonding between layers. The underdrain outlet pipes, manholes mad valves, along with pipes from the surge pond to the pump station, were installed during the dike construction phase.

Erosion and sedimentation control was maintained throughout construction. Silt fences were installed for temporary erosion and sedimentation control prior to beginning construction. Permanent erosion prevention was incorporated by establishing vegetation. All disturbed areas were grassed except for an access ramp road, dike crests and area underlain by the synthetic liner. Areas that were grassed include outboard dike slopes, ditches and road shoulders.

2.3.2 Composite Liner

The composite liner was comprised of a clay liner component and a synthetic liner compound. Each is described below.

2.3.2.1 Clay Liner Component

Prior to placement of the clayey soils, the subgrade surface was scarified to permit proper bonding with the clay liner. Clayey fill materials for construction of the clay liner were obtained from on-site, and from near-site borrow sources located in areas adjacent to the west and northwest site limits. The clay liner was constructed using upper horizon soils meeting the following requirements:

- The clay soil shall consist of clayey sand to sandy clay free from deleterious materials (e.g., wood, roots, organic matter, debris, etc.) with an organic content less than 5 percent. The clay liner material shall not contain lumps or boulders exceeding 1 inch in diameter (further, the finished surface of the clay liner shall be free of all rocks, stones and gravel exceeding 1/4-inch in diameter).

- The clay soil shall have more than 40 percent by dry weight of material passing the U.S. Standard No. 200 sieve (ASTM D-1140) and a liquid limit and plasticity index in excess of 35% and 11%, respectively (ASTM D-4318). The clay borrow shall classify as an SC-type clayey sand for soils with less than 50 percent passing the U.S. Standard No. 200 sieve and either a CL-type sandy lean clay or CH-type sandy fat clay for soils with greater than 50 percent passing the U.S. Standard No. 200 sieve in accordance with ASTM standard D-2487.

Project specifications further required that clay liner shall: (i) be wetted or dried and homogenized prior to compaction to obtain a uniform molding moisture content in the range of 0 to 5 percent higher than the standard Proctor optimum moisture content (ASTM D-698); (ii) be compacted to a dry density equal to or in excess of 98% of the standard Proctor dry density at the corresponding molding moisture content; and (iii) achieve an average laboratory coefficient of permeability equal to or less than $1x10^{-7}$ cm/sec, with a maximum coefficient of permeability determined for any single test sample of $3x10^{-7}$ cm/sec. (As discussed in Section 3.2.2, the compaction criteria for the clay liner was modified during construction because higher field densities were needed to consistently meet the permeability requirements).

The compacted clay liner was constructed by placement and compaction of a single lift of sufficient loose thickness to result in a final minimum compacted thickness of 12 inches. The clayey soil was thoroughly kneaded by rolling with a sheeps-foot roller and compacted with a loaded, rubber-tired scraper pan with a sufficient number of passes to produce a visually homogeneous clay liner satisfying the specified molding moisture content, compaction and permeability criteria. The top surface of the clay liner was made smooth by rolling with a steel-drum roller. The finished surface of the clay liner was made free of all rocks in excess of 1/4-inch in diameter in preparation for deployment and placement of the synthetic liner. Completed sections of the clay liner were maintained and restored, as needed, to the degree of compaction, allowable range of moisture contents and specified surface appearance. The surface was rolled smooth just prior to deployment and placement of the HDPE liner so that a direct and continuous contact between the two surfaces could be established.

2.3.2.2 Synthetic Liner

The synthetic liner was installed by Comanco Environmental Corporation of Tampa, Florida, and full-time independent quality control inspection and testing was provided by Ardaman & Associates, Inc.

The 60-mil high density polyethylene (HDPE) synthetic liner was installed in direct contact with the clay liner within the base areas and inboard containment dike slopes of the gypsum, gypsum-fly ash and surge ponds. The earthen liner around the perimeter of the two disposal areas was covered by "textured" liner which was field-bonded to a "smooth" liner, installed within the central portion of the disposal areas and within the surge pond (Figures A4 and A5, Appendix A). Both the "smooth" and "textured" geomembrane liners consisted of unreinforced HDPE, designed and manufactured specifically for the purpose of liquid containment.

The liner material was manufactured from HDPE base resin with properties equivalent to ASTM D-1248, Type III, Category 4 or 5, and Grade P34. The resin contains more than 97% of the base polymer, and not less than 2 percent carbon black as defined in ASTM D-1248, Class C, to impart maximum weather resistance. The HDPE liner product contains no more than 3% carbon black, anti-oxidants and heat stabilizers combined, and no other additives, fillers or extenders, and is manufactured from virgin resin, with no more than 3 percent regrind material.

Installation of the liner was required to be in compliance with project specifications and with the manufacturer's standard guidelines and specifications for liner installation, subject to approval by the engineer, including, but not limited to: handling and site storage requirements; unrolling of panels and laying of liner sheets; field seaming or welding techniques; pipe penetration details; anchor trench and temporary ballast loading.

The liner was anchored around the exterior perimeter of the facility in an anchor trench having a minimum width of 18 inches and minimum depth of 24 inches (Detail C on Figure A-8, App. A). After placement of the liner along one side and across the bottom of the trench, the trench was backfilled with compacted soil in order to prevent movement of the liner. Panels were deployed such that all seams were oriented down the slope of the perimeter earthen dikes, (i.e., all seams were oriented perpendicular to the top of slope or crest road of the perimeter dike).

The field seams used to join adjacent panels were made using either continuous extrusion or double wedge fusion welds with automated welding equipment. Adjoining liner sheets were overlapped a minimum of 4 inches in preparation for field seaming after the edges were wiped and cleaned thoroughly to remove any dirt, dust, moisture, or other foreign materials. Adjacent liner sheets were continuously and tightly bonded.

All liner defects (scratches, punctures, pinholes, etc.) were marked and repaired by completely covering the defect with an oval-shaped piece of the corresponding HDPE membrane material, and continuously welding the patch to the liner sheet using an extrusion weld. Holes created by removal of samples or coupons for destructive testing were likewise repaired.

Pipe penetrations through the HDPE liner were made using a boot, extrusion welded to the liner and the pipe (or HDPE pipe boot sleeve in the case of non-HDPE pipes) by the installer in accordance with the liner manufacturer's recommendations. Penetration of the HDPE liner was required for the underdrain outlet pipes, gas vent pipes, PVC valve stem riser casings and pipes associated with the surge pond pump station and the decant structures. The boot sleeves used with non-HDPE pipes consisted of 60-mil smooth HDPE tightly wrapped around the non-HDPE pipe and held tightly against the pipe to insure a leak proof connection using straps and compressible gaskets between the pipe and the boot sleeve.

In addition to the independent quality control inspection and testing summarized in the following section, the liner installer was responsible for: (i) initial and daily qualifying tests performed for each welding machine and operator; (ii) continuous non-destructive testing of every field weld (i.e., 100% of all field seams), performed in the presence of the engineer, using either a vacuum suction box (ASTM D-4437) in the case of extrusion welds or a air pressure test within the channel of the double-wedge fusion welds; (iii) destructive testing of field seams for strength in peel and in shear; and (iv) visual inspection of the entire liner surface for any defects.

2.3.3 Drains and Outlets

The gypsum and gypsum-fly ash stack underdrains, underdrain outlets and decant outfall pipes were installed by Georgia Power Company at the locations and to the lines, grades, and dimensions shown on the Drawings in Appendix A.

Pressure-rated, smooth-walled HDPE pipes were used for decant outfalls, underdrain outlets and surface water culverts. Slotted, corrugated HDPE pipe was used for the underdrain collector pipes.

2.3.4 Inspection and Quality Control Testing

Ardaman & Associates, Inc. was retained by Georgia Power Company to provide quality control inspection and testing services during construction of the disposal facility to document that the pond bases, dikes, composite bottom liner and underdrain system were completed in accordance with the quality control plan outlined in the D & O Plan (Design and Operating Plan for the Coweta County - Georgia Power Plant Yates Private Industry Waste Disposal Site). Results of the quality control program, along with an engineering certification for the completed facility, were previously reported by Ardaman & Associates, Inc. [9]. Quality control inspection and testing performed during construction of the facility is summarized in this section.

Quality control inspection activities associated with site preparation included observing that (i) all organic matter, debris and other objectionable materials resting on and protruding above ground surface within the limits of grading were removed and that all roots and matted roots were grubbed to at least 12 inches below the proposed subgrade surface; (ii) surface dewatering measures were sufficient to maintain the base well-drained and dry during construction; (iii) in-situ subgrade materials and all fill materials met the subgrade material requirements; (iv) existing years. Although utilization tests appear promising, gypsum marketing had not actually begun; therefore it was prudent to initiate the permitting process for more disposal space.

Essentially, Georgia Power has submitted an official request to EPD that the existing stacking areas be constructed to higher elevations, then the two separate areas combined into a single facility which could be constructed to a still higher elevation. This procedure would involve filling the gypsum stack to its currently permitted top elevation of 780 (MSL), with dike crest at EL 785. In addition the gypsum-fly ash stack would be filled to EL 800, followed by filling of the gypsum stack to EL 800. Next the dike separating the two stacks would be breached, creating a single storage compartment which could be filled to EL 825 (dike crest at EL 830).

Implementation of this plan, if needed, would increase total storage volume from 73 acre-ft to approximately 130 acre-ft., an increase of 78 percent. At current gypsum production rates (burning a lower sulfur coal), it is estimated that the expansion would provide approximately six years additional capacity, versus 2-3 years capacity with the existing configuration.

2.3 Construction

This portion of the report summarizes key features regarding construction of the gypsum stacking area -- gypsum stack, gypsum-fly ash stack, and surge pond. Specific topics are general earthwork, dike construction, drainage mechanisms, and the composite liner system underlying all facilities. Details of the construction process and final configuration of the facilities are available in various reports including the design (Ardaman, 1990) and liner construction quality assurance (Ardaman, 1992) reports, as well as the synthetic liner installation manual (Comanco, 1992).

The disposal facility was constructed during March through September, 1992. The site preparation, earthen dike and clay liner construction, and drain and outlets installation was undertaken by Georgia Power Company (Nettleton, 1995). The synthetic liner was installed by Comanco Environmental Corporation of Tampa, Florida. Ardaman and Associates, Inc. was retained by Georgia Power to perform quality control inspection and testing during construction.

criteria was adopted which specified that the clay liner be compacted to dry densities not less than 98% of the standard Proctor dry density for samples with molding moisture contents greater than the standard Proctor optimum moisture content and not less that 95% of the modified Proctor dry density for molding moisture contents greater than the modified Proctor optimum moisture content and less than the standard Proctor optimum moisture content.

Quality control inspection activities associated with dike construction included observing that (i) on-site clayey soils stockpiled during site preparation activities and near-site clayey borrow materials met the clay liner material requirements, including removal of particles larger than the specified maximum particle size; (ii) placement and compaction of the clay liner was in accordance with project specifications including moisture content, degree of compaction, lift thickness and uniformity of compactive effort and (iii) maintenance of completed portions of the clay liner prior to installation of the synthetic liner was in accordance with project specifications including thickness, grade tolerances, maximum particle size, moisture content and density.

Quality control inspection activities associated with HDPE liner installation included observing that (i) the HDPE liner was installed only over portions of the clay liner that had been maintained in accordance with project specifications; (ii) the HDPE liner was handled, installed, anchored and field bonded in accordance with the specified installation procedures; (iii) the Installer's quality control testing program was implemented in accordance with project specifications including qualifying tests for welders, destructive testing of field seams and continuous, non-destructive testing of field seams; and (iv) any defective seams, penetrations for obtaining destructive test samples and any other portion of the liner suspected to have been damaged was properly repaired or patched and tested.

Quality control inspection activities associated with underdrain construction included observing that (i) the HDPE pipes and fittings are in compliance with specifications requirements including pipe diameter, perforation dimensions, SDR rating, etc.; (ii) all pipe and filter fabric was installed as specified including joining of pipes, field seaming of filter fabric, placement and compaction of gravel and fine sand; and (iii) the HDPE manholes and valves were installed as specified including placement and compaction of backfill, joints with HDPE pipes and boot connections around valve stems that penetrate the HDPE liner.

On September 3, 1992 the senior project engineer inspected the site for compliance with the specifications with regard to the containment system and associated underdrain system. The facility appeared to be constructed in compliance with the specifications. Based on the quality control program including inspections and testing, and the engineer's inspection of the completed work, it was Ardaman's professional opinion that the containment dikes, composite liner system and underdrain system are constructed in accordance with the specifications outlined in the approved D & O Plan.

2.4 Test Plan

2.4.1 Stacking Management Plan

Gypsum stack management techniques typically vary from one facility to another and will depend to a great degree on the physical properties of the gypsum produced, the gypsum production rate, settling pond design and geometry, construction equipment and experience of the operational personnel. The management plan for operation of the Plant Yates FGD gypsum and gypsum-fly ash stacks incorporated construction and raising using slurry deposition and rim-ditch techniques in conjunction with the "upstream" method of construction. The fundamentals of this type of construction are described in this section.

Byproduct gypsum was slurried into the smaller of the two storage ponds. A total of 28,600 tons of gypsum was expected to be produced and deposited into the small pond over a nine (9) month period with an estimated 65 percent operational factor. The corresponding average rate of gypsum production during operational periods was expected to be approximately 160 tons per day. The material was slurried into the pond through a pipe distribution system at a total flow rate on the order of 2.0 cubic feet per second (cfs) with a solids content of approximately 3 percent.

The anticipated gypsum-fly ash production was 92,600 tons over a period of 15 months. Considering an operational factor of 65 percent, this material was expected to be slurried into the pond at a solids content of approximately 5 percent with a total flow rate on the order of 2.0 cfs. This flow equates to an average gypsum-fly ash production rate of approximately 312 tons per day.

Both stacks would be raised using the upstream method of construction. Figure 2-11 illustrates the concepts associated with this construction technique. In general, a perimeter earthen starter dike is constructed and partially filled with water to form a clarification pond for the gypsum slurry. As the gypsum settles in the pond and the surface elevation of the sedimented gypsum approaches the crest elevation of the original starter dike, a dragline or excavator is used to dig a portion of the sedimented materials and cast them on the inboard (upstream) side of the original dike to form a new, elevated dike.

Slurry operations are continued until the surface elevation of the sedimented gypsum again approaches the crest elevation of the new, gypsum starter dike and the operation is repeated.

A variation of the upstream method of construction utilizes the "rim-ditch" method of slurry deposition. In general, a rim-ditch is an elevated ditch located immediately inboard of the starter dike and is used to route and control the patterns of gypsum slurry deposition within the clarification pond. A conceptual illustration of an elevated rim-ditch in presented in Figure 2-12. The primary benefits of the rim-ditch are:

- The elevated ditch promotes more rapid drainage of the sedimented materials within the ditch, which, in turn, facilitates excavation and handling during subsequent lifts of the starter dike.

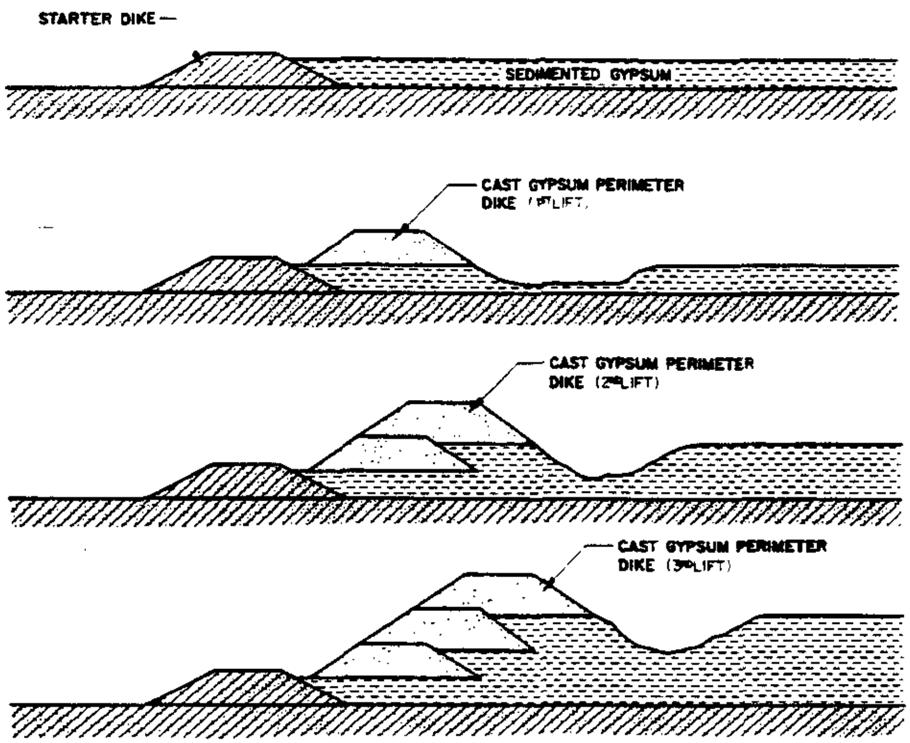


Figure 2-11. Upstream Method of Gypsum Stack Construction

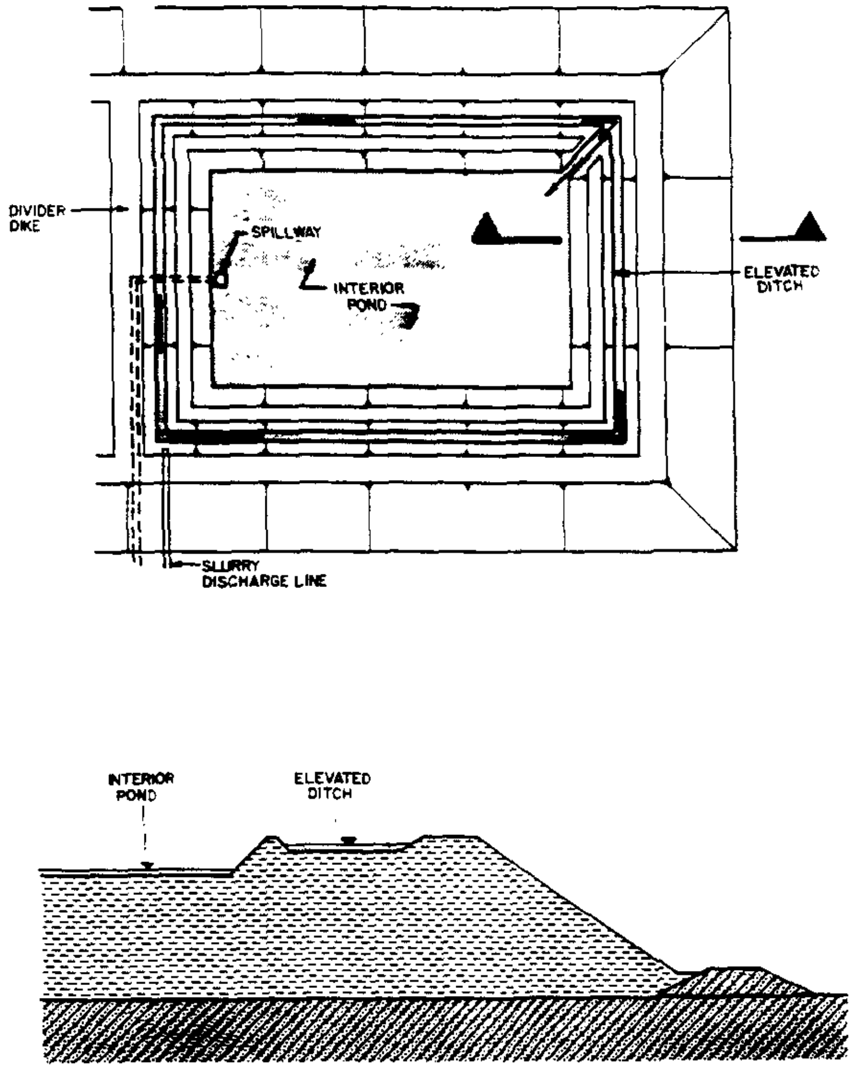


Figure 2-12. Schematic of Elevated Rim Ditch Used to Sediment Coarse Gypsum Around Stack Perimeter

- The coarser, or larger sized, gypsum particles tend to settle more rapidly than the finer particles in the slurry and will be deposited directly in the rim-ditch. These coarser materials are generally more pervious than the finer particles, which further promotes rapid drainage and handling (i.e., excavation and construction of subsequent lifts of the rim-ditch and starter dike).

- Utilization of an elevated rim-ditch permits the gypsum slurry to be routed around the perimeter of the stack and discharged at any desired location. This feature gives the facility operator/manager more control over the location and shape of the sedimented deposits and the configuration of the clarification pond.

Water used to slurry the gypsum or gypsum-fly ash into the disposal areas is decanted from the clarification pond and flows by gravity to the surge pond located at the west end of the facility. From there, the clarified water will be returned (i.e., via a concrete sump and electric pump station) to the plant for reuse. Initially, all slurry water charged into the disposal areas will be returned through the underdrains and there will be no requirement of a decant spillway. As the top of the drain becomes covered with sedimented materials, however, the rate of flow into the underdrain will be sharply curtailed and discharge from the decant structures will be required.

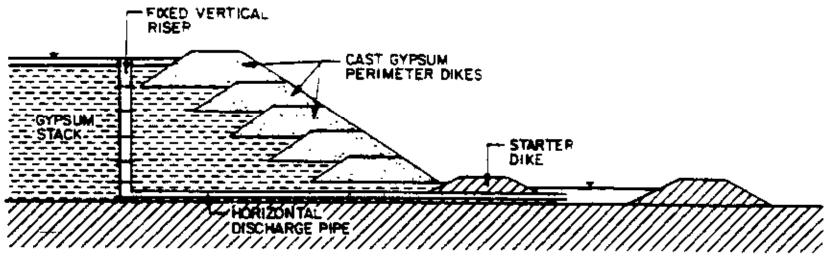
Figure 2-13 conceptually illustrates the two types of decant structures commonly used in the phosphogypsum industry. The first is a fixed decant structure and the second is a movable, stage decant structure. Both decants are provided with adjustable weir mechanisms that permit raising or lowering the weir elevation to produce a corresponding change in the ponded water elevation and depth. Fixed decant structures are proposed for the Plant Yates facility but movable stage decants may also be used as necessary to improve stack management techniques and/or to gain experience in the two technologies for later use on full scale projects.

The location of the decant and the depth of water in the pond will influence the effectiveness of the pond in clarifying the slurry input. Relative to improved clarification, the depth of water and the length of the flow path between the decant and the slurry input point should be maximized.

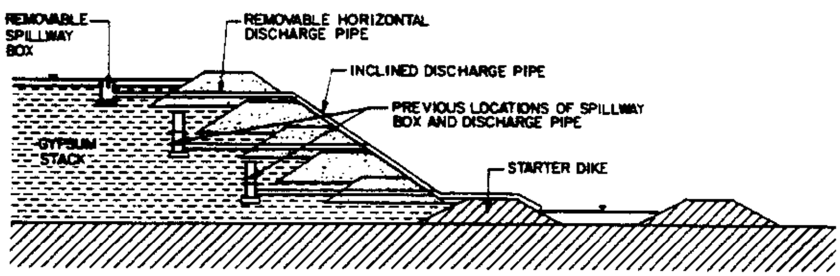
surfaces were compacted to a depth of 6 inches beneath the finished surface prior to placement of any fill materials; (v) fill placement and compaction was in accordance with project specifications; (vi) and the condition and appearance of the subgrade surface was adequately maintained.

Quality control inspection activities associated with dike construction included observing that (i) erosion and sedimentation control measures were implemented and adequately maintained and that eroded sediments within the pond construction limits were removed; (ii) all borrow materials met the dike fill material requirements; (iii) fill placement and compaction was in accordance with project specifications; (iv) installation of the HDPE pipes within the earthen dikes associated with the surge pond pump station and underdrain outlets was in accordance with project specifications including pipe sizes and materials, procedures for installation, procedures for joining pipes and placement and compaction of backfill; (v) installation of HDPE manholes and valves associated with the underdrain outlets was in accordance with project specifications including materials, installation procedures and placement and compaction of backfill and (vi) the condition and appearance of the dike surfaces were adequately maintained.

A clay liner test strip was constructed to verify that the required coefficient of permeability could be achieved using the borrow materials, construction equipment, installation procedures and specified degree of compaction. Results of laboratory permeability tests performed on field compacted samples obtained using a thin-walled sampling tube indicated that the clay liner test strip was not in compliance with the specified maximum coefficient of permeability. Additional permeability tests were subsequently performed on laboratory compacted samples of material taken from the clay liner borrow stockpile. The test results indicated that the degree of compaction specified in the D & O Plan (i.e., dry density equal to or in excess of 98% of the standard Proctor dry density at molding moisture contents greater than the standard Proctor optimum moisture content) would not be sufficient to achieve the specified average coefficient of permeability. However, a coefficient of permeability significantly below the specified average coefficient of permeability could be achieved for samples compacted to dry densities corresponding to the modified Proctor (ASTM D-1557) dry density at the molding moisture content. Based upon the results of these additional tests, a more stringent clay liner compaction



Fixed Vertical Riser Decant System



Moveable Decant System

Figure 2-13. Stage Decant Systems

In terms of facility safety, operational water storage and surge requirements and facility shut down and close-out considerations, however, it is desirable to minimize the volume of water stored in the clarification pond on top of the stack.

In general, if the depth of water in the pond and/or flow path length are not sufficient (i.e., weir elevation is set too low or slurry input too close to decant) adequate clarification of the gypsum slurry will not be realized and carry-over of suspended sediments into the surge pond may occur. If carry-over is occurring, either of the two variables must be increased to improve the clarity of the decanted water.

Adjustments of the decant weir height will be manifested by changes in the depth and volume of water stored in the clarification pond. For the proposed closed system, which has a limited volume of water stored in the surge pond, changes in the clarification pond water elevation will be limited by operational constraints of the surge pond.

A typical sequence of construction operations used to initially raise the starter dikes and rim-ditch includes the following stages. In some cases this original plan was modified as necessary for Plant Yates. Reasons are explained here and in a later section.

Stage 1

- Prior to excavation and construction of the new, elevated starter dike the sedimented gypsum will slope slightly from the crest of the dike toward the clarification pond. Excavation will not commence until the surface of the sedimented gypsum is within two to three feet of the dike crest elevation.

Stage 2

- Excavation of the first phase of the rim-ditch will be accomplished with either a dragline or hydraulic excavator (backhoe) with a minimum reach of about 40 feet. Equipment with a greater reach is acceptable and generally preferred but equipment with a lesser reach may not be suitable and will have to be evaluated on an individual basis.

- Low bearing pressure, tracked equipment is best suited for this type of work. Bucket capacities in the range of 1.5 to 2.0 cubic yard are generally used for phosphogypsum. Due to the relatively low gypsum production rate for this project, however, bucket sizes as small as 1.0 cubic yard should be suitable.

- Hydraulic excavators offer greater bucket control than do draglines and are generally preferred in applications where easily damaged synthetics are used as bottom liners. The equipment operators should ensure that the depth and lateral location of the excavation is such that the bucket is always a minimum of three (3) feet away from the synthetic liner.

- It is recommended that the slurry supply pipeline be located on the outside edge of the dike (i.e., away from the pond) to minimize interference with construction equipment.

- It is anticipated that the sedimented gypsum initially excavated from the rim-ditch channel will be relatively wet and, in some cases, will be excavated from beneath the water surface. This wet material may be difficult to handle and stack until the height of the new berm is elevated sufficiently to promote rapid drainage. It is recommended that a small ditch be left between the original starter dike and the new gypsum berm to collect spills and drainage generated from consolidation of the wet gypsum.

<u>Stage 3</u>

- The rim-ditch is refilled with gypsum slurry and additional wet gypsum is cast onto the outer berm of the rim-ditch. This step will be repeated until a relatively substantial outer berm is created.

<u>Stage 4</u>

- The cast material in the outer berm is spread and lightly compacted with a small dozer (i.e., such as a low ground pressure Caterpillar D5 or D6) to form an elevated working surface for the excavator. The surface of the graded fill should slope slightly to the inside to control runoff and spills from subsequent casting operations.

- The excavator is then moved partially onto the shaped fill and the inner berm of the rim-ditch is excavated and moved inboard (i.e., to the limits of the equipment reach). The top elevation of the inner berm is usually maintained slightly lower than that of the outer berm. This feature will result in the rim-ditch spilling inboard if it is inadvertently over filled.

Stages 5 and 6

- The rim-ditch is refilled with slurry and the excavator is moved fully onto the first lift of shaped gypsum fill. The sedimented materials are again excavated and cast on the inboard sides of the inner and outer berms.

- The process is repeated and the excavator and rim-ditch are moved progressively inboard and elevated. Dozer spreading and leveling of the cast gypsum is periodically required.

Stage 7

- As the height of the rim-ditch increases, the quantity of cast fill required to raise the inner berm will also increase. It is necessary to periodically cut through the inner berm of the rim-ditch and deposit gypsum on the inside of the berm to raise the elevation of the gypsum base. To achieve this end, a corresponding increase in the elevation of the ponded water surface may be required. For stability and ease of construction, the fill height of the inner berm should typically not exceed about three feet.

Stage 8

- When the outer berm of the elevated rim-ditch is not less than about 20 feet wide and generally aligned with the proposed final geometry of the gypsum stack, the perimeter seepage/runoff collection ditch at the toe of the side slope is excavated and maintained.

- Subsequent lifts of the rim-ditch continue to follow the projected side slope geometry of the gypsum stack.

The actual geometries and management techniques required for the proposed facilities were determined after production and deposition had begun and the many variables (e.g., production rate, percent solids and rate of flow, settled density, permeability, rate of consolidation, material strength, construction equipment, experience and capabilities of facility operators and managers, etc.) had been defined. Fundamental concepts common to both facilities include the following:

- The gypsum or gypsum-fly ash particles will stay in suspension in the slurry discharge stream from the plant until the stream encounters the ponded water and flow velocities are reduced sufficiently to promote settlement of the suspended particles. Deposition, therefore, begins at the edge of the ponded water surface and works its way back upslope to the point of discharge. If unimpeded by mechanical restraints, the sedimented deposits from a single slurry discharge point will eventually form a semi-circular delta. The slope of the sedimented materials above the water elevation will typically be very flat, whereas, the slope of the sedimented materials below the water level will be relatively steep.

- The slope of the sedimented materials above the water level will be fairly constant for a given material and will be dictated by the engineering properties of the material (i.e., such as particle size and shape, shear strength, etc.). To increase the elevation of the sedimented deposits at the slurry discharge point, therefore, requires that the horizontal distance from the discharge to the pond be increased or that the water elevation in the pond be raised. Lateral expansion of the sedimented deposits will be limited in most cases by the location of the decant structures (i.e., if slurry is deposited too close to the decant, carry-over of suspended particles to the retention pond will occur).

- If carry-over of suspended solids is occurring, the total retention time needs to be increased by either increasing the ponded water depth or increasing the distance from the slurry discharge point to the decant structure.

Due to the relatively small size of the gypsum storage area and clarification pond and the need for continued operation (i.e., with a single disposal area it will not be possible to alternate operations between ponds to permit a drying cycle in the inactive pond), two slurry discharge points and two decant structures were recommended. The primary advantage of the two discharge points is improved slurry deposition patterns and control during the initial stages of operation, prior to the development of the first rim-ditch.

The weir height of the decant will need to be adjusted frequently based on observed performance of the slurry operations. If the weir is initially set too high, an excessively large volume of water will be stored in the pond, resulting in possible depletion of the design surge volume established in the retention pond. If the weir height is set too low, a sufficient depth of water may not be available for clarification of the gypsum slurry and carry-over of sediments into the retention pond may occur. In general, weir height adjustments and resulting changes in the pond water elevation should be less than one foot to minimize water surge requirements. The average depth of water between the decant and the active slurry input point should be not less than two to three feet to provide adequate retention time and clarification. In general, the sedimented deposits will radiate outward from the point of discharge and progress across the pond toward the decant structure. The sedimented materials will displace the water in the pond causing a surge in the retention pond equal to the volume of gypsum deposited below the water surface.

Slurry deposition from any point should be discontinued or the pond water elevation raised when there is insufficient water for clarification or when the surface elevation of the sedimented materials threatens to overtop the idle decant structure. We recommend that the depth of water at the decant be maintained at not less than one foot. Greater depths will improve clarification, however, and minimum operational depths of two to three feet are recommended.

Due to the small size of the project, the slurry discharge point needs to be moved frequently. More frequent alternation of the discharge slurry point to refill excavated portions of the rim-ditch may also be desirable during early development of the rim-ditch. When slurry is discharging from locations near the center of the rim-ditch alignment, better clarification may be achieved by operating both decant structures at the same elevation (i.e., reduced flow velocity and greater retention time).

The fundamental stack management concepts presented above for the gypsum stack are, for the most part, directly applicable to the gypsum-fly ash stack. Principal differences are that the gypsum-fly ash will probably be deposited at a much flatter slope and may be more difficult to handle due to an initial low density and strength. The sloping pond bottom and location of the underdrains within the gypsum-fly ash stack will also alter management techniques during the initial stages of operation. In general, the underdrains will serve in place of the decant structure until the drains become covered with sedimented materials when the pond is near an elevation of 790 feet (MSL).

Due to the large size of the gypsum-fly ash pond, a single decant structure will be adequate for pond operations and clarification. Until the ponded water level reaches approximately Elevation 790 feet (MSL), clarified slurry water will be returned to the retention pond through the underdrain piping. When the underdrains become covered with sedimented materials, the quantity of flow entering the drains will be significantly reduced and will be less than the flow entering the pond. The fixed spillway structure will then be used to decant the excess water from the pond. The decant will be located near the center of the stack and will be founded at a base elevation of approximately 780 feet (MSL).

2.4.2 Utilization

Specific objectives pertaining to byproduct utilization included demonstration of the following:

- Use of FGD gypsum as an agricultural soil amendment;
- Horizontal belt vacuum filtration to lower chloride and moisture levels in gypsum; and
- Use of processed gypsum as a replacement for mined gypsum in wallboard and cement manufacturing processes.

2.4.2.1 Agriculture

The following specific objectives were addressed in the agricultural evaluation of byproduct gypsum, conducted with the overall objective of evaluating the agronomic value and potential agricultural usage of flue gas desulfurization (FGD) gypsum:

- To determine the yield response of important forage and grain crops to various rates and application methods of FGD gypsum on representative Southeastern soils, and to identify accessory management techniques to enhance the effect of such applications;
- To assess food chain and environmental effects, if any, of cropland amendment with FGD gypsum and gypsum-fly ash mixtures, with particular emphasis on forage uptake and leaching of As, B, Mo, and Se;

- To quantify the effects of surface applied gypsum on soil physical properties such as clay dispersion, infiltration, and soil loss, and determine the longevity of such effects on representative soils;

- To evaluate the use of annuals in crop rotation after perennials, in terms of yield and rooting depth, as a step toward long-term improvement of Southeastern soil productivity;

- To determine plant species and management practices useful in temporary or permanent vegetation establishment on FGD gypsum stacks.

The fundamental approach used in conducting this research was to collect and characterize coal combustion byproducts (CCB) including fly ash and FGD materials from representative Southern Company generating plants, and to assess crop growth and potential environmental hazards in laboratory and greenhouse studies as a first step in designing field experiments. After these initial studies had identified key properties of soil-CCB systems and suggested appropriate applications rates for field trials, experimental sites were established at three locations in the state (Calhoun, in the north Georgia mountain region; Athens, in the central Georgia Piedmont region; and Tifton, in the southern Coastal Plain region) having different soil types and cropping patterns; these sites are further representative of the entire southeastern U.S. , stretching from Mississippi to Virginia, in their diversity of soil types. Typical agronomic crops were grown on these sites for three growing seasons following CCB applications (gypsum and gypsum-fly ash mixture) at three rates; crop yield response and contaminant movement were assessed over this time period. Accessory experiments were performed on the field plots and in greenhouse studies to clarify the effect of CCB amendment on rooting patterns, yield response, and water quality effects. The data summaries in this report are aimed at documenting the agronomic advantages of such CCB amendment, and any potential environmental impacts that might result from such usage.

2.4.2.2 Wallboard and Cement

Other utilization opportunities which were planned for evaluation include use of FGD gypsum as raw material for wallboard and cement manufacturing. Note that ash/gypsum material was not included in these plans, since ash contents greater than 2% cause problems with wallboard discoloration, drying, and improper board formation.

Wallboard and cement companies are interested in locating sources of man-made gypsum to replace natural gypsum which is transported longer distances to manufacturing sites. In fact, the wallboard manufacturers, who use > 90% gypsum in their final product, are interested in ultimately locating manufacturing facilities adjacent to power plants which could produce suitable gypsum. This would greatly reduce transportation costs for raw material to the plant and for the finished product to the market. In addition, Portland cement manufacturers use 2-5% gypsum as a set retarder and as a grinding aid when cement clinker is ground to produce the cement product.

Several manufacturers -- National Cement, U. S. Gypsum, Domtar, Georgia-Pacific, and Celotex/Center for Applied Engineering -- agreed to participate in this proposed work at Plant Yates by taking quantities of processed gypsum and performing typical manufacturing and testing activities at their facilities.

Manufacturers are interested in FGD gypsum as a potential raw material to replace mined gypsum; however, the processes require low chlorides and moisture to prevent corrosion of nails (wallboard) and rebar (concrete), and to ensure that wallboard paper will bond securely to the gypsum core. Typical gypsum specifications employed by wallboard and cement companies (or typical gypsum analysis) include: gypsum purity greater than 95%, free moisture less than 10%, ash less than 1%, and chlorides (in gypsum) less than 100 ppm.

These specifications present a problem for the Yates material. Use of FRP construction material avoids corrosion damage without the cost of a prescrubber. However, this raises the chlorides level in the process (up to 30,000 ppm in the surge pond liquor). In addition, gravity dewatering at the stack will reduce moisture content to 30% or less. Both these values are significantly higher than current raw material specifications for wallboard and cement. As a result, the project plan also included installation of pilot equipment to wash and dewater gypsum. Specifically, this involved a horizontal belt vacuum filter to process approximately 5000 tons of FGD gypsum to meet raw material specifications and provide adequate quantities for commercial production runs at operating plants.

2.5 Schedule

Key dates in the life of the byproduct stacking and utilization effort included:

- October 1992 -- Begin scrubber and gypsum stack operation
- March 1994 -- Close gypsum stack operation and begin to collect ash in scrubber, with placement of resulting gypsum/ash mix in gypsum/fly ash stack
- January 1995 -- Close demonstration period and begin commercial operation of scrubber -- (discontinue collection of ash in scrubber and place gypsum in gypsum/fly ash stack)
- 1993-1996 -- Agricultural field evaluation (see Section 3.3.1)

3.0 DISCUSSION OF RESULTS

3.1 Differences in Planned vs. Actual Activities

Most activities originally scheduled were successfully completed during the project period. Two exceptions were:

1. Field testing on the ash/gypsum stack -- Although the design and size of this facility was based on a 15-month period for ash collection in the scrubber (and 9 months production for gypsum without ash), the actual operating time was approximately reversed. Consequently, the ash/gypsum stack was oversized for the quantity of material actually produced. Final stack geometry was not achieved (and unable to be evaluated with in-situ testing) at the time that the demonstration period was completed and commercial operation began in January 1995. Material produced during the commercial period to date has not included an ash component; therefore, material in the top layers of this stack is the same as the ash-free gypsum in the first stack.

2. Ash processing for manufacturing applications -- Plans described in Section 2.4.2.2 called for additional work to include vacuum filtration equipment to lower chloride and moisture levels, followed by manufacturer evaluation of the processed FGD gypsum byproduct. This work was not in the original plan and was submitted as an additional scope of work, subject to approval and funding. Although plans were complete, total necessary funding was not available from all sources. Preliminary laboratory testing by the manufacturers indicated that the material was likely to be suitable, if processing was completed to the desired specifications.

3.2 Stacking

At this point the gypsum stack is inactive, while the ash/gypsum stack is in use. The latter facility was designed to contain ash/gypsum blends produced during the period in which the scrubber was tested for particulate collection. It is now receiving gypsum slurry from commercial operation.

Since the smaller gypsum stack has now been through its life cycle (except closeout), there are observations which can be offered in reference to design features and general operating procedures. The brief description below summarizes some of the important information derived from experiences at Yates, as well as estimated quantities of byproduct material stored in each facility. Related information is found in the recommendations of Section 4.1.

3.2.1 Byproduct Characterization and Evaluation of Engineering Properties

Field and laboratory testing programs were conducted by Ardaman & Associates, Inc. to characterize geotechnical engineering properties of the FGD gypsum produced during the first phase of the demonstration project at Plant Yates. The objectives of the testing programs were to:

1. Characterize behavior relevant to the wet-stacking disposal method;
2. Evaluate geotechnical engineering properties through comparison with results of previous FGD gypsum testing associated with other projects and
3. Provide the basis for recommendations regarding material properties for design and operation of a full-scale wet-stacking disposal facility.

A summary and evaluation of the field and laboratory tests results and geotechnical engineering properties of the Plant Yates FGD gypsum is presented in this section. Detailed test data are presented in Appendix B. The FGD gypsum-fly ash disposal area is currently active in conjunction with the second phase of the demonstration project. Field and laboratory testing of this material has not been undertaken at this time.

A field testing and sampling program consisting of test borings and piezometer installations was performed by Ardaman & Associates, Inc. in July 1994 (after completion gypsum stacking). The drilling program consisted of Standard Penetration Test (SPT) borings; and rotary wash and hollow-stem auger borings performed to obtain thin-walled tube samples and to install piezometers. The boring and piezometer locations are shown on Figure 3-1.

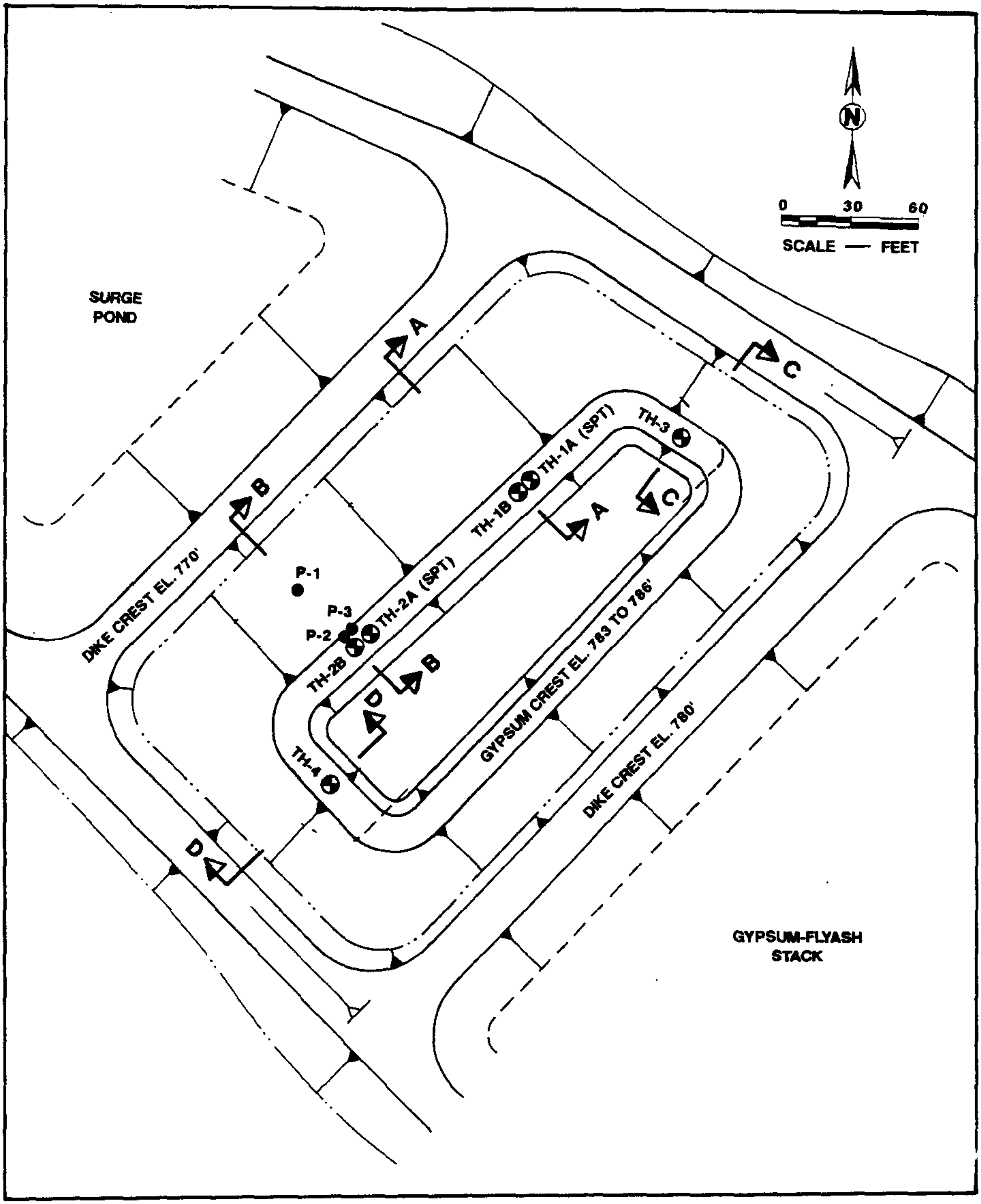


Figure 3-1. Approximate As-Built Plan and Field Test Location Plan for Gypsum Stack

Two SPT borings, TH-1A and TH-2A, were performed at the locations indicated on Figure 3-1 from the surface of the gypsum dike crest with continuous testing and sampling down to a depth of 21 feet. The measured SPT resistance in the upper cast gypsum dike typically ranged from 20 to 30 blows per foot. The SPT resistance in the underlying sedimented gypsum ranged from 30 to 100 blows per foot, and generally increased with depth down to the elevation of the perimeter dike crest (Figure 3-2). The measured SPT resistance values suggest that the relative density (i.e., density relative to the maximum density as determined by ASTM D 4253) of the sedimented FGD gypsum is nearly 100 percent, which indicates favorable settling and consolidation behavior with regard to the wet stacking method of disposal. A portion of each split-barrel sample was retained for laboratory classification and index testing. Visual descriptions of the split-barrel samples and the SPT resistance values are summarized on the boring logs in Appendix B.

Four test borings were advanced by rotary wash techniques or hollow-stem auger and thin-walled tube samples recovered from selected depth intervals. The sampling borings were performed from the surface of the gypsum dike crest down to depths ranging from 16 to 20 feet at the locations shown on Figure 3-1. The samples were sealed in the sampling tubes to prevent moisture loss and were subsequently used for laboratory testing. The depth intervals and visual descriptions of the samples for borings TH-1B, TH-2B, TH-3 and TH-4 are summarized on the boring logs in Appendix B.

The surface profiles, boring depths and stack stratigraphy (i.e., sedimented, cast or disturbed/mixed gypsum) are shown on the cross sections in Figures 3-3 and 3-4. Since the test borings were performed from the surface of the cast gypsum dike (the drill rig could not access the middle of the stack), the stratigraphy encountered reflected disturbance related to prior gypsum excavation and casting operations with horizontally stratified, sedimented gypsum encountered only in the bottom few feet of each boring.

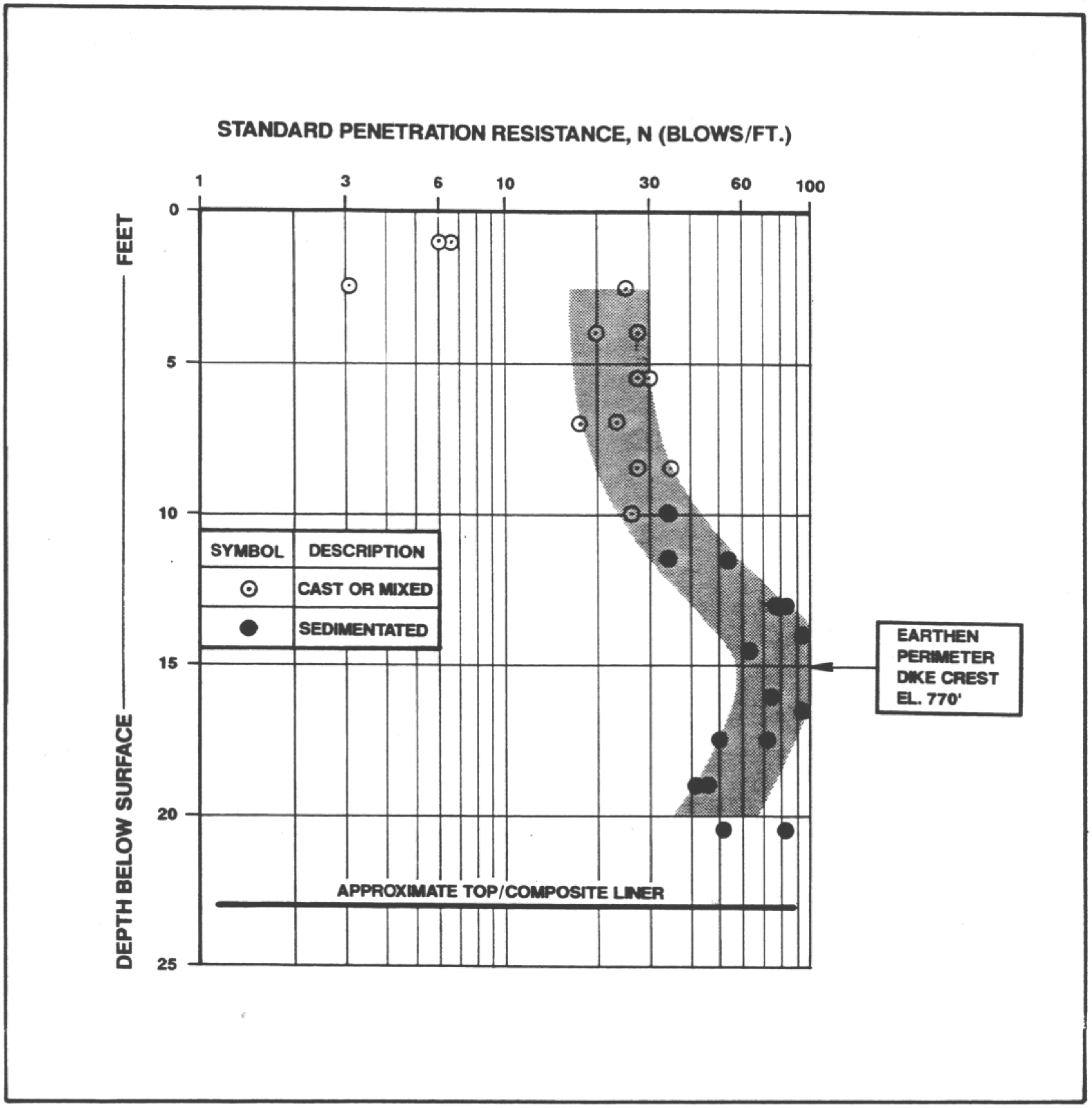


Figure 3-2. Standard Penetration Test Resistance Versus Depth for Plant Yates Gypsum Stack

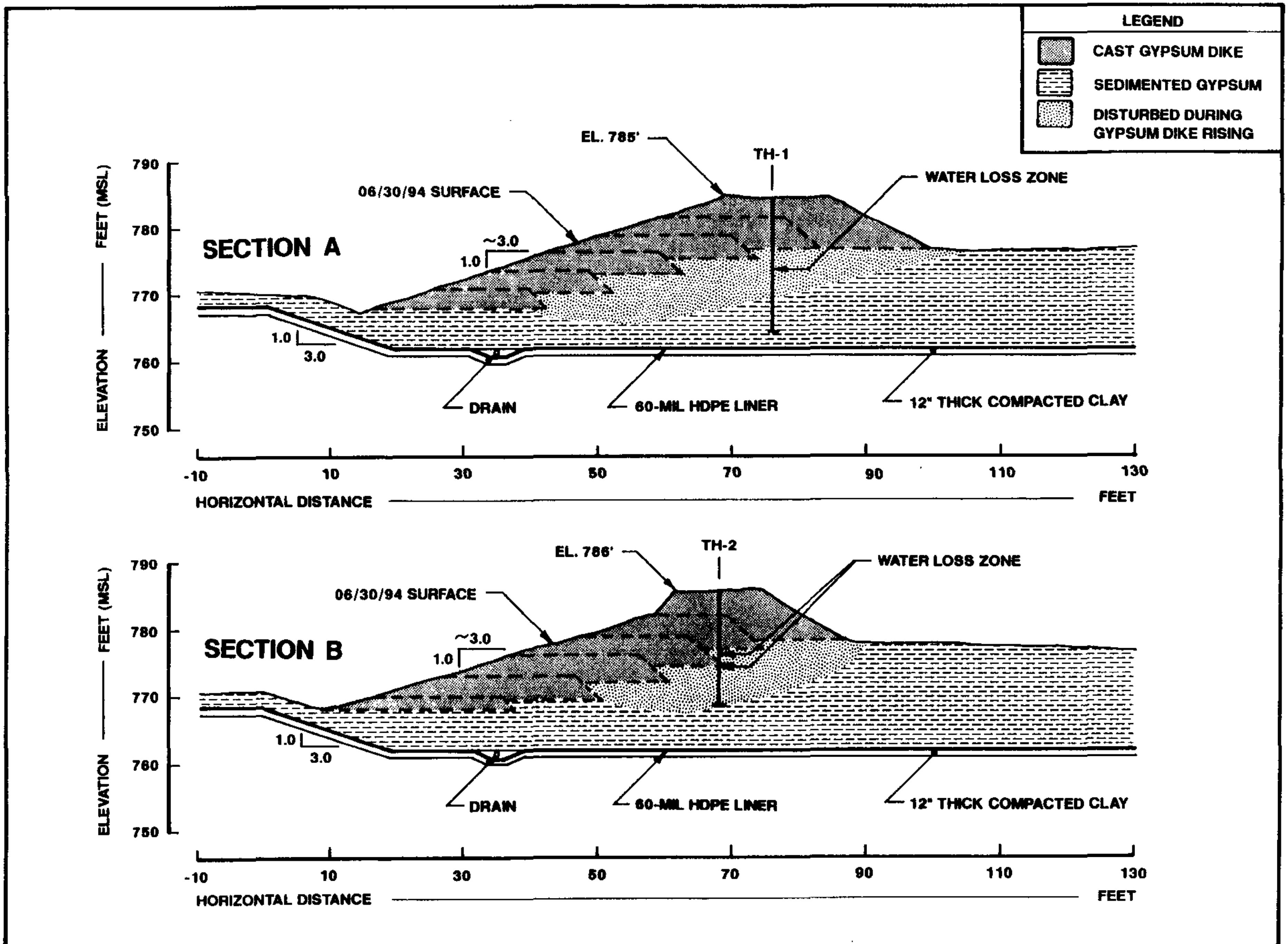


Figure 3-3. Gypsum Stack Cross Sections A & B

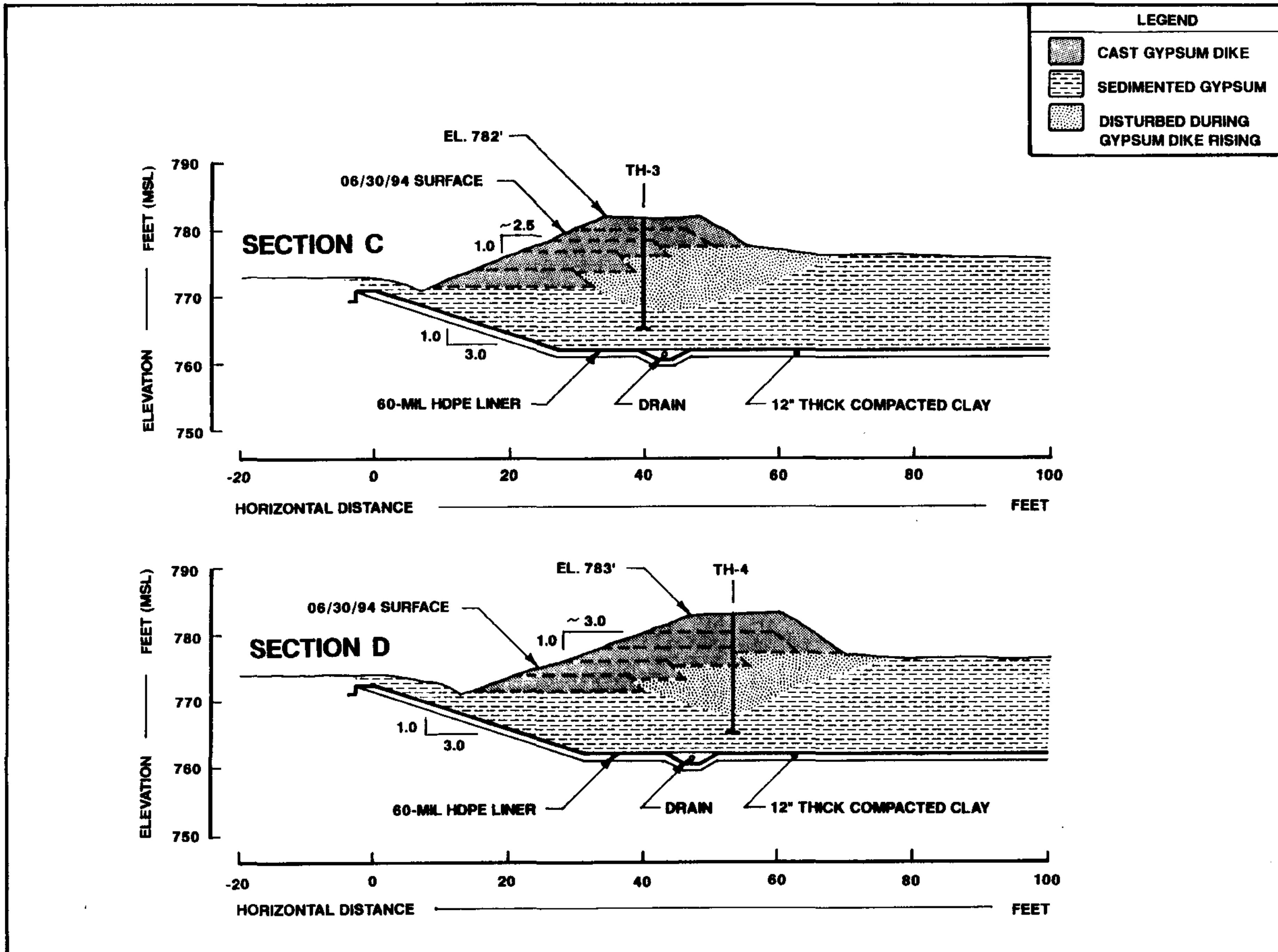


Figure 3-4. Gypsum Stack Cross-Sections C & D

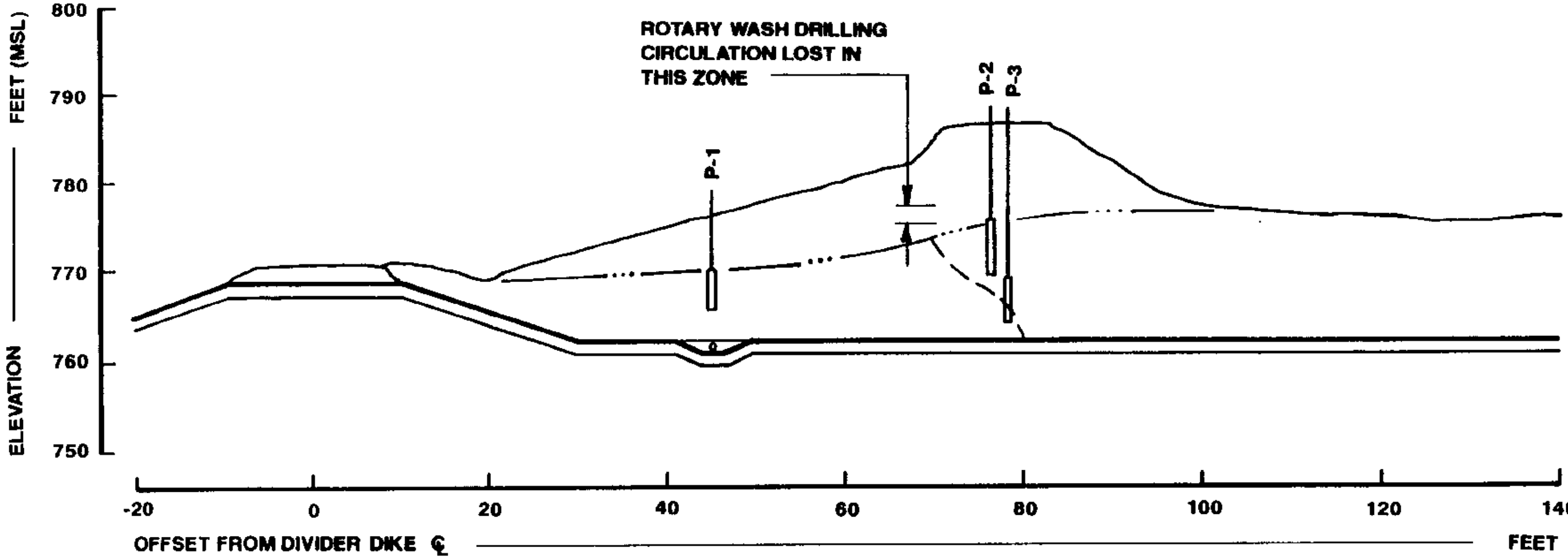
Figure 3-5 shows the locations and depths of three piezometers that were installed to determine the location of the stack phreatic surface and for use in conducting in situ permeability measurements in the gypsum by rising and falling head testing. The field permeability test results are summarized on Figure 3-5, and are discussed later in this section with results of laboratory permeability tests. The measured water level in the stack reflect partial drainage of the gypsum that occurred after deactivation and prior to the start of the field testing program.

In addition to the samples obtained during the drilling program, bulk samples of Plant Yates FGD gypsum were periodically taken from the surface of the stack during the demonstration period. Visual descriptions of seven bulk gypsum samples (and laboratory segregated subsamples) are summarized in Table 3-1.

TABLE 3-1
VISUAL DESCRIPTION OF BULK GYPSUM SAMPLES

Sample No.	Sample Date	Visual Description
X	12/92	Light yellowish-brown gypsum
I		Light yellowish-brown gypsum with some sand-sized particles (unreacted crushed limerock carryover)
I-A	3/93	Same; finest particle sizes, 33% of sample I (dry wt. basis)
I-B		Same; intermediate particle sizes, 23% of sample I
I-C		Same; coarsest particle sizes, 44% of sample I
II	3/93	Orange-brown gypsum
III		Light yellowish-brown gypsum with trace sand-sized particles
III-A		Reddish-brown gypsum; finer 22% of sample III
III-B	7/93	Light yellowish-brown gypsum; coarser 78% of sample III
III-AA		Reddish-brown clayey fines; finer 13% of subsample III-A
III-AB		Light yellowish-brown gypsum; coarser 87% of sample III-A
GS-1		Light yellowish-brown gypsum
GS-2	7/94	Light yellowish-brown gypsum
GS-3		Light yellowish-brown gypsum

A representative portion of the gypsum sample GS-2 was selected for scanning electron microscopy (SEM) to determine the size and morphology of the gypsum crystals. A portion of Subsample III-AA was also selected for SEM to determine the nature of clayey fines that were present in Sample III. Specimens were thoroughly air-dried, and then both intact lumps of the air dried gypsum and powder produced by light crushing were mounted for examination. The



GYPSUM STACK SECTION AT PIEZOMETER STATION (SECTION B-B)

IN-SITU PERMEABILITY TEST RESULTS		
PIEZOMETER NO.	COLLECTION ZONE DEPTH RANGE (FT.)	PERMEABILITY K_h (cm/s) (1)
P-1	6.0 - 10.5	4×10^{-4}
P-2	10.0 - 16.5	6×10^{-3} (2)
P-3	17.0 - 21.5	4×10^{-4}

NOTES:
1. PERMEABILITY ESTIMATED FROM RESULTS OF RISING AND FALLING HEAD TESTS.
2. PERMEABILITY (RISING HEAD TEST) LIKELY REFLECTS THE INFLUENCE OF CONCENTRATED FLOW WIYHIN "LOSS ZONE"

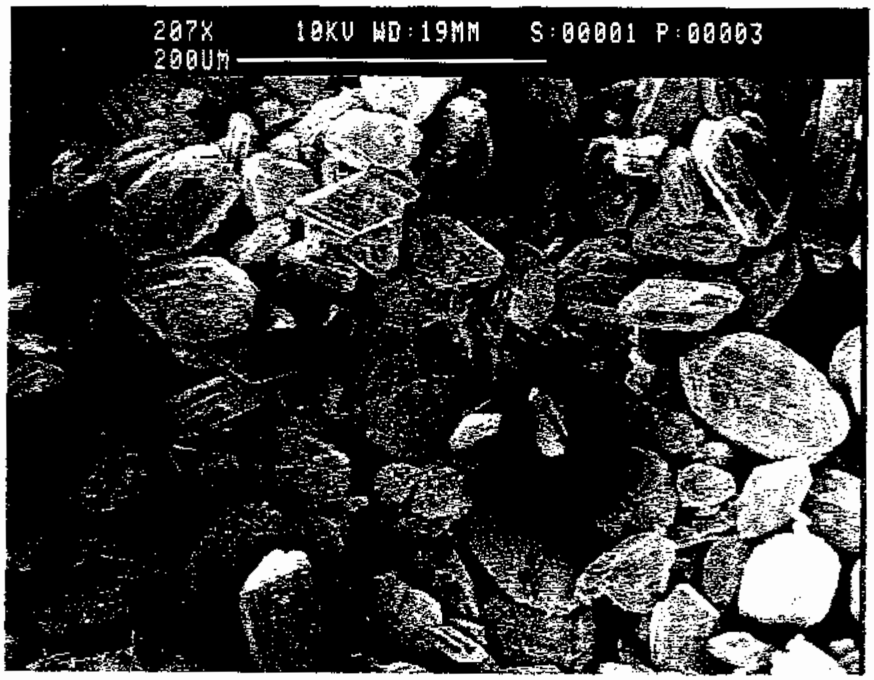
Figure 3-5. Summary of Gypsum Stack Piezometer Data specimens were mounted on carbon studs, using colloidal carbon, and were carbon coated to eliminate interference with chemistry analyses performed during the SEM examination via energy dispersive analyses by x-ray (EDAX).

Photomicrographs of the gypsum crystals magnified 209 and 837 times are presented in Figure 3-6 (the magnification and scale are shown at the top of each photomicrograph). As shown, the gypsum crystals are relatively small and "stubby". The gypsum crystals appear less than 100 μm in the largest dimension, and the axial ratio is typically less than 2. The chemistry of the gypsum determined via EDAX indicated approximately equal peak amplitudes of Ca and SO_4 with no other elements present.

Photomicrographs of Sample III-AA magnified 209 and 1720 times are presented in Figure 3-7. As shown, the particles are predominantly very fine gypsum crystals. The water insoluble fraction of Sample III-AA was isolated by repeated washing with tap water and high speed centrifuging. The chemistry of the non-gypsum fraction determined via EDAX indicated Si, SO_4, K, Ca and Fe in relative proportions that would be expected from the weathering of fly ash.

One specific gravity determination was made in general accordance with the test procedures outlined in ASTM standard D 854. The measured specific gravity of Sample X was 2.35 which is slightly greater than the value typical of pure gypsum (G_s=2.33). The specific gravity of the CT-121 FGD gypsum produced at Plant Scholz varied between 2.27 and 2.44 with an average value of 2.34.

Particle size distributions are presented for six gypsum samples in Figure 3-8. The gradations were determined by sieve and hydrometer analyses (ASTM D 421 and 422). The test results indicate that the Plant Yates FGD gypsum consists mainly of silt-sized particles with 100 percent of the samples generally finer than the U.S. No. 40 sieve size. Plant Yates gypsum has an average particle diameter ranging from 0.028 to 0.045 mm and average uniformity coefficient of 1.5 ($C_u=D_{60}/D_{10}$ where D_{60} and D_{10} are the diameters for 60 percent and 10 percent finer by dry weight, respectively).



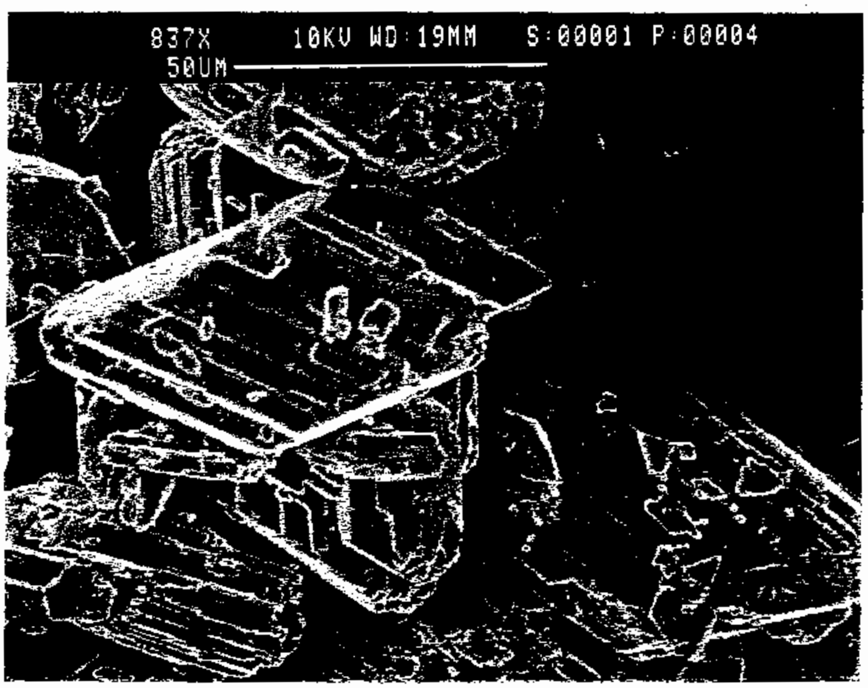


Figure 3-6. Photomicrographs of Plant Yates FGD Gypsum

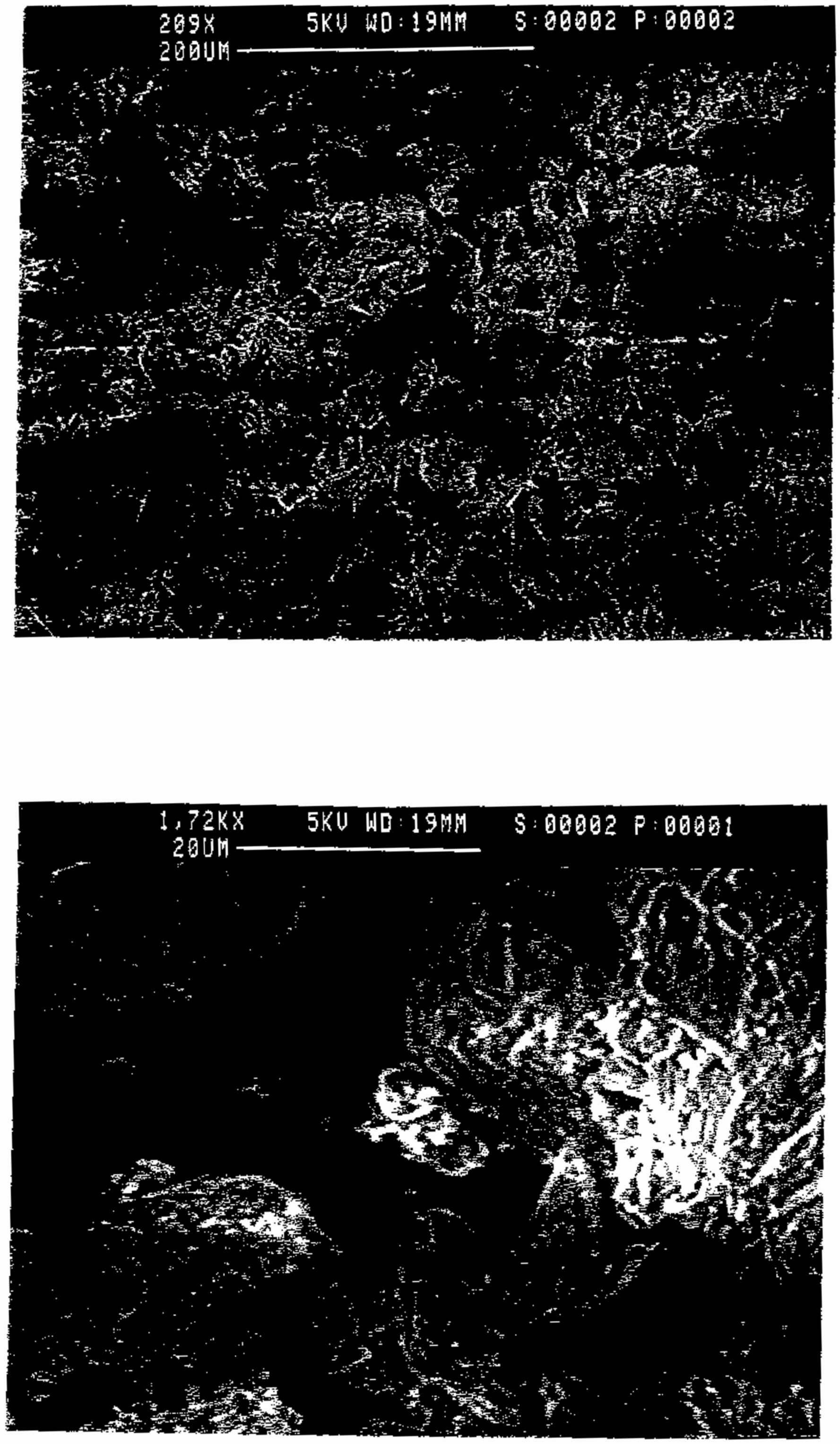
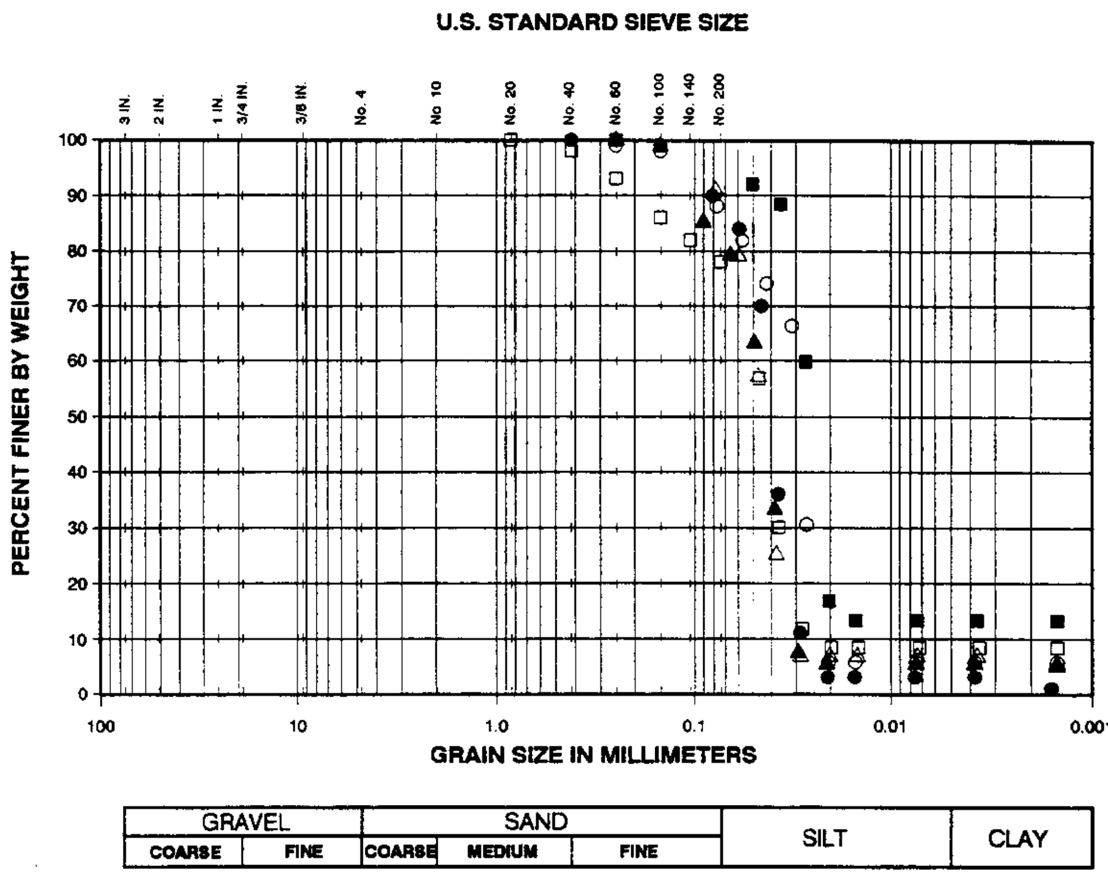


Figure 3-7. Photomicrographs of Segregated Gypsum Fines



SAMPLE NO.	DATE SAMPLED	SYMBOL	SAMPLE DESCRIPTION
X	12/92	●	LIGHT YELLOWISH-BROWN GYPSUM
I	3/93	▲	LIGHT YELLOWISH-BROWN GYPSUM
II	3/93	■	ORANGE-BROWN GYPSUM
III	7/93	○	LIGHT YELLOWISH-BROWN GYPSUM
GS-2	7/94	△	LIGHT YELLOWISH-BROWN GYPSUM
GS-3	7/94	□	LIGHT YELLOWISH-BROWN GYPSUM

Figure 3-8. Particle Size Distributions for Plant Yates FGD Gypsum Samples

The range of particle size distributions for the light yellowish-brown Plant Yates FGD gypsum (i.e., excluding Sample II) is shown, along with reported data for Plant Scholz FGD gypsum and the typical range for FGD gypsums, in Figure 3-9. As shown, the Plant Yates gypsum is typically finer than the FGD gypsum that was produced at Plant Scholz. However, the measured range of particle sizes distributions for Plant Yates gypsum is consistent with reported typical range for FGD gypsum.

The test results also indicate that the orange-brown gypsum Sample II is finer than the typical yellowish-brown Plant Yates gypsum. As noted above, Samples I and II were taken from the gypsum disposal area concurrently but a different locations relative to the slurry discharge points. The difference in the particle size distributions for these samples is likely due to the size-dependent settling rates of the slurried solids and the difference in distance from the active discharge point corresponding to the two sample locations. Therefore, significant stratification with respect to particle size distribution, and related engineering properties such as permeability, should be expected to occur within the gypsum stack.

Gypsum, or calcium sulfate dehydrate ($CaSO_4 \cdot 2H_2O$), contains chemically bonded water. At drying temperatures greater than about 60°C, gypsum starts to expel chemically bonded water. At temperatures greater than 180°C, most of the chemically bonded water is expelled and the gypsum has converted to the anhydride form (i.e., $CaSO_3$). Accordingly, a temperature of 40°C is commonly used to prevent the loss of the chemically bonded water while drying samples to determine the free water content.

The change in apparent moisture content with drying temperature, where the apparent moisture content is defined as the ratio of the weight of water at a given temperature to the weight of dry solids at 40°C, can give an indication of gypsum purity. The theoretical change in the apparent moisture content of pure calcium sulfate as the drying temperature is increased from 40°C to above 180°C is 20.9 percent. The gypsum content in a sample can, therefore, be estimated as the

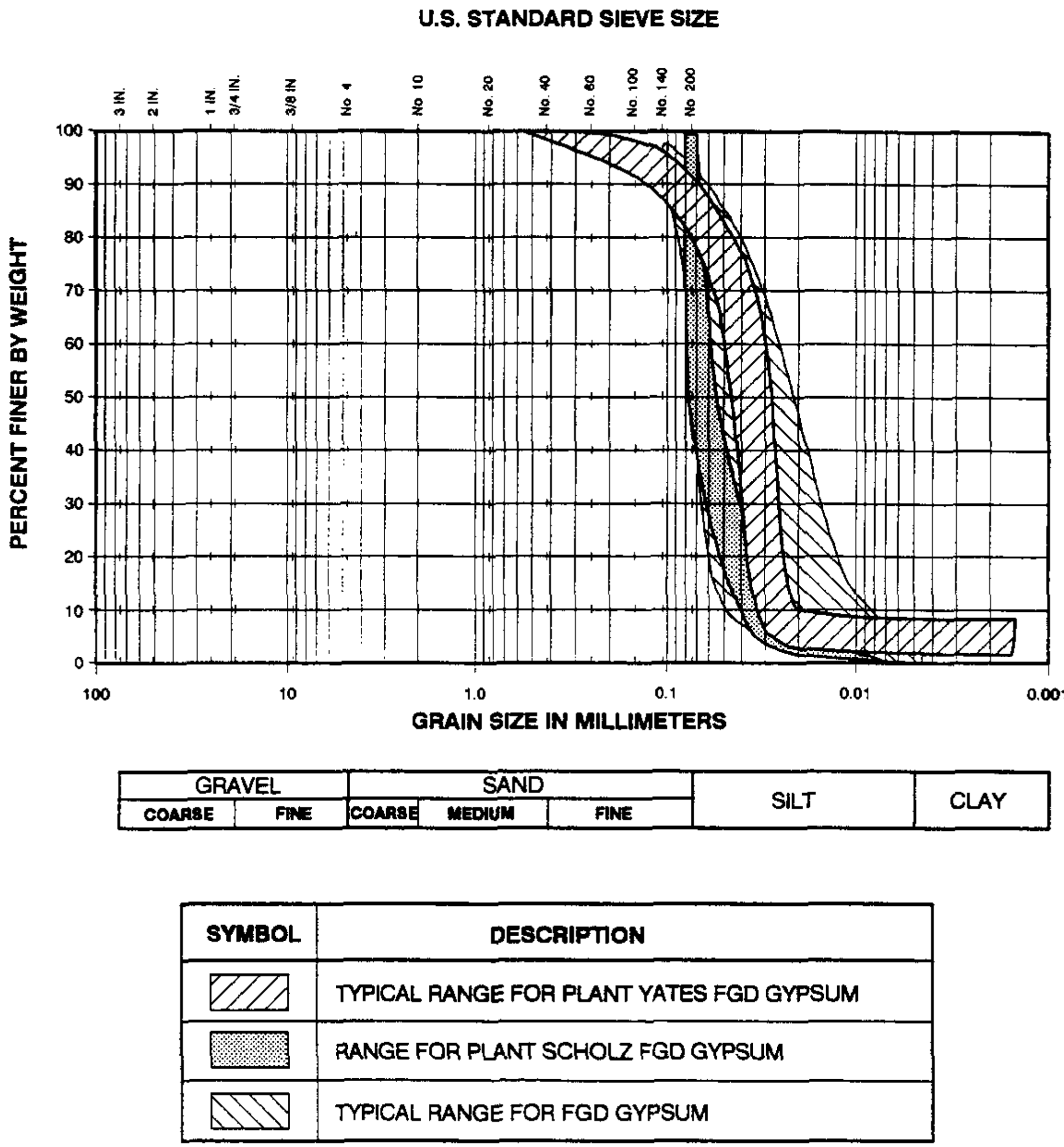


Figure 3-9. Particle Size Distribution for FGD Gypsum

ratio of the measured chemically bonded water content to the theoretical value of 20.9%. Gypsum contents less than 100 percent indicate the presence of impurities in the sample, such as limerock or fly ash particles.

The natural moisture of the SPT split-barrel samples and thin-walled tube samples were determined by oven drying at a temperature of 40°C. The test results are presented versus depth in Figure 3-10. As shown, natural moisture contents of samples obtained from depths corresponding to the cast gypsum dike (and above the phreatic surface in the gypsum stack) generally increased with depth and varied from 10 to 28 percent. Natural moisture contents of samples of the underlying sedimented gypsum also tended to increase with depth and varied from 18 to 30 percent.

Apparent moisture contents of Sample X and thirteen of the SPT split barrel samples from test boring Nos. TH-1A and TH-2A were determined at elevated temperatures to evaluate drying characteristics and to estimate gypsum purity. The test results are summarized in Table B-1 (Appendix B) and presented, along with drying curves reported for other FGD gypsum samples, in Figure 3-11. Based on these results, the samples tested are not pure gypsum as evidenced by measured chemically bonded water contents less than 20.9 percent. The range of estimated pure gypsum contents of the split barrel samples based on the chemically bonded water content data, is 91 to 98 percent at SPT boring No. TH-1A, and 95 to 100 percent at TH-2A. Similarly, the gypsum contents of the surface samples I and II ranged from 58 to 86 percent. (The elevated fraction of impurities in these surface samples is likely due to an elevated amount of unreacted limerock carryover from the reactor during March 1993 as discussed below).

Carbonate contents of the bulk gypsum samples and thirteen of the SPT split barrel samples from test boring nos. TH-1A and TH-2A were determined to evaluate the nature of the impurities indicated by the measured chemically bonded water contents discussed above. Results of the carbonate content determinations are summarized in Table B-2 (Appendix B) and suggest that the impurities in the gypsum samples tested are predominately $CaCO_3$ in that the non-gypsum

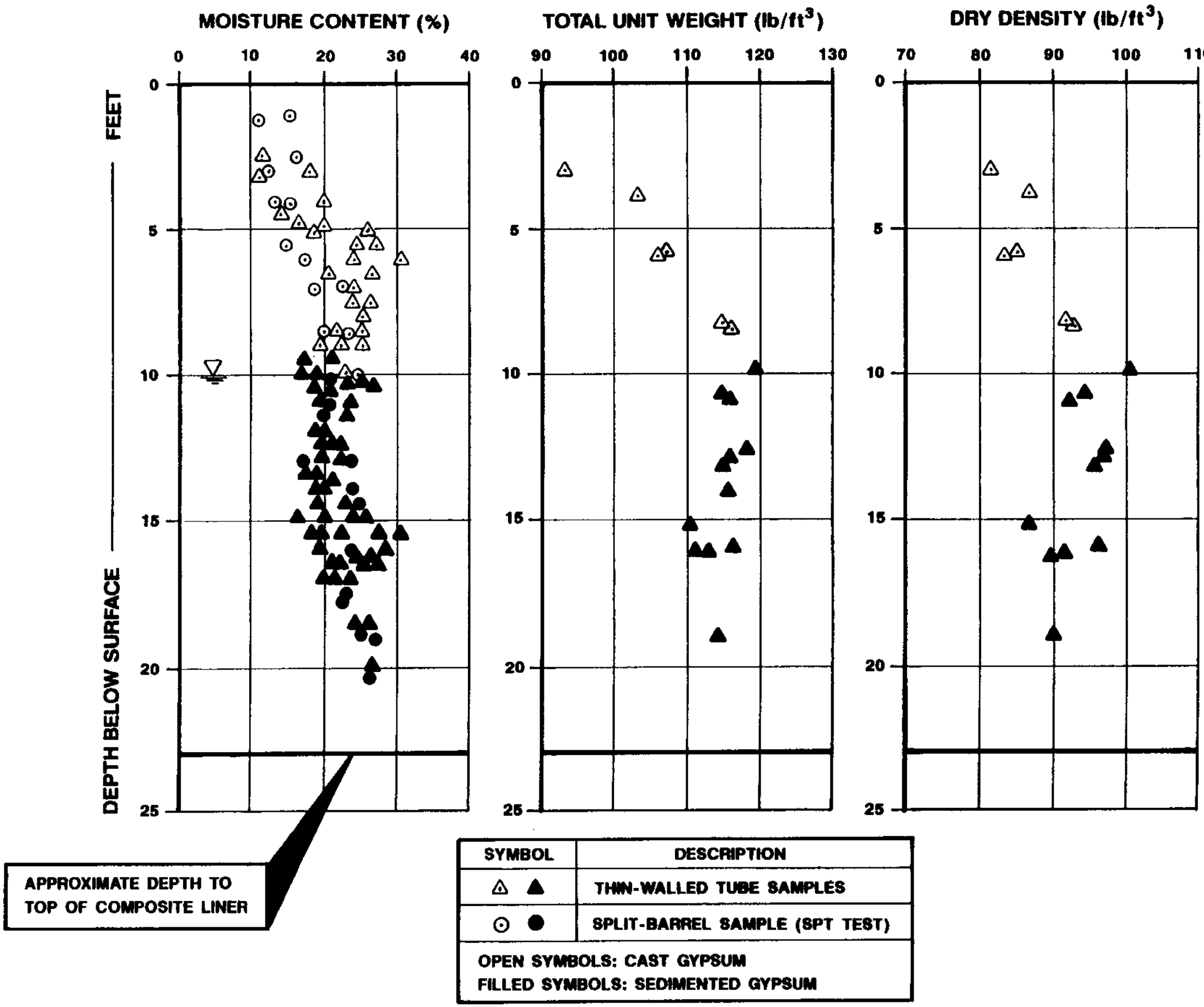


Figure 3-10. In Situ Moisture Content and Density Versus Depth for Plant Yates Gypsum Stack

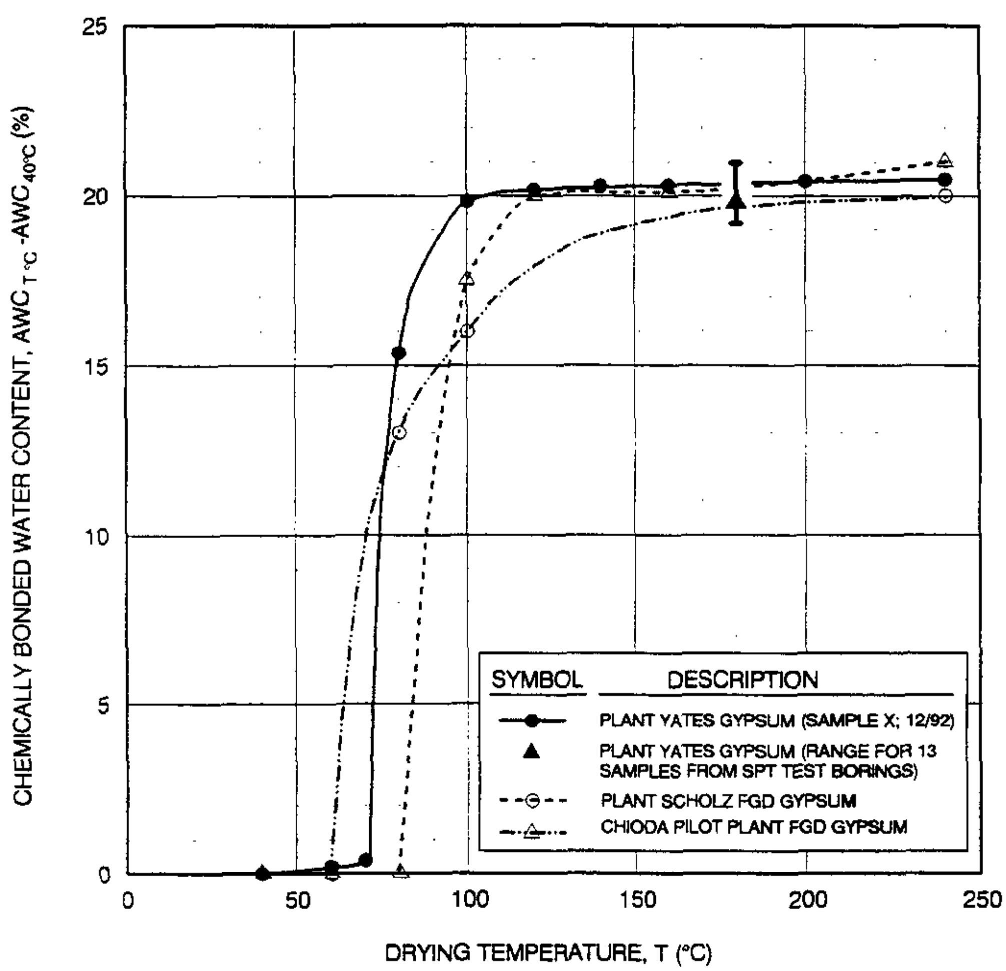


Figure 3-11. Chemically Bonded Water Content Versus Drying Temperature for Plant Yates FGD Gypsum

contents based on measured chemically bonded water contents are generally consistent with the corresponding measured carbonate contents (Figure 3-12). Unreacted limerock particle carryover from the reactor is suspected to be the source of the carbonates present in the gypsum.

In situ total and dry density measured on the thin-walled tube samples are presented, along with the measured natural moisture contents, versus depth in Figure 3-10. The measured dry density of cast gypsum ranged from 82 to 94 lb/ft^3 and generally increases with depth. The dry density of sedimented gypsum samples generally ranged from 90 to 98 lb/ft^3. These dry densities are similar to, and slightly higher than, those reported for Plant Scholz FGD gypsum.

Laboratory settling tests were performed to evaluate settling velocity and solids content after hydraulic deposition within the impoundment. The settling behavior of the slurried solids strongly influences the design of settling areas for sufficient retention time for sedimentation and clarification of the decanted process water. The settling tests were performed using initial solids contents ranging from 4 to 40 percent in Plexiglas graduated cylinders 10.4 cm in diameter and 30 cm high with initial slurry heights of about 27 cm. The slurried specimens were thoroughly mixed after deposition in the cylinders with a perforated plunger to produce a uniform initial solids content throughout the suspension. The settling tests were then performed by observing the height of the interface between the settled suspension and supernatant with time.

The results of settling tests on the gypsum samples are summarized in Table B-3 (Appendix B) and typical test results are presented in Figure 3-13 (Note that only data from the initial 30 minutes of the test are shown in this figure). The initial settling velocity was determined from the slope of the initial linear portion of the height versus time curve (Figure 3-13). The gypsum samples displayed initial settling velocities, v_S, ranging from 1.3 to 7.5 cm/minute and varying inversely with initial solids content (Figure 3-14).

The "final" settled solids contents observed at the end of the tests (i.e., after 24 to 25 hours) are summarized in Table B-3 (Appendix B) and presented on Figure 3-14. The "final" settled solids

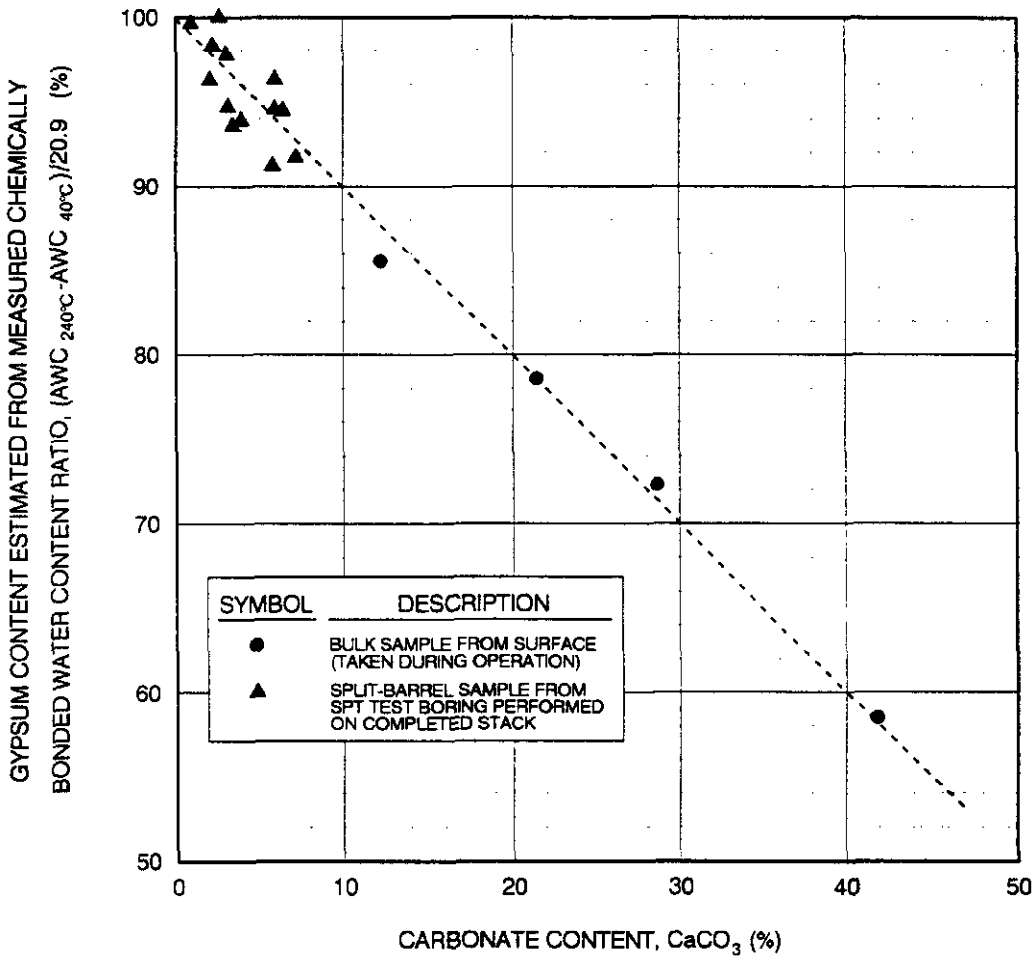


Figure 3-12. Gypsum Content Versus Carbonate Content for Plant Yates FGD Gypsum

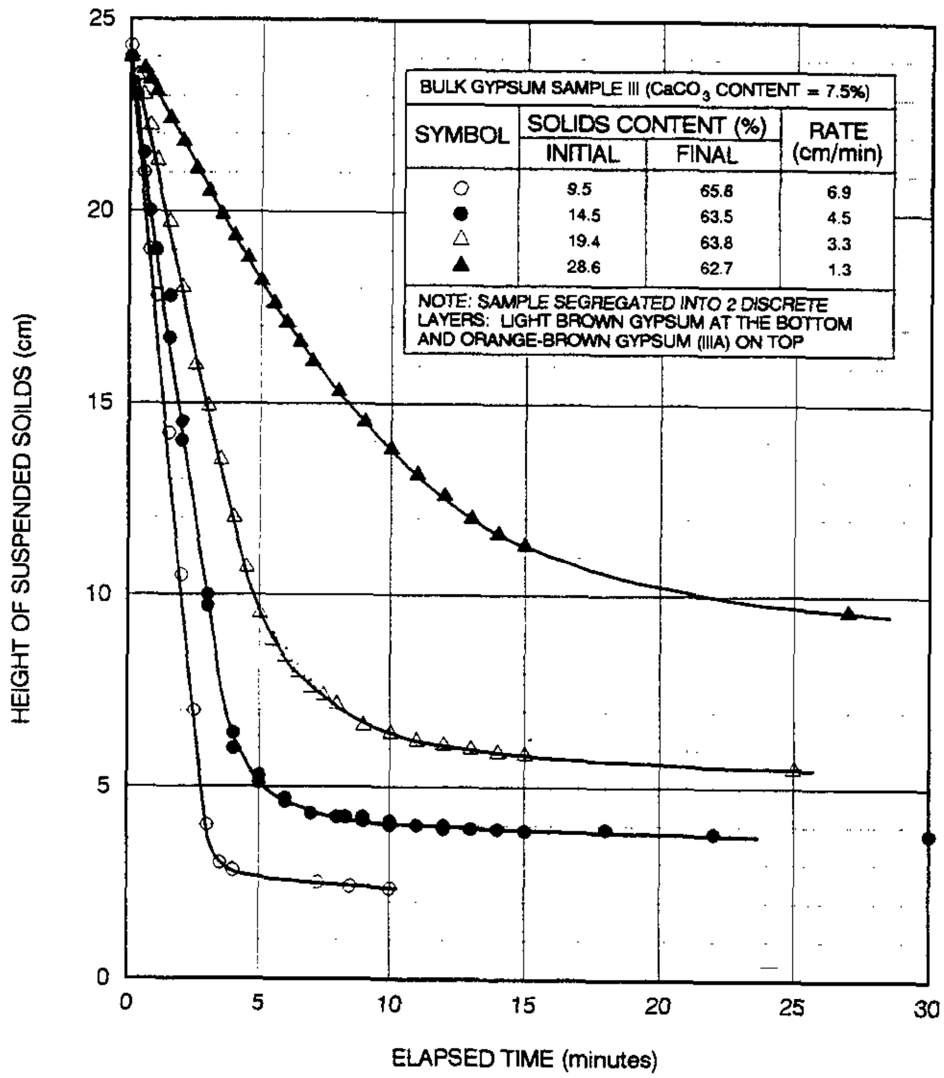


Figure 3-13. Settling Test Results for Gypsum Sample III

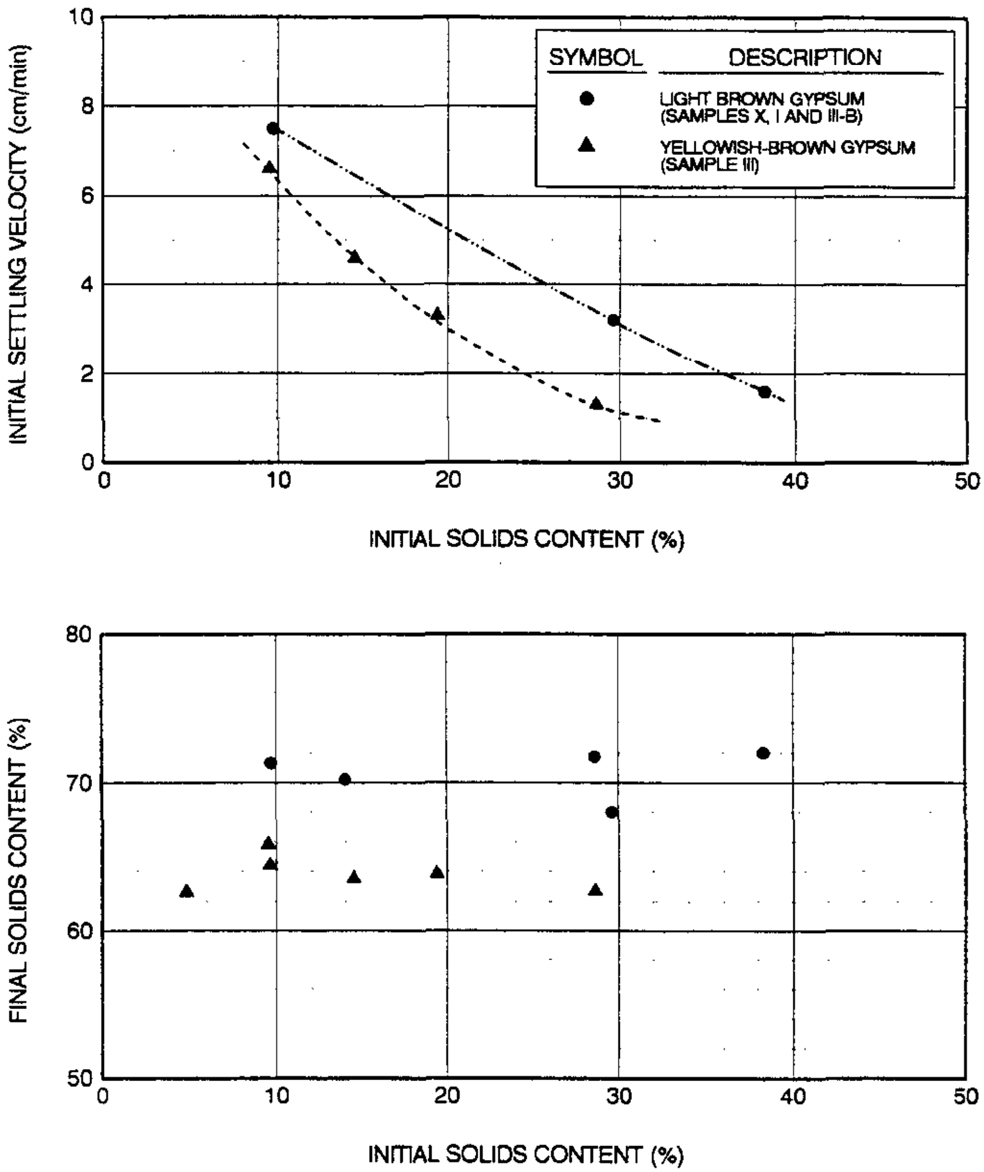


Figure 3-14. Initial Settling Rate and Final Solids Content from Laboratory Settling Tests

contents of light yellowish-brown gypsum (Samples X, I and IIIB) varied from about 70 to 72 percent (corresponding to dry densities of 73 to 76 lb/ft^3) for initial solids contents ranging from about 10 to 38 percent. These values are very similar to final settled solids content measured for Plant Scholz FGD gypsum (71 to 72 percent).

Gypsum sample III displayed discrete segregation in the sedimentation column as shown in Figure 3-15. The yellowish brown slurry segregated in to light yellowish brown particles (larger fraction settling to the bottom; subsample IIIB) and orange-brown fine particles settled on top (subsample IIIA). The settling characteristics of subsample IIIB were similar to those of samples X and I, and the settling characteristics of subsample X were similar to those of sample II (which was purposely selected from the gypsum pond surface at a location that was remote from the slurry discharge point). The settling velocity of the subsample III-A is approximately 10 times less than for the typical light yellowish-brown gypsum. The final settled dry density of the fine orange-brown particles ranged from 17 to 27 lb/ft^3.

Vertical coefficients of permeability were determined for test specimens remolded or resedimented from the bulk gypsum samples and for test specimens trimmed from thin-walled tube samples. Results of the permeability tests are presented in Tables B4 and B5 (Appendix B) and are summarized below:

- The measured vertical coefficient of permeability for light brown gypsum (both undisturbed and lab prepared specimens) ranged from 1.0×10^{-4} to 6.5×10^{-4} cm/sec with an average value of 3.0×10^{-4}.

- The measured vertical coefficient of permeability for orange-brown gypsum (both undisturbed and lab prepared specimens) ranged from 6.2×10^{-6} to 4.6×10^{-5} cm/sec with an average value of 2.2×10^{-5}; approximately 10 times less permeable than the light brown gypsum.

- The measured vertical coefficient of permeability for undisturbed light brown samples layered with orange-brown gypsum ranged from 2.4×10^{-6} to 4.6×10^{-5} cm/sec with an average value of 2.1×10^{-5}; similar to the orange-brown gypsum, as expected.

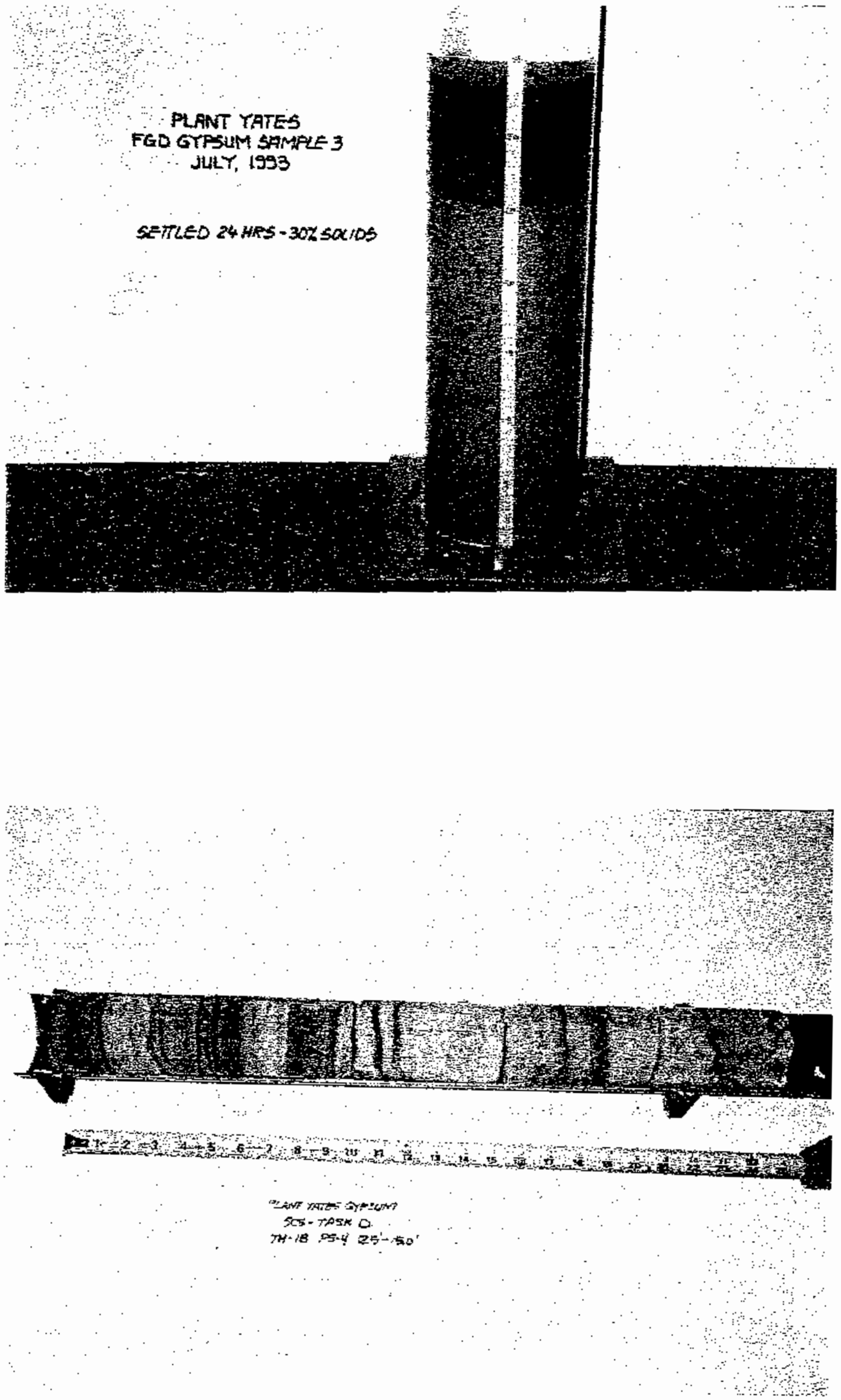


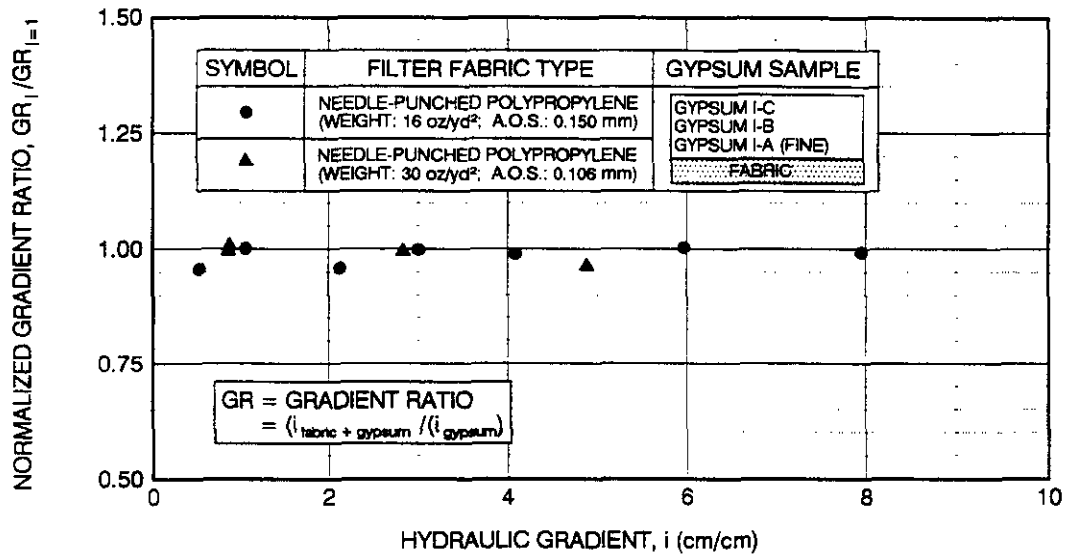
Figure 3-15. Gypsum Slurry Segregation in Laboratory Settling Column and Field Sample

- The measured vertical coefficient of permeability for a remolded sample of the clayey fines subsample III-AA was 1.2×10^{-7} cm/sec.

A series of gradient ratio tests were performed to confirm the compatibility, in terms of retention and clogging, of the underdrain filter fabric with the Plant Yates FGD gypsum. In this test, gypsum is sedimented in a tall column over the top of the filter fabric and water flows through the system under incrementally increasing constant heads. The ratio of the head loss across the fabric and that through the gypsum is computed as a function of the flow gradient. Increasing gradient ratios, therefore, indicate that the fabric is may not be an effective filter for the gypsum (i.e., the fabric tends to clog). Two filter fabric samples were used, a 16 oz./yd^2 non-woven, needle punched polypropylene fabric (same fabric used in construction of the underdrains) and a thicker fabric sample of the same type. The laboratory segregated gypsum subsamples I-A, I-B and I-C were used, with the finer subsample I-A sedimented directly above the fabric. Normalized test results, shown in Figure 3-16, suggest that the fabric is compatible with the Plant Yates gypsum sample used.

The consolidation behavior of interest for evaluating the stackability of a material as well as for evaluating consolidation during and subsequent to filling of a disposal area for estimating storage capacity and storage life include the void ratio versus effective stress relationship, and coefficients of consolidation and secondary compression versus effective stress relationships. To evaluate these properties for Plant Yates FGD gypsum, three one-dimensional consolidation tests were performed. Test specimens were selected from three of the thin-walled tube samples recovered from test boring no. TH-1B.

The tests were performed using conventional odometers. During the test, the height of the specimen under each applied load was monitored with time. Plots of specimen height versus the logarithm of time (Figure 3-17) are prepared to evaluate the deformation behavior of the specimen. These type plots are conventionally used to determine when primary consolidation under each load increment is complete, to graphically interpret the coefficient of consolidation, and to graphically determine the coefficient of secondary compression.



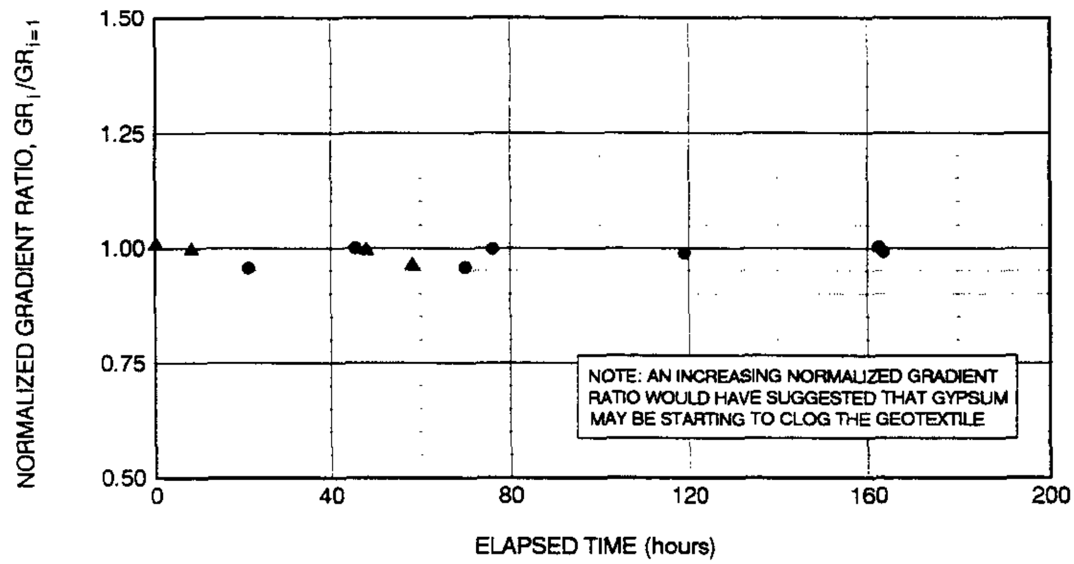


Figure 3-16. Gradient Ratio Test Results

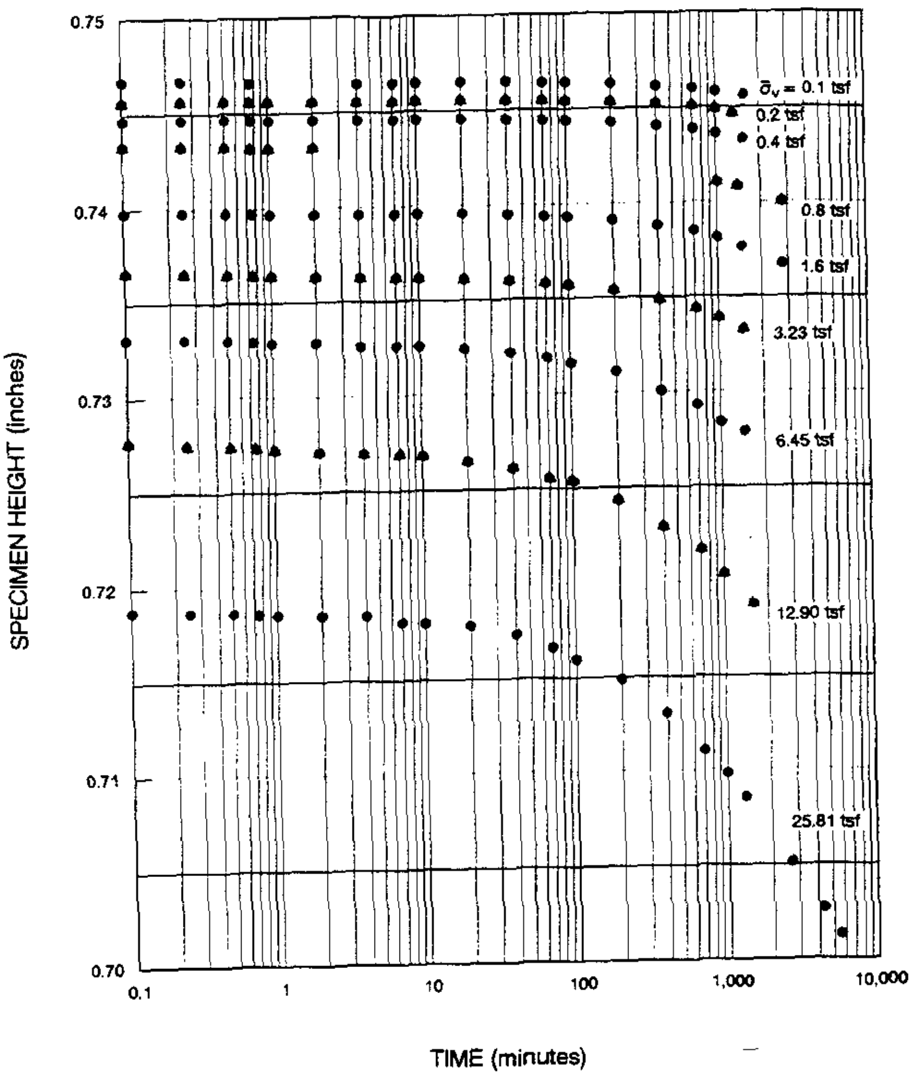


Figure 3-17. Typical One-Dimensional Consolidation Test Data for Plant Yates FGD Gypsum

The coefficient of consolidation, c_v, governs the time rate at which primary consolidation, or dissipation of excess pore water pressure generated by the increase in the total applied stress, occurs. The deformation versus time behavior Figure 3-17 typical of the Plant Yates FGD gypsum, however, does not allow interpretation of the coefficient of consolidation using conventional graphical techniques because of the relatively high permeability and a compressibility that is governed largely by drained creep rather than primary consolidation.

The void ratio measured after application of each effective vertical consolidation stress is presented in Figure 3-18. Because the Plant Yates FGD gypsum is relatively permeable and displays a compressibility that is governed largely by drained creep rather than consolidation, the determination of the end of primary consolidation with conventional graphical interpretation techniques using the deformation-time curves is not applicable. Instead, the void ratio has been plotted on Figure 3-18 at a time of 4 minutes.

The one-dimensional coefficient of secondary compression, C_α, was computed for each load increment from the slope of the relatively linear portion of the deformation versus time curves beyond a time of 600 minutes (Figure 3-19). The coefficient of secondary compression reflects the time rate at which secondary compression or drained creep occurs after primary consolidation is complete and is defined by the relationship: $C_\alpha = \Delta e/[(1+e_o) \log (t_1/t_2)]$, where Δe is the change in void ratio between times t_1 and t_2, and e_o is the initial void ratio for the load increment. This expression assumes a linear relationship between strain (and void ratio) and the logarithm of time. The linear relationship is also generally assumed to be valid over at least 2 to 3 log cycles of time beyond that achieved during the consolidation test.

As shown in Figure 3-19, the coefficient of secondary compression generally increased with increasing effective vertical consolidation stress from 0.4 %/log t at low stress levels to 1.5%/log t at high stress levels.

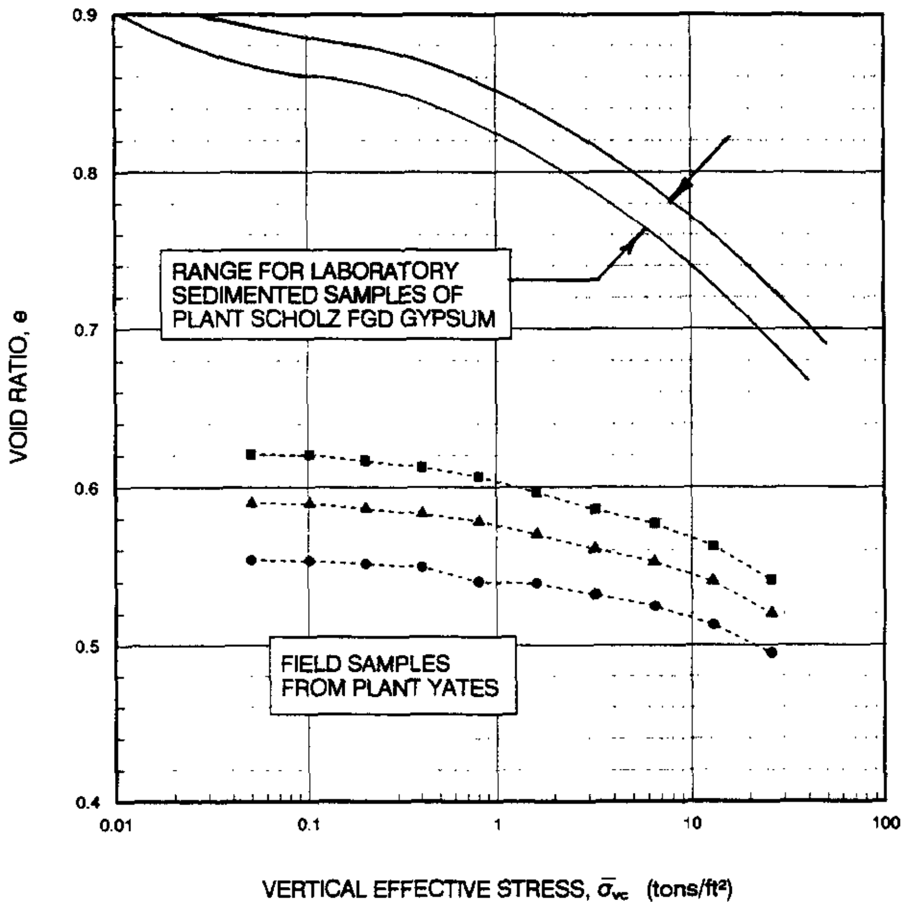


Figure 3-18. Void Ratio Versus Effective Consolidation for Plant Yates and Plant Scholz FGD Gypsum

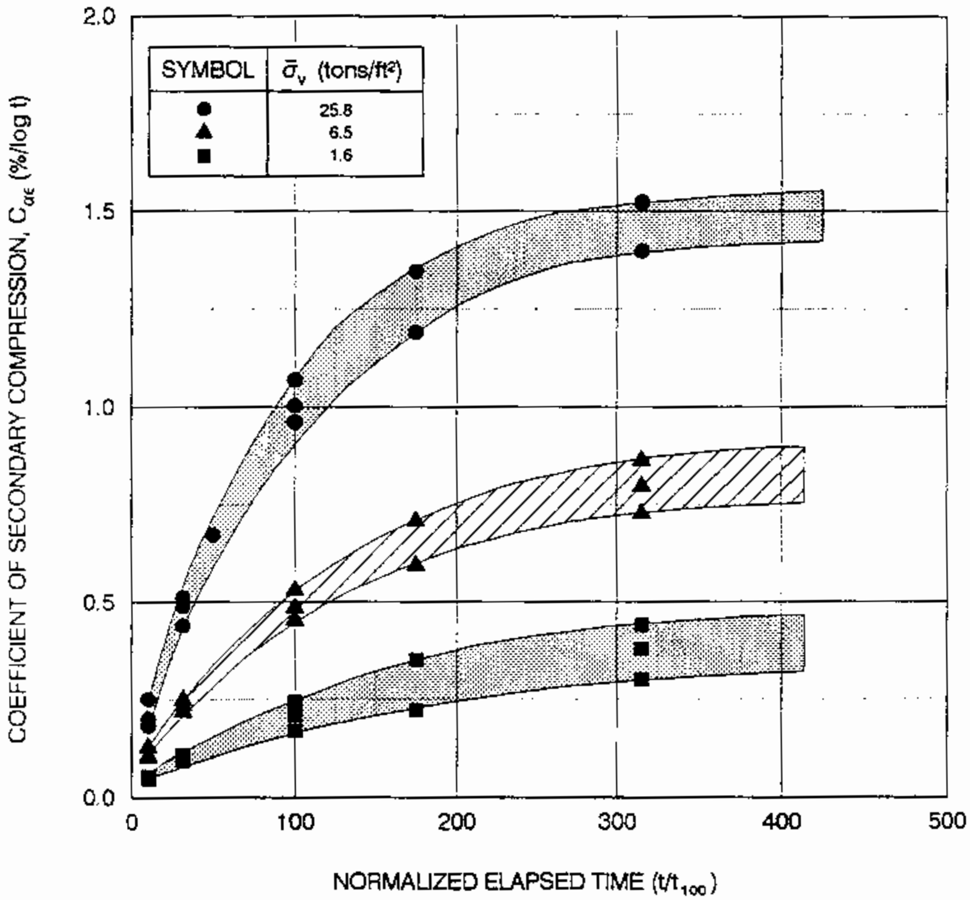


Figure 3-19. Coefficient of Secondary Compression Versus Time Consolidation Tests on Plant Yates FGD Gypsum

The shear strength properties of the Plant Yates FGD gypsum needed to perform stability analyses for evaluating the relationship between stack slope and height for design (for given seepage and foundation conditions) include the Mohr-Coulomb effective stress strength parameters for cohesion (c) and internal friction angle (ϕ) of the gypsum and the friction angle between the gypsum and underlying liner system. In the case of the wet-stacking disposal facility at Plant Yates, the liner interface involves the synthetic (HDPE) component.

Triaxial tests performed to evaluate the stress-strain-strength properties of Plant Yates FGD gypsum consisted of strain controlled, isotropically consolidated, undrained triaxial compression tests with pore pressure measurements (CIUC tests). Triaxial tests were performed on one laboratory remolded specimen and on three specimens trimmed from thin-walled tube samples.

The remolded specimen was prepared by compacting to an initial dry density of 90.0 lb/ft^3 within an 8.0-cm high, 3.57 cm diameter mold. The test specimens selected from the thin-walled tube samples were trimmed to similar dimensions. The specimens were encased in latex membranes and placed within the triaxial cell which was subsequently filled with deaired water. The specimens were backpressure saturated and then consolidated for a period of about 24 hours under isotropic effective stresses ranging from 0.5 to 1.5 kg/cm^2. Specimens were then sheared at a constant rate of 1.25 percent per hour.

The undrained stress-strain behavior, effective stress paths and Mohr-Coulomb effective stress strength parameters are presented in Figures 3-20 through 3-22. The initial and pre-shear moisture content and dry density, isotropic effective consolidation stress, σ_C, and degree of saturation, S, for each test are listed on the figures.

The undrained effective stress paths and effective stress strength envelopes (K_f envelopes) have been drawn on p versus q plots where $p=½(\sigma_1 + \sigma_3)$ and $q=½(\sigma_1 - \sigma_3)$, where σ_1 and σ_3 are the major and minor principal stresses and σ_1 and σ_3 are the major and minor principal effective stresses (Figure 22). A Mohr-Coulomb circle of stresses can be obtained for any point,

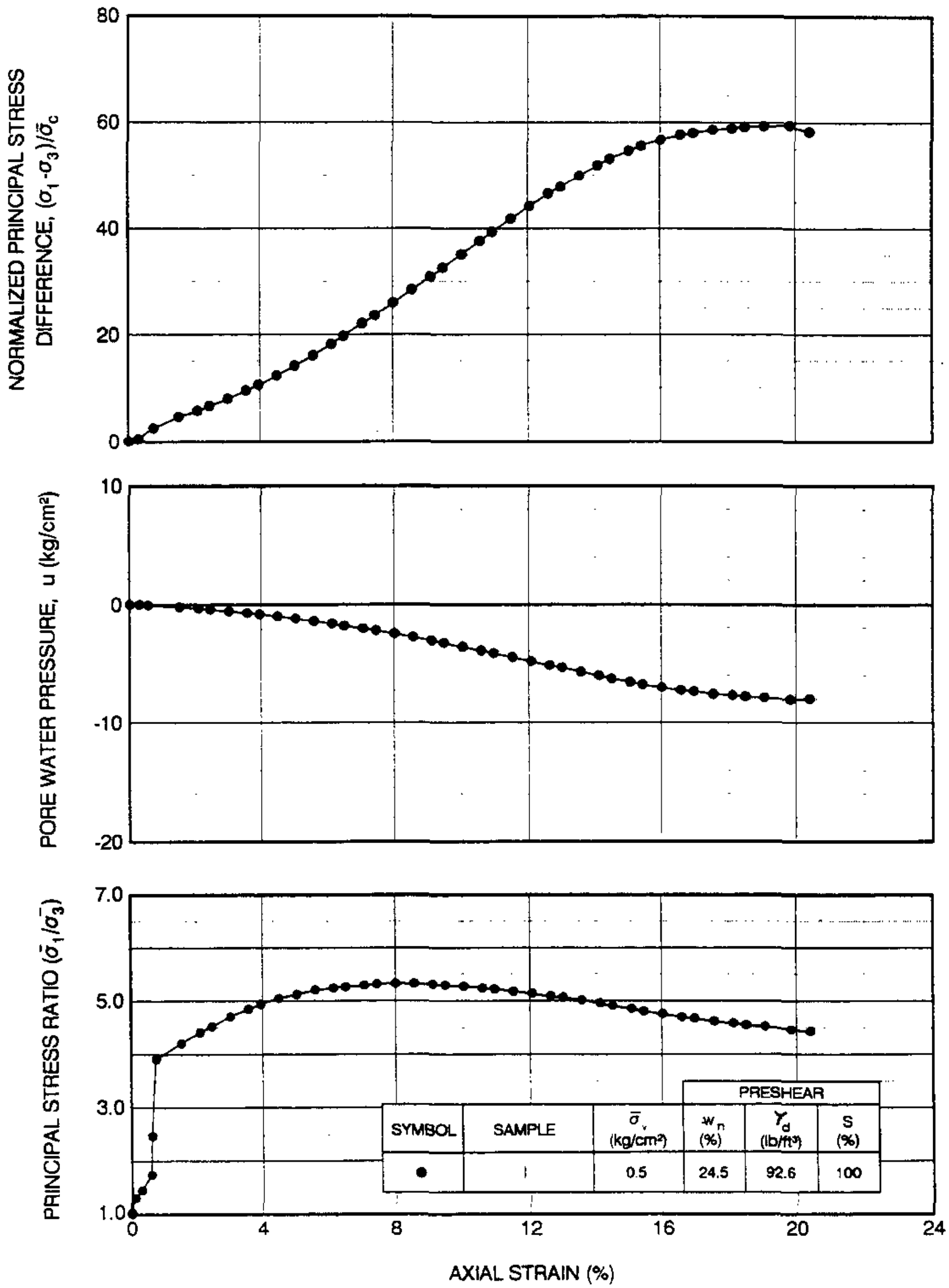


Figure 3-20. Undrained Stress-Strain Behavior from CIUC Test on Laboratory Sedimented Plant Yates FGD Gypsum

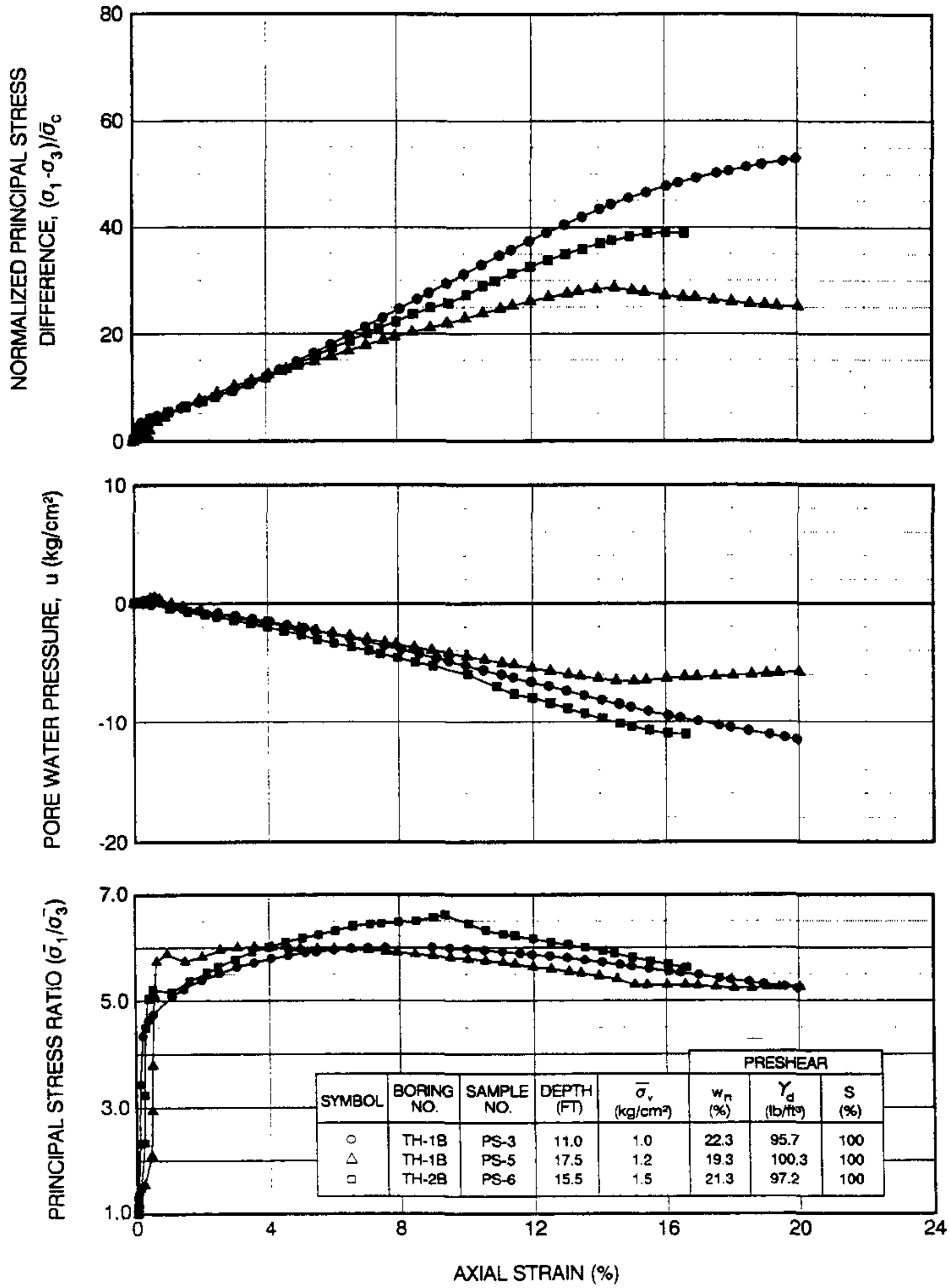


Figure 3-21. Undrained Stress-Strain Behavior from CIUC Tests on Field Samples of Plant Yates FGD Gypsum

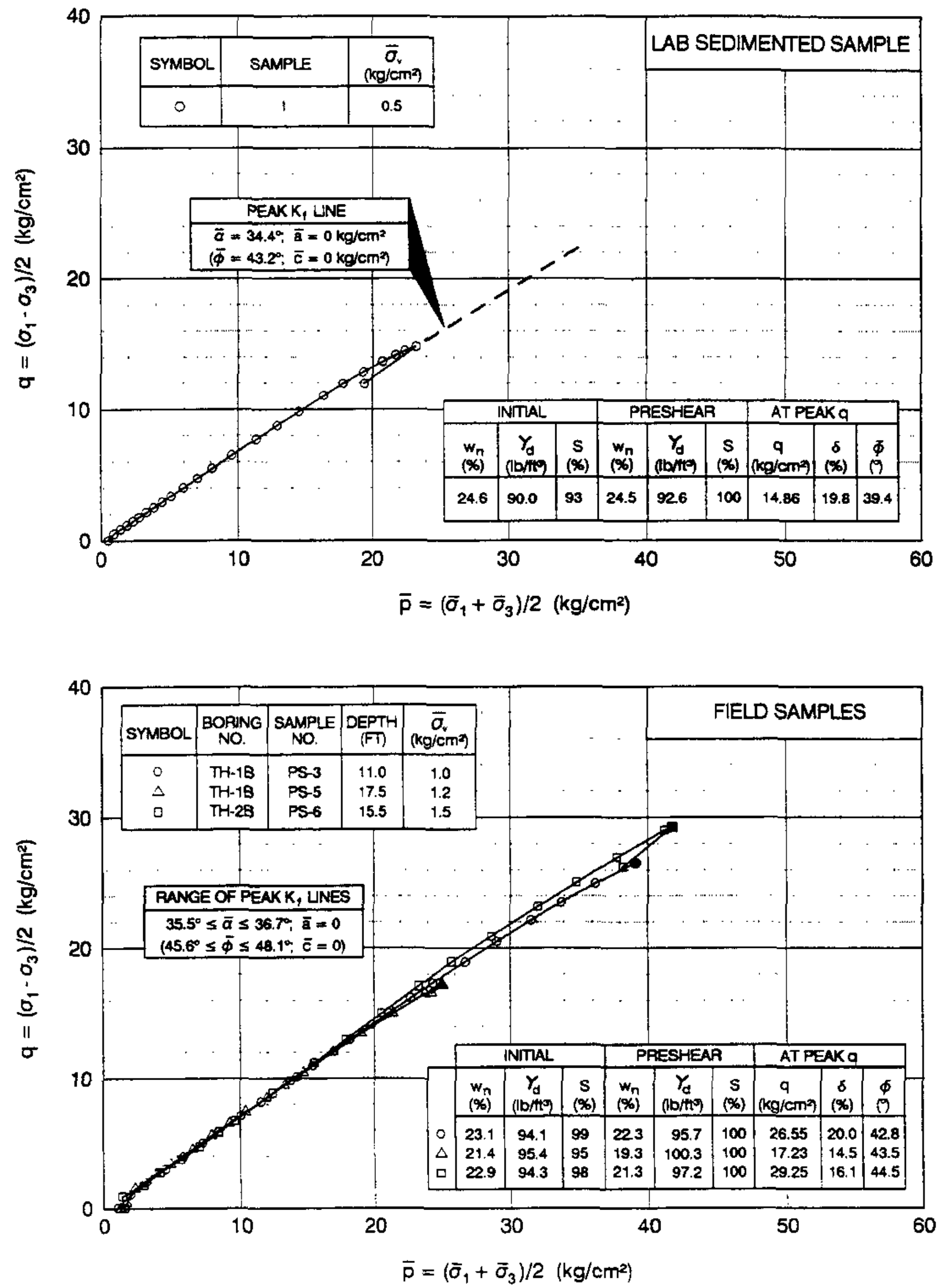


Figure 3-22. Undrained Effective Stress Paths and Mohr-Coulomb Strength Parameters from CIUC Tests on FGD Gypsum

($\bar{p}$, q), on such a plot by drawing through the point a circle whose radius is equal to the ordinate, q, and whose center lies on the $\bar{p}$-axis at a distance $\bar{p}$ from the origin. The trigonometric relations between the Mohr-Coulomb effective stress parameters, $\bar{c}$ and ϕ; and the q-intercept, $\bar{a}$, and angle $\bar{\alpha}$ of the $\bar{p}$ - q envelope are:

$$\tan \bar{\alpha} = \sin \bar{\phi} \qquad \bar{c} = \bar{a}/\cos \bar{\phi}$$

The angle and intercept of the K_f envelopes obtained on the $\bar{p}$ - q plots have been converted using the above relations and only the values of the Mohr-Coulomb effective stress strength parameters $\bar{c}$ and ϕ are given.

The following undrained stress-strain-strength behavior is exhibited by Plant Yates FGD gypsum.

- The gypsum exhibits strain-hardening stress-strain behavior in undrained shear (Figures 3-20 and 3-21) until peak shear strengths are mobilized at relatively large strains, typically in excess of 15%. The gypsum generates large negative excess pore pressures, or exhibits dilatant behavior, during undrained shear with the resultant effective stress paths running along and defining the K_f-envelope (Figure 3-23).

- The effective friction angle measured in undrained shear over the range of pre-shear dry densities of 92 to 100 lb/ft^3 can be characterized by values of about 43 to 48 with zero effective cohesion (Figure 3-22) based upon both K_f-envelopes drawn tangent to the effective stress paths and the peak mobilized shear strength (q_{max}).

The shear resistance at the interface between gypsum and the synthetic component of the composite liner (smooth and textured HDPE) is typically less than the shear strength of the gypsum itself. In order to evaluate frictional resistance at the interface between the FGD gypsum and HDPE liner, a series of six drained direct (box) shear tests were performed. Tests were performed using three samples each of the smooth and textured HDPE liner products installed during construction of the Plant Yates disposal facility. Gypsum was compacted over the synthetic liner within the test apparatus to dry densities ranging from about 87 to 93 lb/ft^3,

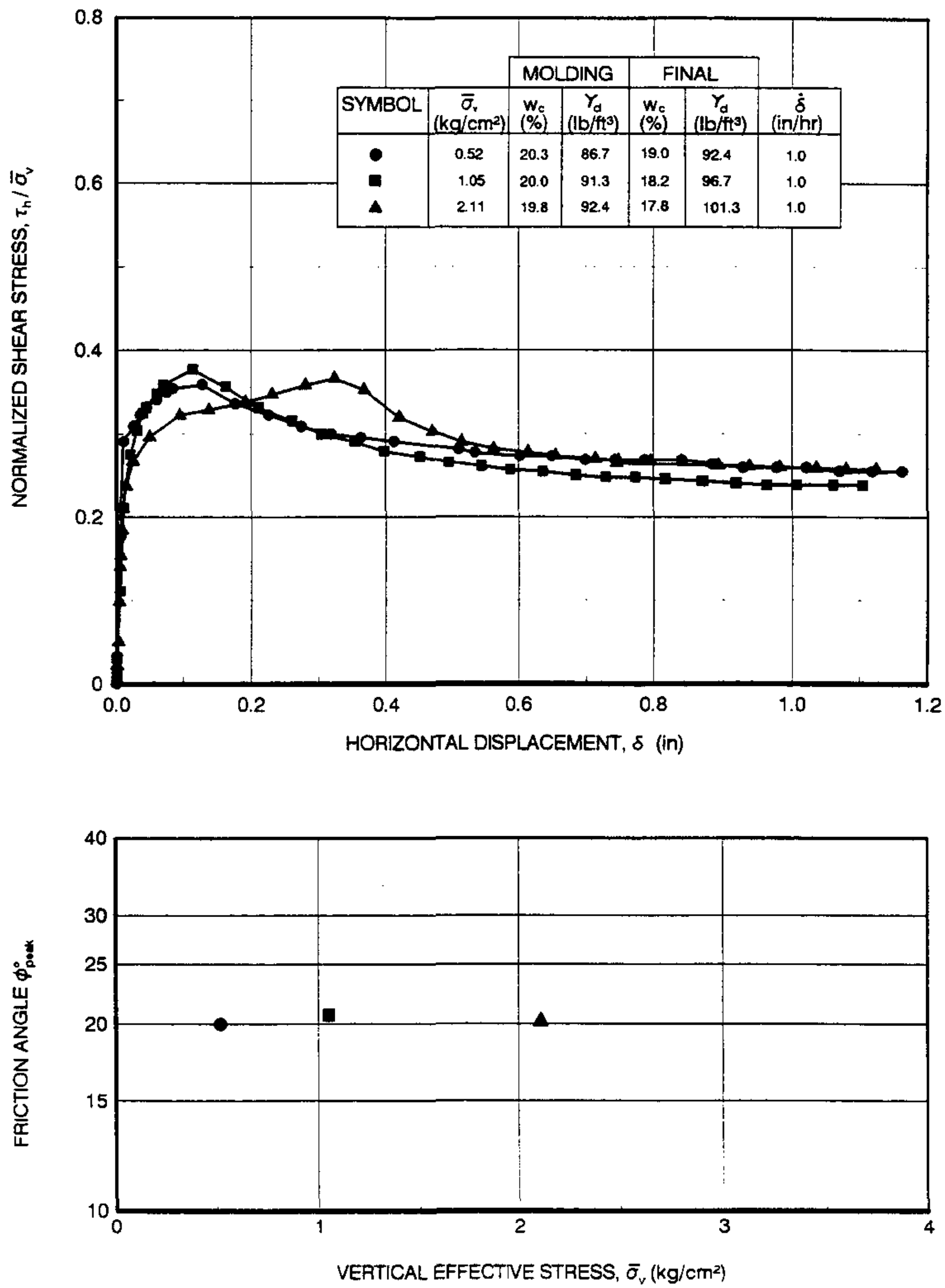


Figure 3-23. Direct Shear Test Results for Interface Between FGD Gypsum and Smooth HDPE Liner

and then consolidated to effective vertical stresses of about 0.5 to 2.0 kg/cm^2. The specimens were sheared along the interface at a constant rate of 1.0 in/hr.

Results of the direct shear tests for the smooth and textured HDPE liner interfaces are shown on Figures 3-23 and 3-24, respectively. As shown, peak interface resistance for the smooth liner interface occurs at relative small displacements and the peak friction angle is independent of the effective consolidation stress (Figure 3-23). Conversely, the peak resistance for the textured liner interface occurs at large displacements and the peak friction angle decreases with increasing effective consolidation stress (Figure 3-24).

3.2.2 Stack Operation

At this point the gypsum stack is inactive, while the ash/gypsum stack is in use. The latter facility was designed to contain ash/gypsum blends produced during the period in which the scrubber was tested for particulate collection. It is now receiving gypsum slurry from commercial operation.

Since the smaller gypsum stack has now been through its life cycle (except closeout), there are observations which can be offered in reference to design features and general operating procedures. The brief description below summarizes some of the important information derived from experiences at Yates, as well as estimated quantities of byproduct material stored in each facility. Related information is found in the recommendations of Section 4.1.

3.2.2.1 Equipment and Manpower

Operation of the Yates stacks was accomplished largely with only a single operator and two pieces of equipment -- a dragline with 0.5 and 0.75 yd^3 buckets plus a small D4 size bulldozer. The smaller relative size of the Yates stacks required that a method of stacking be used which relies on moving more of the sedimented material with the dragline as opposed to using rim ditches which allow much of the slurry to be hydraulically deposited in the ditch and the stack.

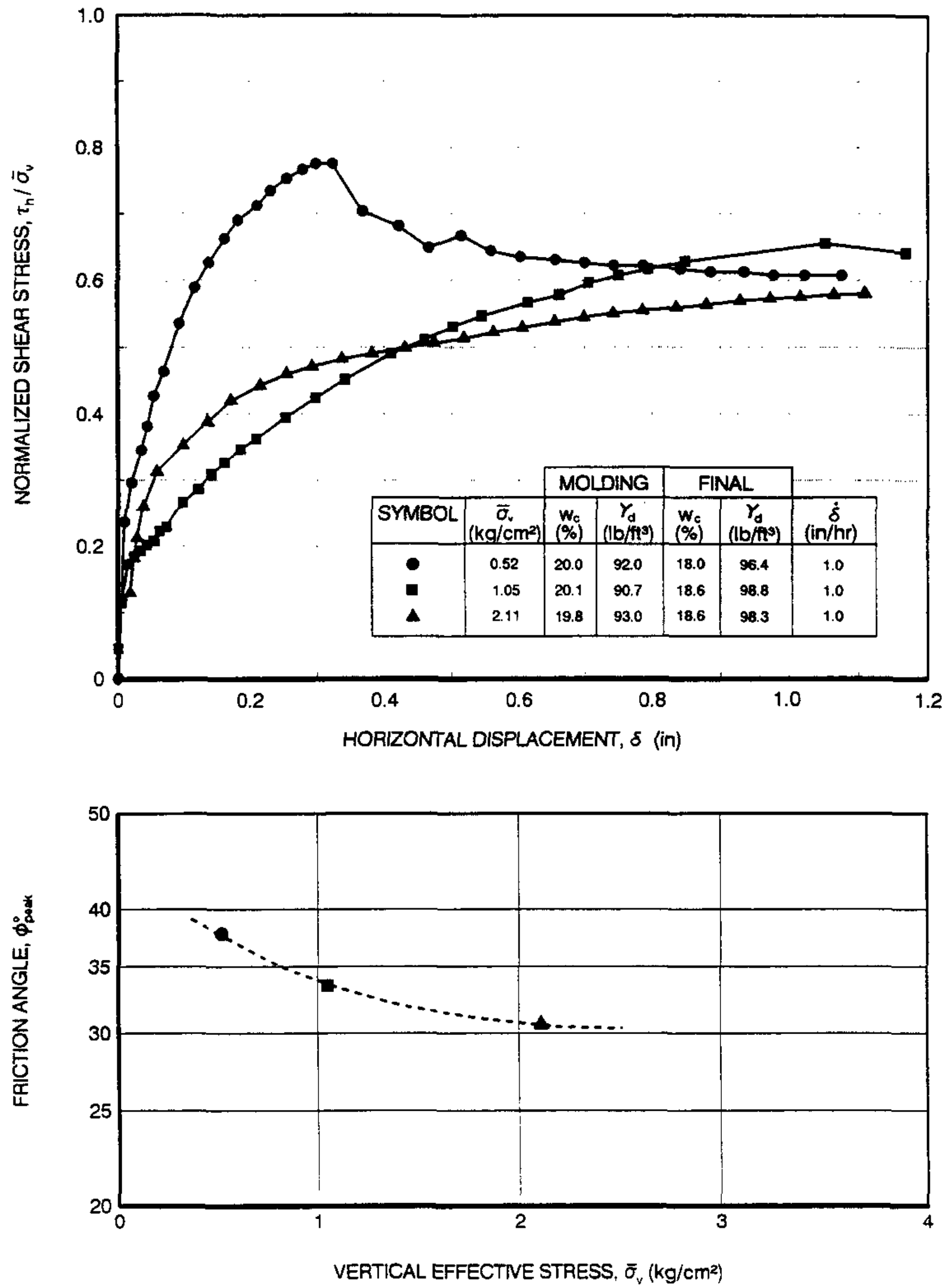


Figure 3-24. Direct Shear Test Results for Interface Between FGD Gypsum and Textured HDPE Liner

As described elsewhere, this procedure involves depositing slurry into a ditch cut into the top of the dike. Cast material is drier and only needs to be moved a short distance by the excavating equipment.

The dragline has a longer reach, necessary when operating from the soil dike. However, this equipment has a slower production rate than a hydraulic backhoe. The backhoe would be more efficient for operation from the *gypsum* dike, where the smaller top area will accommodate the backhoe's shorter reach. This is especially true for stack construction using the rim ditch method. Following excavation, the only other equipment used has been a bulldozer to spread cast material and to occasionally shape the exterior dike slopes and perimeter ditch.

3.2.2.2 Material Handling and Stacking Procedures

In general, the stackability of FGD gypsum and ash/gypsum appears to be fully acceptable. The degree of success with ash/gypsum is actually a pleasant surprise, since the large ash component (up to 50%) was expected to significantly degrade dewatering and handling characteristics of the material. For both stacks, the procedure adopted involved excavating sedimented material and casting loosely onto the existing dike to allow gravity dewatering. Then the material was spread with the dozer in loose lifts of approximately one-foot thickness. Of course, no compaction was necessary other than that provided by the dragline and dozer during other movement on the dike. Care was taken to maintain an external dike slope of 3.5 or greater to prevent seepage and possible dike instability.

3.2.2.3 Byproduct Quantities Stored

Since the time that use of the gypsum stack was discontinued in March 1994, the stack has been surveyed twice to determine the volume of gypsum contained in the dikes and interior areas. Using a representative laboratory dry density value of 75 lb/ft^3, the weight of material is calculated as 24,00 tons. The ash/gypsum stack is still in use; therefore, volumes of ash/gypsum and gypsum deposits are not reported for that facility.

3.2.3 Field Evaluation of Stacking

CT-121 FGD gypsum and gypsum-fly ash were successfully stored/disposed using slurry deposition and wet-stacking with upstream construction techniques during the demonstration period at Plant Yates. Although modifications to the original management plan were needed and implemented in response to actual byproduct material behavior, facility size and performance, much of the basic design and operational experience gained during the demonstration project will be directly applicable to a full-scale disposal facility.

The original management plan included an elevated rim ditch to be developed during the early stages of upstream construction and maintained throughout stack raising. The proposed rim ditch technique generally improves stack operation by promoting deposition of the more coarse particles around the perimeter and allowing for more rapid dewatering of the perimeter sediments since they are deposited above the water level of the central settling pond. Upstream stack raising through excavating and casting the materials from the elevated rim ditch can generally be accomplished with steeper slopes and in larger vertical increments than if the cast materials are excavated from within the central settling pond. Due to the relatively flat depositional surface slope of the Plant Yates FGD gypsum, slurry discharge location and decant management, and limited size of the demonstration facility, an elevated rim ditch was not fully developed. The absence of the rim ditch resulted in increased construction effort required to raise the stack due to the limited height that could be achieved during each lift.

The design side slopes for both the gypsum and gypsum-fly ash stacks were 2.0H to 1.0V, which is theoretically stable provided that no seepage from the interior of the stack exits on the face of the slope. The gypsum and gypsum-fly ash stack underdrains were included, in part, to prevent seepage at the outer slopes. However, these drains were apparently not fully effective (as discussed in Section 4.1.1) and the lower portion of the stack slopes accordingly raised using somewhat flatter side slopes on the order of 3H to 1V as shown in Figures 3-3 and 3-4.

3.3 Byproduct Utilization

3.3.1 Agriculture

3.3.1.1 Agronomic Response

The objective of this task was to evaluate the agronomic response of various crops to various rates of gypsum and gypsum-fly ash mixtures on a number of different soil types at three locations representative of the different agro-ecological regions in the State of Georgia. Preliminary greenhouse experiments (described in detail under 3.3.1.2, Environmental Aspects) using spinach, corn, and wheat were used to select approximate rates of application of FGD gypsum and gypsum-fly ash mixtures for field use; however, it was realized early on that detrimental effects of ash applications observed in the greenhouse were due to the limited rooting environment and lack of leaching in the small pots, conditions which do not occur in field soils. Therefore, rates were also chosen based on those commonly used in other studies described in the literature, and on investigators' judgement as to what might be economically viable based on earlier work done with other types of gypsum. Rates finally chosen were 5, 10, and 30 mt/ha; FGD gypsum was collected from the stack at Plant Yates in July 1993, as was fly ash from the first hopper row of the same unit. A 1:1 mixture of FGD gypsum and fly ash was prepared by physically mixing the two materials. Detailed characterization of these materials was completed and data are presented in Section 3.3.1.2, Environmental Aspects.

3.3.1.1.1 Field Plot Design

Field plots were established at three locations on University of Georgia Agricultural Experiment Stations lands, chosen to represent diverse soil and climatic conditions spanning the range of conditions present in the Southeastern U.S. The most northerly site was near Calhoun (Floyd Co.), GA, at the Northwest Georgia Branch Station (latitude 34° 29' N, longitude 84°58' W), on Tupelo silty clay loam soil (Aquic Hapludalf) formed on limestone and shale residuum. This site is representative of a range of mountain soils formed on sedimentary rocks stretching from northern Mississippi, Alabama, and Georgia, through Tennessee and eastern Kentucky into West Virginia and western Virginia. The climate is moderate, with mean annual temperature of 60 F and average rainfall of 139 cm (25 yr data). The second site, near Athens (Oconee Co.), GA, is representative in climate and soils of the Piedmont/Blue Ridge province, which extends from central Alabama through Georgia, west and central North and South Carolina into Virginia. The Plant Sciences Farm (latitude 33° 52' N, longitude 83°32' W) site was located on Cecil sandy loam soil (Typic Kandhapludult) formed in granite/gneiss parent materials on gently sloping topography; the climate is somewhat hotter and drier, with mean annual temperature of 62 F and average rainfall of 126 cm (31 yr. data). The most southerly site, located on the Tobacco Research Farm at the Coastal Plain Experiment Station near Tifton (Tift Co.), GA (latitude 31° 26' N, longitude 83°35' W) is representative of the Coastal Plain province, which extends from southern Mississippi, Alabama, and Georgia into eastern North and South Carolina and Virginia. The climate is nearing subtropical conditions, with a mean annual temperature of 66°F and average rainfall of 117 cm (35 yr. data). The soil here is a Pelham loamy sand (Arenic Paleaquult) formed in marine sediments in nearly flat upland depressions.

At each site, two plot areas were established to contain treatment areas for annual row crops and for perennial forage crops. The experimental design was a randomized complete block, with three blocks of plots each containing one replication of each treatment. Three rates of each of the two materials (FGD gypsum and gypsum:ash mixture) constituted the treatments; in addition, 1 or 2 control (untreated) plots were established in each block, and if space allowed, a fly ash only treatment was also installed at some locations. Row crop plots were roughly 4 m x 8 m, and forage plots were 2.5 m x 4 m. Treatments were applied by hand-spreading CCB amendments in July 1993 at all three locations. This date was later than optimum due to delays in the production and procurement of the CCB materials. Amendments were immediately tilled into the top 10 cm of soil with a rotary tiller; on row crop plots, soybean (Glycine max) was planted within 5 days on all plots. Alfalfa (Medicago sativa) was planted at all sites on the forage plots during the fall of 1993, and allowed to establish itself over the winter. At the Athens locations, an additional plot area was established to alfalfa with identical treatments on an extremely acidic Appling loamy sand (Typic Kanduldults) site at the Plant Sciences Farm to assess the performance of FGD gypsum and gypsum:ash mixtures on an unlimed, acidic soil.

Plots were cropped during the 1993, 1994, and 1995 growing seasons using normal best management practices for the selected crops; for row crops, soybean, wheat, barley, sorghum and corn were grown on the plots at various locations. Planting was done in tilled seedbeds after the initial one-time application of CCB using machine planters with appropriate fertilizer additions as determined by soil testing for P and K. Harvesting was done either by small plot mechanical combine, or by hand. For the forage plots, harvesting of alfalfa forage was done throughout the growing seasons of 1994 and 1995 using a sickle bar mowing machine 1.2 m wide; fertilizer and weed control was accomplished as needed.

Harvested biomass was dried and yield results express on a per hectare (ha) dry weight basis. Harvested tissue was digested in hot nitric acid and analyzed for selected plant nutrients and contaminant element uptake using appropriate methods (flame and graphite furnace atomic absorption spectroscopy and inductively coupled plasma spectroscopy). Typically boron (B), arsenic (As), and lead (Pb) were the contaminants chosen for in-depth study, but molybdenum (Mo) and selenium (Se) were also determined in selected tissues.

Soil was sampled from the field plots during the winter of 1994 using a tube-type sampler to a depth of 0.6-1.0 m. Samples were divided in 20 cm depth increments and composited by depth in each plot, with 8-10 individual samples per plot. Analyses run on these samples included exchangeable basic cations (Ca, Mg, K, and Na) as well as exchangeable aluminum (Al); selected contaminants were also determined as a function of depth to assess potential movement of these elements within the soil profile.

3.3.1.1.2 Field Plot Results: Forages

Results for the field plot yields for alfalfa at the four plot areas (three locations with two plot areas at Athens) are summarized for the 1994 growing season in Tables 3-2 through 3-5. No

TABLE 3-2
ALFALFA YIELDS AT ATHENS (PIEDMONT SITE), LIMED PLOTS, 1994 (COMPLETE)

Treatment	Rate	Plant Density	Alfalfa Yield					
	mt/ha	Jan. 21	Apr. 26	June 14	Aug. 2	Sept. 1	Oct. 21	Total
		plants/ft	Lbs forage / acre					
Control 1	0	30.6	4484	1416	3108	1938	652	11684
Control 2	0	28.6	4623	1378	3233	1798	678	11624
FGD	5	27.8	4324	1361	3647	1864	686	11882
FGD	10	35.9	4640	1324	3337	2136	757	12194
FGD	20	35.4	4451	1587	3608	2056	916	12718
FA + FGD	2.5 + 2.5	31.5	4228	1558	3728	2136	804	12454
FA + FGD	5 + 5	35.1	4758	1372	3965	2062	777	12934
FA + FGD	10 + 10	33.6	4427	1499	3498	2164	842	12430
LSD (5%)		NS	NS	NS	NS	NS	158	NS

TABLE 3-3
ALFALFA YIELDS AT ATHENS (PIEDMONT SITE), UNLIMED PLOTS, 1994 (COMPLETE)

Treatment	Rate	Plant Density		Alfalfa Yield				
	mt/ha	Jan. 21	July 22	May 25	July 19	Aug. 26	Oct. 11	Total
		Plants / ft^2		lbs forage / acre				
Control 1	0	13.3	1.5	87	0	0	0	87
Control 2	0	15.5	1.1	134	0	0	0	134
FGD	5	31.5	9.1	192	428	319	66	1005
FGD	10	25.8	11.1	396	1116	589	288	2367
FGD	20	34.1	15.5	939	2212	1145	750	5046
FA + FGD	2.5 + 2.5	16.3	4.5	128	197	105	36	466
FA + FGD	5 + 5	19.1	7.1	100	302	155	31	588
FA + FGD	10 + 10	18.5	9.8	252	1187	585	257	2181
CV (%)		26	34	88	39	45	76	39
LSD (5%)		8.2	3.7	359	387	241	197	851

TABLE 3-4
ALFALFA YIELDS AT TIFTON (COASTAL PLAIN SITE), 1994 (COMPLETE)

Treatment	Rate	Stand	Alfalfa Yield			
	mt/ha	Jan. 11	Apr. 21	June 30	Aug.25	Total
		plants/ft^2	lbs forage / acre			
Control 1	0	24.1	364	853	716	1,933
Control 2	0	25.4	359	862	856	2,077
FGD	5	33.9	418	945	749	2,112
FGD	10	24.9	420	1,017	1,015	2,452
FGD	20	27.0	385	1,227	1,156	2,768
FA + FGD	2.5 + 2.5	28.9	495	946	713	2,154
FA + FGD	5 + 5	30.3	501	988	925	2,414
FA + FGD	10 + 10	34.1	472	1,038	1,147	2,657
CV (%)		--	--	15	25	16
LSD (p=0.05)		NS	NS	212	333	547

TABLE 3-5
ALFALFA YIELDS AT CALHOUN (MOUNTAIN SITE), 1994 (COMPLETE)

Treatment	Rate	Stand	Alfalfa Yields					
	Mt/ha	Mar. 10	Apr. 29	June 13	July 19	Aug. 27	Oct. 21	Total
		plants/ft^2	lbs forage / acre					
Control 1	0	13.6	1998	2095	2576	1841	1318	9947
Control 2	0	16.6	2291	1859	2246	1843	1437	9557
FGD	5	19	2458	2273	2481	1989	1521	10722
FGD	10	19	2440	2527	2774	2062	1467	11270
FGD	20	20.3	2737	2891	2556	1986	1508	11678
FA + FGD	2.5 + 2.5	16.5	2419	2323	2819	1968	1842	11371
FA + FGD	5 + 5	17.4	2452	2423	2816	2002	1578	11271
FA + FGD	10 + 10	20	2886	2721	2821	2014	1594	12036
CV (%)		--	--	11	--	--	--	8
LSD (p=0.05)		NS	NS	387	NS	NS	NS	1224

appreciable yields were obtained in 1993 due to slow initial growth of the alfalfa during fall of that year. The 1994 growing season was reasonably wet and warm at all locations, and yields at the Calhoun mountain site and at Athens were generally good. The wet conditions at Tifton were apparently detrimental to the alfalfa grown there; the plot area was located in a depressional area, and excess water appeared to inhibit growth, despite the installation of tile drainage during the summer months on this soil.

Yield data from Athens did not show a significant effect of CCB additions on yield at any application rate on the limed Cecil soil plots (Table 3-2); yields were in the range of 11-12 mt/ha, which is an excellent yield for this area. Clearly there were no yield-limiting factors on this site that were ameliorated by the CCB applications, either in terms of nutrient availability or water uptake. On the unlimed Appling soil plots (Table 3-3), however, a quite spectacular yield effect was observed at all rates and for both types of CCB amendment. The control plots on this site had essentially died out by mid-summer due to extremely acidic, infertile soil conditions; FGD and mixed treatments showed increasing yield with each increased rate of addition, with the highest FGD gypsum treatment giving yield roughly half those of the limed plots. Interestingly, the gypsum:ash mix showed a clear gypsum response, yielding about one-half as much as the corresponding gypsum treatment. Thus, here it did not appear that the fly ash component in the mixture had any beneficial (or negative) impact on yield.

Yields at Tifton (Table 3-4) were much poorer, due to the excessively wet conditions on this site; only about 2 mt/ha were harvested, although there were significant yield increases with CCB additions at the highest rate applied (20 mt/ha). Plant vigor on this site overall was poor by the end of the growing season, and current estimates are not favorable that this stand will produce during the 1995 growing season.

At the mountain site at Calhoun, yields were also high during 1994; only one cutting showed a significant yield effect, and over the entire year only the highest rates of mixed gypsum ash addition was significantly higher than the control. The high rates of gypsum treatment were nearly equal in yield, but not significantly at the 5% level.

The 1995 growing season was less favorable than 1994 in having several hot, dry spells that stressed plants at the Athens and Calhoun sites; yields at Athens were, however, good, compared to somewhat poorer performance at Calhoun. The acid site at Athens was not harvested, as stand-in control plots were completely lost by the spring of 1995; the CCB-treated plots, however, maintained the alfalfa plants in reasonable condition visually, although no harvesting was performed. The Tifton site was occasionally too wet during parts of the season, and yields were overall poor; this may also have been due to grazing by deer, which has been a problem on this site . Treatment effects were apparent at both Athens and Calhoun (Tables 3-6 and 3-7), showing increased yields to both FGD and FGD+FA at the higher rates; the admixture of fly ash apparently had no detrimental effect on production, as yields were equivalent using the mixed product compared to the FGD alone. Maximum yield increases at Athens were about 10% above control, while at Calhoun increases were as much as 35%; at the Tifton site forage yield increased by almost two times with higher FGD treatments, but control plots were very low-yielding due to problems mentioned above (Table 3-8).

The overall conclusions from the two growing seasons for forage crop amendment is that yield increases due to FGD additions are clearly possible, as previous work at Georgia with

TABLE 3-6
FORAGE YIELD OF ALFAGRAZE ALFALFA AS AFFECTED BY SOIL AMENDMENTS (FGD GYPSUM AND FLY ASH) AT ATHENS IN 1995

		Pounds / acre oven dry forage						
Amendment	**Rate mt/ha**	**May 15**	**June 19**	**Aug. 18**	**Sept. 21**	**Nov. 6**	**Total**	**Two year avg.**
FGD Gypsum	20	3127	3050	2744	953	675	10549	11633 a*
	10	3054	2590	2564	885	638	9731	10962 ab
	5	3035	2874	2374	720	622	9625	10753 b
Fly ash + FGD	20	3419	2888	2687	878	700	10572	11501 a
	10	3312	2912	2324	918	687	10153	11544 a
	5	3095	2601	2457	778	626	9557	11005 ab
Control		3251	2927	2375	717	578	9848	10736 b
Control		2902	2803	2154	658	554	9071	10378 b
CV %		NS	NS	NS	NS	NS	NS	7
LSD								704

Planted: September 15, 1993.
* Means within a column followed by the same letter are not significantly different at the 5 % level.

TABLE 3-7
PLANT NUMBER AND YIELD OF ALFAGRAZE ALFALFA AS AFFECTED BY SOIL AMENDMENTS (FGD GYPSUM AND FLY ASH) AT CALHOUN IN 1995

		Shoots/ft²	Plants/ft²	Pounds / acre oven dry forage					
Amendment	Rate mt/ha	Jan. 26, 1995	Dec. 14, 1995	May 3	Jun 13	Jul 14	Aug. 15	Oct. 19	Total
FGD Gypsum	20	31.3 c*	4.7 abc	2297 a	2529 ab	1722	1482	338	8368 ab
	10	38.3 bc	3.4 bc	2098 ab	2288 bc	1760	1386	315	7847 bc
	5	31.8 bc	3.3 bc	1728 de	2224 bc	1707	1049	85	6793 cd
Fly ash + FGD	20	44.3 ab	5.8 a	2305 a	2812 a	1974	1441	714	9246 a
	10	51.6 a	4.7 abc	2195 ab	2520 ab	1889	1338	495	8437 ab
	5	44.1 ab	5.0 ab	2052 bc	2472 ab	1925	1215	296	7960 bc
Control		32.1 bc	2.9 c	1527 e	1927 c	1526	723	190	5893 d
Control		26.6 c	4.0 bc	1850 cd	2257 bc	1563	1037	40	6747 cd
CV %		27	29	8	13	NS	NS	NS	11
LSD(alpha=.05)		12.5	1.8	232	439				1242

Planted: September 17, 1993.
* Means within a column followed by the same letter are not significantly different at the 5% level.

TABLE 3-8
PLANT NUMBER AND YIELD OF ALFAGRAZE ALFALFA AS AFFECTED BY SOIL AMENDMENT (FGD GYPSUM AND FLY ASH) AT TIFTON IN 1995

		Pounds / acre oven dry forage			
Amendment	Rate mt/ha	May 3	July 11	Aug. 30	Total to date
FGD Gypsum	20	486 a*	242	385	1113 a
	10	337 ab	103	375	815 ab
	5	248 bc	85	277	610 b
Fly ash + FGD	20	484 a	248	385	1117 a
	10	404 ab	134	386	924 ab
	5	284 bc	106	275	665 b
Control		312 abc	109	265	686 b
Control		122 c	79	362	563 b
CV %		58			34
LSD		198	NS	NS	409

Planted: October 22, 1993.
* Means within a column followed by the same letter are not significantly different at the 5 % level.

phosphogypsum has suggested. Both growing seasons were relatively favorable, although 1995 was a more stressful year in terms of drought, which favors a gypsum yield response due to increased rooting depth with gypsum amendment compared to control plots. Strong yield response was shown on a very poor site at Athens in 1994, demonstrating that gypsum can to some degree substitute for lime on very acid soils. However, the Tifton site gave extremely poor yields both years due to limiting drainage conditions and other factors, indicating gypsum cannot overcome other site deficiencies in growing alfalfa. Both the moderate-pH Athens and Calhoun sites, where yields were good both years, showed a strong response to both FGD and FGD+FA; economic analyses presented in section 5.0 will indicate that the value of these increases may justify a significant cost of purchase and application of these by-products in alfalfa production.

It should be noted that visual examination of both the Athens and Calhoun sites in the spring of 1996 showed continued obvious treatment effects, with CCB-treated plots clearly out-performing control plots. This is particularly true at Calhoun, where estimates are that forage growth on high-rate FGD and mixed amendment plots is roughly double control levels.

3.3.1.1.3 Field Plot Results: Row Crops

Soybeans were planted late in 1993 at all three sites due to delays in obtaining and applying the CCB products; as a result, yields were poor overall at the three field site locations (Table 3-9). At the Oconee Co. site near Athens and the Tifton site, yields were not affected by CCB applications; yields were very poor overall at Athens, but better at the Coastal Plain Tifton site. Several weeks after emergence the plants at Athens looked very poor, with clear B toxicity symptoms of leaf necrosis (browning). The stand at Athens was also rather spotty, perhaps the result of amendment but also potentially due to nematode infestation. The remaining plants recovered, however, and grew normally after midseason. At the Mountain site at Calhoun, yields were generally poor due to late planting, but were somewhat variable with CCB treatment. The highest FGD gypsum treatment appeared to be somewhat lower in yield, and the highest mixed ash+gypsum treatment was higher in yield, than the other treatments; however, no treatment was significantly different than the untreated control as determined by analysis of variance (Table 3-9).

TABLE 3-9
SOYBEAN YIELDS AT THREE FIELD PLOT LOCATIONS, 1993 SEASON

Treatment	Oconee	Tifton	Calhoun
	Grain yield (kg/ha)		
Control	503.1 a	1302.3 a	586.25 ab
FGD: 5 t	572.1 a	2041.8 a	571.95 ab
FGD: 10 t	694.3 a	1974.7 a	671.12 ab
FGD: 20 t	523.4 a	1519.0 a	519.87 b
Ash+FGD: 5 t	678.3 a	1750.9 a	680.75 ab
Ash+FGD: 10 t	635.3 a	1799.8 a	709.60 ab
Ash+FGD: 20 t	672.7 a	1231.2 a	834.85 a
Ash only: 10 t	175.3 a	1398.3 a	560.77 b

Different letters within column indicate significant yield differences at p=0.05

Wheat (Athens and Tifton) and barley (Calhoun) yields from field plots planted following the soybean crop are given in Table 3-10. The wheat crop at Athens was a failure due to poor stand establishment as a result of wet weather and cold temperatures; therefore yields are presented only for the Tifton and Calhoun sites. Wheat yields at Tifton, on a sandy soil, were significantly affected by CCB additions: yields roughly doubled at all rates of application of both CCB materials. Fly ash applied alone, however, had minimal effect, suggesting that the FGD gypsum was the major stimulus to plant growth. At Calhoun, yields were overall much higher, and gypsum had only a modest effect on yields at this location; the mixed ash:gypsum product showed no effect on barley yield.

During the 1994 summer growing season, corn was planted at the Athens (Oconee Co.) Piedmont field site. Plants were harvested at the kernel dough stage, simulating harvest for silage; whole plants were cut 4-6" above the soil surface and weighed fresh and after drying for yield analysis. The results (Table 3-11) show that while there appears to be some trend in increased yield with CCB additions, treatment yields were not significantly different from the control plots by statistical analysis.

TABLE 3-10
WHEAT YIELDS AT TIFTON AND BARLEY YIELDS AT CALHOUN, 1993-1994 SEASON

Treatment	Rate	Wheat : Tifton	Barley: Calhoun
	mt/ha	Grain yield (kg/ha)	
Control	---	893a	2486a
Fly ash only	10	1166ab	nd
FGD Gypsum	5	1859c	2338a
	10	1915c	3462b
	20	1575bc	2901a
Fly ash-FGD mix (1:1)	5	1679c	2817a
	10	2071cd	2153a
	20	2075cd	2891a

Different letters within column indicate significant yield differences at p=0.05

TABLE 3-11
CORN YIELDS (HARVESTED AS SILAGE) AT ATHENS, 1994

Treatment	Rate	Yield	
	mt/ha	kg/ha	
Control	0	12,269	abc
FGD	5	12,769	abc
FGD	10	14,652	a
FGD	20	13,593	abc
FA + FGD	2.5 + 2.5	10,857	c
FA + FGD	5 + 5	11,151	bc
FA + FGD	10 + 10	13,416	abc
FA	10	14,299	ab

Different letters within column indicate significant yield differences at p=0.05

Soybeans for the 1994 growing season at Tifton and Calhoun yielded much better than in 1993 due to earlier planting and better growing season conditions. Yields (Table 3-12) were generally not affected by treatments, except for the fly ash only treatment at Tifton; this may have been an anomaly, since all other CCB treatment yields fell roughly within 10-15% of the control plot yields. Yields at Calhoun were high, and not consistently affected by CCB amendments.

TABLE 3-12
SOYBEAN YIELDS AT TIFTON AND CALHOUN FOR THE 1994 GROWING SEASON

Tifton		Calhoun	
Treatment	kg/ha	Treatment	kg/ha
Control	2328 bc	Control	2850 ab
FGD: 5	2319 bc	Control	3129 ab
FGD: 10	2134 c	FGD: 5	3134 ab
FGD: 20 h	1854 c	FGD: 10	2717 b
FA+FGD:5	2742 ab	FGD: 20	2621 b
FA+FGD:10	2115 c	FA+FGD:5	3132 ab
FA+FGD:20	2155 c	FA+FGD:10	3519 a
Fly ash only	2903 a	FA+FGD:20	3108 ab

Different letters within column indicate significant yield differences at p=0.05
Note: 2 control blocks planted at Calhoun; fly ash only treatment present only at Tifton
Tifton harvested 11/17/94; Calhoun harvested 11/01/94.

Wheat was planted at the Athens and Tifton sites, and barley at the Calhoun site, in fall 1994 and harvested in June 1995; the barley crop at Calhoun was lost due to near complete lodging of the crop during a heavy wind and rain storm just prior to harvest, and no data were collectable. The wheat yields (Table 3-13) were good at Athens, and were somewhat increased by CCB additions, although only one treatment (20 t/ha rate of ash+gypsum) was statistically higher than the control. At Tifton, very wet weather caused poor yields overall, and no significant effect of CCB amendment was evident.

TABLE 3-13
WHEAT YIELDS AT ATHENS (OCONEE)
AND TIFTON, 1994 SEASON

Treatment	Athens	Tifton
	Grain Yield (kg/ha)	
Control	1811.6 b	400.73 a
5 mt/ha FGD	2082.8 ab	444.71 a
10 mt/ha FGD	2353.4 ab	381.17 a
20 mt/ha FGD	2355.5 ab	463.12 a
5 mt/ha FGD:FA mix	1944.5 ab	450.06 a
10 mt/ha FGD:FA mix	1828.1 ab	399.55 a
20 mt/ha FGD:FA mix	2536.4 a	455.77 a
20 mt/ha FA only	1896.4 ab	407.69 a

Different letters within column indicate significant yield differences at p=0.05

For the 1995 summer season, grain sorghum was planted at Athens and Tifton, and corn at Calhoun. Yields are available for the grain sorghum crop, but poor pollination of the grain occurred on the corn at Calhoun, and no grain yields were obtained. The sorghum crop (Table 3-14) yielded well at both locations. Appreciable deer grazing damage caused rather high variability within the treatment plots, and no consistent statistical differences were observed in response to the treatments. Yields tended to be higher on all CCB-amended plots, particularly the higher rates, but statistical analyses did not bear out these differences.

TABLE 3-14
GRAIN SORGHUM YIELDS, 1995 FIELD PLOTS

Treatment	Rate (mt/ha)	Tifton	Athens
		Grain yield (kg/ha)	
Control	0	2229.98a	2756.48
FGD	5	2268.60ab	3232.15
FGD	10	3122.38ab	3305.33
FGD	20	2463.75ab	3415.1
FA + FGD	5	2992.28ab	2902.84
FA + FGD	10	2130.37ab	3524.87
FA + FGD	20	3496.42b	3439.49
FA	10	2610.11ab	3317.53
LSD			NS

Values within a column with the same letter are not significantly different at p=0.05

In conclusion, row crop yields were not consistently affected by CCB treatments; wheat planted the fall after application showed the strongest response at all three locations, and occasional yield responses to FGD gypsum, but not the fly ash mixed material, were obtained at all three locations. It is significant that even soybeans planted immediately after application of the CCB material did not show yield declines; initial B toxicity was alleviated by leaching and root elongation into underlying soil. The reason for the yield increases observed is not clear, and was further explored by soil analyses described below.

3.3.1.1.4 Field Plot Soil Analyses

Soils from the field plots were sampled during the winter 1994- spring 1995 in order to characterize changes in soil chemistry resulting from CCB applications. Samples were taken from replicate locations at segmented depths up to 1 meter within each plot, and analyzed for exchangeable cations (Ca, Mg, K, Na, and Al) by extraction with ammonium acetate (for basic cations) or by KCl (for Al), and analyzed by atomic absorption spectroscopy. The hypothesis under which this analysis was performed was that Ca supplied by the FGD gypsum would be reflected in higher exchangeable Ca and lower exchangeable Al, even at lower depths in the soil, given the high water-solubility of gypsum. It was also thought that high Ca input in FGD gypsum may cause displacement of Mg and/or K from the surface soil, potentially resulting in poor crop growth due to deficiency of these elements.

The complete data set for these analyses is shown in Appendix A as Tables A1-A12; the trends in these data are described below for each site, and a summary statement follows. At the Calhoun site, the soil is an acidic clayey Ultisol, initially with moderate to low fertility; the exchangeable cations were affected by the CCB treatments in the surface soil (0-20 cm depth), and somewhat deeper for Ca (Table A1-A4). The 10 and 20 mt/ha FGD gypsum treatment, and the 20 mt/ha FA+gypsum, both increased Ca significantly above the control at depths down to approximately 50 cm. This indicates that the gypsum was effective in leaching down the soil profile to about 0.5 m, and increasing Ca levels over that segment of the profile. Magnesium (Mg), on the other hand, was decreased slightly in the top 20 cm depth by CCB additions; reductions in the medium and high FGD gypsum and FA+gypsum treatments were about one-half to two-thirds of the control Mg level. No effect was found below that depth, and substantial Mg remained even in the CCB treatments. Potassium (K) was not affected by these treatments; K levels were relatively high in this soil, and it was not effectively displaced by the added Ca in the FGD gypsum treatments. Exchangeable aluminum (Al) was somewhat decreased in the top 20 cm depth layer by CCB additions at rates of > 10 mt/ha FGD; about one-half the exchangeable Al was either displaced or precipitated by the $CaSO_4$ additions. However, no effect was seen at lower depth, as has been reported in the literature for other types of by-product additions.

The Athens site has a sandy topsoil with heavy clay below to about 1 m depth; Ca levels were affected by CCB treatment (especially FGD gypsum) in the top 30 cm only (Tables A5-A8). Exchangeable Ca levels were relatively high on this site in the subsoil, and gypsum additions did not increase them above control levels at depths below 30 to 40 cm. This lesser effect here compared to the Calhoun site may be due to less water flow through the heavier textured Bt subsoil horizon at the Athens site. Mg was affected in the 0-30 cm depth in a similar fashion by the higher rates of CCB, especially FGD gypsum , where at the higher rates, loss of over half of the exchangeable Mg was observed. Depths deeper than 30 cm were unaffected, and sufficient Mg remained for adequate plant growth even in high treatments. On this soil, K was somewhat decreased in the topsoil (0-20 cm) by FGD applications; however, K remained at adequate levels (>0.1 $cmol_c/kg$). Exchangeable Al was quite low in this soil, as it had been in cultivation and limed repeatedly over the years; Al levels were quite low in the top 40 cm, and no significant effect of CCB additions on Al was observed in any deeper samples.

At the Coastal Plain site at Tifton, the very sandy Pelham soil there was strongly affected by CCB treatments, due to the rapid water flow through the soil and low initial fertility (Tables A9-A12). For Ca this effect was much more pronounced in the gypsum compared to the mixed FA+FGD treatments; with the two higher rates of gypsum , exchangeable Ca was increased down to 60 cm depth, increasing up to three times over controls. With the mixed treatment, for some unknown reason, the response was much less, with only slight increases in the top 30 cm soil depth. Fly ash only, applied here at 10 mt/ha, had no effect on soil Ca. Mg levels were similarly affected due to leaching by added Ca: in FGD treatments >10 mt/ha, Mg decreased relative to controls to depths of 50 cm, and to quite low levels (< 0.04 $cmol_c$/kg). Mixed FA+FGD also caused declines in Mg in the top 30-40 cm. K also declined on this soil with CCB amendment at the highest rate of addition, to a depth of 20-30 cm. Fly ash added alone had no effect on exchangeable K. For Al, exchangeable Al was quite low in the top 50 cm, and no effects of CCB were observed on levels of Al within the profile.

In summary, CCB amendment had a limited effect on soil properties as reflected in exchangeable cation composition within the top 1 m depth. Calcium levels increased significantly within the top 30 cm in all three soils, but deep effects appeared to be dependent on soil profile permeability: the sandier soil at Tifton had higher Ca to depths of > 0.5 m due to higher subsoil permeability. Magnesium typically decreased in the top 20 cm, and may have reached critically low levels on the sandy soil at Tifton (although yield results do not bear out a Mg deficiency). Potassium was not greatly affected by CCB treatments; fly ash K was evidently not present in a soluble form, and the effects cited above were most closely associated with gypsum application, rather than the fly ash component. Exchangeable Al was reduced in the top 20 cm of one soil, but not detectably changed in subsoil horizons.

The documented increases in soil Ca may be sufficient to explain the yield increases observed in these experiments, especially for alfalfa and at the Athens site, where the soil was relatively low in Ca initially; certainly the alfalfa results on the unlimed plots are significant in showing that Ca from FGD gypsum can result in nearly acceptable growth at pH values much lower than ever imagined to support alfalfa growth. Negative effects on Mg and K do not seem to have affected yields at any site. However, expected decreases in soil Al, which is a major limitation to good root growth in subsoils, was not observed; this may be due to the limited time of leaching (< 2 yrs), or may simply not have been resolved from the fairly high variability observed within the sampling set.

3.3.1.2 Environmental Aspects

The objective of this task was to assess the environmental impacts of land application of CCB materials, including FGD gypsum and fly ash materials, with particular reference to potential trace metal toxicity to plants and animals via food chain accumulation or leaching to groundwaters. Under this task preliminary studies of ash and FGD gypsum characterization, as well as greenhouse studies, and laboratory experiments on trace contaminant mobility were conducted during the project. In addition, field experiments established previously to study agronomic response (described in 3.3.1.1) were analyzed for plant and soil contamination under this objective.

3.3.1.2.1 Fly Ash and FGD Gypsum Characterization

Samples of fly ashes were collected from five power plants in the Georgia Power system; these were used in initial characterization, along with several FGD gypsum samples obtained from other sources not part of the Southern Company system. The FGD gypsum used in field experiments was obtained later from the Yates Chiyoda scrubber, once it came on-line. These materials were used in an effort to obtain a range in properties of CCB materials, so that some knowledge of the range to be expected might be obtained.

A combination of solvent leaching with bulk multi-elemental analyses and with surface microanalyses was used to provide the information necessary to construct a composite picture of the physico-chemical characteristics of the surface regions of fly ash particles. Physical, chemical, and mineralogical methods were employed to get as complete a picture as possible of the materials, both from the view of agronomic value and to help in predicting potential benefits. The chemistry of nutrient and contaminant elements, both total contents and their solubility, was studied in particular in order to understand how they might affect plant yield both in greenhouse and field trials.

3.3.1.2.1.1 Particle Physical Properties

Both dry and wet sieving methods were used for particle size distribution. For the wet method, the particle size distribution was determined by the micro-pipet method of Miller and Miller (1987) using sodium hexametaphosphate as dispersing agent. Based on the specific gravity of the ash particles, the settling velocity was calculated according to Stokes' Law. For the FGD gypsum, the particle size distribution was performed by dry sieving the sand sized material on graded wire sieves.

Knowledge of particle size distribution is important since many researchers (Davison et al., 1974; Klein et al., 1975; Block and Dams, 1975; Coles et al., 1979) have shown that toxic elements in fly ash increase in concentration with decreasing particle size. These elements, or their compounds, are vaporized at the high temperatures (1300 - 1600°C) encountered in the coal combustion zone, and the vapors then condense (and, possibly crystallize) on the surfaces of co-entrained fly ash particles as the temperature falls. Since the specific surface area of a spherical particle increases with decreasing particle diameter, such a process would give rise to the observed size dependence. Besides, size distribution and surface area tend to influence soil texture and sorptivity as a medium for plant growth if fly ash is land applied. Knowledge of particle size distribution is useful in terms of land application of the ash since silt-sized materials are easily removed in surface runoff. Among the fly ashes used in this study, the Yates, Bowen, and Branch ashes have "floury" consistency and the Gaston and Scherer ashes have fine-granular texture. A summary of the physical properties of the ashes is presented in Table 3-15.

Both the dry and wet sieving methods were used for particle size distribution determination (Table 3-16). Because particles of fly ash have a strong static attraction for each other, dry sieving might not give a true picture of the particle size distribution. An error incurred in wet sieving arises from the amount of cenospheres (hollow spheres) present because these spheres tend to float. Tenney and Echelberger (1970) reported that fly ash particle settling rate was faster than that predicted by Stokes' law which suggested that the particles did not settle as discrete particles but as agglomerations of the individual fly ash particles. This is more true for the finer particles (Redwine, 1982). For this reason, particle size analysis of some ash samples do not seem to

TABLE 3-15
PHYSICAL CHARACTERISTICS OF THE ASHES STUDIED

Parameter	Yates	$Yates_{Lag}$	$Yates_{Art}$	Gaston	Scherer	Bowen	Branch
PH	10.75	8.27	9.28	12.31	4.98	9.03	7.39
EC (dS/m)	2.03	0.54	0.62	4.2	0.56	1.43	1.98
SG	1.73	1.88	1.78	1.76	1.90	1.60	1.69
BD (mt/m^3)	0.91	nd	nd	0.76	0.76	0.98	0.87
SA§ (m^2/g)	1.14	3.30	3.48	3.46	2.06	0.65	1.02
< 2 µm	1.2	1.4	0.8	6.1	0.5	0	0
2-50 µm	67.8	57.2	72.8	46.6	74.4	87.0	92.1
> 50 µm	30.9	41.4	26.4	47.3	25.1	13.0	7.9
WHC¶ @ 33 kPa	29.5	16.4	33.4	37.4	27.5	33.0	41.0
WHC @ 1500 kPa	8.2	4.5	4.2	27.1	8.7	6.5	4.5
LOI† (%)	2.87	3.58	4.48	7.00	3.67	1.56	3.49
Magnetic fraction (% of ash wt)	33.53	50.17	40.15	33.75	1.58	9.63	8.78

BD = Bulk density
§ SA = Surface area
Particle size distribution by wet method
¶ WHC = Water holding capacity
† LOI = Loss on ignition

TABLE 3-16
COMPARISON OF DRY- AND WET-SIEVING METHODS OF PARTICLE SIZE ANALYSIS

Size (µm)	Yates (%)	Gaston (%)	Scherer (%)	Bowen (%)	Branch (%)
Dry-sieving method					
2000-1000	0.11	0.47	0.24	0.0	0.0
1000-500	4.97	1.57	0.09	0.0	0.14
500-250	8.53	2.45	0.80	0.65	0.22
250-106	10.65	14.02	10.43	3.83	2.09
106-53	11.26	34.65	23.55	15.81	10.56
< 53	63.68	46.69	64.67	78.99	86.70
Wet-sieving method					
2000-1000	0.03	0.45	0.02	0.0	0.0
1000-500	0.28	1.79	0.06	0.02	0.0
500-250	0.80	2.32	0.51	0.23	0.03
250-106	6.17	11.00	6.82	2.71	1.32
106-53	14.21	31.75	17.70	9.99	6.58
< 53	78.51	52.69	74.89	87.05	92.07

exhibit clay-sized particles (even in the presence of a dispersing agent) but particles of this size were observed during SEM and electron microprobe imaging. Most fly ash particles in this study lie in the silt-sized range of 2-50 mm. The wet method gives higher values for coarse sand especially in the Yates ash. Most particles in the ashes studies are in the silt-sized range of 2-50 mm.

The particle size distributions of the FGD gypsum materials are presented in Table 3-17. Particle size distribution of FGD gypsum is determined by reactor conditions such as pH in the slurry, stirring rate and rate of withdrawal from the reactor. These differences have been shown to affect the rate of gypsum dissolution in aqueous solutions and thus the efficiency as a soil amendment (Keren and Shainberg, 1981; Bolan et al., 1991). The rate of FGD gypsum dissolution is presented in Figure 3-25. FGD gypsum has a similar or greater rate of dissolution than phosphogypsum. The differences in particle size distribution and the degree of crystallinity (wetting and drying cycles during scrubbing and storage) are two factors which affect the rate of dissolution. The Jacksonville FGD gypsum , which has the highest content of particles < 53 mm, has the fastest dissolution rate. The similar dissolution rates of the gypsums with the phosphogypsum indicates these materials should be adequate in supplying electrolytes to soils during rainfall, thereby retarding crusting. There was no correlation between surface area (Table 3-5) and particle size distribution of the FGD gypsum sources tested; all were also moderate in pH, with electrical conductivities (EC) similar to that of pure gypsum (Table 3-18).

The specific gravity (SG) of the ashes was determined by the pycnometer method. The bottle was filled with water and weighed. Then the bottle was half filled with water and 5.0 g of the oven-dry ash was placed in the bottle which was placed on a boiling water-bath to expel air after which it was cooled and filled to capacity and reweighed. The difference in the weight of water was due to the weight of water displaced by the ash. The specific gravity of the fly ashes used in this study (Table 3-15) are within the range of values reported in literature (Mattigod et al., 1990). The specific gravity for Yates is high due to the presence of a high percentage of magnetic fraction (33.53%). On the other hand, although Gaston has just as high a percentage of magnetic fraction

TABLE 3-17
PARTICLE SIZE DISTRIBUTION OF GYPSUM MATERIALS BY THE DRY-SEIVING METHOD

Size (μm)	Yates FGD (%)	Illinois FGD (%)	Jacksonville FGD (%)	Springfield FGD (%)
2000-1000		26.55	1.75	0.06
1000-500		8.45	0.25	25.26
500-250		5.25	0.30	57.65
250-106		12.30	1.85	12.41
106-53		22.50	18.35	4.16
< 53		24.40	77.45	0.05

TABLE 3-18
PHYSICAL AND CHEMICAL PROPERTIES OF VARIOUS GYPSUM MATERIALS

Parameter	Florida Phosphogypsum	Illinois FGD	Jacksonville FGD	Springfield FGD	Yates FGD
$pH_{Sat\ Soln}$	6.13	7.18	7.39	8.15	7.77
EC (dS/m)	2.09	2.10	2.07	1.76	13.9
SA (m^2/g)	8.95	6.87	6.78	12.85	10.90
Total H_2O (%)	20.65	19.15	18.25	19.84	32.0

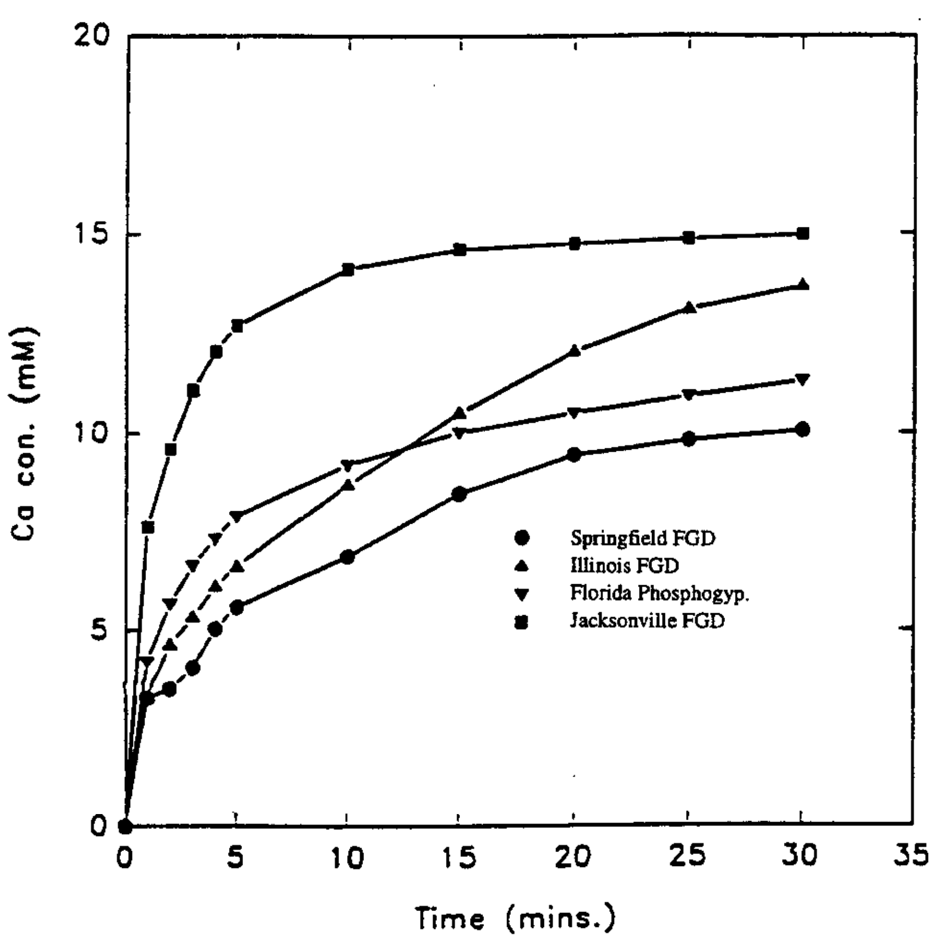


Figure 3-25. Dissolution Rates of Various Flue Gas Desulfurization Gypsum Samples and a Phosphogypsum Sample

(33.75%), its specific gravity is low due to the presence of high amounts of unburned coal. The surface area was determined by the Brunnauer-Emmett-Teller (BET) method using a Micrometrics Flow Sorb II 2300 N_2 gas absorption instrument. The surface areas of all the fly ashes are low (Table 3-15). Among the fly ashes studied, Gaston has the highest specific surface area due to large number of spongy irregular carbon-rich particles of partially unburned coal. Although the specific surface area was high, the value obtained appeared to be appreciably lower than those expected (refer to surface area of spongy material in SEM photo). It has been suggested (Mahajan, 1982) that at the temperature used in the BET technique (-196°C), micropores in coals are not completely accessible to N_2 molecules due to an activated diffusion process and/or shrinkage of pores.

The water holding capacity (WHC) was determined gravimetrically using a pressure-plate apparatus at pressures of 33 and 1500 kPa with equilibration times of 2 and 5 days, respectively. The water holding capacities of the ashes (Table 3-15) at field capacity (33 kPa) are generally higher than those of the soils of the Southeastern US. Therefore it is likely that mixing the ash with soil at fairly high rates (10%) may result in increased water holding capacity and thus productivity. The Gaston ash seems to exhibit a higher water-holding capacity at 1500 kPa probably due to the presence of large amount of spongy texture unburned carbon particulates (see ESM photos).

3.3.1.2.1.2 Mineralogy of Fly Ash and FGD Gypsum

The total amount of magnetic material was determined by placing a magnetic rod in a water slurry of the ash, stirring vigorously, rinsing the magnetic material off the rod and drying overnight at 60°C and weighing. X-ray diffraction (XRD) patterns of the magnetic and non-magnetic fractions of the ashes and FGD gypsum were obtained using a Philips APD 3520 instrument with a PW 1729 X-ray generator. Samples were scanned as random powder mounts using Cu K_a (0.15418 nm) X-radiation generated at 35 kV and 20 mA.

Scanning Electron Microscope (SEM) analyses were performed on ash samples attached to Al support stubs with electrically conducting glue. Coating of specimens was effected by sputtering using low-pressure ionized gas plasma (argon) to etch a target of Pt. The instrument used was a Philips 505 SEM. Yates and Gaston fly ashes were analyzed with the JXA-8600 Microprobe using a wavelength dispersive spectrometer. The beam current was 15 nA and the accelerating voltage was 15 kV. The magnetic and nonmagnetic fractions were embedded in an electric resin (consisting of styrene monomer and unsaturated polyester resin) and the surface polished with coarse (20 mm) and fine (5 mm) aluminum oxide paste. No depth profiling was possible with this instrument.

Since the magnetic crystals are fused to siliceous and other nonmagnetic materials, the water separation method only provides a rough estimate of the magnetic fraction. The magnetic phases are of concern since they are probably less inert in natural waters than the silicate phases, and could thus act as agents for the slow release of toxic elements into the environment. This may be particularly significant for first-row transition metals, which have been reported to be concentrated in the magnetic phases (Norton et al., 1986). It has been suggested that removal of the magnetic phases from coal fly ash before burial would significantly diminish groundwater pollution by first-row, transition-metal ions, especially Cr and Ni (Hansen et al., 1981).

The proportion of magnetic fraction in the ashes is presented in Table 3-15. Among the ashes studied, Gaston has particles with strong, well-developed magnetic properties. The amount of magnetic material in an ash is proportional to its Fe content. Lagooning or landfilling of ash increases the magnetic fraction, probably as a result of the loss of lighter fractions which tend to float or are otherwise segregated.

X-ray diffractograms for the magnetic and nonmagnetic fractions for Scherer ash are presented in Figure 3-26. All fly ashes studied had similar X-ray diffraction patterns indicating similarity of their mineralogical composition. None of the secondary minerals observed in electron micrographs after lagooning were identified by X-ray analysis probably because they occur in concentrations below the detection limit. Mineralogical analyses of the fly ash samples indicated that the ashes contained the crystalline minerals quartz (SiO_2), mullite ($Al_6Si_2O_{13}$), and various Fe oxide minerals such as magnetite (Fe_3O_4) and hematite (Fe_2O_3). Mullite is not a naturally occurring mineral in coal and therefore must have formed by decomposition of naturally occurring aluminosilicates during the combustion process. Mullite is generally accepted to result from a phase transformation of kaolinite during combustion (Rai et al., 1987). It is apparently formed by focal crystallization within spheres of molten aluminosilicates as they cool. The amount of mullite formed will depend on the rate of cooling compared to the rate of crystallization from the melt . Magnetic iron oxides were also assumed to have been formed during the combustion process since these oxides are not normally associated with coal. The presence of these oxides are believed to be a conversion product of other iron minerals, primarily pyrite, during coal combustion (Hansen et al., 1981). The magnetic fraction is composed mainly of magnetite and hematite, as shown by the strong peaks for these minerals in the X-ray diffractograms (Figure 3-26), and the nonmagnetic fraction is composed mainly of mullite.

X-ray diffractograms of the various FGD samples were similar to patterns obtained for analytical grade gypsum. This supports the conclusion of Selmeczi and Knight (1974) that Chiyoda process gypsum is essentially pure gypsum.

Morphology: Morphology can affect physical and chemical properties of the ash, which in turn relate to environmental and technological aspects of fly ash disposal and utilization. It is hoped that the characterization of the fly ash samples will improve the understanding and the ability to predict the consequences, both short and long term, of fly ash utilization. Precise characterization of fly ash is difficult because the material is composed of a heterogeneous population of microscopically small particles. Knowledge of the bulk composition alone is insufficient because the inorganic material in coal is not uniformly distributed either within a lump or within individual particles of pulverized coal. Consequently, its behavior differs from one coal particle to another and may be extremely complex even within single particles.

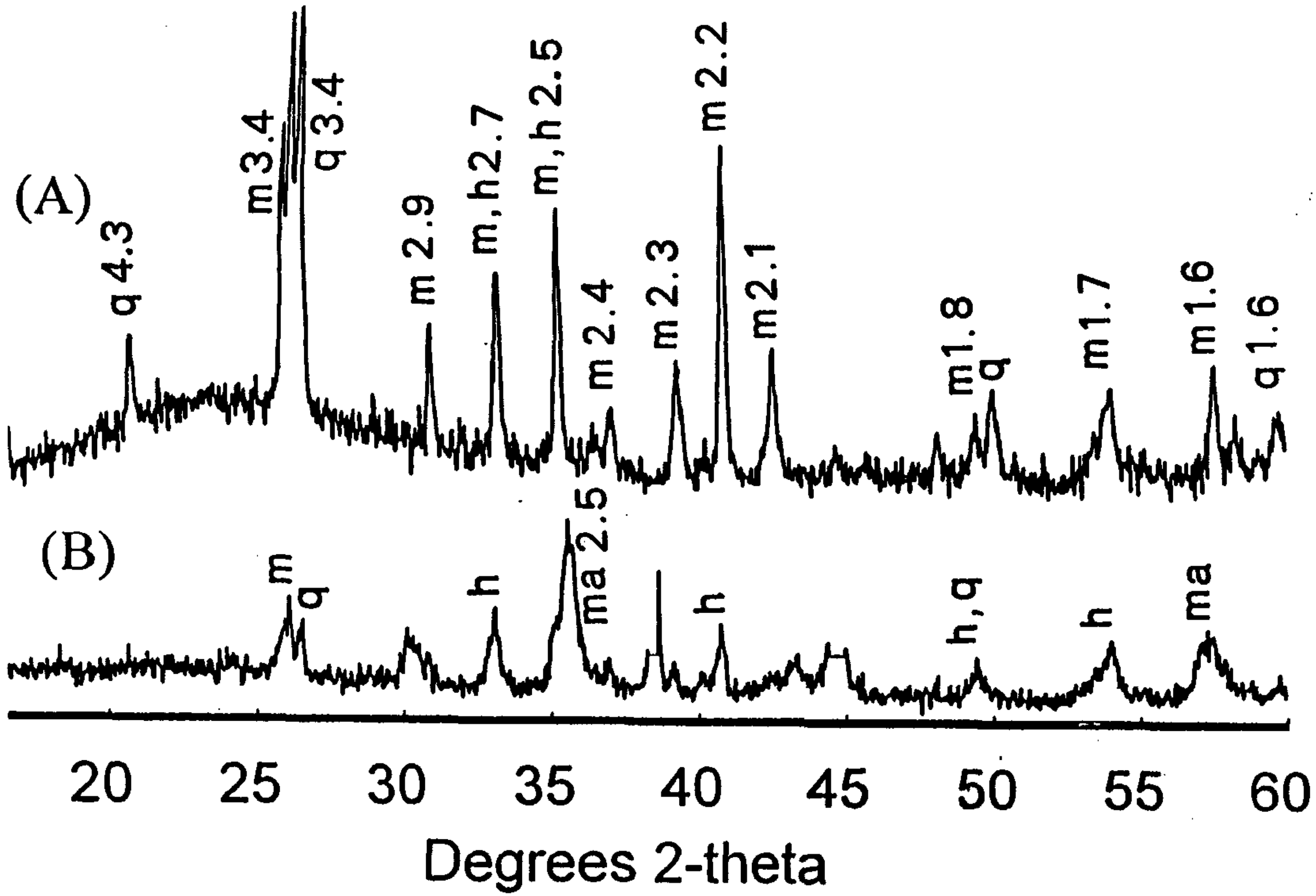


Figure 3-26. X-Ray Diffraction of Magnetic and Nonmagnetic Fractions of Scherer Fly Ash (CuK_{α}, λ=0.15418 nm; m=mullite, ma=magnetite, h=hematite, q=quartz)

Scanning electron microscopy (SEM) was used to obtain information on the morphological characteristics and to be able to accurately size fly ash particles. The sphere, which is the most common particle shape, arises because ash particles fuse from droplets within the combustion chamber (Redwine, 1982). The particles observed could be classified into the following groupings:

- Irregular spongy particles were commonly visible as cavity fillings within large fragments of unburned fusinite char where they were protected from complete fusion by the unburned fusinite cell walls (Figure 3-27a).

- Vesicular colorless glass in the form of irregular particles and cenospheres derived from viscous melts (Figure 3-27b & c). Some of these particles have broken fragments while some are thin walled (Figure 3-27d & e). It is obvious that these are plerospheres, that is, these spheres have smaller spheres within them. One possible explanation for encapsulation is that the molten droplet initially formed is partially inflated by generation of carbon dioxide produced by reaction between residual carbon and iron oxides at the high temperature (1300-1600°C) of the combustion zone. The particle surface rapidly solidifies on leaving the combustion region, the internal pressure drops below atmospheric and droplets of the molten interior surface bud off to form small spherical particles inside the host particle (Natusch et al., 1975).

- Solid glass mostly in the form of spherical particles and sometimes pigmented derived from fluid melts (Figure 3-27f).

- Unburned char particles.

- Crystalline oxide (probably) surfaces in the Yates ash from the lagoon (Figure 3-27c).

SEM is generally less satisfactory than energy dispersive X-Ray (EDAX) when accurate quantitative analyses are required. However, attempts to quantify trace inorganic elements by EDAX were not successful due to low amounts present in the field that was imaged.

Electron microprobe analysis has been used to determine the inorganic chemical composition of individual fly ash particles. Electron microprobe analyses of Yates and Gaston fly ashes revealed that even after separation into magnetic and nonmagnetic fractions, the elemental composition of

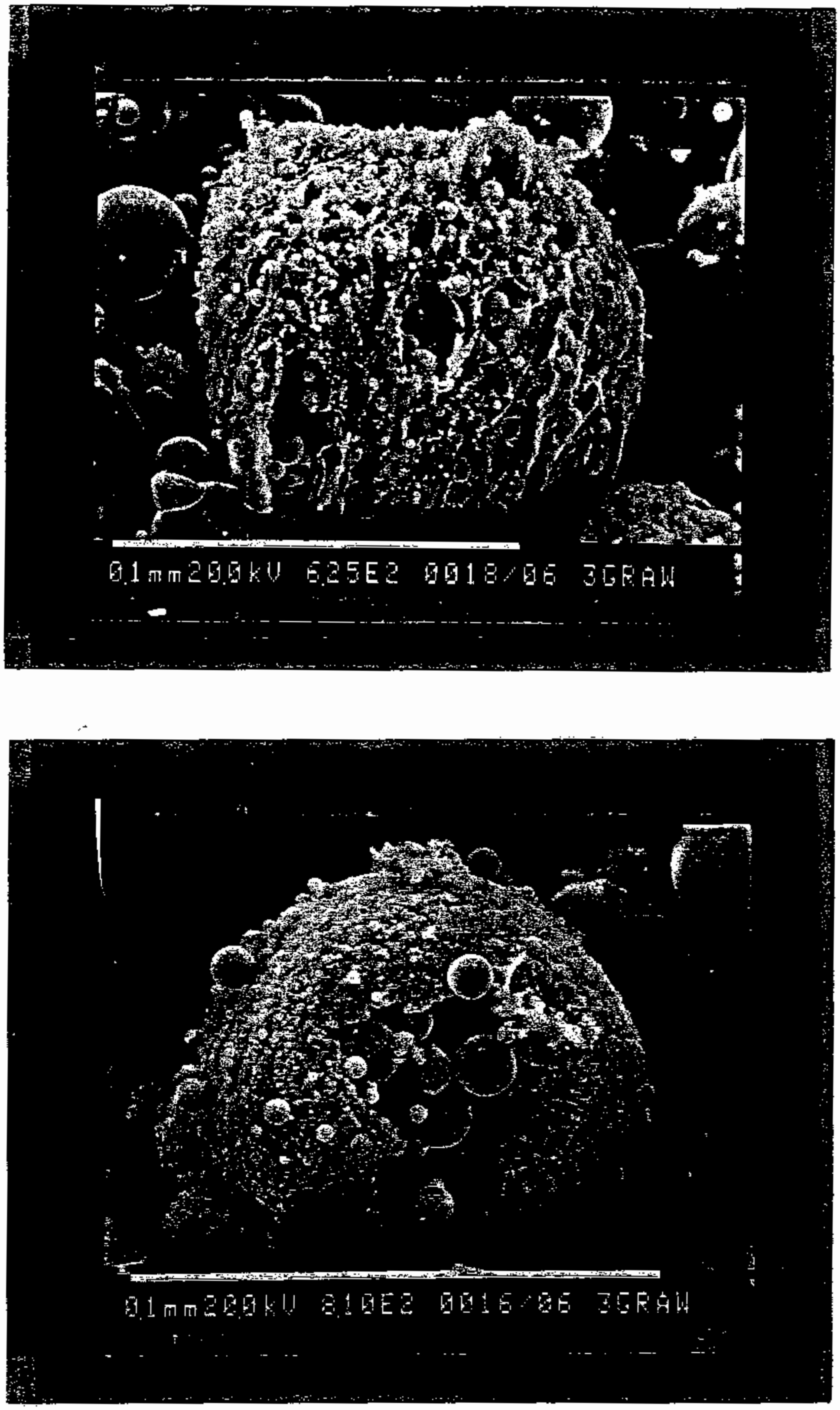


Figure 3-27 a,b. Scanning Electron Microscope Images of Ash Particles - Plant Gaston

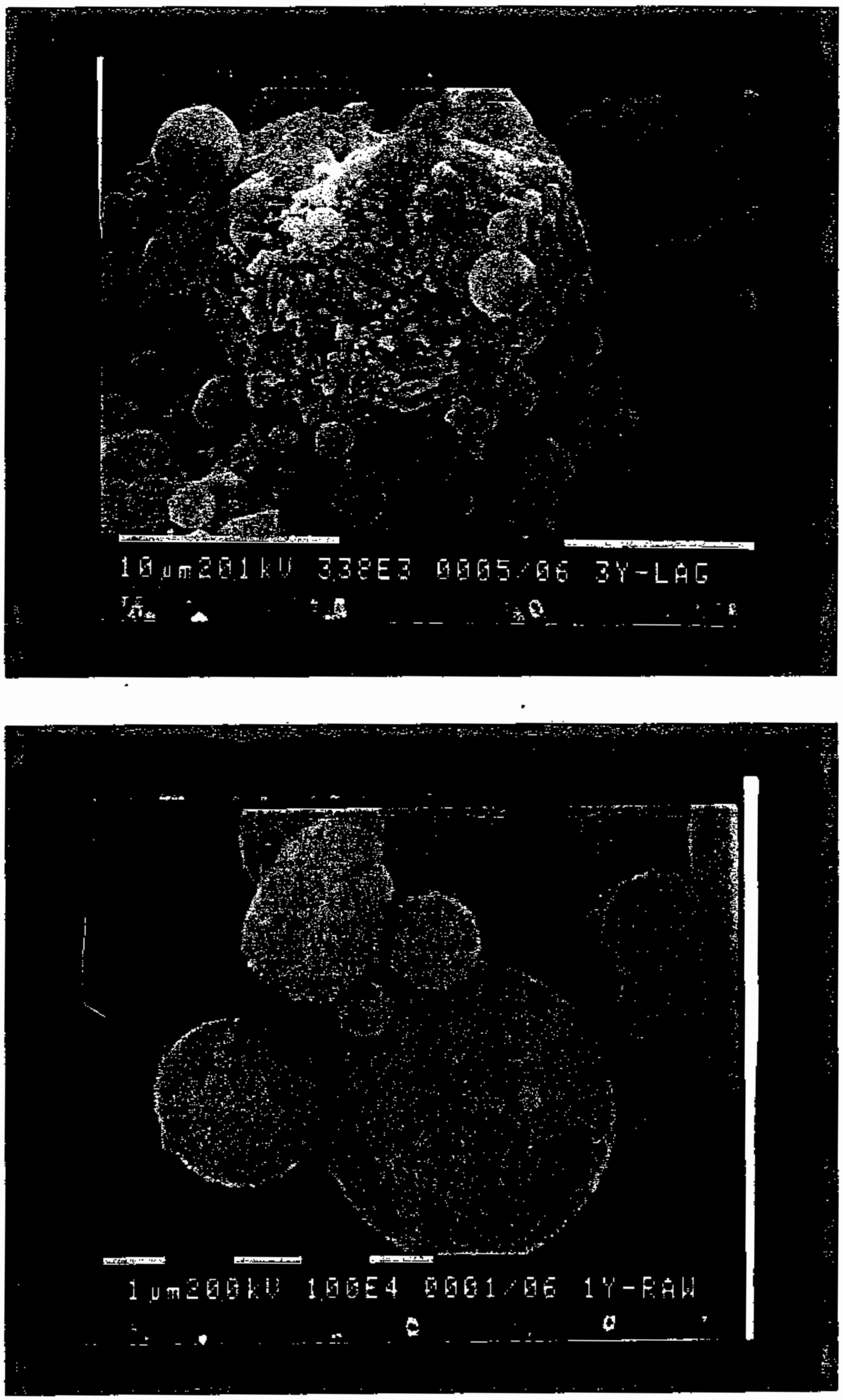


Figure 3-27 c,d. Scanning Electron Microscope Images of Ash Particles Plant Yates - (c) Pond (d) ESP Hopper

Figure 3-27 e,f. Scanning Electron Microscope Images of Ash Particles (e) Plant Yates Artificially Weathered Ash (f) Plant Scherer

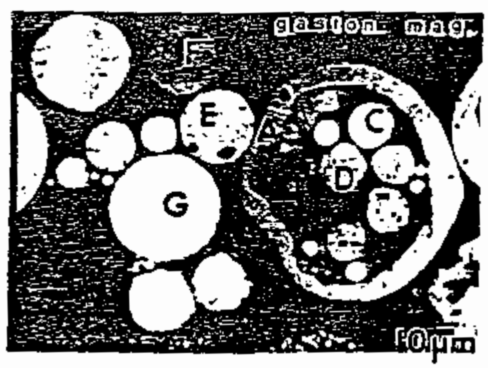
fly ash is very heterogeneous. Also, heterogeneity within a single magnetite particle of Yates ash was observed (Figure 3-28a) where the bright has a higher percentage of Fe and the darker part is richer in Si. Bright, usually spherical particles predominating in the magnetic fraction are Fe rich magnetic particles. Brightness of particles is related to their iron oxide content. The magnetic fraction of Gaston fly ash contains bright grains composed of iron oxide and sulfur, probably a mixture of magnetite and pyrite. This supports the theory of pyretic origin of magnetite in fly ash. Magnetic fractions of both Gaston and Yates fly ashes are mostly spherical in shape, but nonspherical, vesiculate or spongy particles were also present (Figure 3-28b & c). Different forms of iron oxide inclusions are shown in Figure 3-28b. In some particles, iron crystals were trapped in an aluminosilicate melt, some particles were composed of almost pure iron oxide, while others contain Fe evenly distributed in the aluminosilicate matrix. A cross section of a plerosphere (Figure 3-28b) revealed its internal structure where the shell is composed of dark aluminosilicate material with bright Fe rich spheres (particle C) trapped inside. Bright parts of particle E contain about 80% iron oxide but darker parts were enriched in aluminosilicate material and Ca. Grains of the nonmagnetic fractions of fly ashes gave a much darker image on the electron microprobe (Figure 3-28d). Particles A, B and C in Figure 3-28d were composed of mullite and particle D of glass.

3.3.1.2.1.3 Total Elemental Analysis

Total elemental analysis was performed on all ash and FGD samples. Prior to analysis samples were ashed in a muffle at gradually increasing temperature (275 for 1 h, 550 for 2 h and 750°C for 2 h). About 0.25 g (major elements) or 0.5 g (minor elements) of the ashed material was dissolved in a mixture of 5 mL aqua regia and 2 mL HF in a Parr bomb by heating in an oven at 110°C for 2 h. After cooling, the contents were transferred to a plastic volumetric flask. One g H_3BO_3 was added and the samples heated on a waterbath for 15 min. For the determination of total B, no H_3BO_3 was added. The solutions were filtered and diluted to 100 mL. The FGD gypsum samples were digested in a similar manner using only aqua regia. Major and minor elements were assayed using inductively coupled plasma (ICP) spectrometry. Boron was determined by the azomethine

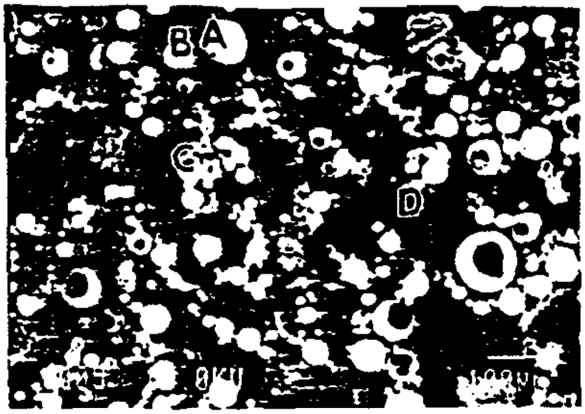
	Bright Part	Dark Part
	%	%
SiO_2	0.28	22.96
TiO_2	0.11	0.27
Al_2O_3	2.58	4.41
FeO	90.60	62.32
MgO	0.06	0.06
MnO	0.06	0.07
CaO	0.03	0.98
K_2O	0.02	0.57
Na_2O	0.00	0.11
Cr_2O_3	0.00	0.00
SO_3	0.00	0.02
Cl	0.00	0.00
P_2O_5	0.00	0.10
Total	93.74	91.86

Particle	A
%	Shell
SiO_2	53.84
TiO_2	1.15
Al_2O_3	32.71
FeO	4.91
MgO	1.51
CaO	0.17
K_2O	2.84
Na_2O	0.21

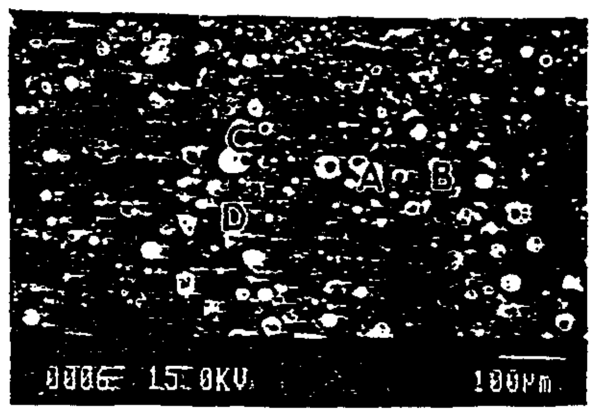


Particle	C	D	E	E	F	G
%			dark	bright		
SiO_2	38.76	49.03	50.73	0.24	53.07	1.55
TiO_2	0.85	0.87	0.84	0.35	0.30	0.06
Al_2O_3	21.72	33.86	20.39	9.74	30.68	0.76
FeO	31.17	6.58	19.12	82.75	7.42	88.92
MgO	1.15	2.66	0.54	0.50	2.63	0.06
CaO	0.79	0.39	5.22	0.10	0.09	0.12
K_2O	2.60	4.25	0.51	0.01	3.66	0.02
Na_2O	0.13	0.38	0.19	0.00	0.59	0.04

Figure 3-28 a,b. Electron Microprobe Images - (a) Magnetite Particle in Yates Ash (b) Magnetic Fraction of Gaston Ash



Particle	A	B	C	D
SiO_2 (%)	36.73	2.28	8.44	9.56
TiO_2 (%)	0.69	0.03	0.20	0.13
Al_2O_3 (%)	12.76	0.65	4.20	5.15
FeO (%)	22.04	91.21	79.51	78.97
MgO (%)	2.25	0.09	0.10	0.07
CaO (%)	22.09	0.14	0.40	0.14
K_2O (%)	1.21	0	0	0.02
Na_2O (%)	0.29	0	0	0



Particle	A	B	C	D
SiO_2 (%)	54.35	45.06	46.08	95.16
TiO_2 (%)	2.02	0.28	2.28	0.01
Al_2O_3 (%)	32.34	32.85	25.72	0.49
FeO (%)	5.60	16.64	15.64	0.06
MgO (%)	1.03	0.60	1.78	0
CaO (%)	0.82	0.44	3.77	0.02
K_2O (%)	2.56	1.86	1.37	0.03
Na_2O (%)	0.36	0.22	0.36	0.04

Figure 3-28 c,d. Electron Microprobe Images - Yates Ash
(c) Magnetic Fraction (d) Nonmagnetic Fraction

method of Bingham (1982). Arsenic (As) was determined using both a Perkin Elmer graphite furnace Atomic Absorption Spectrometer (4100ZL) with Zeeman background correction, and by hydride generation on a flame atomic absorption spectrometer. Blank corrections were included in all determinations.

To check the reliability of the analytical methods used in the total elemental analyses in fly ash, the NBS standard SRM 2689 was used as a reference (Table 3-19). Agreement with published values for all elements was good other than for Si.

Despite the large range in chemical properties, there was little variation in the Si and Al contents of the fly ashes. Iron and Ca contents were quite variable (Table 3-20), which was reflected in ash pH ranging from strongly alkaline to acidic (Table 3-15). Gaston ash had the highest total Ca and pH followed by Yates. Scherer ash had the lowest Ca and pH values. The effect of total Fe on ash pH is difficult to ascertain. Theis and Wirth (1977) found that the Ca content created the potential for alkalinity and amorphous Fe (oxalate extractable) for acidity.

The minor element concentrations in the fly ashes (Table 3-21) fall within ranges typical of bituminous coal ash (Summers et al., 1983). Boron is the element in the present group of ashes of greatest concern, particularly in the Yates material which would have a potential for phytotoxicity at high rates. However storage in a lagoon reduces the B concentration substantially ($Yates_{Lag}$) but other soluble materials such as Ca salts will also be lost reducing the acid neutralizing capacity of the ash. Branch has a relatively high As content, which is explored further in greenhouse and field trials as to potential for toxicity and leaching. Selenium (Se) and Mo have also been noted as environmental concerns; Se is quite low, and may actually be a benefit in Southeastern US soils naturally low in Se. Mo is in the moderate range, somewhat higher than soil contents. Other metals potentially of concern, such as Ni, Pb, and Cd, are all low in the fly ashes.

TABLE 3-19
COMPARISON OF ANALYTICAL VALUES OBTAINED ON AN NBS SAMPLE

Element	SRM 2689 (%)	This study† (%)
Al	12.94±0.21	13.07±0.52
Ca	2.18±0.06	2.07±0.14
Fe	9.32±0.06	8.95±0.34
K	2.20±0.03	1.53±0.06
Mg	0.61±0.05	0.45±0.01
Ba	(0.08)	0.07±0.02
Mn	(0.03)	0.02±0.001
Na	0.25±0.03	0.22±0.03
P	0.10±0.01	0.08±0.02
Si	24.06±0.08	19.67±3.06
Sr	(0.07)	0.06±0.004
Ti	0.75±0.01	0.66±0.04
Loss on ignition	(1.76)	2.14±0.07

Values in brackets are still uncertain
† Values are means of 3 replicates

TABLE 3-20
TOTAL CONCENTRATIONS OF MAJOR ELEMENTS IN FLY ASHES

Element	Yates	$Yates_{La}$	$Yates_{Art}$	Gaston	Scherer	Bowen	Branch
	%						
LOI	2.87	3.58	4.48	7.00	3.67	1.56	3.49
SiO_2	59.03	52.71	56.74	48.61	59.82	56.97	56.25
Al_2O_3	22.45	21.11	23.79	20.45	26.36	22.63	20.01
TiO_2	1.05	0.97	1.02	1.02	1.40	1.43	1.39
Fe_2O_3	11.48	21.98	11.56	15.07	3.05	8.39	8.28
CaO	3.01	2.52	3.12	4.43	0.66	1.58	1.68
MgO	0.73	0.72	0.73	0.95	0.61	0.73	1.07
K_2O	1.89	1.35	1.63	1.91	2.08	2.08	2.31
Na_2O	0.46	0.38	0.38	0.30	0.57	0.25	0.42
P_2O_5	0.34	0.38	0.36	0.43	0.14	0.43	0.67
SrO	0.05	0.06	0.05	0.07	0.01	0.05	0.06
BaO	0.12	0.09	0.06	0.18	0.05	0.08	0.11
MnO	0.02	0.04	0.02	0.03	0.01	0.02	0.03

LOI = Loss on ignition

TABLE 3-21
TOTAL CONCENTRATIONS OF MINOR ELEMENTS IN FLY ASHES

Element	Yates	$Yates_{Lag}$	$Yates_{Art}$	Gaston	Scherer	Bowen	Branch
			%				
As	34	40	40	70	18	89	283
B	586	290	320	103	76	143	131
Be	9	10	12	8	16	15	16
Bi	67	91	62	59	37	52	45
Cd	12	5	5	11	4	8	8
Co	33	42	38	42	74	56	60
Cr	135	137	147	102	164	143	141
Cu	72	109	99	137	113	154	182
Mo	36	34	56	21	12	21	23
Ni	83	93	58	77	92	85	97
Pb	120	158	124	61	83	90	121
Se	6	nd	nd	2	1	6	9
V	230	217	235	224	256	260	293
Zn	381	329	390	48	81	123	172

final analyses: July 1995

Total concentrations of major and minor elements in the Yates gypsum and several other FGD gypsum samples are presented in Table 3-22. In general the Yates sample is similar in composition to the other samples obtained, being somewhat higher in Fe and B than the others.

The B concentration is, however, lower than most of the ashes studied, as is true of As and most other metals. All elements are in the range where there is unlikely to be any adverse environmental concern when these materials are applied to land at agronomic rates (0.5-30 mt/ha). Based on total elemental analyses, fly ashes can be classified into groups based on varying criteria. The Roy and Griffin (1982) system uses seven taxonomic classes based on sialic, calcic and ferric components; in the selection of ashes evaluated here, the high sialic (Si) component of all ashes tended to place them in the modic group; their alkaline reaction and moderate calcic component placed all except Scherer in the "alkaline modic" taxonomic class (Table 3-23). Under the ASTM classification system, based on both composition and hydration/pozzolization properties, the high (Si + Al + Fe) contents of the ashes (and correspondingly lower alkaline metal contents) places them in the "F" category (Table 3-24). Such classification is common in ashes derived from eastern US bituminous coals which are lower in alkali metals and higher in S.

TABLE 3-22
TOTAL CONCENTRATION OF ELEMENTS IN FGD MATERIALS

Element	Springfield	Illinois	Jacksonville	Yates
		%		
Al	291	84	248	722
Ca	264,300	244,900	257,600	265,000
Fe	476	287	254	1759
K	170	nd†	nd	nd
Mg	421	895	158	335
Ba	2	15	1	3
Mn	14	5	3	76
Na	37	10	3	10
P	76	nd	37	69
Si	429	214	347	30
Sr	72	168	114	60
Ti	9	nd	9	44
As	0.2	0.2	nd	0.3
B	93	18	13	119
Be	0.1	0.3	0.1	0.1
Cd	0.3	0.4	0.3	<0.1
Co	0.9	nd	0.3	0.6
Cr	1.5	nd	2	10
Cu	9	6	9	12
Li	0.2	nd	nd	nd
Ni	nd	nd	nd	nd
Sb	16	nd	nd	nd
V	4	nd	3	3
Zn	14	112	13	10

† nd = not detectable

TABLE 3-23
TAXONOMIC ASH CLASSIFICATION BASED ON THE ROY AND GRIFFITH (1981) CLASSIFICATION SCHEME

Sample	Sialic component	Calcic component	Ferric component	Taxonomic Group
		%		
Yates	82.5	6.1	12.2	Alk. Modic
Yates (lagoon)	74.8	5.0	22.0	Alk. Modic
Yates (weathered)	81.5	5.9	11.6	Alk. Modic
Gaston	70.1	7.6	15.4	Alk. Modic
Scherer	87.6	3.9	3.1	Acidic Modic
Bowen	81.0	4.6	8.5	Alk. Modic
Branch	77.6	5.5	8.3	Alk. Modic

(SO_2 content included in ferric component; data from So. Co. files [Yates: 0.7%; Gaston: 0.4%; Scherer: 0.05%; Bowen: 0.15%; Branch: 0.14%])

TABLE 3-24
UTILITARIAN CLASSIFICATION SCHEME DEVELOPED BY THE AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

Sample	$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	Class
Yates	93.0	F
Yates (lagoon)	95.8	F
Yates (weathered)	92.1	F
Gaston	84.1	F
Scherer	89.2	F
Bowen	88.0	F
Branch	84.6	F

3.3.1.2.1.4 Other Chemical Properties

Acid neutralizing capacity (ANC) was determined as a measure of alkalinity or liming equivalency of the materials. One g fly ash was equilibrated with 25 mL deionized water, and the mixture was automatically titrated using a Radiometer Titrimeter (CDM 80) to pH 6.5 with 0.1 M HCl. This titration was repeated on the same sample daily for 7 d with the neutralization capacity being the sum of the H^+ consumed in the 7 titrations. Ash was also equilibrated with 25 mL water for 8 d ("aged ashes") before titration. As a check on the above procedure, a batch titration in which different volumes of 0.5 M HCl were added to 10 g ash, was conducted and the final volume made up to 25 mL with DI water. These samples were allowed to equilibrate for 48 h before the pH was measured.

The neutralization capacity is usually referred to as "titratable alkalinity" and is expressed in equivalents of hydronium ion consumed per unit weight of fly ash (Hodgson et al., 1982). The neutralization of acid by fly ash is a relatively slow process that mainly involves the particle surfaces (Hodgson et al., 1982). The most common technique for the determination of neutralization capacity has been repeated acid titration for long periods of time.

Batch titration curves for the different ashes are presented in Figure 3-29. The titrations were performed on fresh and aged (8 d incubation submerged in water) ashes. The neutralizing power of fly ash is variable but generally much lower than that of lime. Therefore, considerably larger quantities of fly ash compared to lime may be required to raise the pH of soil to the desired level. Similar results were obtained by the batch and continuous titration procedures. Theis and Wirth (1977) found that the property of fly ash that appeared to correlate best with its potential to produce alkalinity was its water-soluble Ca content, while acid-producing potential was best measured by its amorphous (oxalate-extractable) iron. The ashes used in this study have some alkalinity associated with Ca and Mg oxide content. The ANC expressed as a percentage of pure $CaCO_3$ for Yates, Gaston, and Bowen ashes are 1.9, 4.4, and 0.7 %, respectively.

The neutralization reaction for Yates and Gaston fly ashes showed two distinct buffer zones: a high pH region (pH 11.5-12) and a second region (pH 9-10). According to Green and Manahan (1978), the first buffering zone was due to the soluble alkali fraction (Ca). Magnesium oxides are essentially inert and are not expected to hydrolyze appreciably. The Ca can be present both as oxide and carbonate. The reaction of concentrated HCl with the ash indicated that the $Yates_{Lag}$ ash contained about 10% $CaCO_3$ while $Yates_{Art}$ contained less than 5% and the Yates, 0%. The fraction of the ash contributing to the second buffer zone is not known with certainty. It is possible that it could be due to the silanol group present in mullite. The "aged" ashes did not exhibit the high pH buffer zone possibly due to the removal of Ca salts. On the other hand, the $Yates_{Lag}$ and Bowen ashes did not display any buffering zones during the titration. In the $Yates_{Lag}$, most of the soluble alkali salts have been leached out due to the prolonged ponding. On the other hand, Bowen had a high concentration of alkali salts compared to Gaston and Yates ashes.

Cation and anion exchange capacities (CEC and AEC) were measured on the CCB materials in order to assess their role in adsorbing soluble anions and cations from solution. The compulsive exchange method (Gillman and Sumpter, 1986) was used to determine CEC and AEC. The ashes that were previously leached in the short term leaching study (described below, 3.3.1.2.5) were air dried and used for this purpose.

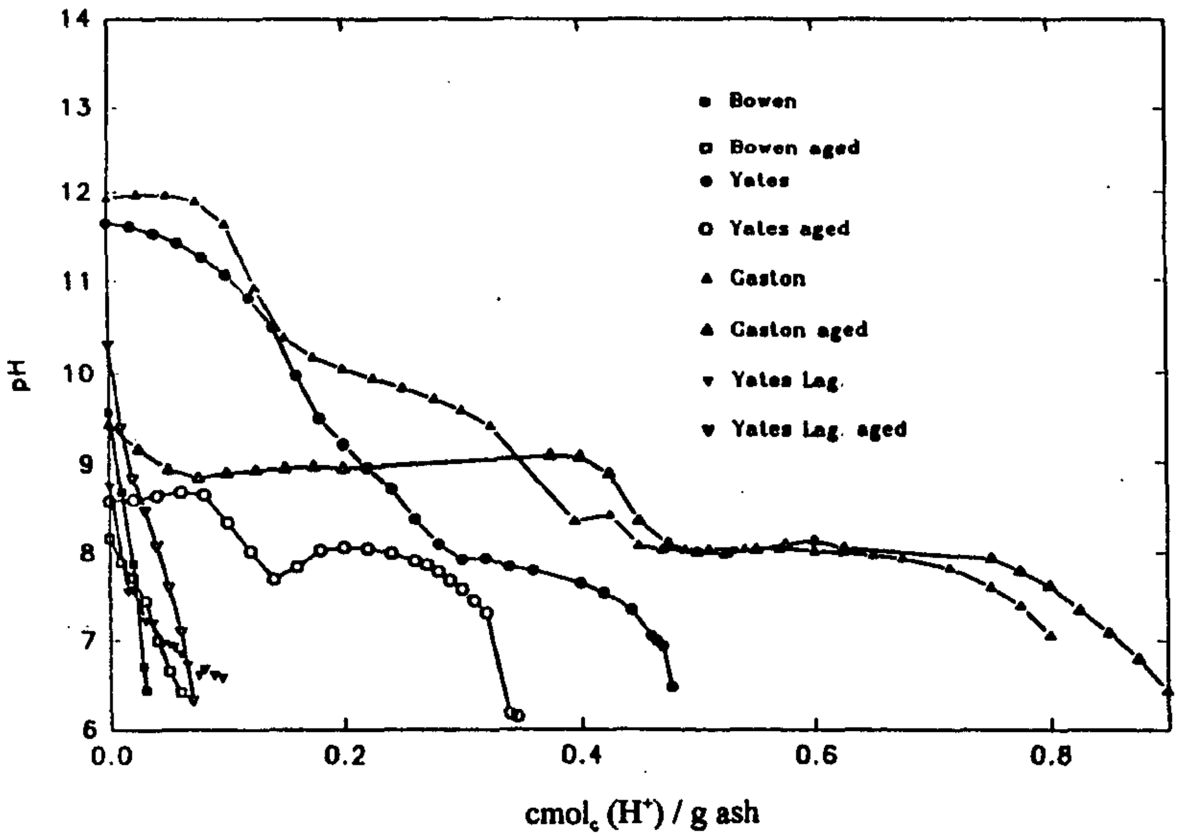


Figure 3-29. Continuous Titration Curves of Raw and Aged Ashes

Measured cation and anion retention (Table 3-25) were small on the ash materials, as expected from their largely siliceous composition. All values were <1 $cmol_c/kg$, which is low compared to soils having charged clay minerals. Gaston and Yates ashes had the highest values, probably due to their higher contents of Fe oxide and organic carbon (LOI, loss on ignition), which may have contributed both negative and positive charges. These determinations do point out that ashes have charge, however small compared to soils, and therefore may retain both native metals and anions present in the ash, and may adsorb or desorb these constituents in equilibrium with an aqueous phase.

TABLE 3-25
PH, CEC AND AEC OF VARIOUS FLY ASH MATERIALS

Material	pH_{Water}	$pH_{0.002MBaC12}$	CEC ($cmol_c/kg$)	AEC ($cmol_c/kg$)
Yates	10.75	10.85	0.99	0.20
Gaston	12.31	10.63	0.97	0.36
Bowen	9.03	9.24	0.58	0.16
Branch	7.39	8.73	0.59	0.12
Scherer	4.98	6.75	0.23	0.37

3.3.1.2.1.5 Leachability Studies

Batch elemental solubility studies were performed in order to assess the solubility in water and other solvents of major elements (nutrients and contaminants) in the ashes and FGD . Varying ash:water mixtures were shaken for 16 h and filtered through 0.45 mm filters and B determined. For the FGD , 3 g of material in 1 L deionized water was minimally stirred. Five mL aliquots of the slurry were collected and filtered through 0.45 mm filters at the appropriate time. This process was repeated for 30 min. The resultant EC and Ca concentration of the slurry were analyzed over the sampling period.

The behavior of the various elements during leaching or solubility studies is largely controlled by pH. Theis and Wirth (1977) and EPRI (1979) stated that the pH of the ash system (leachate or solution system) may be controlled by the proportion of free lime to Fe present in the ash. The solubility characteristics of the various chemical species associated with fly ash are dependent on factors specific to the extraction procedure such as the nature, time and number of the extractions, the ash to solution ratio and pH (Elseewi et al., 1980a; Elseewi and Page, 1984; Harris and Silberman, 1983). Thus it may be more useful to consider relative solubility from different ash samples rather than actual amounts that are soluble.

Various techniques were used to evaluate micro-element solubility in the ashes and FGD gypsum in order to predict mobility and plant availability of these elements in the environment. Solubility in water was initially examined, but many of the elements of environmental interest were below the limit of detection of the available instrumentation. For As, water solubility for the ashes and gypsum samples studied is shown in Table 3-26, using a 10:1 dilution of water:solid. For the ashes, the concentrations in solution were in all cases very low, irrespective of total As content; for the two FGD gypsum samples, As solubility was much higher, but the total As was very low compared to the ashes. When equilibrated with increasing concentrations of HCl, the lower pH caused more As to become soluble (Table 3-26); however, 1 M acid (pH<0) was required to solublize more than 50% of the As from the ashes. As in the Springfield gypsum was clearly more soluble than that in the Illinois gypsum , although the reason for this behavior is not known.

TABLE 3-26
ARSENIC SOLUBILITY IN WATER AND ACID EXTRACTS FOR CCB MATERIALS

			Extractable, M of HCl		
CCB	**Total As**	**Soluble As**	**0.05**	**0.1**	**1.0**
	mg/kg		**% of total As**		
Yates ash	46	0.04	0.1	0.3	58
Branch ash	180	0.10	10.0	8.3	66
Bowen ash	123	0.04	5.9	8.3	77
Gaston ash	112	<0.01	0.01	1.2	68
Scherer ash	30	0.10	11.0	34.0	60
Springfield FGD	0.2	14.0	53.0	71.0	99
Illinois FGD	0.4	0.50	2.2	6.2	12

Solubility of B in water was evaluated at different water:ash ratios, to examine the dilution effect on B release into solution (Table 3-27). The values in the table express soluble B on both solution (mg/mL) or solid-phase (mg/g) bases; as the ratio increases, more water is being added, providing a greater sink for soluble B. At the highest ratio (20:1), a large percentage of the total B (see Table 3-21) is soluble in the Yates ash, while for Bowen and Branch, roughly ½ is soluble at the highest dilution. For Gaston, only a very small percentage becomes soluble at any dilution. Overall the conclusion appears that for higher total contents of B, a greater percentage of the total is readily soluble in water, and this solubility is a high percentage (50-90%) of the total B content. While B is not toxic to animals and relatively benign environmentally, its significant toxicity to plants will be exacerbated at high rates of Yates ash addition to soils, as demonstrated in the greenhouse and field studies.

TABLE 3-27
COLD WATER SOLUBLE B AT DIFFERENT WATER:SOLID RATIOS

Material	0.5:1		2:1		20:1	
	Solution (mg/L)	Ash (mg/kg)	Solution (mg/L)	Ash (mg/kg)	Solution (mg/L)	Ash (mg/kg)
Yates	186	61	77	155	24	480
Gaston	1.0	0.6	0.2	0.4	0.2	5
Scherer	30	19	12	25	1.2	25
Bowen	32	11	20	40	3.3	68
Branch	50	18	24	48	3.0	60
Illinois FGD	18	5	3	7	0.4	8

Solubilities of Pb and Mo, other environmentally interesting elements, were examined as a function of pH. Lead solubility as a function of pH (Figure 3-30) showed a similar trend for the fly ashes and FGD materials tested, but was overall much less soluble than B; only at pH < 3 were appreciable amounts of Pb released to the solution. In the soil environment at pH 5-6, very little Pb solubility would be expected. For Mo, testing of the ash samples showed that Mo is soluble at both high and low pH, with a minimum in the range pH 3-5; this could be due to precipitation reactions of Mo with other soil constituents in this pH range (Figure 3-31). Mo solubility was quite high at pH >6 and < 2; in field soils, high pH should be avoided, since Mo and other oxyanions (As, Se) are more soluble at these pHs and may become environmental hazards.

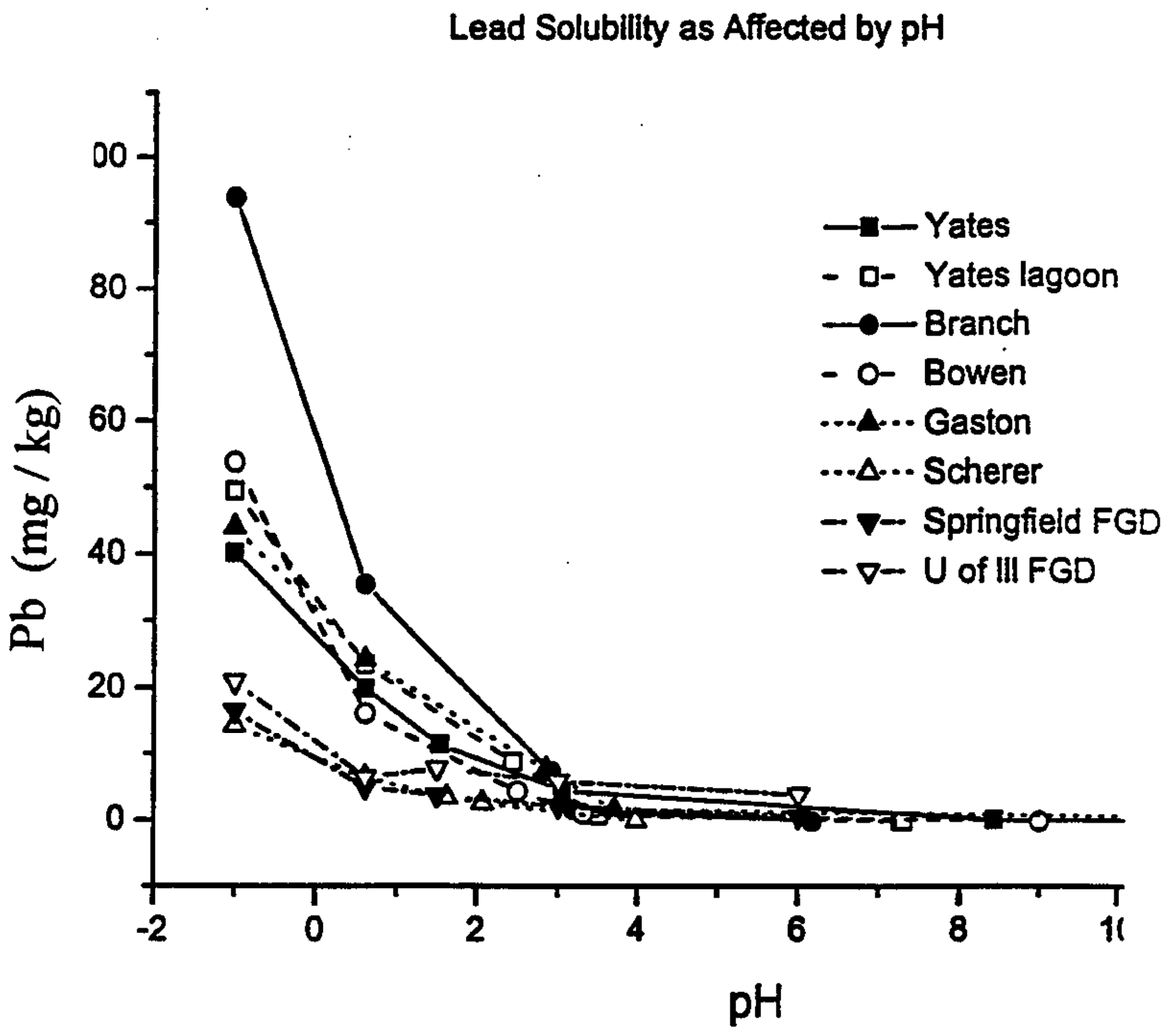


Figure 3-30. Effect of pH on Pb Solubility

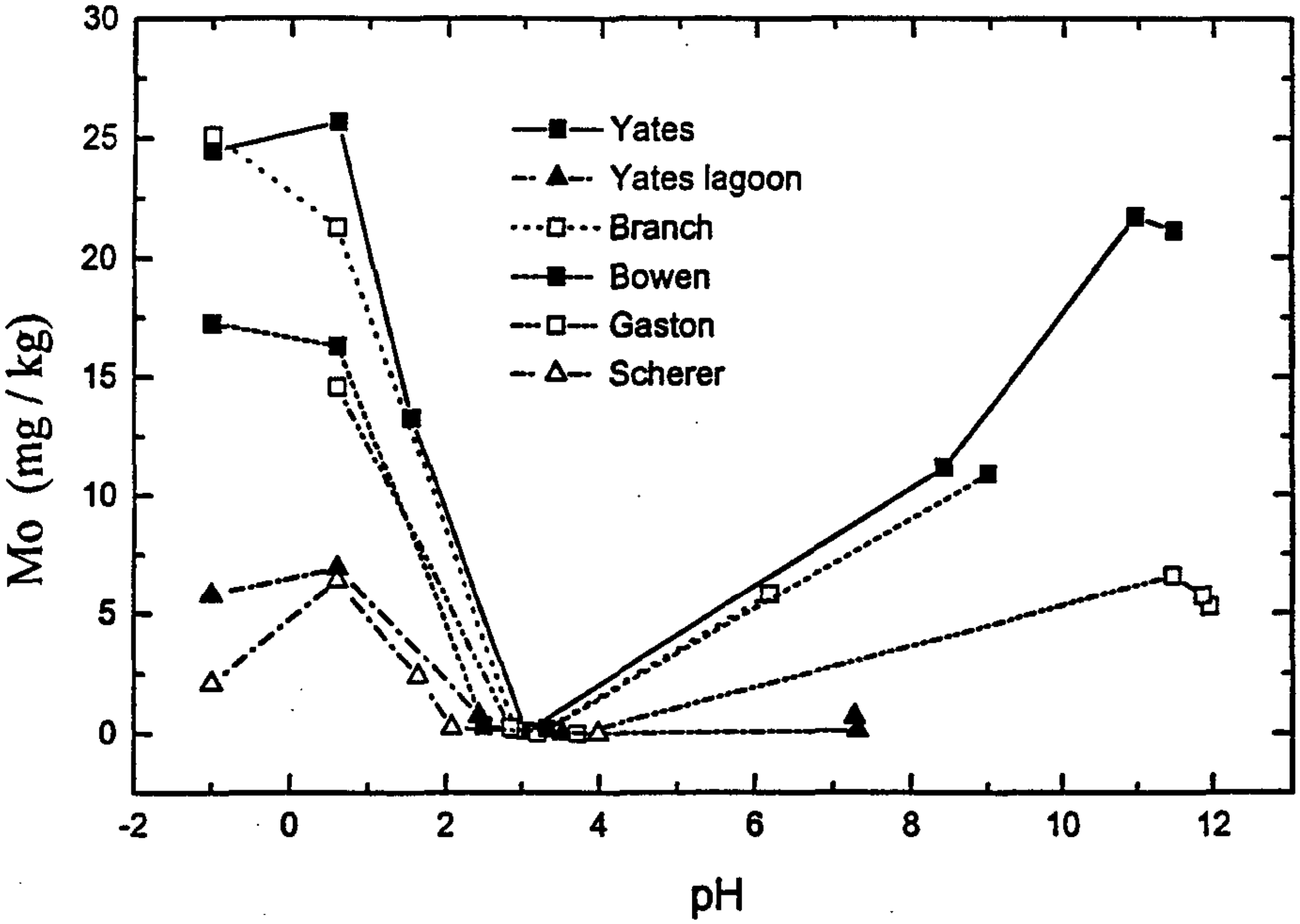


Figure 3-31. Effect of pH on Mo Solubility

Short-term leaching studies were performed on the CCB materials to determine leaching behavior of major contaminant elements. A 100 g sample of each ash was placed on a filter paper in a Buchner funnel and 3 L of DI water were passed through the sample and 250 mL sample fractions collected. Minimal suction was applied to speed up the process. EC was measured on a Radiometer CDM 80 conductivity bridge and elemental analyses of the percolate were performed by ICP. B was determined by the azomethine method (Bingham, 1982).

Analyses of leachate from the funnels for the five fly ashes tested showed that the major cations Ca, Mg, Na, and K rapidly solubilized within the first 1.0 L of percolate; Ca, being at much higher concentrations, required somewhat longer to leach from the ash (Figure 3-32). Gaston and Yates had the highest Ca levels, while Branch had the higher K and Mg levels. For K and Mg, only about 5% of the total content of these elements (Figure 3-32) was removed by the leaching procedure used, indicating that the plant-availability of these elements may be limited.

Trace element leaching for the ashes was similar to the macro-elements for Mo and B; both were rapidly leached within 1 liter (Figure 3-33). For B, quite high initial soluble levels were measured, as suggested by other solubility studies. For As and Se, a delayed leaching behavior was observed, with maxima being observed for several ashes around 1.0-1.5 L. For Se, Scherer and Branch ashes gave values in the range of 0.1-0.5 mg/kg; for As, Bowen and Branch were significantly higher than the other ashes, in the range of 1-2 mg/kg (Figure 3-33). Bowen and Branch were higher in total As than the other ashes (Table 3-21), although for Se, Scherer was not a particularly high Se ash. Again it appears that high total contents correlate with higher solubility, although only in the case of Bowen with its high As levels does there appear to be a concern environmentally.

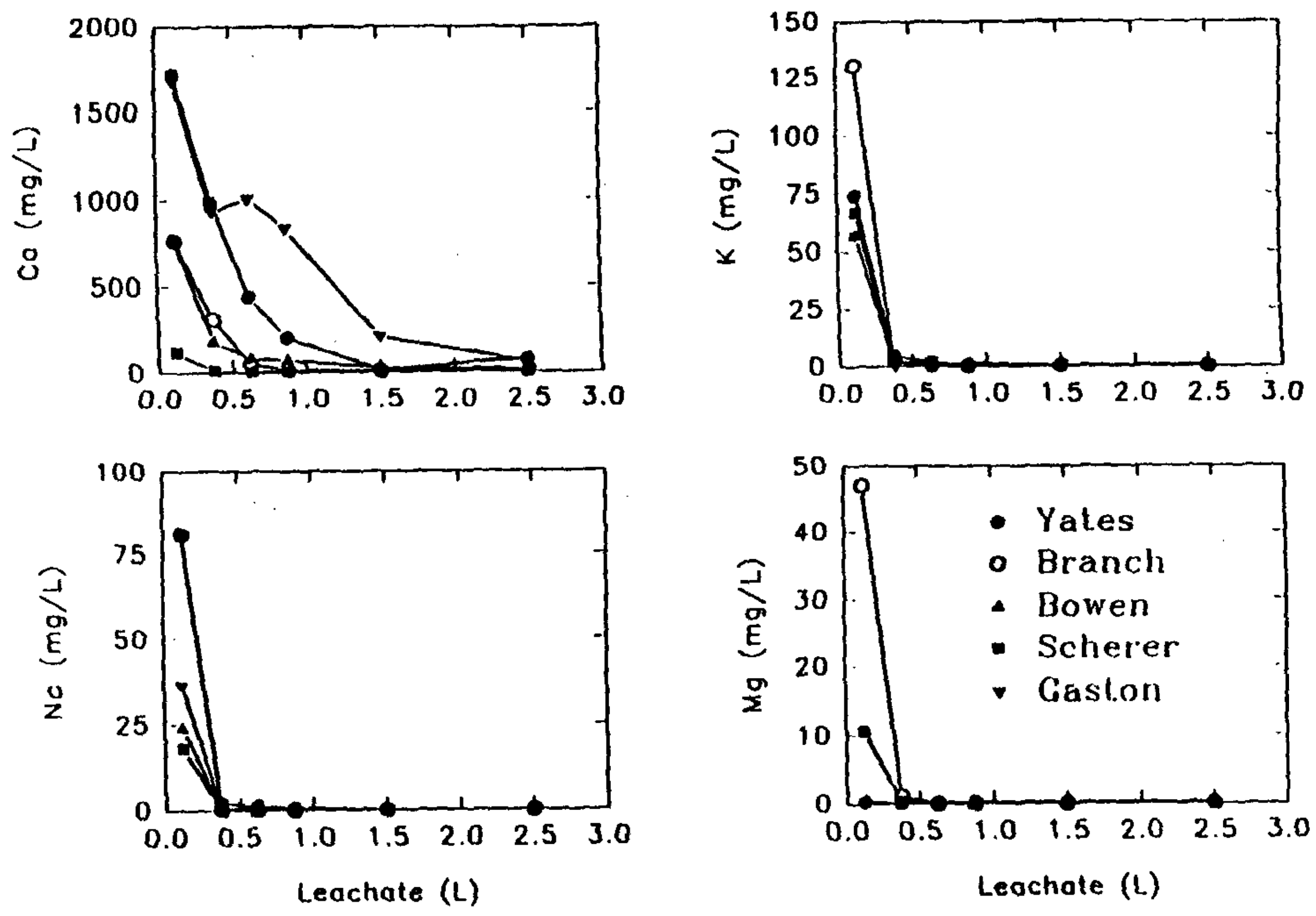


Figure 3-32. Short-Term Leachability (3L) of Macro Elements Present in the Different Ash Samples

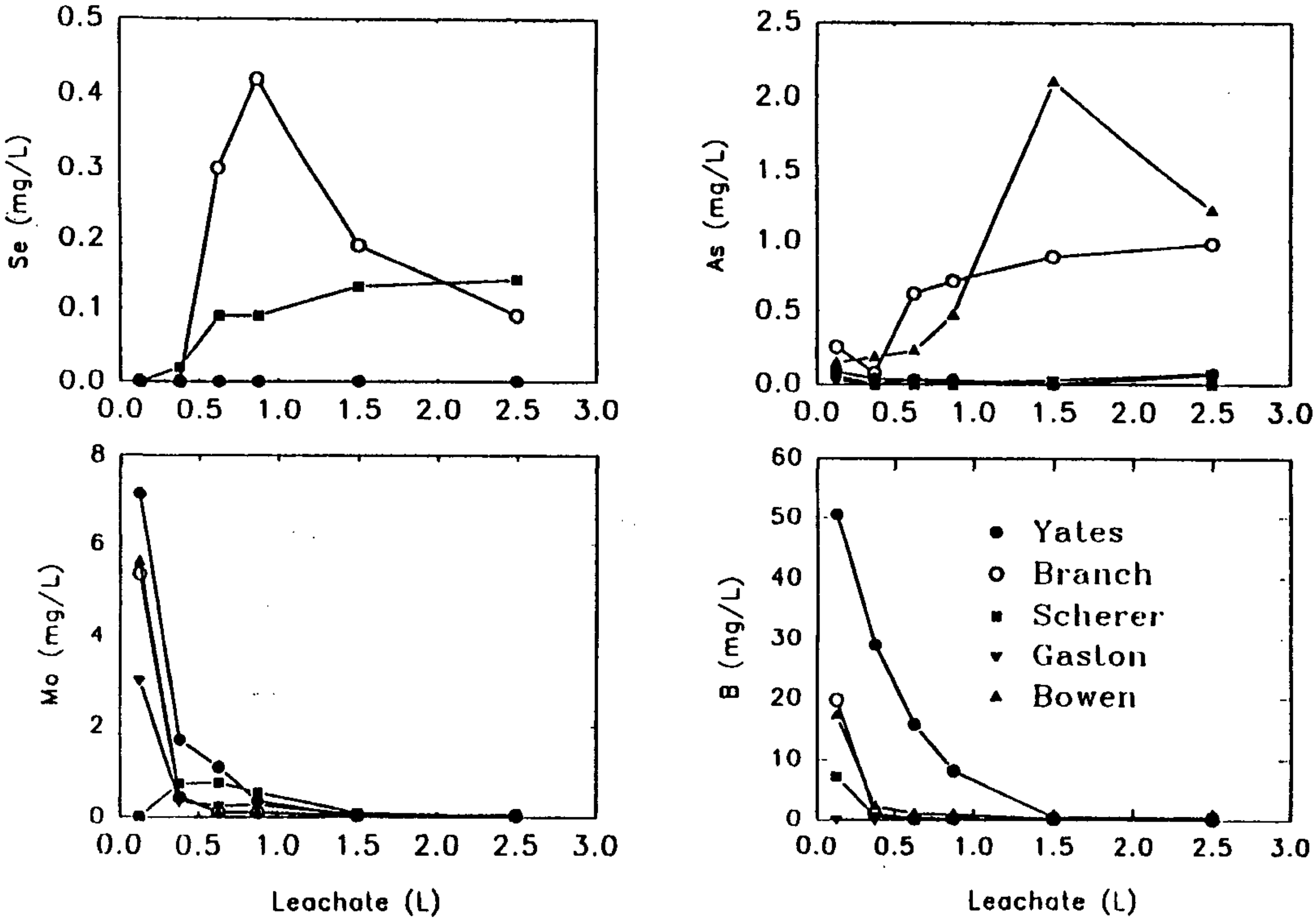


Figure 3-33. Micro Element Leaching

3.3.1.2.2 Element Mobility and Leaching from CCB-Amended Soil

The solubility studies above suggest that some elements of environmental importance in CCBs may become soluble when added to the soil environment. The studies described in this section were designed to establish how these elements may interact with soil solids in CCB-amended soils, and assess the overall potential for their movement to groundwaters via leaching, or their uptake by plants.

3.3.1.2.2.1 Laboratory Leaching Column Studies

In an effort to assess potential environmental implications of CCB use on soils, intact and repacked soil columns of Appling loamy sand were employed to study the mobility of major constituents of environmental interest. Two of the contaminants that were closely monitored in this study were B and As. The objective of this study was to assess the leaching behavior of these inorganic contaminants in soil amended with fly ash and FGD gypsum.

Undisturbed soil columns (10.2 cm in diameter and about 30 cm depth) of Appling soil (clayey, kaolinitic, thermic family of the Typic Hapludults) were collected at Athens, Georgia by pushing 10.2 cm diameter PVC pipes into the ground with a truck-mounted hydraulic probe. The intact soil columns, which consisted of a deep Ap horizon (30 cm), were then carefully dug out by removing the soil around the PVC pipes to ensure minimal disturbance of the intact soil columns. The cores were gently pushed out from the PVC pipes and placed on PVC end-cap bases that were filled with about 3 cm of acid-washed sand. To prevent any flow along walls, the side walls of columns were sealed with two coatings of liquid Saran (1:7 mixture of Saran to acetone). Aluminum flashing was then strapped around the base, and hot molten paraffin wax was poured into the gap between the aluminum flashing and the soil core. All the prepared columns were stored at 4°C to minimize biological activity. To check for side-wall flow, 3 L of 4 g/L methylene blue dye were run through several randomly selected columns. The columns were then sectioned to observe flow paths along the column walls. Prior to the leaching experiments, columns were saturated from the bottom overnight. The pH and EC of the column leachates were monitored and selected fractions were analyzed for water-soluble Ca, K, Mg, Na, B, and, water-soluble and colloidal As.

The alkaline fly ash (FA) was sampled from Plant Yates and the FGD from the Springfield (Illinois) Power Plant. The CCB treatments replicated 3 times were: 10 mt/ha FA, 10 and 20 mt/ha 1:1 mixture of FA and FGD, applied as powder on the surface of the soil columns. The columns were leached with 8 L of deionized water under a constant hydraulic head of 2 cm. Unfiltered leachates were analyzed by ICP for the primary constituents, with the exception of As which was assayed by graphite furnace atomic absorption spectrophotometer (GFAAS) with Zeeman background correction. After leaching was completed, the drained columns were sectioned at 5 cm increments, dried, passed through a 2 mm sieve, and analyzed to determine the vertical distribution of chemical constituents. A soil to solution ratio of 1:2.5 was used to obtain extracts and pH (Radiometer pHM 85) and EC (Radiometer CDM 80) measurements. The centrifuge tubes with the soil mixtures were shaken slightly and left to stand overnight.

Disturbed soil (repacked) columns were constructed as follows: Plexiglas columns (5 cm interior diameter and 10 cm long) were packed with soil to a uniform bulk density of 1.7 mt m^{-3}. Above and below the soil, sand layers were placed to help disperse flow throughout the column. The incorporated and surface applied treatments consisted of mixing ash (10 and 50 mt/ha) with the topsoil prior to packing or surface applying once the topsoil was in place. The two-layer columns consisted of 3.5 cm layers of Ap over B horizon material, respectively; some columns were constructed with the Ap horizon (7 cm) material only. The columns were oriented vertically and slowly saturated from the outlet with deionized water (< 0.25 mL min^{-1}). After saturation, the columns were turned horizontally and flow was initiated at a constant rate of 1 cm h^{-1} with deionized water for at least 6 pore volumes using a constant flux, variable pressure head peristaltic pump system. Column pore volume was 73 mL. The EC, pH, and turbidity of the effluent were monitored continuously, and leachate fractions were collected for B and As determination. The pressure head was measured from the water column that was set up at the inlet of the soil column as an indicator of saturated hydraulic conductivity (K_s) and column plugging.

Boron was determined using the azomethine colorimetric method (Bingham, 1982) and As was determined by graphite furnace atomic absorption spectrophotometer (Perkin Elmer 4100Z). In the initial run, leachates were sent for analyses by ICP-AES to provide the information as to which trace elements should be monitored in the subsequent experiments.

For total As and B determination, 2 g of soil from each soil section was digested for 4 h with 20 mL of concentrated HNO_3. The digested samples were then made up to 100 mL with deionized water in volumetric flasks. Water extractable As and B were determined using 10 g of soil from each section and 20 mL of deionized water and the centrifuge tubes with the soil mixtures were shaken for 12 h. The same soil to solution ratio was used to obtain extracts with 0.1 M HCl and dilute double acid (0.025 M H_2SO_4 and 0.05 M HCl) and the tubes were shaken for 0.5 h. All these soil mixtures were super-centrifuged and the extracts filtered through Whatman 42 filter paper.

Selected physical and chemical properties of the soil used in this study are given in Table 3-28. The dominant clay mineral in the Appling series is kaolinite, with lesser amounts of goethite, hydroxy-interlayer vermiculite (HIV), and gibbsite. Selected properties of the FA and FGD gypsum were presented previously. Flow velocities have been shown to have an effect on the attenuation of trace elements by different soils (Wangen et al., 1982). Such effects should be expected given the rates of different chemical reactions and the physical and chemical complexity of soil materials. Even though the pore velocity in the intact columns was quite variable (Table 3-29), the total amount of B eluted was not affected, suggesting that B solubility was not kinetically-limited in these systems.

TABLE 3-28
PHYSICAL AND CHEMICAL CHARACTERISTICS OF APPLING AP AND BT HORIZONS

Property	Ap horizon	Bt horizon
Sand (g/kg)	790	610
Silt (g/kg)	150	190
Clay (g/kg)	60	20
Surface area (m^2/g)	2.53	12.45
Organic C (%)	0.43	0.25
pH_{H2O}	5.9	4.7
$pH_{0.01\ MCaCl2}$	5.0	4.2

TABLE 3-29
PORE VELOCITY AND SATURATED HYDRAULIC CONDUCTIVITY (K_D) IN CONTROL AND TREATED UNDISTURBED COLUMNS

Parameter	Control	Fly ash (10 mt/ha)	Fly ash + Gypsum (10 mt/ha)	Fly ash + Gypsum (20 mt/ha)
Pore velocity (cm/min)	0.063	0.114	0.031	0.074
K_d (cm/min)	0.016	0.038	0.009	0.020

For the undisturbed columns, turbidity measurements were not made; however, it was observed that the effluent turbidity was greatest for the control, but considerably less than that observed for repacked columns (see discussion below). The stable structure of the intact soil column presumably resulted in some preferential water flow through macropores; thus less soil would disperse under these conditions compared to that of disturbed, repacked soil columns. The columns with the FA+FGD mixture were initially turbid, but the leachate cleared after one pore volume had percolated. The highest EC values obtained in the percolates (1.2 dS/m; Figure 3-34) are significantly below those required for inhibition of plant growth due to salinity (Golden, 1983). The same was true in this study where there was not much difference in leachate pH between FA and FA+FGD treatments and the control which supports Sakata's (1987b) findings. If fact, the pH of the treatments that included FGD gypsum were lower than the control and FA treatments because of the salt effect (Figure 3-34).

Leachates from the columns treated with FGD gypsum were higher in Ca, K and Mg than the control or FA only columns (Figure 3-35). Similar results were obtained by other investigators, who found that Mg and to some extent K were preferentially leached out of topsoils as a result of gypsum application (Lemus Grob, 1985; O'Brien and Sumner, 1988). In coarse textured soils, high rates of gypsum application (> 5 mt/ha) may induce Mg and K deficiency problems by enhancing leaching of those elements from the rooting zone (Syed-Omar and Sumner, 1991). Even though not all of the soluble Ca present in the leachates was from FGD gypsum, Ca levels can still be roughly used as an indicator of the amount of SO_4^{2-} present in the leachates. Water quality standards recommend sulfate levels of less than 250 mg/mL due to taste and laxative effects, ideal drinking water having none or a trace amount.

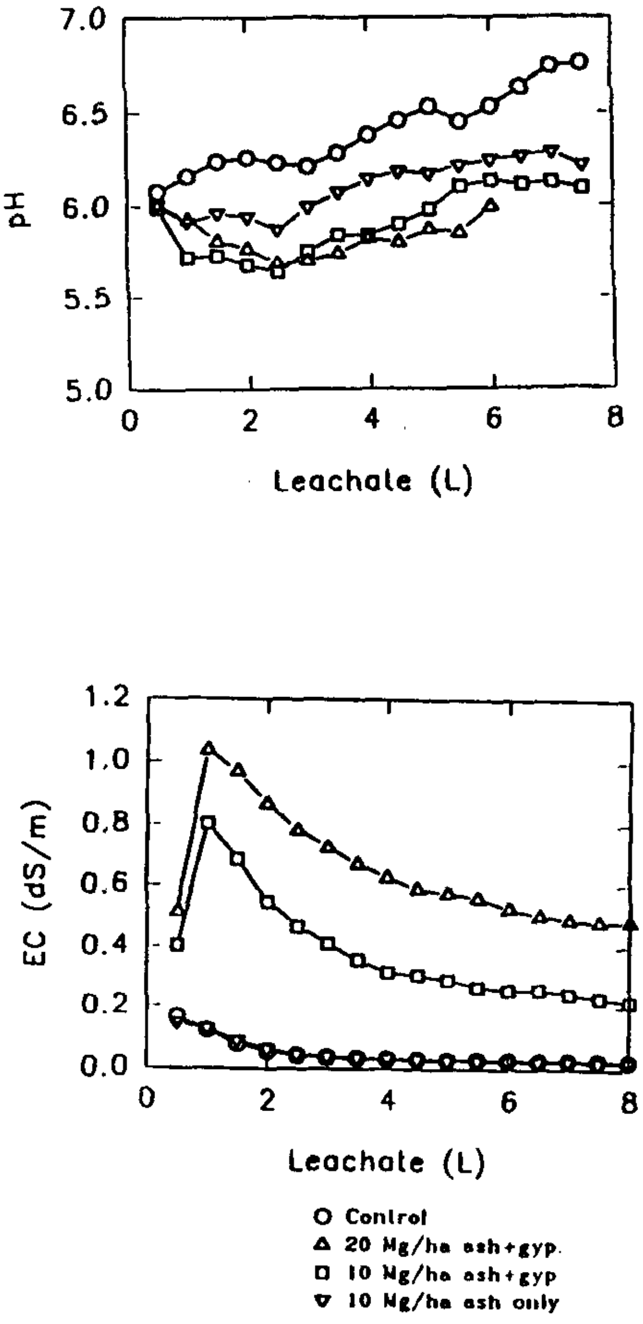


Figure 3-34. pH and EC of Leachates from Intact Soil Columns of Various Treatments

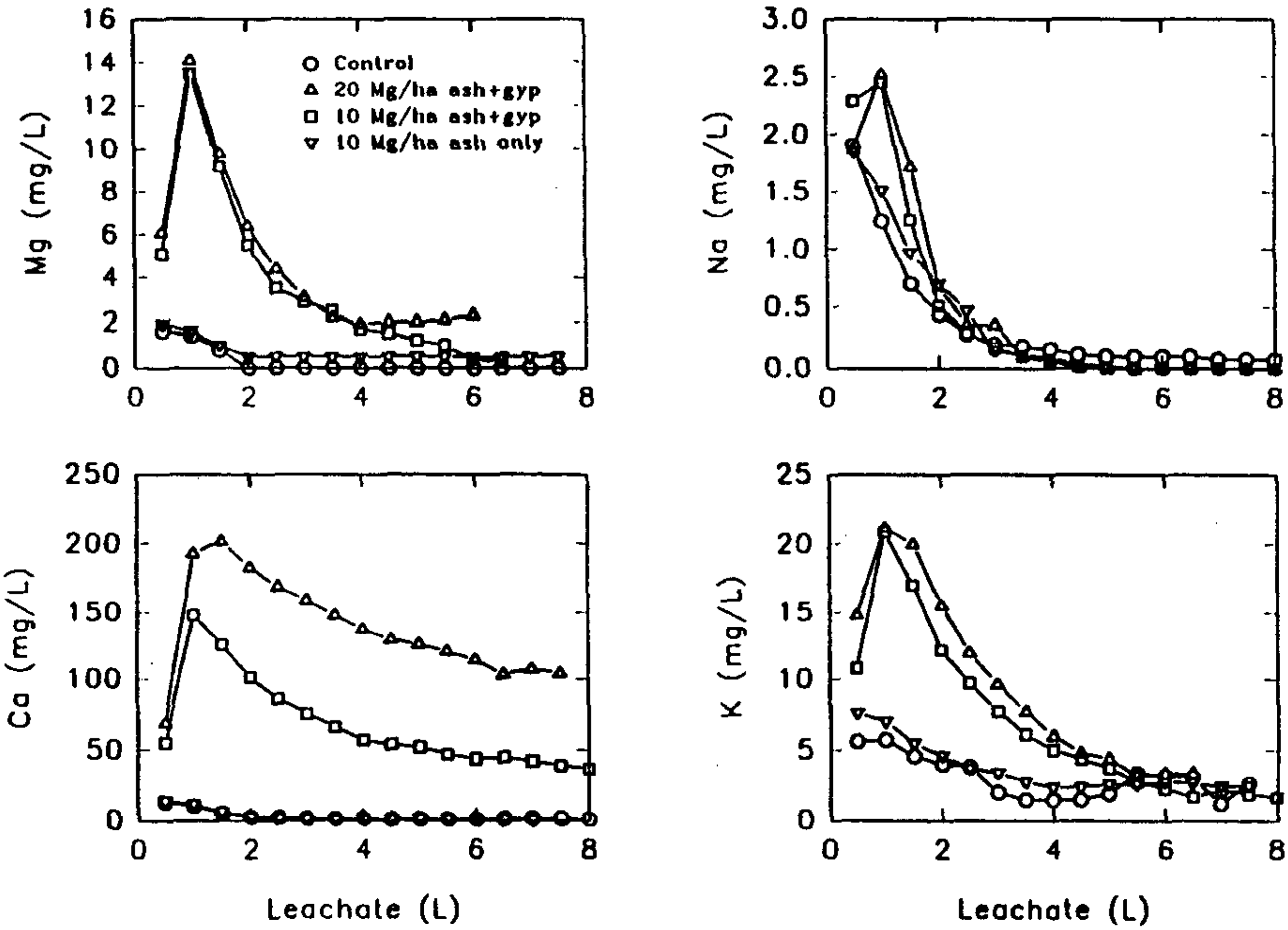


Figure 3-35. Leachability of Mg, Na, Ca, and K from Intact Soil Columns of Various Treatments

No significant levels of trace elements other than B above background were detected in any leachate from any column. In spite of the variations in flux for the different columns, the similarity in B breakthrough curves within treatments suggested that the solubility of B was not kinetically limited in this case (Figure 3-36). Although no drinking water standard for B exists, high levels above 1-2 mg L^{-1} which were only reached for a short time in the highest FA + FGD treatment, can be toxic for some sensitive plant species. Boron is expected to leach rapidly out of the profile because of limited sorption in the soil. Boron toxicity is most often observed in greenhouse studies where leaching is restricted. Consequently B is likely to pose no environmental threat to man or animal. In the presence of FGD gypsum, B movement was enhanced. This will be further investigated in packed soil columns where the leachate flux can be maintained constant. At the completion of the experiment, water-soluble B could not be detected in any section of the soil columns.

Appreciable levels of As were only found in turbid leachates where it was probably present in an adsorbed form on colloids (Figure 3-36). Arsenic concentrations in leachates from the control and FA columns were similar and higher than those in columns treated with gypsum, which is consistent with the above statement. Past use of As in pesticides may have resulted in the relatively high background levels of As in the Appling soil (Langdale et al.,1979).

At the conclusion of the leaching phase of the experiment, soil columns were cut into sections and pH, EC, total, acid and water soluble As and B analyzed (Figure 3-37). The acid neutralizing effect of FA was limited to the topsoil which agrees with the findings of Sakata (1987b). The elevated EC in the top 5 cm of the soil reflects the presence of soluble gypsum. There is some evidence of enrichment in total As to a depth of 20 cm where fly ash and gypsum treatments were surface applied. The As extracted with deionized water actually reflects the sum of water soluble and colloidal As since the soil extracts were turbid even after filtering due to the dispersive nature of the Appling topsoil. In the topsoil where the EC was higher in the gypsum treatments, the clay was flocculated and the level of As was much lower than for the dispersed soil in the control and FA treatments. In the double acid (Mehlich) extraction which is routinely used to test for readily available P in weathered acid soils of the Southeastern U.S., fly ash

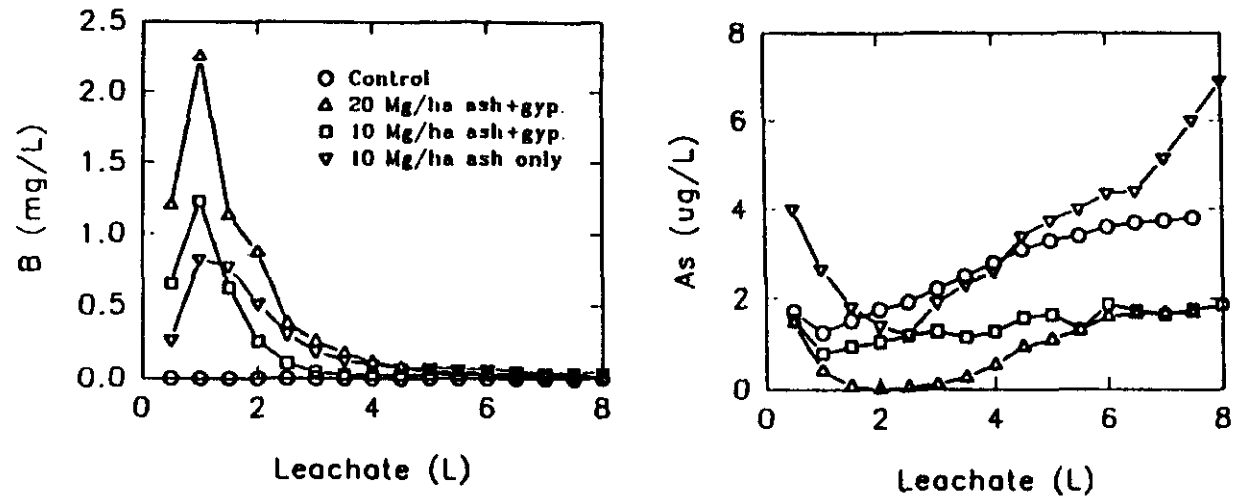


Figure 3-36. Leachability of B and As from Intact Soil Columns of Various Treatments

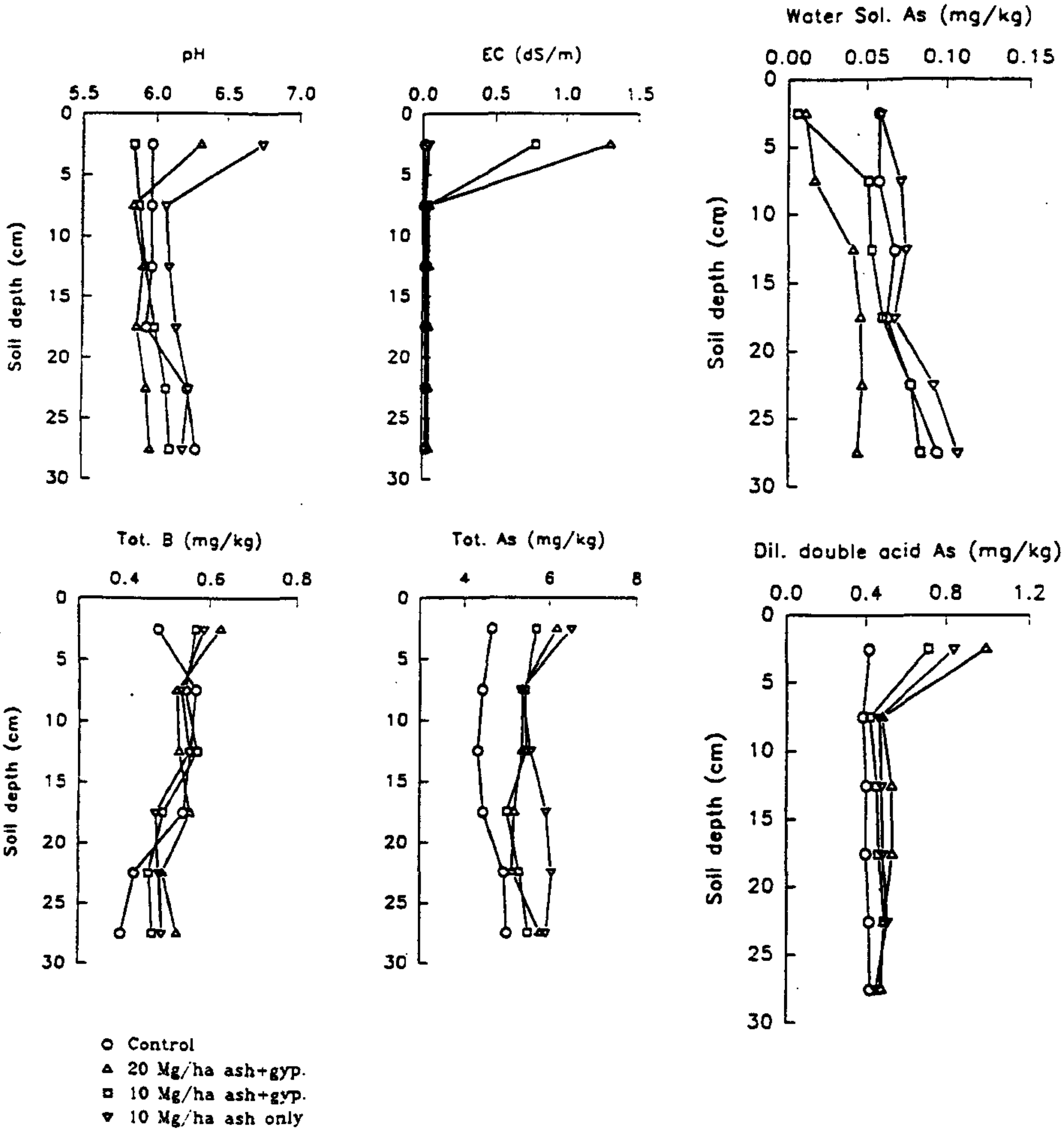


Figure 3-37. Distribution of Various Elements in the Intact Soil Columns with Depth after Leaching

treatments slightly increased As levels in the topsoil. Total B remaining in the soil was largely unaffected by CCB treatments, as most had been leached out during the prior leaching treatment (Figure 3-37).

For the disturbed (re-packed) columns, the Yates and Scherer ashes (alkaline and acid, respectively) were ineffective in reducing significant natural clay dispersion of the Appling soil except at the 50 mt/ha rate of Scherer ash, which decreased the water dispersible clay by about 20 % relative to the control. When FGD gypsum was included with the ashes, the soil was well flocculated at all ash levels due to the high EC subtended by gypsum. The B horizon soil was well flocculated in its natural state; however, the 50 mt/ha Yates ash treatment slightly increased the amount of dispersible clay (1.5%), presumably by raising the pH and exchangeable Na levels in the absence of insufficient salt to cause flocculation. All of the ash and gypsum treatments increased the EC of the effluent solutions, with the exception of incorporation of the Scherer ash in the Ap horizon (Figure 3-38). All the EC values are below 3000 mS/cm, which is the upper limit set for the ash-soil mixture from a plant growth point of view (Sharma et al., 1989). In general, the ECs were higher for the incorporated treatments compared to their surface applied equivalents for the Yates ash with the reverse being true for the Scherer ash. The Yates ash resulted in higher ECs than the Scherer due to more soluble constituents. The FGD gypsum treatments caused much higher maximum EC values which remained elevated throughout the experiment.

When incorporated, the Yates ash increased effluent pH to 6.5, but surface application initially caused no change in pH (5.5-6.0) above the control (Figure 3-39). This probably resulted from better contact between the soil and ash as the water passed through the incorporated treatments. In addition, the soil acted as a sink for the soluble ions, reducing their activity in the solution and enhancing further dissolution. This renders the less soluble fraction of the ash more soluble resulting in the observation that pH increased when the ash was incorporated. For the B horizon, incorporation of the Yates ash was not effective in increasing leachate pH. The pH of the incorporated Yates ash treatment in the two-layer column was the same as that in the two-layer control column (Figure 3-39). In fact, the leachates had lower pH values than the control. For

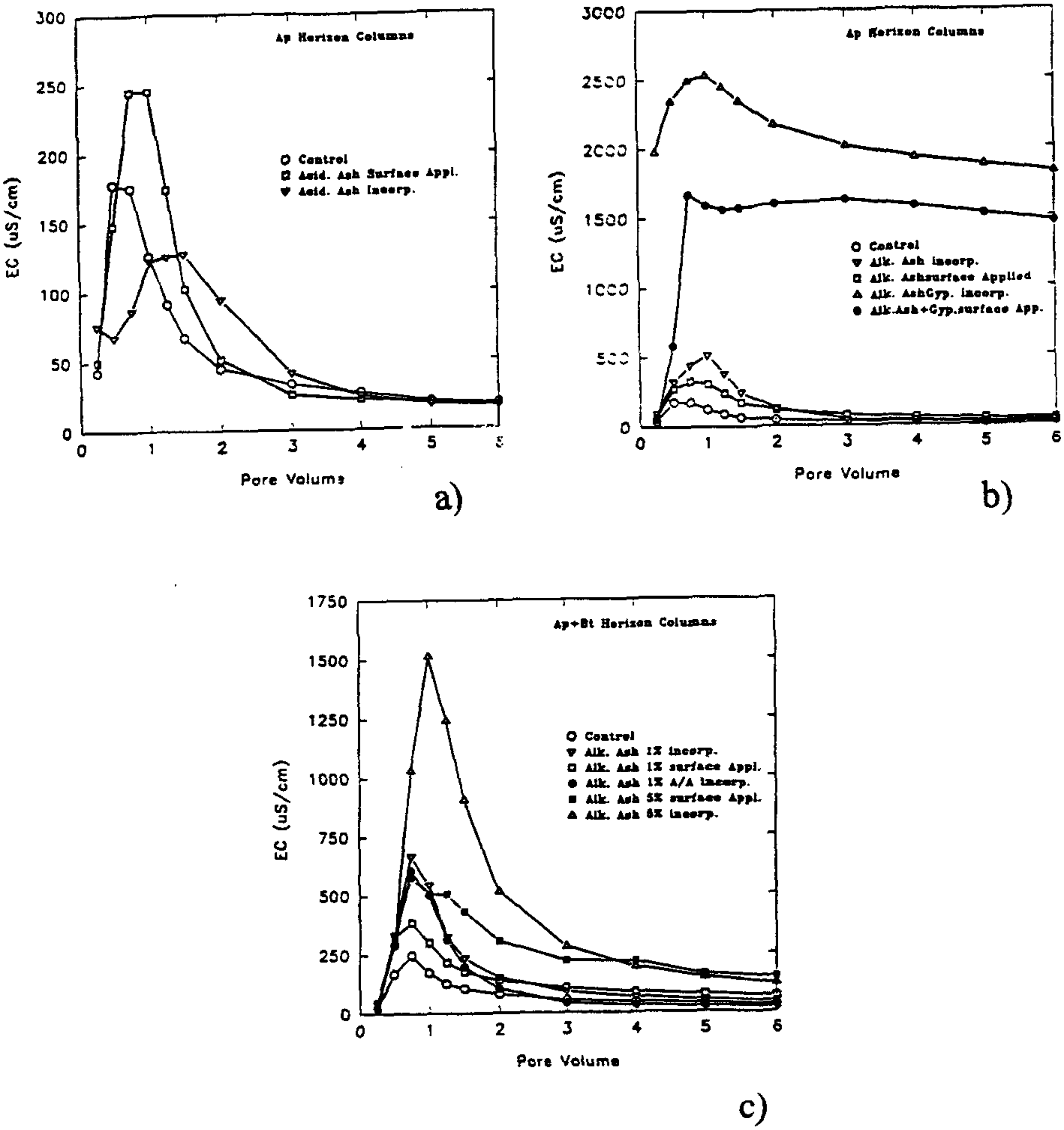


Figure 3-38. Effluent EC from 1% (a) Alkaline (b) Acidic Fly Ash Treatments for the Ap Horizon (c) 1% and 5% Alkaline Ash Treatments for the Two-Layer Columns

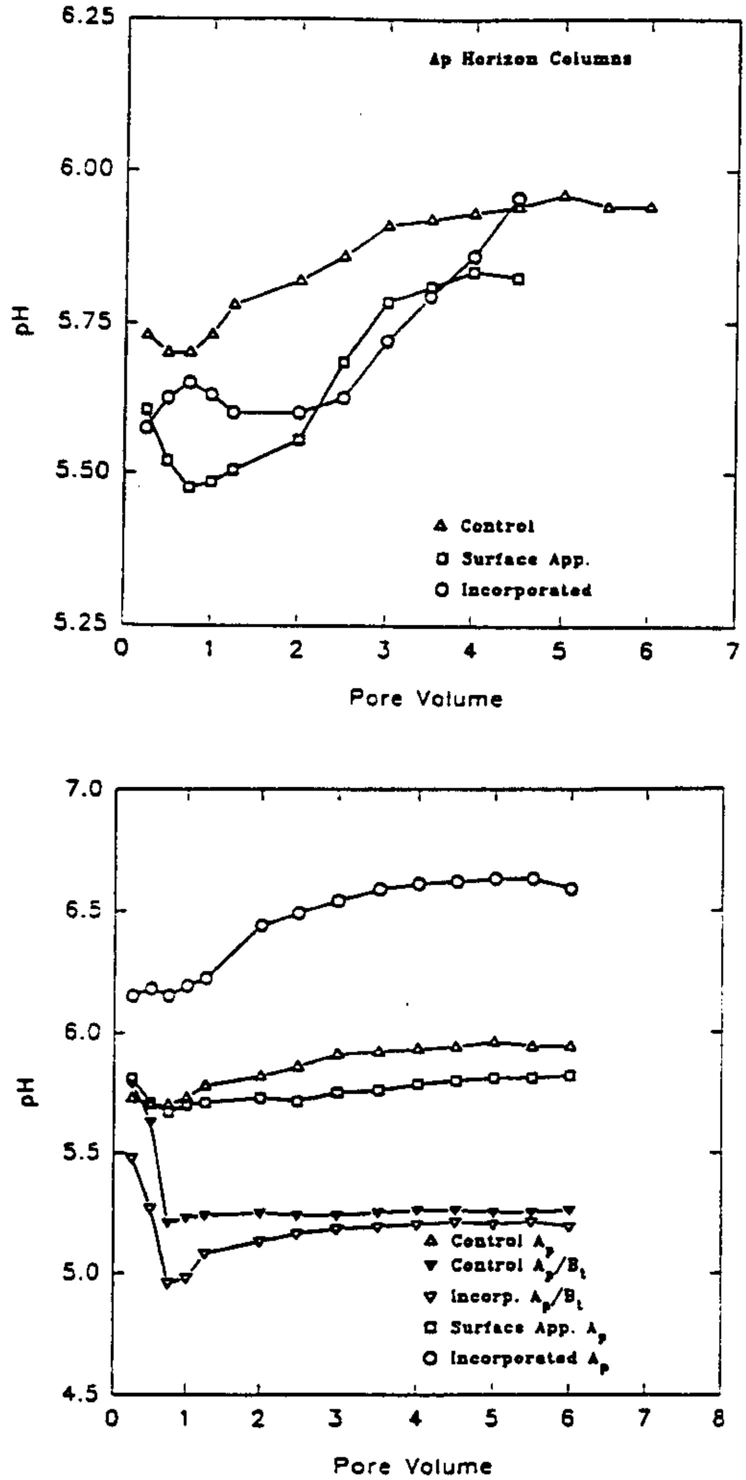


Figure 3-39. Effluent pH from 1% (a) Alkaline (b) Acidic Fly Ash Treatments for the Ap and Ap/Bt Horizons

the Scherer ash, both methods of application significantly decreased leachate pH compared to the control, but there was no difference between incorporation and surface applied treatments (Figure 3-39).

As was the case for intact soil columns, most of the B added in the incorporated Yates ash treatment was eluted in the first 3 pore volumes. The maximum B concentration for the surface applied treatment was less than that of the incorporated treatment, but effluent concentrations remained elevated for several pore volumes longer than the incorporated treatments (Figure 3-40). Incorporation, by mixing the ash throughout the column, increased B solubility by increasing the duration of exposure of the ash to the percolating solution. The addition of FGD gypsum increased both the maximum B concentration and enhanced the movement of B through the column, while reducing the effluent concentration differences between application methods. The increase in B from the FGD gypsum and ash mixture cannot be accounted for by the amount of B present in the gypsum. The increase in B can be explained by (1) diverse ion effect on solubility of B compounds; and, 2) competition on sorption sites between borate and sulfate ions. Sulfate released by the FGD gypsum can decrease the adsorption of some cations by complexing them in solution. By the same token, it can also decrease the adsorption of some anions, such as borate, through competition for adsorption sites, thus resulting in more leaching of B from the soil. Boron movement in the Scherer ash treatment was considerably less than that of the Yates, due to lower total and soluble B present in the former (Tables 3-21 and Figure 3-41). The maximum B concentration in the Scherer ash treatment without gypsum was less than 2 mg L^{-1}. Columns containing a B horizon were not effective in attenuating B movement through the profile (Figure 3-40). This is contradictory to the result obtained from the batch adsorption study, which suggests that the kinetics of the sorption reactions might have a stronger influence in the column.

Arsenic is generally strongly sorbed by highly weathered soils. In this study, As moved by colloid-facilitated transport; very little soluble As was present as can be observed from the difference between filtered and non-filtered leachate from the Ap horizon (Figure 3-42). The level of As present in the leachates from columns which had FGD gypsum present in the

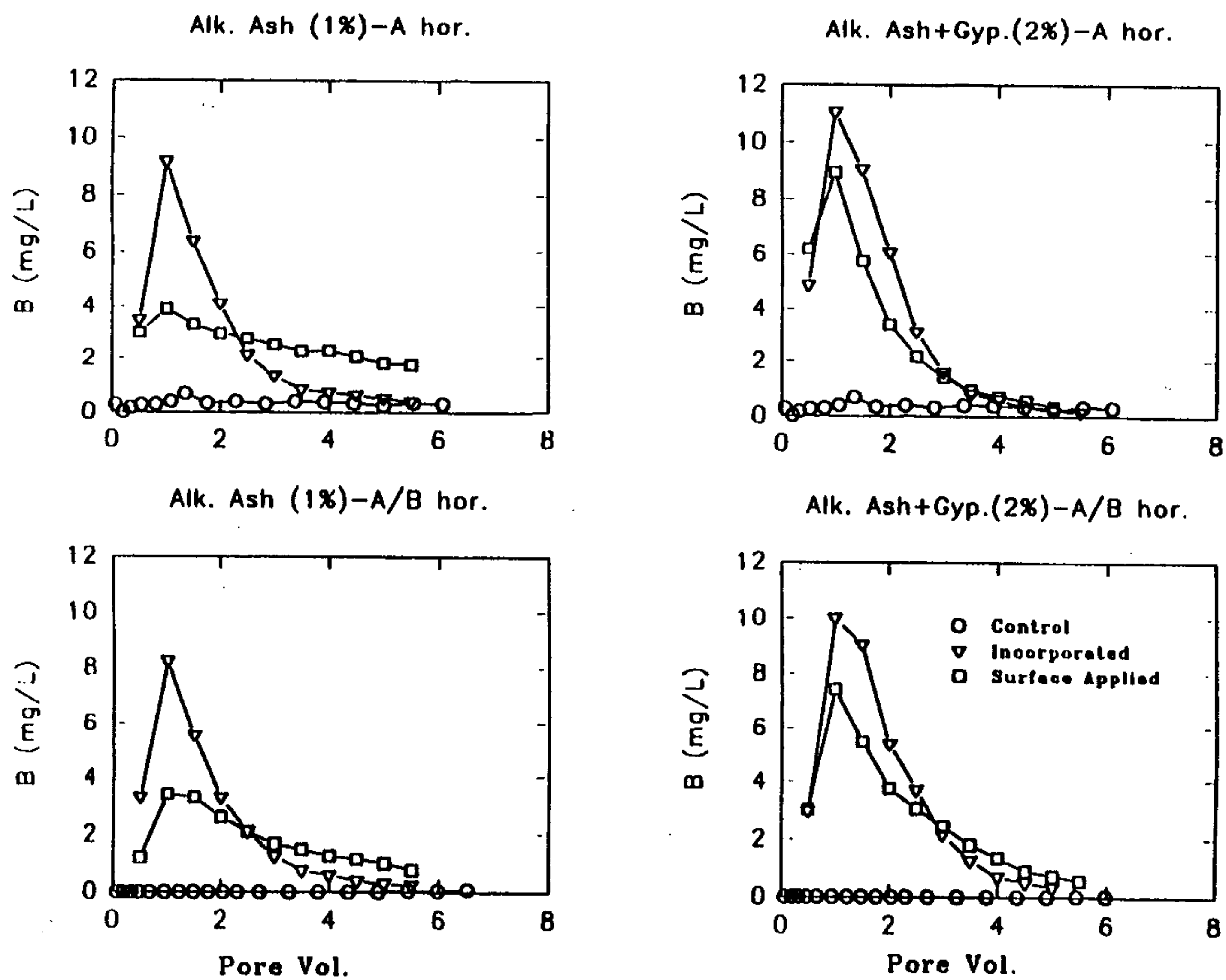


Figure 3-40. Effluent Boron Concentrations from Alkaline Fly Ash Treatments for the Ap and Ap/Bt Horizon Columns

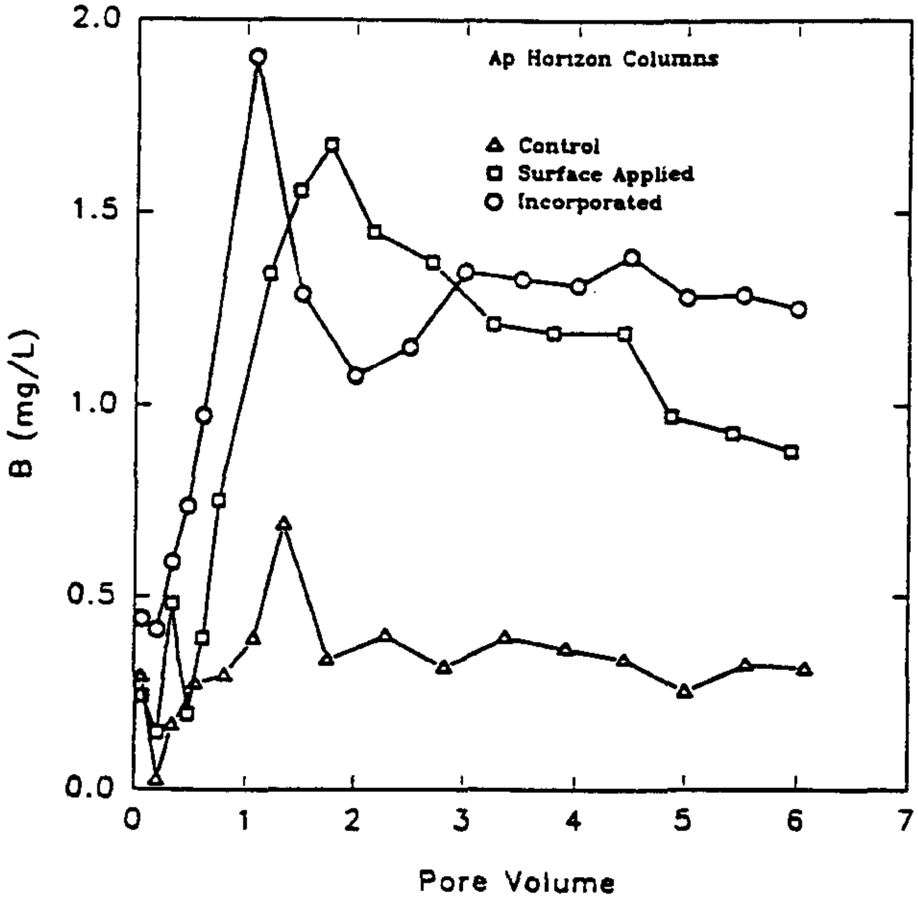


Figure 3-41. Effluent Boron Concentration for 1% Acidic Fly Ash Treatments for the Ap Horizon

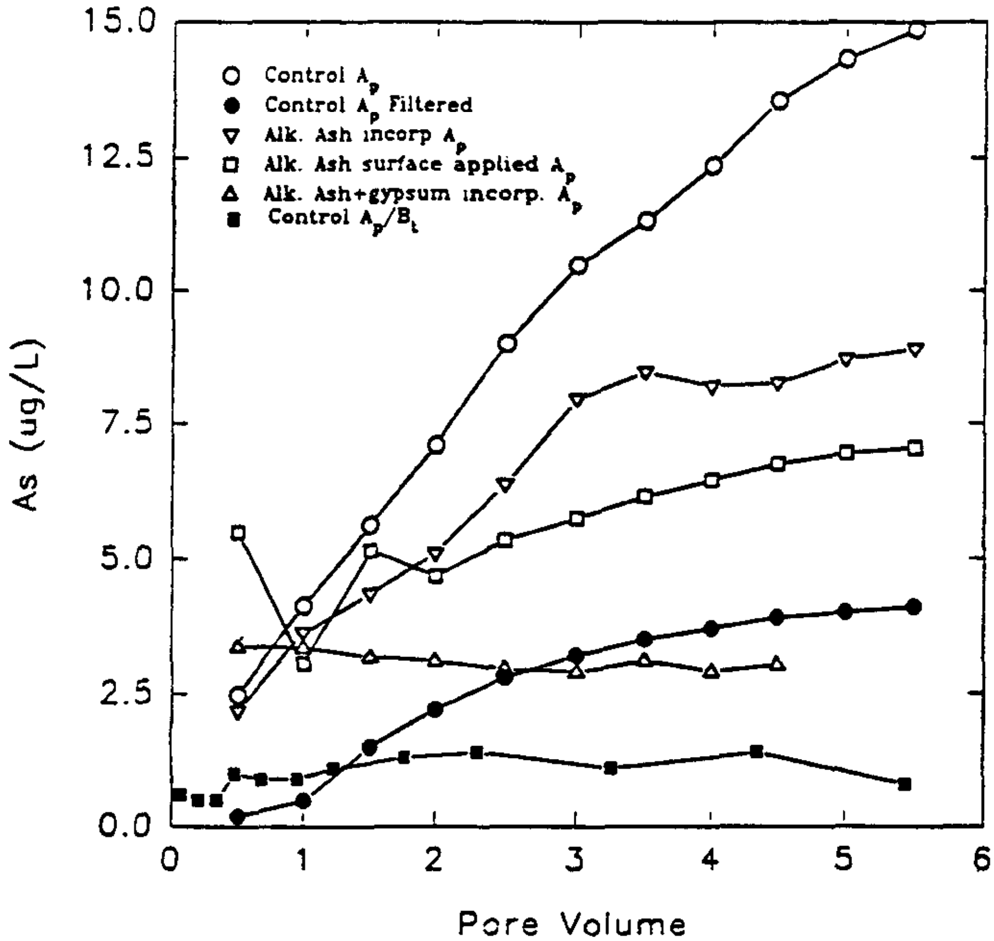


Figure 3-42. Effluent Arsenic Concentration from 1% Alkaline Fly Ash Treatments for the Ap and Ap/Bt Horizon

treatment, or leachates from two-layer columns, was comparable to the filtered leachate from the Ap horizon. This implied that in all these cases, what was determined in the leachates was the water-soluble As fraction only. The leachates from the other treatments in Figure 3-42 were not filtered and appeared turbid; thus what was determined in those cases, was the water-soluble+colloidal As. Surface application of the ash resulted in a more random movement of As in the soil profile as compared to incorporation of ash.

In this study, at the rate of ash application, only trace amount of As were detected in the leachate from the fly ash treatments, indicating soluble As movement over the leaching period was insignificant compared to the native As present in the soil. Columns containing a B horizon were effective in filtering the colloids even in the 5% ash treatments, thus preventing colloidal As from being carried down the soil profile. The As breakthrough curves seem to coincide with turbidity (see Figure 3-43, discussed below; Puls and Powell, 1992).

Effluent turbidity (in units of NTU) for the incorporated Yates ash was much less than that of the control, while the turbidity of the surface-applied Yates ash was comparable to that of the control for the first pore volume before decreasing to a level similar to that of the incorporated treatment (Figure 3-43). When FGD gypsum was incorporated with the ash, the effluent turbidity was the lowest of all of the Yates ash treatments, and leachate solutions were essentially clear. Leachate turbidity from the Scherer ash treatments was quite variable, but the incorporated ash and the control columns tended to produce higher effluent turbidities than those where ash was surface applied (Figure 3-43). When a B horizon was included in the column, the effluent turbidity was negligible due to flocculation and filtering of colloids from the Ap in the B horizon material. Batch results confirmed that the B horizon was non-dispersive and mixtures of the Ap and B horizon also tended to flocculate (Table 3-20).

It has been reported that soil saturated hydraulic conductivity (K_s) improved at lower rates of fly ash application but deteriorated when the rate of ash amendment exceeded 10% in acidic soils (Sharma et al.,1989). At high rates, this may result from an alteration of texture as much as a

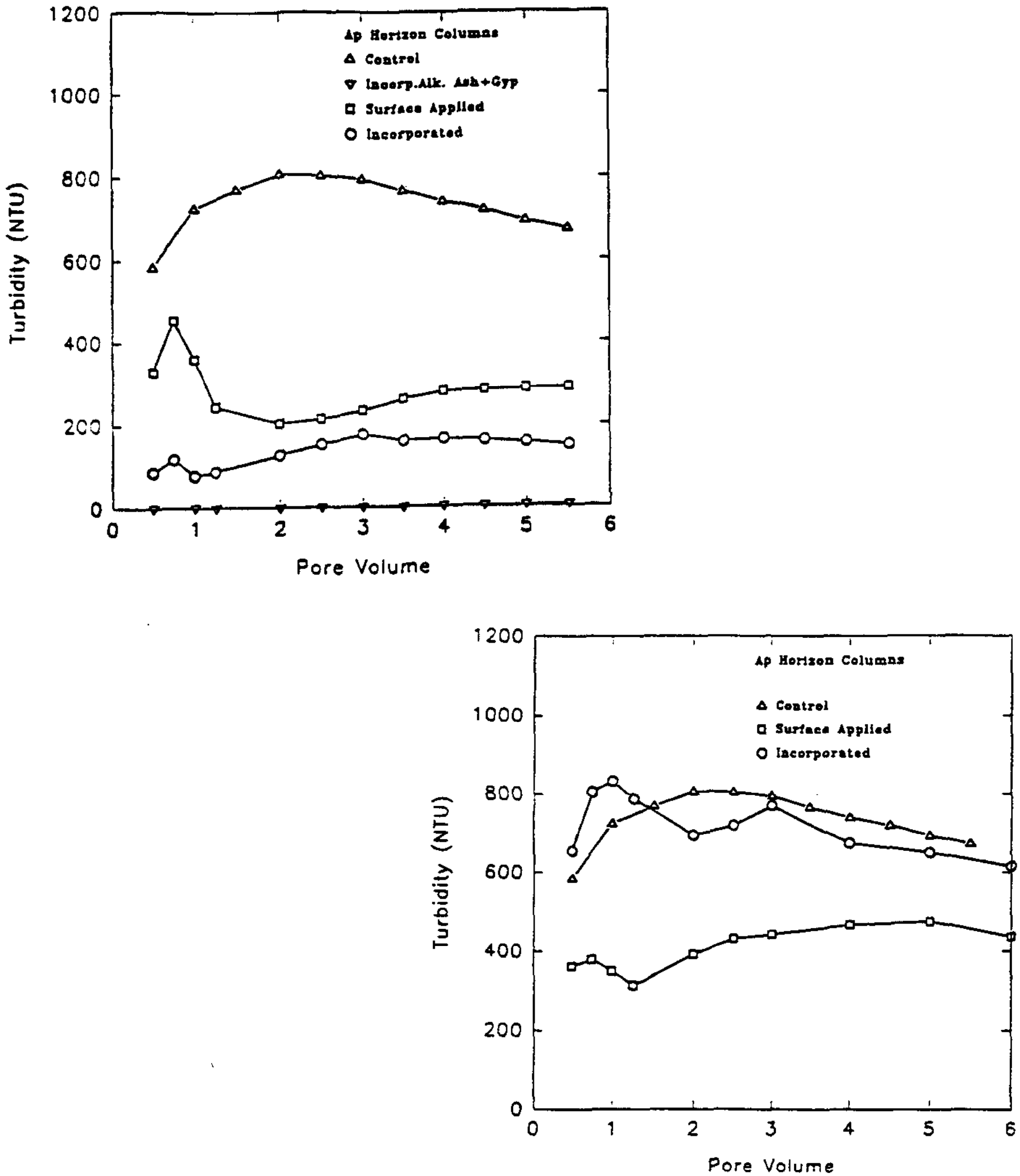


Figure 3-43. Effluent Turbidity (NTU) from 1% (a) Alkaline and and (b) Acidic Ash Treatments for Ap Columns

change in the chemical properties of the soil, as indicated by an increase in water holding capacity. The pressure head developed during the leaching of the columns is displayed in Figure 3-44. The control exhibited a gradual increase in pressure head over time, indicating some clogging of the pores due to clay movement. Both Scherer and Yates ashes, when combined with FGD gypsum, displayed the least head buildup during leaching. The incorporated Yates ash had the greatest increase in head over time while displaying a lower effluent turbidity (Figure 3-43). The lower effluent turbidity and increase in pressure head for the Yates ash would tend to indicate that there is a dispersion threshold at which more of the dispersed clay is captured in the column, thus clogging transmission pores and reducing the K_s for that column. Batch studies (Table 3-30) did not predict this behavior, but the result shown in Figure 3-39 indicates an increase in pH on incorporation of the ash. In this case, the pH increase and exchangeable Na associated with the Yates ash treatment may outweigh the effect of a slight increase in ionic strength. At this elevated dispersion level, the pores can become clogged and the effluent appears clearer than under less dispersive conditions. The Scherer ash treatment displayed one of the highest effluent turbidities and one of lowest pressure heads. The Scherer ash treatment may decrease dispersion to some degree by increasing ionic strength, but this lower dispersion level decreases filtering and allows more of the dispersed clay to exit the column.

In conclusion, low levels (1%) of Scherer and Yates ashes had little effect on water dispersible clay in Appling topsoil as measured in batch dispersion studies, but the addition of FGD gypsum induced complete flocculation of the initially dispersive Ap horizon material. When incorporated, the Yates ash and Yates ash+FGD treatments were effective in increasing the effluent pH from the Ap horizon. Results of the incorporated ash treatments indicated that the sparingly soluble Yates ash may act as a dispersing agent by raising the pH and exchangeable Na, while failing to release sufficient salts to encourage flocculation. Although this might cause increased movement of colloid-bound As, such an effect was not observed due to column plugging. The addition of FGD gypsum to the fly ash decreased effluent turbidity and increased the leaching of B from the column. The presence of a B horizon was effective in decreasing effluent turbidity and thus prevented As movement, but failed to retard the leaching of B.

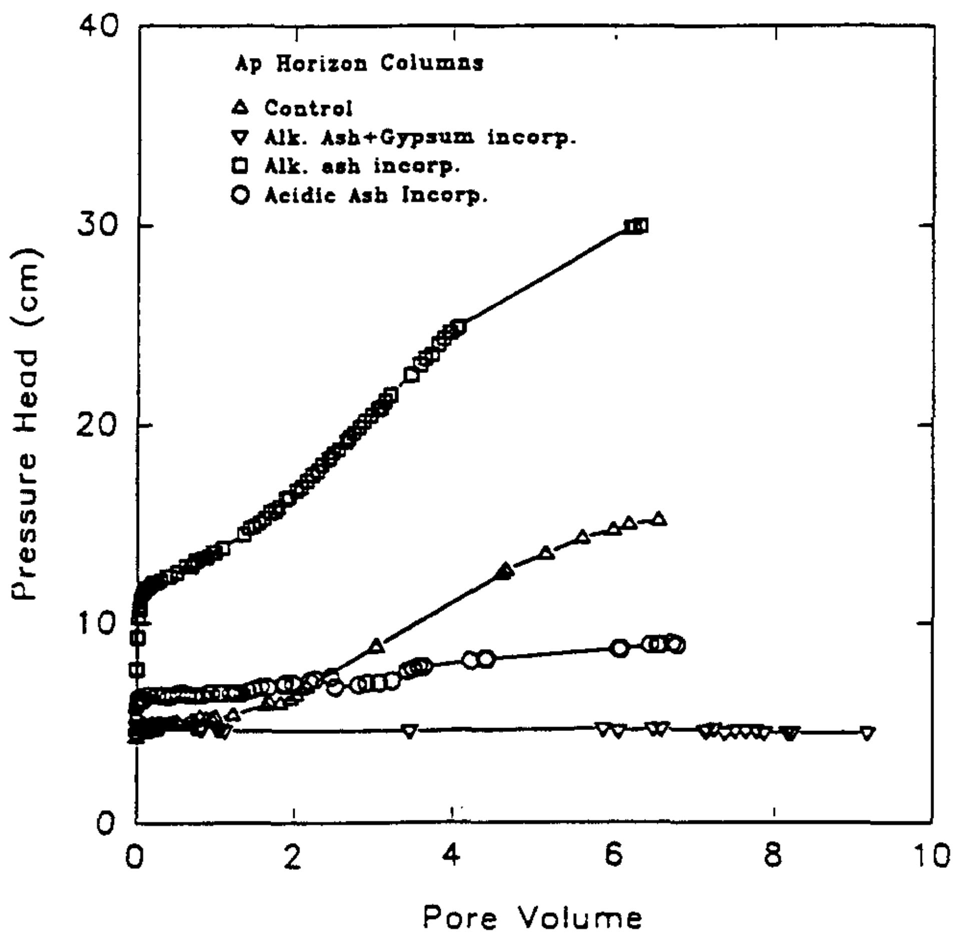


Figure 3-44. Pressure Head at Inlet of Ap Columns from the 1% Fly Ash Treatments

TABLE 3-30
EFFECT OF FLY ASH AND FGD ON WATER-DISPERSIBLE CLAY, PH AND EC OF APPLING TOPSOIL AND SUBSOIL

Treatment	Rate mt/ha	Disp. Clay‡ (g/100g soil)	Clay¤ (% Disp.)	EC (dS/m)	pH
Control Ap		4.90	84.4a	18	5.76
Yates ash	10	4.76	82.1a	44	6.41
	50	4.48	77.2ab	160	8.27
Scherer ash	10	4.56	78.6ab	19	6.08
	50	3.97	68.4b	30	5.93
Yates + FGD	10	-	-	677	6.26
	50	-	-	2310	7.05
Scherer + FGD	10	-	-	638	5.77
	50	-	-	2313	6.06
Control Bt		-	-	38	4.77
Yates ash	10	-	-	58	5.31
	50	0.31	1.5c	201	7.19
Scherer ash	10	-	-	39	4.98
	50	-	-	49	4.93
Mixed Ap+Bt		-	-	33	5.27

† -=Visually flocculated Fisher LSD (0.05)=0.63
‡ Disp. clay - Water dispersible clay expressed as percentage of whole soil
¤ Clay (% disp.) - Water dispersible clay expressed as percentage of total clay

The influence of ionic strength and pH of the ash should be carefully examined when trying to predict the field behavior of treated soil, especially at the low rates of ash application. The results of this study indicate that for alkaline fly ashes, land application may result in decreased hydraulic conductivity of the surface horizon, which could increase the potential for crusting, surface runoff, and soil erosion. However, addition of FGD gypsum to the ash, as proposed in some experimental scrubber systems, may inhibit dispersion and pore clogging associated with the incorporation of alkaline ash. Acidic ashes pose less of a problem in this regard; similarly, surface application of the alkaline ash appears to be less dispersive, although the cementing nature of the ash may enhance surface crusting and runoff. Leaching of As was not observed in any treatment, due to the high adsorption by even this very sandy soil. However, colloid facilitated transport of this element in surface runoff water should be further investigated. Boron was readily leached from the surface soils; this appears to be advantageous, since B is highly toxic to plants but relatively non-toxic to animals.

The results in this study indicate that management of fly-ash amended soils needs to take into account the impact of ash on soil hydraulic properties in order to avoid excessive runoff and surface-water contamination. Also, contaminant transport from a site should include consideration of colloid-associated movement. Using As as a contaminant indicator, no groundwater effects would be predicted under aerobic conditions.

In this study, B was the only trace element showing elevated levels in the leachates collected during leaching of CCB-amended soils. Results from the batch adsorption study suggest that B movement in the soil might be retarded by adsorption in the B horizon. Such a possibility should be further investigated. Boron does not pose a water quality problem, but only a phytotoxicity problem. If B is the only trace element that might be potentially hazardous, there are several ways that this problem can be overcome. Weathering or lagooning of ash prior to application can reduce soluble B levels, or the ash might be applied in areas where B is deficient in the soil or where tolerant plant species are grown. However, B presents no long term problems since it is rapidly leached out of the rooting zone and the application of FGD gypsum enhances the leaching of B. Additionally, the application of gypsum enhanced the leaching of K and Mg that may cause plant deficiency problems if not addressed. In contrast, As movement in the profile was negligible, even in the presence of gypsum. Other elements could still pose environmental problems in runoff or plant uptake and this needs to be further investigated.

3.3.1.2.2.2 Contaminant Adsorption Studies

Trace element solubility from CCB when added to soils is quite low, as described in the leaching studies above, despite significant solubility of these elements in the CCB themselves. The hypothesis explaining this behavior is that most of the important contaminants solubilized from CCB added to soils are quickly adsorbed by soil surfaces, and immobilized. For the oxyanion contaminants such as Mo, As, Se, and B, limited information on adsorption processes on Southeastern U.S. soils is available, so these studies were conducted in order to examine anions adsorption on topsoil and subsoil samples from a typical upland soil from central Georgia. The studies were conducted as batch adsorption isotherms, adding contaminant-spiked solutions to soils and measuring amounts remaining in solution (un-adsorbed) after a period of equilibrium. Studies also included sulfate (SO_4^{2-}) because this is an important anion in CCB that may compete for adsorption sites with the contaminant metals.

The experiments were conducted using 8 g of air dried, 2 mm sieved Appling soil from the Ap and Bt horizons weighed into centrifuge tubes. Boric acid solutions of varying volumes having final concentrations of 0, 0.45, 0.90, 1.35, 1.80, 2.25, 2.70, 3.15, 3.60, 4.05, and 4.50 mM were added, followed by 30 mL of 0.013 M NaCl solution, and the volume in each tube was made up to 40 mL. The tubes were shaken for 48 hours, super-centrifuged and filtered through Whatman 42 filter paper, and pH measured using a combination glass electrode. Boron in the equilibrium solution was determined by the azomethine colorimetric method (Bingham, 1982). The amount of adsorbed ion was calculated as the difference between the amount added and the amount remaining in solution. The adsorption measurements were made in triplicate. A study on the effect of gypsum on B adsorption was carried out using the procedure above and a background $CaSO_4$ concentration of 0.00125 M which is approximately one-tenth saturated gypsum solution.

For the As adsorption isotherm, a similar procedure was carried out with the exception that the soil weight of 4 g, final concentrations of up to 2 mM were used and the soil mixture was shaken for only 24 h. The As concentrations were determined by inductively-coupled plasma (ICP) spectrometry.

The B and As adsorption isotherms for the Ap and Bt horizons were determined to help in understanding the transport processes of these ions in this soil (Figures 3-45 and 3-46). Neither horizon displayed a high capacity to adsorb B, although adsorption was much higher in the Bt horizon due to a higher clay and oxide content. On the other hand, this soil, especially the Bt horizon, has a high capacity to adsorb As(V), approximately four times greater than the Ap horizon (Figure 3-46) . Lower amounts of As (III) were adsorbed by the Appling soil especially by the Bt horizon (Four times less than the As (V) species). Under moderately reducing conditions such as those found in flooded soils, As (III) may be the dominant form. In well drained soils, the more stable As (V) form is predominant (Haswell et al., 1985; Manful et al.,

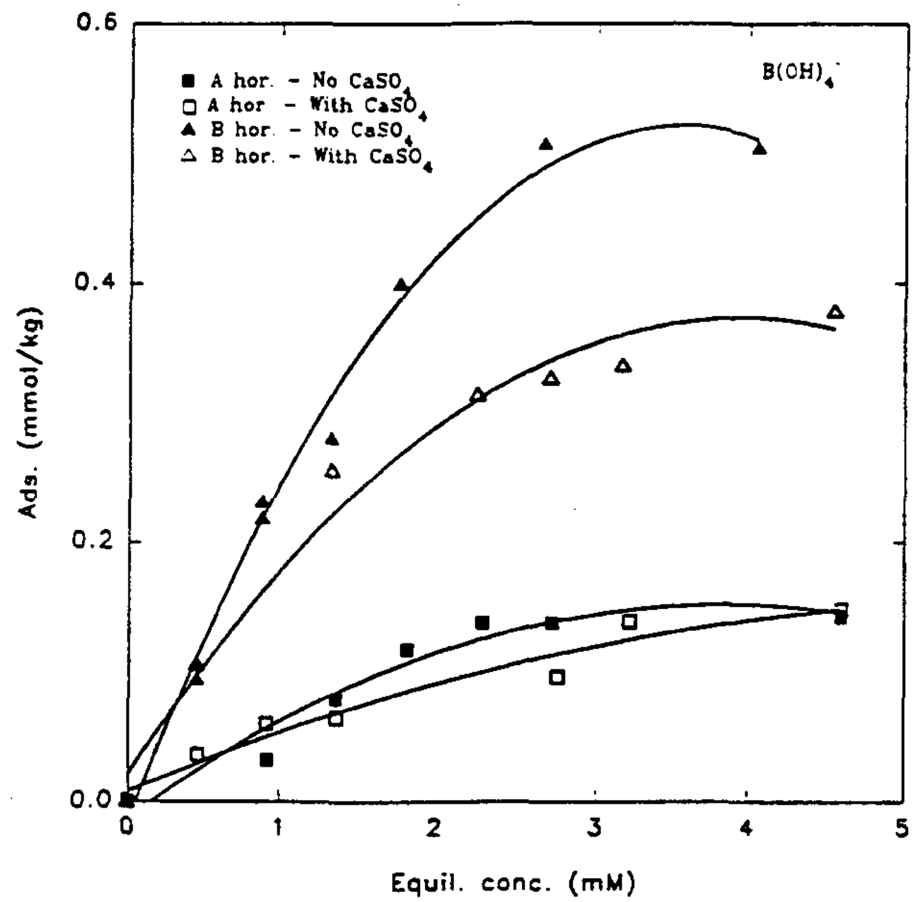


Figure 3-45. Boron Adsorption Isotherms in the Absence and Presence of $CaSO_4$ (0.125 mM) for Application of Ap and Bt Soils

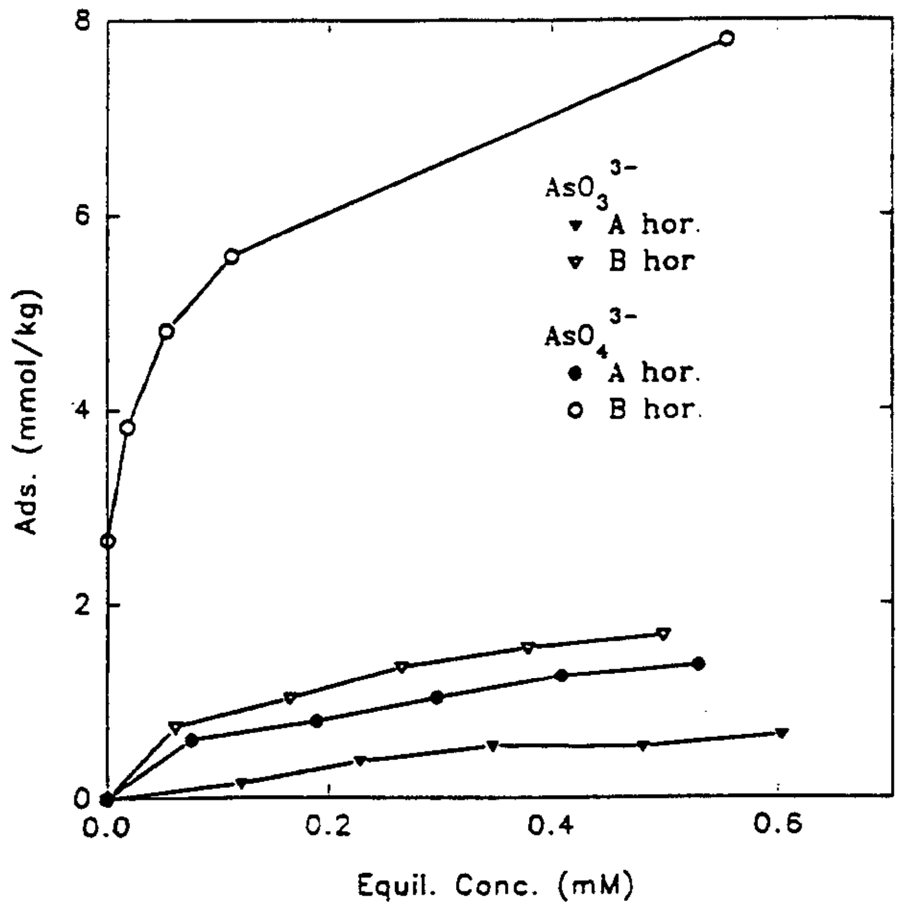


Figure 3-46. Arsenite and Arsenate Adsorption Isotherms for Application of Ap and Bt Soils

1989). Thus, movement of the As contaminant present in leachates of CCB would likely be retarded by the Appling Bt horizon. Less B was adsorbed in the presence of $CaSO_4$, probably due to the competition between the sulfate and B for the adsorption sites (Figure 3-45). The reduction in B adsorption was not significant for the Ap horizon due to the low adsorption capacity of the soil in this horizon. This is consistent with the findings of Sakata (1987a), who observed that B adsorption by soils was slightly affected by the $CaSO_4$ concentration (0-10 mM) in solution.

3.3.1.2.3 Metal Uptake by Plants: Greenhouse Studies

Much research has been conducted to evaluate the potential benefits and negative impacts of fly ash application on agricultural land. Depending on its composition, fly ash may correct Mo, Se, B, and S deficiencies (Plank and Martens, 1974; Elseewi et al., 1980b; Gutenmann et al., 1979) . Alkaline fly ashes can increase soil pH when applied at high rates (5-10%). Furthermore the water holding capacity of coarse texture soils can be improved with high rates of fly ash (Campbell et al., 1983). Laboratory incubation and weathering studies (Warren and Dudas, 1985) suggest that fly ash over time, could increase soil sorptive capacity. On the other hand, investigations of the agricultural usefulness of FGD are more limited because of the more recent appearance of this material. Use of mined gypsum as a nutrient source and soil amendment has been common for many years in the Southeast of the U.S. and elsewhere (Sumner, 1993). Investigations have demonstrated its effectiveness in reducing clay dispersion and consequently improving water infiltration and movement through the soil (Miller et al.,1991). Furthermore, FGD may prove to be a source of B and Se in addition to Ca and S. It has also proved effective in ameliorating the soil acidity syndrome (Sumner et al.,1986). Often mixtures of fly ash and FGD are produced when utilities decide not to separate them or when the electrostatic precipitators fail to efficiently remove the fly ash from the gas stream. There are several factors limiting fly ash and FGD application to agricultural land. Boron (B) toxicity to plants is one of the most often reported (Elseewi et al.,1980b; Walker and Dowdy, 1980; Aitken and Bell,1985). The objective of the present investigation was to examine five fly ashes from the Southeast of the U.S. and one FGD from Illinois to establish acceptable rates of application which would safely supply B for plant growth in Cecil soil typical of this region. In addition, the influence of Ca from two different sources, FGD and calcium hydroxide, on B accumulation in plant tissue was investigated.

Because fly ash contains considerable amounts of B which is often deficient in Southeastern soils, B release from fly ash and its uptake by corn (Zea mays L.), were investigated initially under greenhouse conditions. Boron is an element of great concern because its concentrations in fly ash often considerably exceed those found in most soils. While fly ash can be an effective source of B which is readily available to plants (Plank and Martens, 1974), excessive B contents in fly ash amended soil can result in plant toxicity (Elseewi et al., 1980b), although it is relatively nontoxic to animals and humans (Adriano, 1986). Because information on the agronomic benefits to be derived from Southeastern fly ash materials is very limited, their potential as ameliorants for low B content soils was evaluated. Both soils used have low levels of native hot water extractable B but differ in texture. The fly ashes differ in pH, total B content and B solubility. Because both fly ashes contain substantial amounts of potassium (K), their ability to supply plant available K was also evaluated.

3.3.1.2.3.1 Wheat Studies

An initial pot study was conducted in the greenhouse to evaluate low to medium rates of CCB on growth of wheat using a Cecil sandy loam topsoil. Pots containing 2.5 kg of soil were amended with the equivalent of 0, 1, 2.5, 5, 10, 20 or 30 mt /ha of either Yates, Scherer, Gaston, Branch, or Bowen fly ash, or FGD from Springfield, IL. No basal fertilizer was added to any treatment. Plants were watered as needed, and some minor discharge from pot drainage holes was allowed. After 6 weeks, the aerial plant parts were harvested from the pots, weighed, and analyzed for trace elements.

Yields on the unfertilized soils were all low, and CCB amendment did not significantly affect yields compared to the control treatment (Table 3-31). The rates used were quite low compared to later greenhouse trials (see below), and this in retrospect was not an unexpected result. Analyses of plant tissue showed no significant effect of CCB additions on P, K, or Mg content of

TABLE 3-31

WHEAT YIELDS IN GREENHOUSE EXPERIMENT ON CECIL SOIL AMENDED WITH CCB

Material:	Rate of CCB application (mt/ha equivalent)					
	1	2.5	5	10	20	30
	g / pot					
Yates	1.28	1.39	1.82	1.80	1.79	1.59
Scherer	1.77	1.81	1.73	1.95	1.95	1.86
Gaston	1.62	1.82	1.86	2.00	2.00	2.24
Branch	1.70	1.88	2.28	2.40	2.19	2.53
Bowen	1.59	1.48	1.60	1.84	2.02	2.21
FGD (Ill)	----	1.67	1.97	1.90	1.88	1.80
Control	1.80					

wheat foliage, although higher rates (> 20 mt/ha) did result in increased Ca content in leaves for all the ashes and the FGD (control: 4200 compared to 5000-5900 mg/kg for CCB treatments).

For trace metals in plant tissue, Cu, Zn, and Mn were not affected by CCB addition; B was elevated in tissue (Table 3-32) compared to control for all CCBs except for the FGD, which was low in total B. Yates ash, containing the highest level of total B, gave tissue with very high concentrations, although only weak toxicity symptoms (yellow/brownish leaf margins) were observed, and no effect on yield was observed. Other ashes gave only modest increases in tissue B. Molybdenum (Mo) was also increased over controls in most of the higher rates for fly ash additions (Table 3-33). While these levels (<3 mg/kg in tissue) are not toxic to animals, the Cu:Mo ratio at the highest level of ash additions decreased to quite low levels (approximately 3-7) compared to control (>100); ratios of <10 in forages fed to ruminant animals may have a detrimental effect on animal performance due to Mo-induced Cu deficiency ("molybdosis").

3.3.1.2.3.2 <u>Corn Studies</u>

First Greenhouse Experiment: The Cecil sandy loam soil (clayey, kaolinitic, thermic Typic Kanhapludult) used in this greenhouse experiment had the following properties: pH (H_2O): 4.91,

TABLE 3-32
BORON CONTENTS OF WHEAT TISSUE FROM CCB-AMENDED CECIL SOIL

Material:	**CCB application rate (mt/ha equivalent)**					
	1	2.5	5	10	20	30
	mg B / kg tissue					
Yates	11	23	31	75	225	495
Scherer	7	7	16	6	9	20
Gaston	7	4	5	8	7	12
Branch	6	4	7	9	21	25
Bowen	8	5	10	11	20	34
FGD (Ill)	----	9	4	5	3	4
Control	6					

TABLE 3-33
MOLYBDENUM CONTENTS OF WHEAT TISSUE FROM CCB-AMENDED CECIL SOIL

Material:	**CCB application rate (mt/ha equivalent)**					
	1	2.5	5	10	20	30
	mg Mo / kg tissue					
Yates	>0.02	0.38	<0.02	1.00	2.35	3.18
Scherer	<0.02	0.29	<0.02	0.05	0.47	0.94
Gaston	<0.02	0.29	<0.02	0.90	1.53	0.95
Branch	<0.02	<0.02	0.26	<0.02	0.82	0.38
Bowen	<0.02	<0.02	<0.02	0.27	,0.02	1.82
FGD (Ill)	<0.02	<0.02	0.06	<0.02	<0.02	<0.02
Control	0.05					

pH (KCl): 4.13 (soil :solution v/v 1:2.5), CEC: 5.95 $cmol_c$/kg, clay: 104 g/kg, organic carbon: 18.8 g/kg, HWSB: 0.23 mg/kg. Soil was treated with the following rates of fly ash or FGD : 0,6.3, 12.5, 25, 50 and 100 g/kg. Assuming mixing to 20 cm depth in the field, these rates would be equivalent to 0.0, 12.5, 25, 50, 100 and 200 mt/ha. CCB products included were FGD from Springfield, Ill, and ashes from Scherer, Yates, Gaston, Bowen and Branch; three different ashes from Plant Yates were used: a fresh, unweathered ash from the precipitator hopper, an ash from the landfill/lagoon area, which was of unknown age but assumed to be weathered, and a sample of fresh Yates ash weathered in the laboratory by repeated leaching with deionized water.

Nutrients were applied at rates of 195 kg N/ha as NH_4NO_3, 195 kg P/ha as triple superphosphate and 2 mt Ca/ha as $Ca(OH)_2$. Pots containing 2.5 kg soil with double plastic liners were arranged in random order in three replications. Soil moisture was maintained at 60 - 80% field water capacity by weight. Pioneer 3320 F-13 corn (Zea mays L.) hybrid was grown for 39 days. After harvesting, corn tops were rinsed with distilled water to remove adhering dust and soil and fly ash particles sticking to the lower parts of stems. Rinsing time did not exceed 30 seconds. Plants were dried to a constant weight at 65°C and ground. Soil samples were taken from each pot for pH and HWSB (hot-water-soluble boron) determination. Saturated extract electrical conductivity was measured only in the samples of soil amended with the highest rate of coal combustion by-products and in the control soil. For B analyses plant tissue was digested in $HClO_4$ / HNO_3 mixture on a hot plate (Allen, 1989). The azomethine-H method was used for B determination in soil extracts and plant tissue digests (Parker and Gardner, 1981).

Initial soil analyses showed that soil pH was significantly increased only at high rates (50 and 100 g/kg) of the most alkaline fly ashes (Yates and Gaston; Table 3-34). Soil amended with alkaline fly ashes (Branch and Bowen) and low rates of Yates and Gaston fly ashes had lower pH than the control soil. This is likely to be due to the salt effect (Sumner, 1994). The increased salt concentration after the addition of fly ashes to soil induced decreases in pH due to exchange of the added cations with H^+ and Al^{3+}. At the low rates of alkaline fly ashes or in the case of very low Ca content in fly ash the salt effect prevails.

TABLE 3-34
ELECTRICAL CONDUCTIVITY OF SOIL SATURATED EXTRACTS AND PH† OF SOIL AMENDED WITH DIFFERENT RATES OF FLY ASHES OR FGD

Fly Ash or FGD Rate	Fly Ash							FGD
	Yates	$Yates_{Art}$	$Yates_{Lag}$	Branch	Bowen	Gaston	Scherer	
g/kg	pH							
0.0	6.87a‡	6.87a	6.87ab	6.87a	6.87a	6.87a	6.87a	6.87a
6.3	6.48b	6.80a	6.75a	6.61b	6.44b	6.69b	6.60b	6.26b
12.5	6.75ab	6.76a	6.81ab	6.59b	6.52b	6.85a	6.61b	6.35bc
25.0	6.84a	6.79a	6.90b	6.61b	6.58bc	7.02c	6.55b	6.43c
50.0	6.85a	7.05b	7.15c	6.64b	6.63bc	7.46d	6.53b	6.45c
100.0	7.63c	7.35c	7.31d	6.63b	6.72ac	7.79e	6.61b	6.81a
	EC (dS/m)							
0.0	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
100.0	3.80	3.55	1.71	2.58	1.98	2.38	1.02	3.20

† pH measured at soil:water ratio v/v 1:2.5
‡ Means within column followed by the same letter are not significantly different at the probability level 0.05.

All fly ashes increased EC of soil saturated extracts over the control soil EC (0.83 dS /m), reaching levels which approached the threshold value (4 dS m^1) for good corn growth (Maas and Hoffman, 1977). Fly ash and FGD addition to soil resulted in a linear increase HWSB in all cases (Table 3-35) with R^2 values >0.98. Although plants have different soil B requirements, HWSB levels below 0.5 mg/kg are considered to be low or insufficient for many crops. While most plant species require more than 0.5 mg B/kg, levels in excess of 5 mg/kg of HWSB are toxic to plants (Bradford,1966; Ponnamperuma et al.,1981; Johnson and Fixen,1990). Fly ashes (Yates and $Yates_{Art}$) at the rates of 6.3 and 12.5 g/kg produced levels of HWSB in the sufficiency range but higher rates resulted in a potential for toxicity. At the highest rate of both fly ashes (100 g/kg) approximately 30 mg/kg of HWSB was present in the soil. The weathering and leaching of fly ash under ponding (field) conditions ($Yates_{Lag}$) resulted in much lower HWSB concentrations in fly ash amended soil with toxic levels being reached only at the highest ash rate. Soil amended with Branch and Bowen fly ashes had HWSB in the toxicity range only at the highest rate while no toxicity problems were encountered with Gaston and Scherer fly ashes and FGD .

Hot water soluble B determined at equilibrium pH does not provide a good basis for estimation of potential B release from fly ash when incorporated into soil because the pH of the fly ash-water system is strongly affected by fly ash chemical properties while the pH of the fly ash-soil system is strongly influenced by soil properties. Even Yates and Gaston fly ashes, having the highest pH and buffer capacity values, did not increase soil pH by more than one unit at the highest fly ash rate.

The Ca content of fly ash could be a very important factor controlling the rate of B solubilization in aquatic environments but is less important in well buffered soil systems. An equation was developed which allows one to estimate the level of HWSB in soil amended with different rates of fly ash, based on the B content of fly ash in a boiling solution adjusted to the pH of the soil. A comparison of predicted and measured HWSB values shows good agreement for all fly ashes (Table 3-35). Predicted values overestimate HWSB probably due to B sorption by soil or an increase in soil pH after application of Yates and Gaston fly ashes or both. The best agreement between predicted and measured HWSB was obtained for fly ashes with a low neutralization capacity (Branch, Bowen and Scherer) which is indicated by the highest values of the D-index

(Table 3-35). The D-index is equal to 1.0 for perfect agreement between predicted and measured values, and approaches 0.0 in case of total failure of prediction. In contrast, estimated HWSB values for FGD amended soil are significantly higher than the measured ones. This leads to the conclusion that B incorporated into soil with fly ash probably underwent much less chemical change during the greenhouse experiment than that incorporated with FGD .

TABLE 3-35
MEASURED AND PREDICTED HOT WATER SOLUBLE BORON IN CECIL SOIL AMENDED WITH DIFFERENT RATES OF FLY ASH OR FGD AND PREDICTION QUALITY EVALUATION (D-INDEX)

Fly Ash or FGD Rate	Hot Water Soluble B							
	Measured Values							
	Fly Ash							FGD
	Yates	Yates$_{Art}$	Yates$_{Liq}$	Branch	Bowen	Gaston	Scherer	
	mg/kg							
0.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
6.3	2.29	2.38	0.71	0.61	0.48	0.37	0.24	0.24
12.5	4.16	4.12	1.21	0.97	0.81	0.63	0.35	0.45
25.0	8.01	8.66	2.26	1.61	1.54	1.10	0.64	0.75
50.0	18.2	16.3	3.80	2.81	2.86	2.00	1.33	1.28
100.0	28.6	30.8	6.28	4.83	5.05	3.22	2.20	2.32
$LSD_{0.05}$	2.22	1.58	0.45	0.33	0.17	0.15	0.16	0.10
a†	0.87	0.54	0.39	0.37	0.25	0.27	0.16	0.18
b‡	0.29	0.31	0.07	0.05	0.05	0.03	0.02	0.02
	Predicted Values							
6.3	2.86	3.36	0.92	0.62	0.62	0.49	0.35	0.57
12.5	5.46	6.44	1.62	1.02	1.02	0.79	0.49	0.94
25.0	10.5	12.4	3.05	1.80	1.84	1.36	0.78	1.65
50.0	20.5	24.3	5.72	3.26	3.34	2.48	1.32	3.03
100.0	40.7	47.9	10.8	6.00	6.27	4.67	2.36	5.68
D	0.94	0.90	0.85	0.97	0.97	0.93	0.99	0.65

† intercept and ‡ slope of linear regression equations for HWSB in soil amended with different rates of fly ash or FGD

All fly ashes and FGD increased the B content in corn tops over the control plants which contained 8.6 mg/kg B (Figure 3-47). This is a low but sufficient value for corn (Bingham,1973; Jones et al., 1990) which is tolerant of low B levels in soil. Yates and Yates$_{Art}$ fly ashes at the 25 mt/ha rate elevated the B level in corn tops above 100 mg/kg which is considered to be toxic

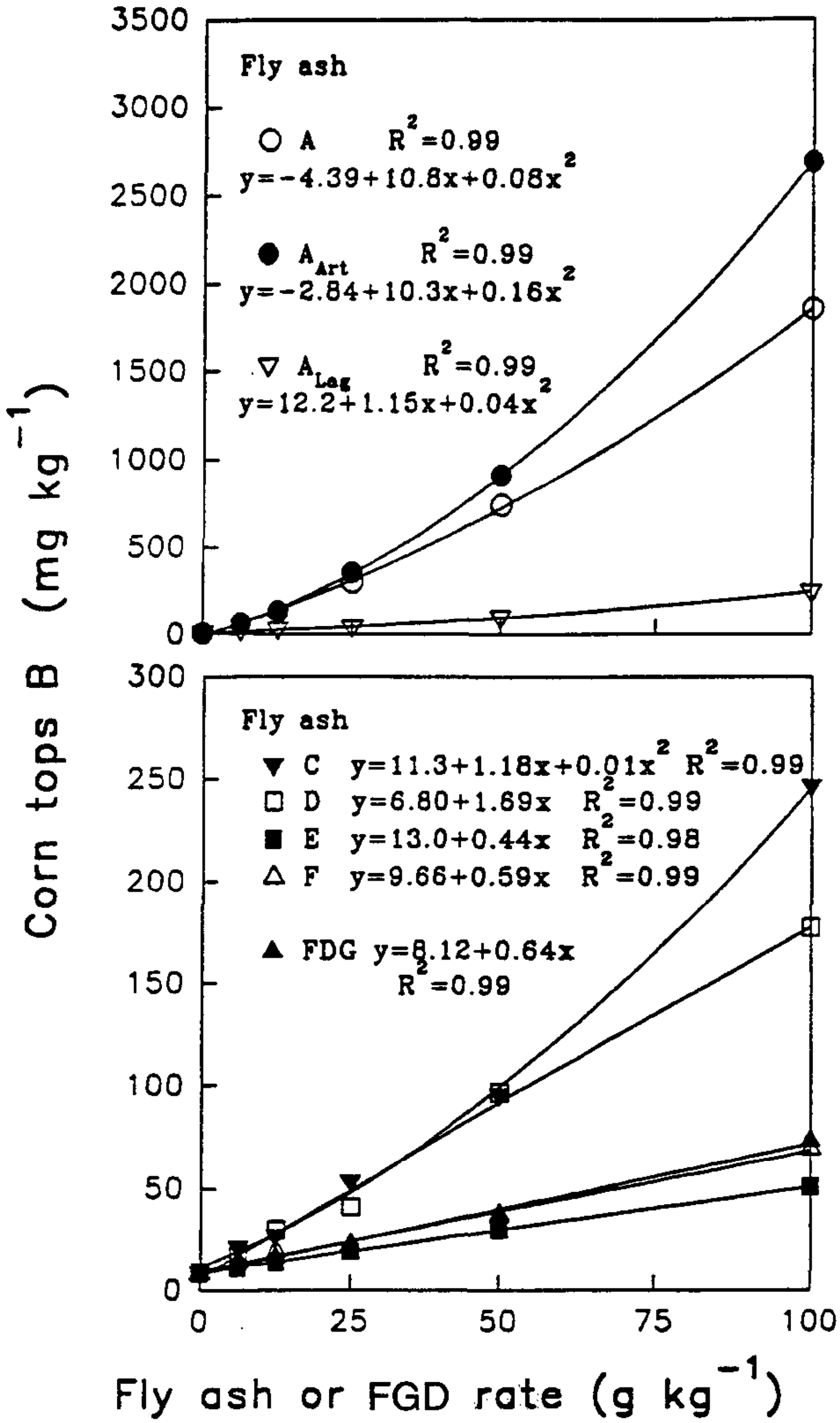


Figure 3-47. Boron in Corn Tops Grown in Soil Amended with Different Rates of Fly Ashes or FGD

(El-Sheikh et al., 1971; Gupta,1983) while at the highest rate (100 g/kg), plants accumulated 1858 and 2633 mg B/kg of dry matter, respectively, associated with very large yield decreases (Table 3-36). Despite similar B levels in soil (Table 3-37), corn tissue from soil amended with $Yates_{Art}$ fly ash was higher in B than that from soil treated with fresh Yates fly ash. All plants grown in soil amended with rates of Yates and $Yates_{Art}$ fly ashes in excess of 6.3 g/kg exhibited leaf damage typical of B toxicity (yellow and brown necrosis of leaf margins and tips) (Oertli and Kohl, 1961; Gupta, 1983). These symptoms were more pronounced at the highest fly ash rates. Toxicity symptoms were more severe in plants grown on soil amended with $Yates_{Art}$ fly ash associated with a large yield reduction which is in agreement with the higher predicted HWSB in this ash in comparison to the fresh material.

Weathering and leaching of Yates fly ash under field conditions significantly decreased the ash B content ($Yates_{Lag}$) and its toxicity. In this respect, the $Yates_{Lag}$ fly ash is similar to Branch and Bowen fly ashes. For these three ashes, toxic B levels in corn tissue occurred at the 50 g/kg ash rate but corn yield was not affected. Gaston and Scherer fly ashes and FGD did not cause any B toxicity problems and therefore these can be applied to soil at high rates without encountering problems. The yield decrease in soil amended with Gaston fly ash (Table 3-36) was probably caused by phosphorus fixation. Plants exhibited very strong P deficiency symptoms, especially at high ash rates which was confirmed by tissue analyses.

A quadratic or simple linear function provides a good description of the relationship between fly ash or gypsum rate and B concentration in corn tops. The B content in corn tops was very closely correlated with measured HWSB values (Figure 3-48). The second order equation describes this relationship well for the combined data from all fly ashes and FGD , except at the two highest rates of Yates and $Yates_{Art}$ fly ashes.

TABLE 3-36
DRY MATTER OF CORN TOPS GROWN IN SOIL AMENDED WITH DIFFERENT RATES OF FLY ASH OR FGD

Fly Ash or FGD Rate	Corn tops dry matter							
	Fly Ash							FGD
	Yates	$Yates_{Art}$	$Yates_{Lag}$	Branch	Bowen	Gaston	Scherer	
	g/kg					g/pot		
0.0	5.78	5.78	5.78	5.78	5.78	5.78	5.78	5.78
6.3	5.42	4.40	5.39	4.66	5.32	5.56	5.66	5.41
12.5	5.03	4.50	6.42	5.59	5.66	4.65	5.04	5.66
25.0	4.67	3.97	5.44	4.95	4.91	5.35	4.88	5.14
50.0	3.15	2.40	5.38	6.36	4.69	4.45	5.27	4.58
100.0	1.12	0.66	5.23	6.37	5.43	3.53	5.50	4.42
LSD 0.05	0.83	0.78	1.18	0.92	0.61	1.18	1.39	0.9

TABLE 3-37
SELECTED PROPERTIES OF CECIL AND LAKELAND SOILS

Soil	pH		CEC	Sand	Silt	Clay	Organic carbon	Soluble B
	H_2O	KCl						
			$cmol_c$/kg		g/kg		g/kg	mg/kg
Cecil	5.00	4.13	5.95	629	267	104	15.5	0.18
Lakeland	5.98	5.14	1.80	879	78	25	4.8	0.13

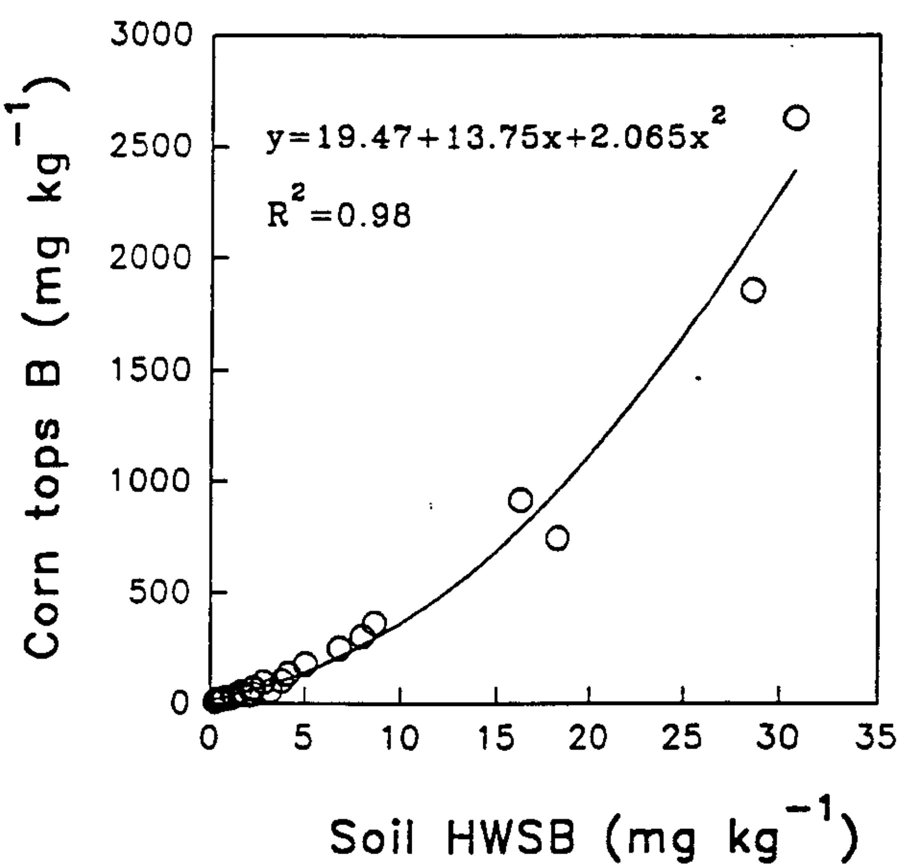


Figure 3-48. Relationship Between Corn Tissue B and Hot Water Extractable Boron in Soil Amended with Different Rates of Fly Ashes or FGD

Arsenic was analyzed in the amended soil using the Mehlich (dilute-acid) extractant immediately after harvest of the corn, and was found to be a roughly linear function of application rate, with the varying CCBs having different slopes to these lines (Figure 3-49). Branch, with the highest total and soluble As, had the highest levels of extractable As, followed by $Yates_{lag}$, Gaston and Bowen. Levels in control soil were < 0.2 mg/kg, indicating significant enrichment in extractable As for all amended soils except for FGD and Scherer treatments.

Corn tissue was analyzed for As by graphite furnace atomic absorption after digestion in concentrated NHO_3; As levels increased with increasing rate of CCBs, and were above 0.2 mg/kg for Branch, $Yates_{lag}$, Gaston, and Bowen (Figure 3-50). The higher solubility of As in the Branch ash was apparent in the tissue data, where up to 0.8 mg/kg was found; this was not as clearly shown in the soil acid-extractable data (Figure 3-49). Levels above 1 mg/kg have been suggested to be of some environmental concern due to bioaccumulation in the food chain; thus, at very high rates of CCB addition (> 100 mt/ha), such effects may need to be considered.

Regression analysis was performed on the data in Figures 3-49 and 3-50 in order to relate soil levels of As to plant tissue uptake; despite the apparent poor relationship between extractable and tissue As for Branch soil (noted above), a significant relationship for all the various ashes was obtained, with a nearly zero intercept and slope of 0.11 (Figure 3-51). For corn at an early stage of growth, an extractable level of roughly 8 mg/kg As would result in about 1 mg/kg As in plant tissue.

Second Greenhouse Experiment: Samples of Cecil (clayey, kaolinitic, thermic Typic Kanhapludult) and Lakeland (thermic, coated Typic Quartzipsamment) soils were collected from 0-0.2 m layer of cultivated fields near Athens and Tifton, GA, respectively. Soil characteristics are presented in Table 3-37. The moist soils were passed through a 10 mm mesh and air-dried. The Cecil soil was amended with $Ca(OH)_2$ at a rate equivalent to 3750 kg/ha while both soils received triple superphosphate equivalent to 450 kg P_2O_5/ha. Nitrogen as NH_4NO_3 was applied at 75 kg N/ha before planting with the remainder (120 kg N/ha) in solution 16 days after germination. Solid fertilizers and lime were mixed with soil in a cement mixer prior to potting in 2.5 kg pots.

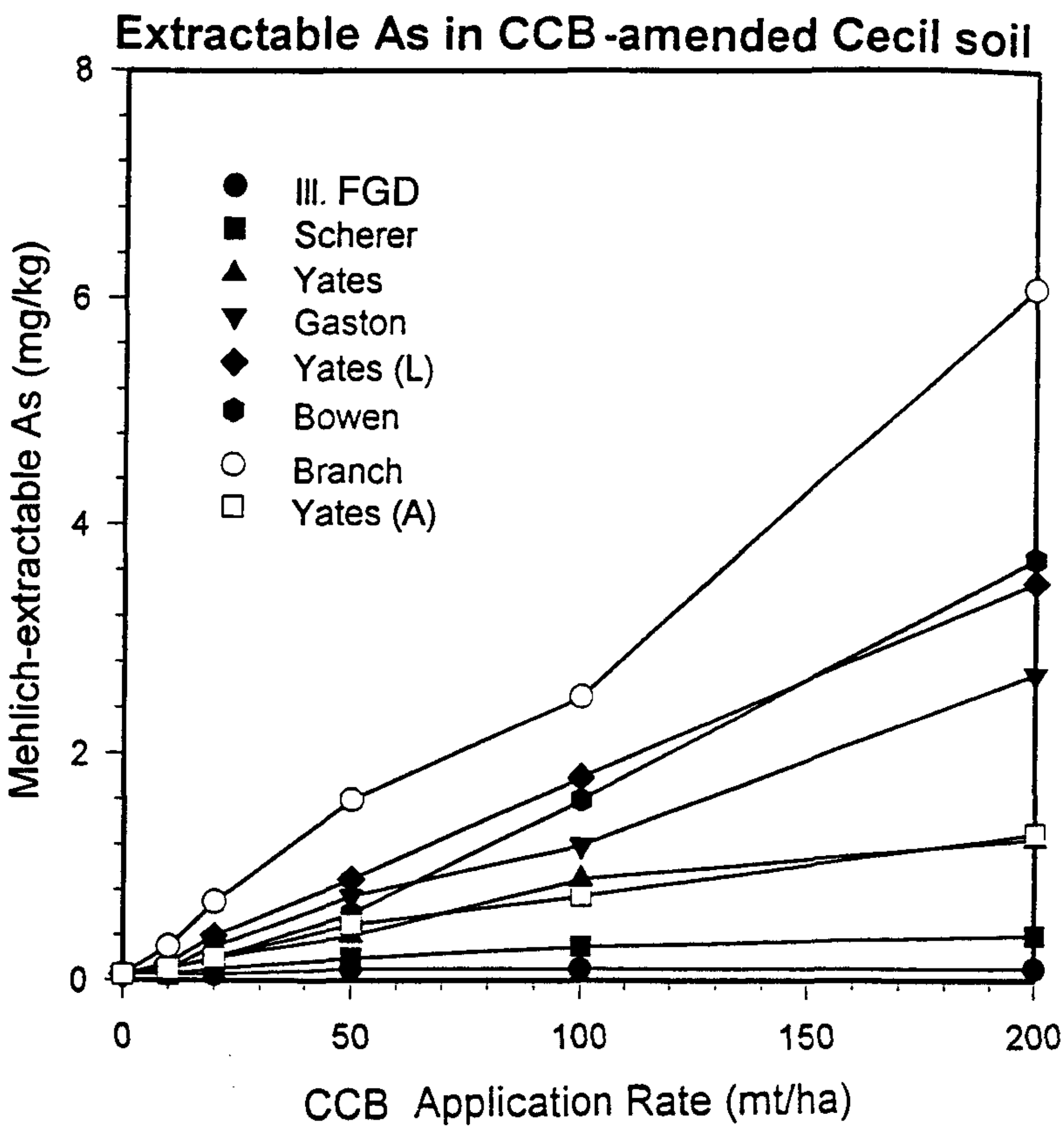


Figure 3-49. Effect of CCB Application on Mehlich As in a Cecil Soil

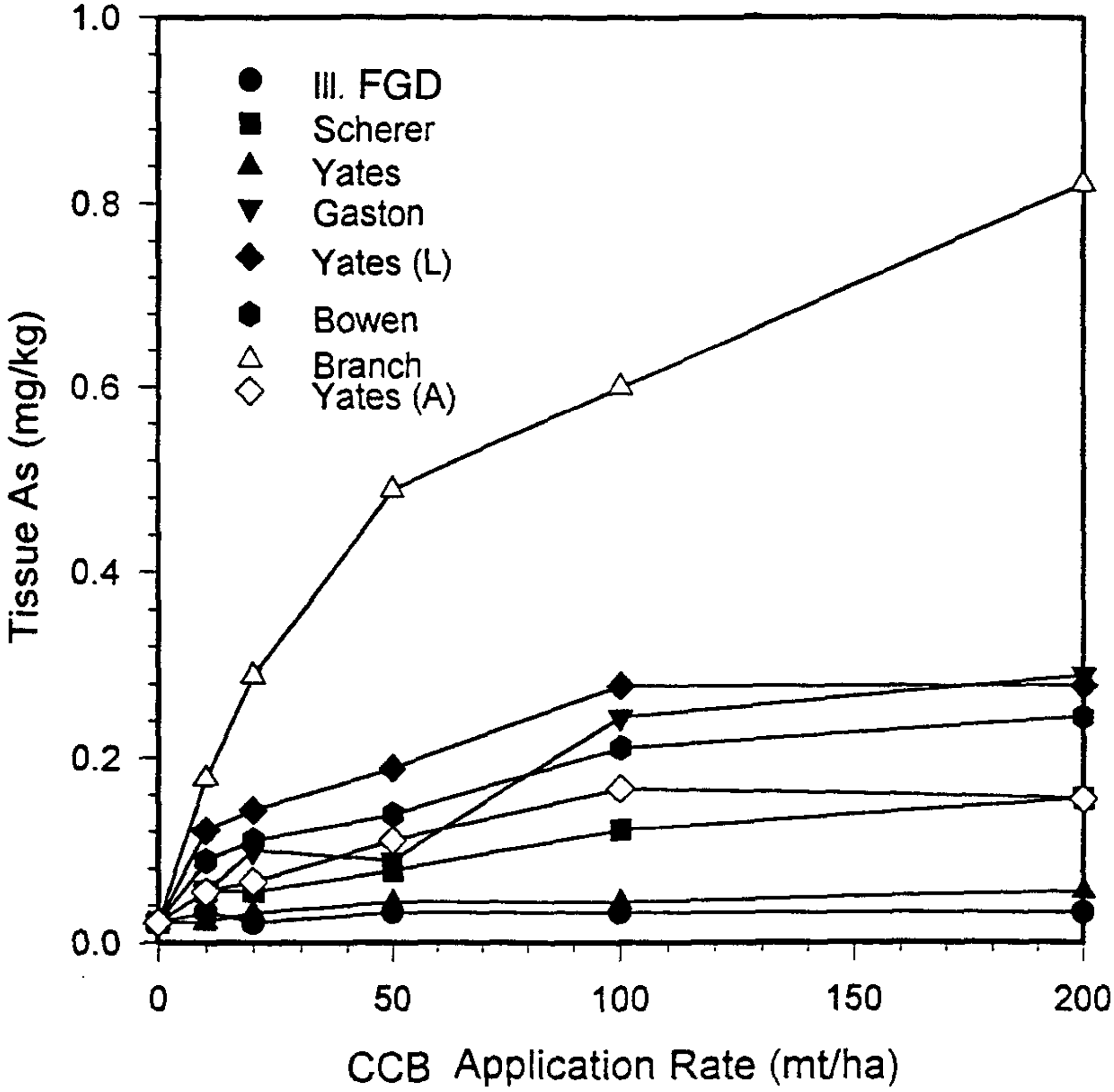


Figure 3-50. Effect of CCB Application on Tissue As

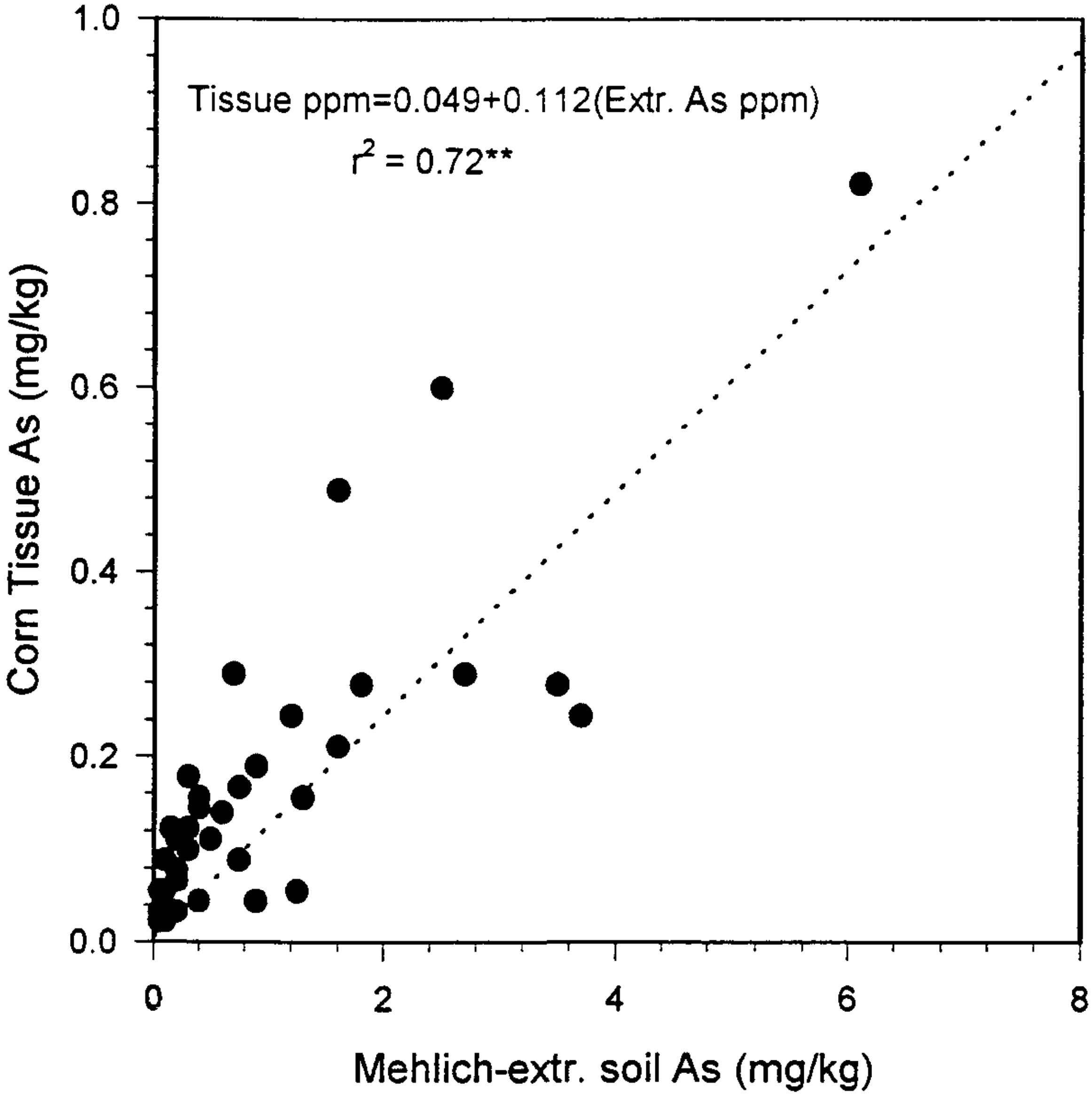


Figure 3-51. Relationship between Mehlich As and Corn Tissue As

Yates and Branch fly ashes were passed through 1-mm mesh screen, homogenized and added at rates of 0, 3.1, 6.3, 12.5, 25, 50 and 100 g/kg (0, 6.3, 12.5, 25.0, 50.0, 100.0 and 200.0 mt/ha to a depth of 0.2 m) to the Cecil, and 0.0, 1.6, 3.1, 6.3, 12.5, 25 and 50 g/kg to the sandier Lakeland soil. Two rates of KCl equivalent to 0 and 100 kg K_2O/ha were combined factorially with the fly ash treatments. Soil in each pot was mixed with the appropriate rate and type of fly ash in plastic bags and then replaced into pots lined with two plastic bags to prevent leaching. All treatments were replicated 3 times in two randomized block designs one for each soil, except controls which had 5 replicates. Field capacity of the soils was measured on a porous plate at the pressure of 10 and 33 kPa for Lakeland and Cecil soil, respectively. The day after watering to 80% of the field capacity with deionized water, 5 seeds of Pioneer 3320 F-13 corn hybrid were planted in each pot. Soil moisture in the pots was maintained at about 80% of field capacity by weight. Because of its lower water capacity, Lakeland soil was watered more often than Cecil. Corn was thinned to 3 plants per pot 12 days after planting and harvested 3 weeks after emergence. Because of the sandy nature of the Lakeland soil, roots could be separated and weighed. Plant tops and roots were dried in an oven at 60-65 °C to constant weight. Plant tissue was digested on a hot plate in a 2:1 HNO_3-$HClO_4$ mixture (Allen, 1989) for B determination. After harvesting, soil samples from each pot were obtained and hot water soluble boron (HWSB) (Bingham,1982), pH and EC determined.

For chemical analysis, 2g samples of fly ash were digested in 20 mL of concentrated HNO_3 and evaporated almost to dryness on a hot plate after which 15 mL 15% HCl was added and diluted with distilled water to 100 mL. Elements released from fly ash by this procedure represent amounts likely to be released under the harshest environmental conditions. Calcium, Mg, K and P were determined by inductively coupled plasma spectrometry (ICP) and B colorimetrically (Parker and Gardner, 1981). Fly ash EC and pH were measured after 24 hours equilibration with distilled water (1:2.5 ash:water). Selected properties of the fly ash materials are presented in Table 3-38. Fly ash HWSB was extracted at different solution pH values by appropriate additions of

TABLE 3-38
SELECTED CHEMICAL PROPERTIES OF FLY ASHES USED IN CORN GREENHOUSE EXPERIMENT

Fly ash	CCE†	pH	EC	Ca	Mg	K	Mg	K	P	B
	%		dS/m					g/kg fly ash		
Yates	4.4	10.2	2.03	15.6	1.4	2.8	1.4	2.8	0.8	0.85
Branch	1.2	8.4	1.98	8.8	2.2	4.3	2.2	4.3	1.5	0.24

† CCE = calcium carbonate equivalent

HNO_3 or NaOH followed by essentially the same procedure as used for soil (Bingham, 1982). Ten g fly ash were boiled with 20 mL of distilled water for 5 min and filtered through Whatman #42 filter paper. The final pH of solution was measured and B was determined. The azomethine-H method (Parker and Gardner, 1981) was used for B determination in all soil and fly ash extracts and digested plant samples. The fly ash calcium carbonate equivalent (CCE) was determined by boiling fly ash with 0.5M HCl and titration of excess acid with NaOH (AOAC, 1990).

Analysis of variance using the GLM procedure (SAS, 1988) and the t-test were used for evaluation of the fly ash effect on soil pH and EC. Regression analysis and analysis of variance were used for description of the effect of K fertilizer and fly ash application on soil HWSB, plant dry matter and tissue B concentration. The analysis of variance was performed separately for each soil on pooled fly ashes data and separately for each ash for comparison of the effects of fly ashes and K fertilizer on the same soil.

Several non-linear models were tested to describe the influence of fly ash rate on corn top and root dry matter. The consistently highest coefficients of determination were obtained for the model.

$$y=a+bx+cx^{1/2} \qquad [1]$$

The ability to predict soil HWSB from the fly ash B solubility test was evaluated using several statistical measures describing different aspects of prediction error (Willmott, 1981). The coefficient of determination (R^2) for the regression equation describing the relationship between actual (B_{act}) and predicted (B_{pred}) soil B values was compared with that for the 1:1 line (R_1^2). The root mean square error (RMSE) and systematic (E_s) and random (E_u) errors which comprise the RMSE were calculated from the following equations:

$$RMSE = (E_s^2 + E_u^2)^{1/2} \quad [2]$$

$$E_s = [N^{-1}S(B_{ri} - B_{acti})^2]^{1/2} \quad [3]$$

$$E_u = [N^{-1}S(B_{predi} - B_{ri})^2]^{1/2} \quad [4]$$

where B_{ri} is calculated from the equation describing the regression line for actual and predicted values:

$$B_{ri} = a + bB_{acti} \quad [5]$$

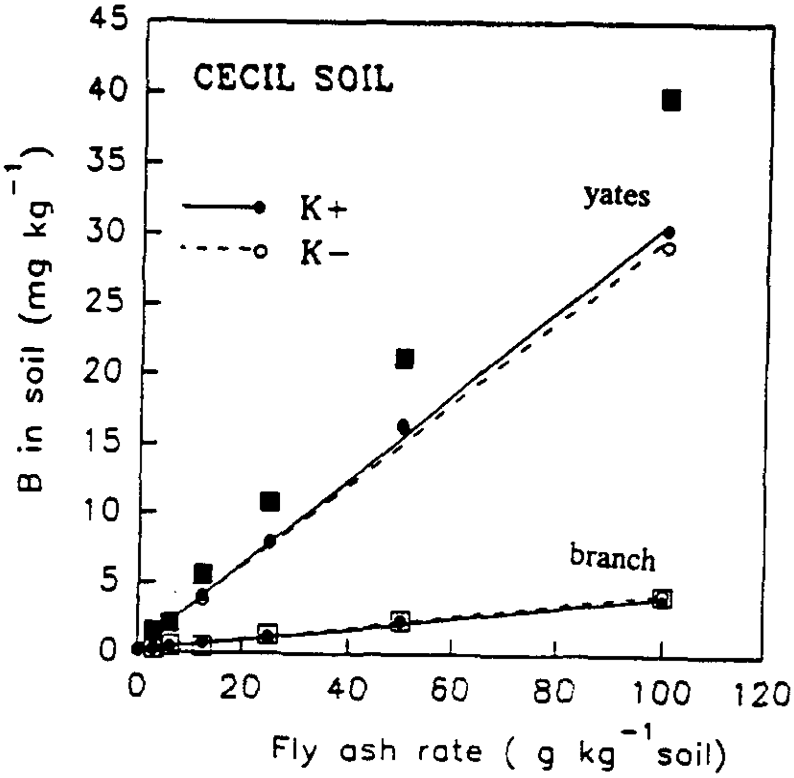
The results of this greenhouse trial showed that both fly ashes were very poor liming agents, with only the highest rate of Yates fly ash increasing the pH of the Cecil soil (Table 3-39). This agrees with laboratory determinations of liming value determined earlier (see section 3.3.1.2.1.4). On the less buffered Lakeland soil, both fly ashes significantly increased pH over that of the control at the higher rates. At the higher rates of both fly ashes, EC was significantly increased in both soils, with Yates fly ash having a significantly ($P < 0.0001$ for each soil) greater effect than the less alkaline Branch fly ash. However, EC did not reach levels likely to cause plant injury in any treatment (Maas and Hoffman, 1977).

A strong correlation was found between fly ash addition rate and HWSB for both Cecil and Lakeland soils (Figure 3-52, Table 3-40), with the Yates ash (richer in soluble B) resulting in significantly higher ($P < 0.0001$ for each soil) values. Fertilizer K had no influence on B

TABLE 3-39
ELECTRICAL CONDUCTIVITY (EC) AND PH OF SOILS AMENDED WITH DIFFERENT RATES OF TWO FLY ASHES†

Fly ash rate	Yates fly ash			Branch fly ash	
	pH	EC		pH	EC
g/kg soil		dS/m			dS/m
			Cecil soil		
0.0	6.89	0.227		6.89	0.227
3.1	6.98	0.234		6.70*	0.198
6.3	6.92	0.264		6.84	0.231
12.5	6.88	0.306*		6.83	0.271*
25.0	6.69	0.395*		6.76	0.317*
50.0	6.90	0.607*		6.79	0.468*
100.0	7.45*	0.926*		6.76	0.698*
			Lakeland soil		
0.0	6.21	0.086		6.21	0.086
1.6	6.27	0.110		6.22	0.089
3.1	6.26	.121*		6.28	0.112
6.3	6.36*	0.166*		6.21	0.108
12.5	6.31	0.305*		6.31*	0.140*
25.0	6.52*	0.496*		6.34*	0.190*
50.0	7.26*	0.696*		6.36*	0.386*

* Significantly different from control at P=0.05 according to T-test
† soil : distilled water 1:2.5, equilibration time 24 hrs



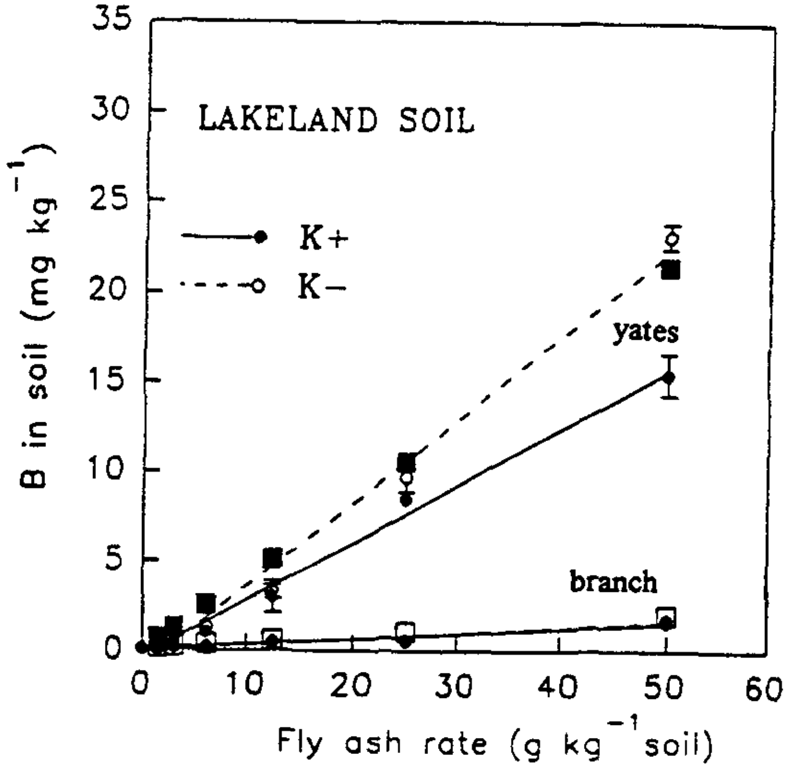


Figure 3-52. Hot Water Soluble B in Cecil and Lakeland Soils Amended with Different Rates of Fly Ashes (Note: circles=measured values and squares=calculated values)

TABLE 3-40
LINEAR REGRESSION EQUATIONS AND COEFFICIENTS OF DETERMINATION (R^2) FOR HOT WATER EXTRACTABLE B IN CECIL AND LAKELAND SOILS AMENDED WITH DIFFERENT RATES OF FLY ASH.

Soil	Fly ash	Equation	R^2
Cecil K+	Yates	y=0.270+0.306x	0.99
Cecil K-	Yates	y=0.354+0.295x	0.99
Cecil K+	Branch	y=0.211+0.039x	0.99
Cecil K-	Branch	y=0.162+0.043x	0.99
Lakeland K+	Yates	y=-0.390+0.321x	0.99
Lakeland K-	Yates	y=-1.092+0.467x	0.99
Lakeland K+	Branch	y=0.085+0.029x	0.97
Lakeland K-	Branch	y=0.012+0.032x	0.95

extractability except on Lakeland soil amended with Yates fly ash, where K additions with fly ash appeared to decrease levels of HWSB (Figure 3-52).

The HWSB in both fly ashes was highly dependent on the pH of the boiling solution (Table 3-41). The more acid the extracting solution the greater the solubility of B. Linear relationships between fly ash significantly ($P < 0.0001$) decreased B solubility. No supporting evidence for this effect could be found in the literature.

Most crops require 0.5-1.0 mg/kg HWSB for normal growth while 5 mg/kg can be toxic for many plants (Bradford, 1966; Ponnamperuma et al., 1981; Johnson and Fixen, 1990). Yates fly ash at the 3.1 g/kg rate would assure B sufficiency in both soils while B toxicity would be likely to occur at rates higher than 12.5 g/kg. Addition of Branch fly ash did not elevate soil HWSB above the potential toxicity level, and the sufficiency level was met at rates of 6.3 to 25 g/kg and 12.5 to 25 g/kg for the Cecil and Lakeland soils, respectively. It is possible to calculate from the regression equations fitted to the data in Table 3-41, the amount of HWSB likely to be released from fly ashes after addition to soil by equating the pH of the extracting solution after boiling to that of the soil. The expected HWSB in soil amended with different rates of fly ash can be calculated from the equation:

TABLE 3-41
EFFECT OF PH ON HOT WATER EXTRACTABLE B IN TWO FLY ASH MATERIALS AND REGRESSION EQUATIONS FOR HOT WATER EXTRACTABLE FLY ASH B AS FUNCTION OF PH

Yates fly ash			Branch fly ash	
pH	**B**		**pH**	**B**
	mg/kg			**mg/kg**
9.79	254		9.06	42.1
9.81	276		7.63	49.8
8.54	341		5.00	51.7
7.56	443		4.11	71.6
4.64	535		3.76	75.8
3.49	578		3.06	80.9
$y=1/(a+bx+cx^2+dx^3)$		$y=a+bx+cx^2+d\exp(x)$		
$a=7.477 \times 10^{-4}$		$a=170.158$		
$b=6.079 \times 10^{-4}$		$b=-36.741$		
$c=-1.262 \times 10^{-4}$		$c=2.850$		
$d=9.779 \times 10^{-6}$		$d=-3.364 \times 10^{-3}$		
$R^2=0.99$		$R^2=0.94$		

$$\text{Expected B (mg/kg)} = \{(RF+WS)/(W+R)\}-U \qquad [6]$$

where

R is rate of fly ash applied to the pot (kg)
F is HWSB in fly ash at pH = soil pH (mg/kg)
S is the native soil HWSB (mg/kg)
W is amount of soil in pot (kg) and
U is B uptake by plants (mg/kg of soil-fly ash mixture).

Plant B uptake for Cecil soil included only that present in stems and leaves since roots were not separated from this soil. The basic assumption of this equation is that simple dilution of fly ash HWSB by soil material accounts for most of the effect. The calculated values of HWSB are indicated by squares in Figure 3-52. Generally, there is good agreement between predicted and measured HWSB, but the quality of prediction varied between different soils and ashes. Cecil soil amended with Branch fly ash showed the best agreement between measured and predicted values indicated by the lowest systematic (E_s), random (E_u), and root mean square (RMSE) errors (Table 3-42). The form of equation for the relationship between measured (B_{act}) and predicted (B_{pred})

HWSB for this particular soil and fly ash is very close to a 1:1 line (y=x) describing an ideal prediction (Figure 3-53). This is confirmed by the close agreement between the values for R^2 (B_{pred}=a+bB_{act}) and R_1^2 (line 1:1). Predicted values of HWSB for Lakeland soil treated with both fly ashes slightly overestimated actual B solubility. Prediction quality for this soil was intermediate. The largest difference between actual and predicted values occurred in the Cecil soil amended with Yates fly ash, probably due to the higher pH of this soil promoting B sorption.

TABLE 3-42
REGRESSION EQUATIONS FOR ACTUAL AND PREDICTED HOT WATER SOLUBLE B IN CECIL AND LAKELAND SOILS AMENDED WITH DIFFERENT RATES OF FLY ASH, AND STATISTICAL PARAMETERS† DESCRIBING PREDICTION QUALITY

Fly ash	Soil	Equation	R^2	R_1^2	E_S	E_u	RMSE
						mg/kg	
Yates	Cecil	y=-0.028+1.328x	0.999	0.877	4.712	0.334	4.723
Yates	Lakeland	y=1.247+1.008x	0.945	0.909	1.391	1.222	1.851
Branch	Cecil	y=-0.033+1.031x	0.990	0.989	0.045	0.232	0.236
Branch	Lakeland	y=0.128+1.153x	0.956	0.831	0.226	0.352	0.418

† R^2 - coefficient of determination for regression equation, R_1^2 - coefficient of determination for 1:1 line, E_2 - systematic error, E_u- random error, RMSE - root mean square error

All indices of prediction quality confirm this. There is a substantial difference between the coefficient of determination (R^2) for the equation describing the relationship between actual and predicted values(R^2=0.999) and that calculated for the 1:1 line (R_1^2=0.877). The higher value for the former indicates that there is a very good linear relationship between actual and predicted soil HWSB values. However, the much lower value of R_1^2 for the 1:1 line indicates that the line plotted from B_{pred}=a+bB_{act} lies relatively far from the 1:1 relationship which is also confirmed by the systematic error of prediction being fourteenfold higher than the random error.

Plant dry matter was influenced by soil properties, fly ash and K rates. Increasing rates of Yates fly ash caused a drastic reduction in plant dry matter (tops and roots) (Figure 3-54, Table 3-43).

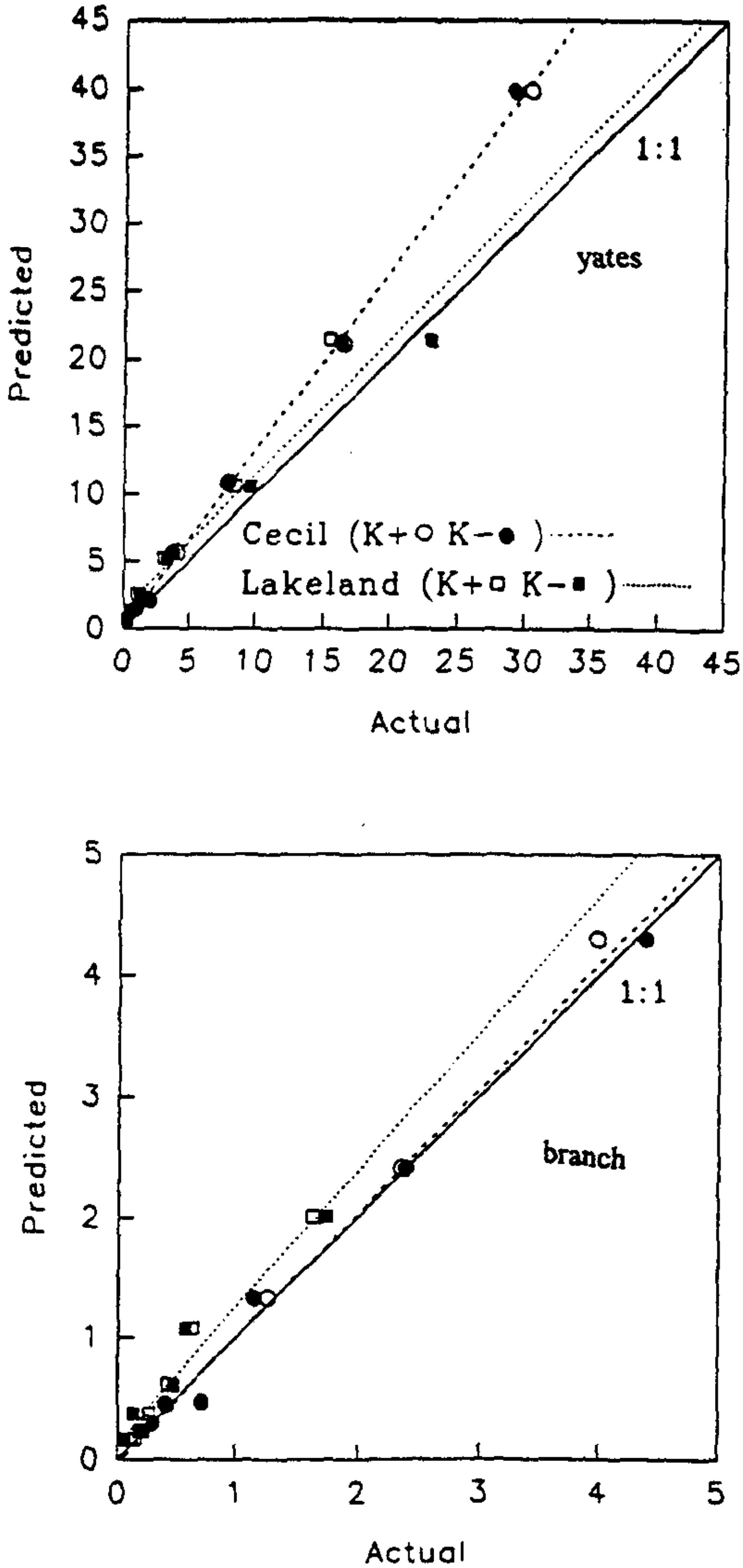


Figure 3-53. Preferred vs. Actual Hot Water Soluble Soil B (Broken Line=Regression)

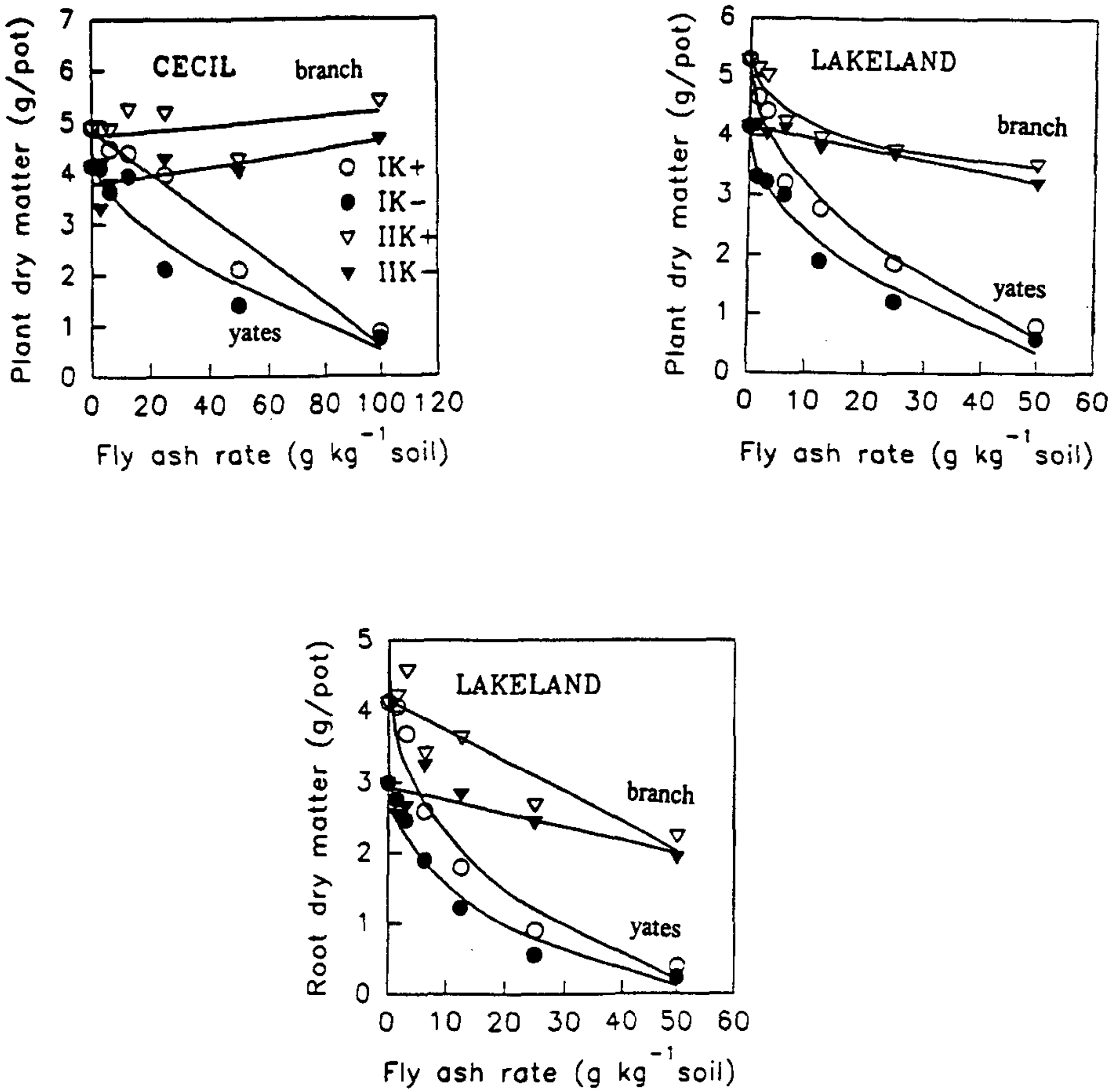


Figure 3-54. Plant Dry Matter (Tops and Roots) of Corn Grown on Cecil and Lakeland Soils withDifferent Rates of Fly Ashes
IK+ Soil Amended with Fly Ash I and K Fertilizer
IK- Soil Amended with Fly Ash I, No K Fertilizer
IIK+ Soil Amended with Fly Ash and K Fertilizer
IIK- Soil Amended with Fly Ash II, no K Feretilizer

TABLE 3-43
REGRESSION EQUATIONS, AND COEFFICIENTS OF DETERMINATION FOR CORN DRY MATTER AND B CONCENTRATION IN PLANT TISSUE AS A FUNCTION OF FLY ASH RATE (SEE FIGURES 3-53 AND 3-54)

Soil fly ash		**Plant dry matter**			**B concentration in plant tissue**	
		Equation	**R^2**		**Equation**	**R^2**
		Aerial parts			**Aerial parts**	
Cecil K+	Yates	$y=4.85-0.042x$	0.96		$y=8.92+6.90x+0.516x^2+0.002x^3$	0.99
Cecil K-	Yates	$y=4.48-0.006x-0.336x^{1/2}$	0.90		$y=-1.63+7.83x+0.949x^2-0.007x^3$	0.99
Cecil K+	Branch	$y=4.75+0.004x$	0.12		$y=11.5+0.880x+0.012x^2$	0.99
Cecil K-	Branch	$y=3.79+0.008x$	0.52		$y=10.7+0.911x0.011x^2$	0.99
		Aerial parts			**Aerial parts**	
Lakeland K+	Yates	$y=5.29-0.662x^{1/2}$	0.98		$y=2.98+48.7x+0.430x^2$	0.99
Lakeland K-	Yates	$y=4.08-0.525x^{1/2}$	0.97		$y=-19.8+58.2x+0.810x^2-0.012x^3$	0.99
Lakeland K+	Branch	$y=5.48+0.027x-0.475x^{1/2}$	0.92		$y=8.40+4.19x+0.030x^2$	0.99
Lakeland K-	Branch	$y=4.17-0.019x$	0.96		$y=17.8+3.93x+0.074x^2$	0.99
		Roots			**Roots**	
Lakeland K+	Yates	$y=4.57+0.027x-0.808x^{1/2}$	0.94		$y=21.8+9.50x+0.126x^2$	0.99
Lakeland K-	Yates	$y=3.25+0.024x-0.614x^{1/2}$	0.96		$y=10.6+15.1x-0.131x^2$	0.99
Lakeland K+	Branch	$y=4.17-0.043x$	0.83		$y=16.9+2.26x-0.009x^2$	0.98
Lakeland K-	Branch	$y=2.94-0.019x$	0.64		$y=13.6+2.01x-0.002x^2$	0.99

- root mean square error

Corn treated with rates of this fly ash in excess of 12.5 g/kg (Cecil soil) and 6.3 g/kg (Lakeland soil) showed B toxicity symptoms (necrosis of leaves tips and margins) (Oertli and Kohl, 1961; Gupta ,1983), but potentially harmful effects of other elements not assayed here cannot be excluded. The highest rates of Yates fly ash (100 and 50 g/kg for Cecil and Lakeland soil, respectively) caused severe damage with about 50% of the leaf surface being destroyed by necrosis, resulting in a dramatic reduction in plant biomass.

Application of Branch fly ash to the Cecil soil not amended with K fertilizer had only a small positive effect on plant growth (Figure 3-54, Table 3-43), and no effect when combined with fertilizer application (no significant correlation between ash rate and corn dry matter). When applied to Lakeland soil, growth of corn tops and roots decreased, but with no visible signs of toxicity. On both soils, K application significantly ($P < 0.0001$) increased corn growth. The higher rates of both fly ashes on Lakeland soil depressed the positive effect of K-fertilizer on corn root dry matter probably due to fly ash toxicity. This was confirmed by analysis of variance (significant K-fly ash rate interaction: Yates $P < 0.01$, Branch $P < 0.001$). The same was true for dry matter of aerial parts of corn grown on the same soil amended with Yates fly ash ($P < 0.002$).

Potassium fertilizer did not significantly influence B concentration in aerial parts of corn, except on Lakeland soil amended with Yates fly ash. Plants grown on this soil amended with K had lower B concentrations ($P < 0.0001$) in comparison to the non-amended treatment. When applied at the 12.5 g/kg rate, both fly ashes supply an amount of K comparable to that of the K-fertilizer used in the experiment, but plant response indicates that, over short time periods, fly ash is not an adequate source of plant available K. Potassium in most fly ashes is associated with aluminosilicate glass limiting its solubility (Hulett et al., 1980). Weathering of fly ash with time may continuously release small quantities of plant available K.

Soils used in this experiment were low in native HWSB which is corroborated by the leaf B contents from Cecil and Lakeland soils not amended with fly ash (10.7 and 14.1 mg/kg B, respectively). The former is close to that considered by some investigators as the lowest sufficiency level for corn (Bergeret et al., 1957; Jones et al., 1990). Boron deficiency symptoms were not observed because corn is tolerant of low soil B levels (Bingham, 1973). Application of both fly ashes to both soils significantly ($P<0.0001$ for each soil and ash) increased the B content of corn tissue (Figure 3-55, Table 3-43). At the 12.5 g/kg level of Yates fly ash on Cecil soil, tissue B content reached 175 mg/kg while the accepted toxicity level is 98-100 mg/kg (El-Sheikh et al., 1971; Gupta, 1983). At the highest rate, tissue B content reached 3,400 mg/kg (soil with K fertilizer).

Tissue B contents on Lakeland soil amended with Yates fly ash at similar rates were two- to fivefold higher than on Cecil soil. The toxic level of leaf B was reached at 3.1 g/kg of Yates fly ash while the highest rate (50 g/kg) resulted in a concentration of 3,514 mg/kg B which is similar to that when 100 g/kg of Yates fly ash was applied to Cecil soil. Addition of Branch fly ash to both soils resulted in much lower leaf B concentrations but at the highest rates, toxic amounts of B accumulated in the leaves on both soils. Corn accumulated more B in aerial parts than in roots.

Arsenic was analyzed in the corn tissue resulting from this experiment, and for the very sandy Lakeland soil showed significant uptake from the Branch ash (Figure 3-56). Surprisingly, K

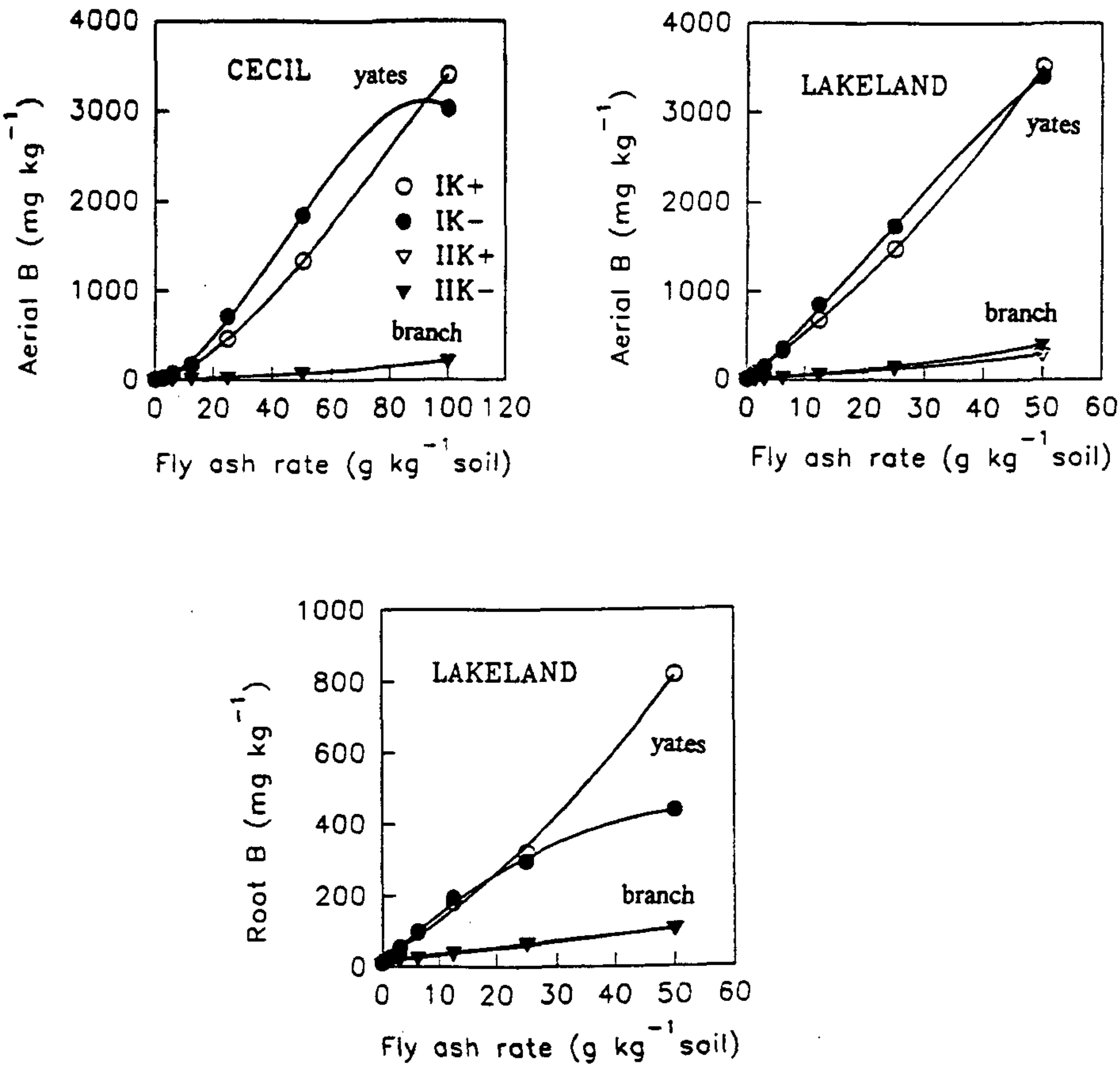


Figure 3-55. Boron Content in Corn Tissue Grown on Cecil and Lakeland Soils Amended with Different Rates of Fly Ashes

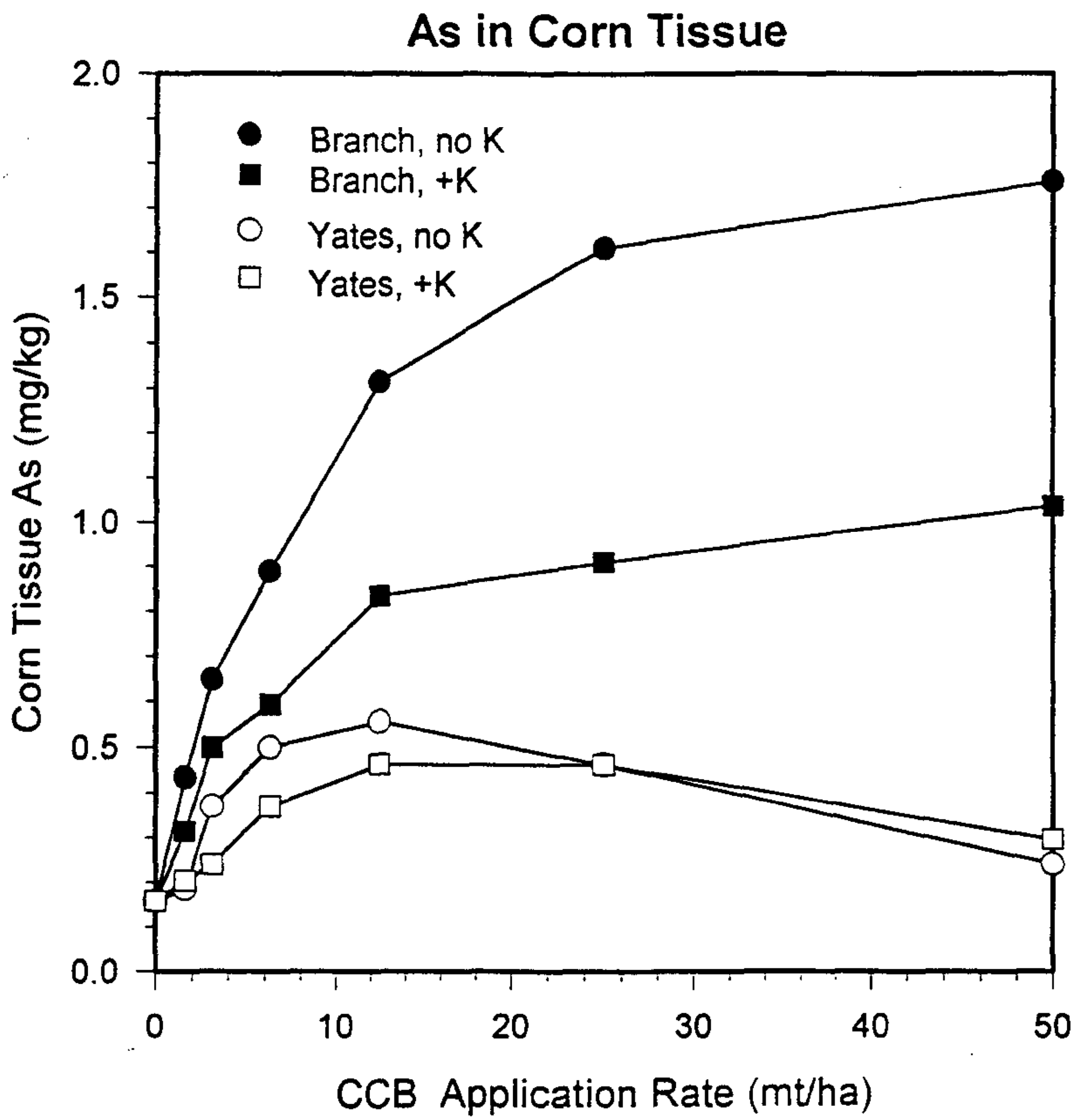


Figure 3-56. Relationship Between CCB Application and Corn Tissue As

fertilizer addition suppressed As uptake by almost 50%, through an unknown mechanism. In the absence of added K, tissue As reached 1.7 mg/kg. For Yates ash, the overall poor growth at rates > 25 mt/ha inhibited dry matter accumulation, and As uptake decreased in these stunted plants; K had no effect in this case.

Results of this experiment showed that B in fly ash is readily available to plants which is in agreement with the results of other investigators (Plank and Martens, 1974; Elseewi et al.,1980). Although synergistic or single toxic effects of other trace elements cannot be excluded, B seems to be the main factor responsible for decreases in corn growth on both soils amended with Yates fly ash. The toxic level of HWSB in Cecil soil occurred at the 12.5 g/kg rate of Yates fly ash at which toxic levels of B were found in tissue exhibiting toxicity symptoms. The yield reduction induced by increases in HWSB was much more pronounced on Lakeland soil which has a lower sorption capacity for B than the Cecil soil (Figure 3-57). It is rather unlikely that the growth decrease on Lakeland soil amended with low rates of Branch fly ash (6.3 g/kg or less) is due to B toxicity because neither corn tissue B nor soil HWSB approached toxicity levels in this range of fly ash application.

There is a close relationship between HWSB in fly ash amended soils and the B content of plant tissue. One equation satisfactorily describes this relationship for a given soil amended with both fly ashes, but different soils must be described by separate equations (Figure 3-58). The equations shown in Figure 3-58 slightly overestimate corn tissue B content at lower soil B levels. For that reason, a new set of equations has been used to obtain smaller function residuals at lower soil B contents (Figure 3-58). Plants grown on coarser Lakeland soil had higher B concentrations in aerial parts at the same HWSB level than those grown on Cecil soil. The effect of soil texture on B availability is well known from field and greenhouse studies with various crops (Keren et al.,1985; Adriano, 1986). Its nature is not well understood, but usually it is connected with differences in sorptive capacity of soils.

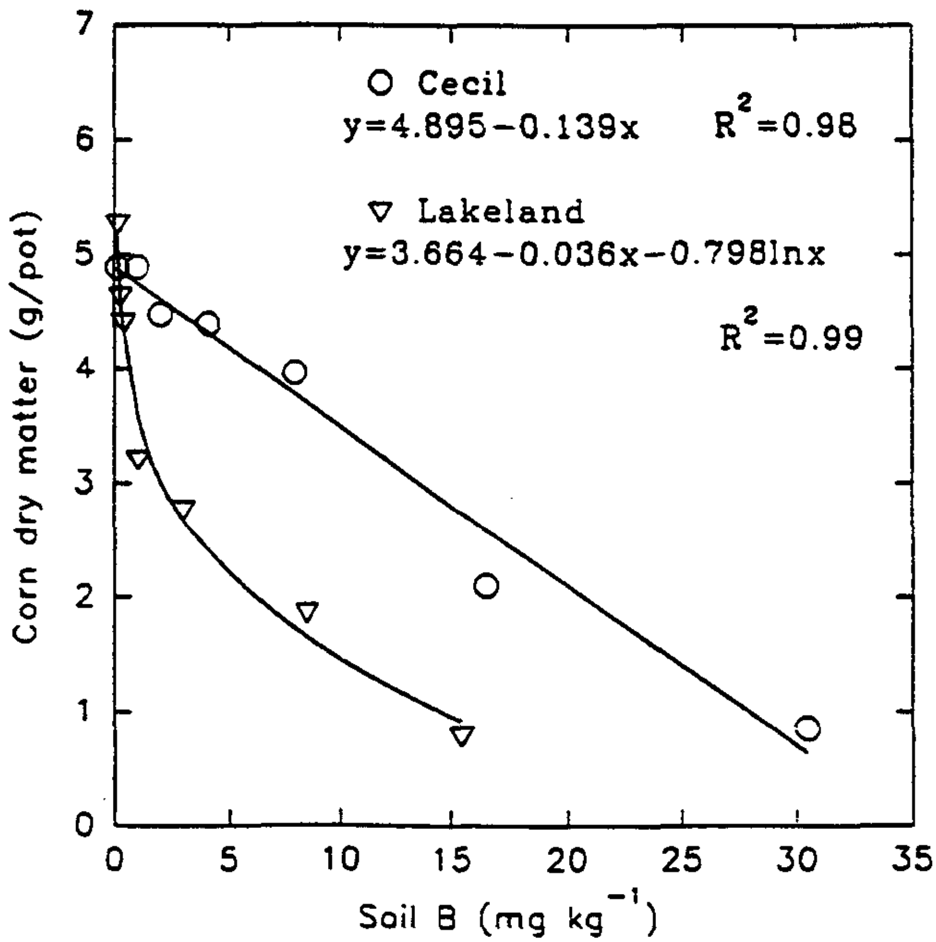


Figure 3-57. Effect on Corn Yield of Hot Water Extractable Boron in Cecil and Lakeland Soils Amended with Different Rates of Yates FGD (Soil Amended with K Fertilizer)

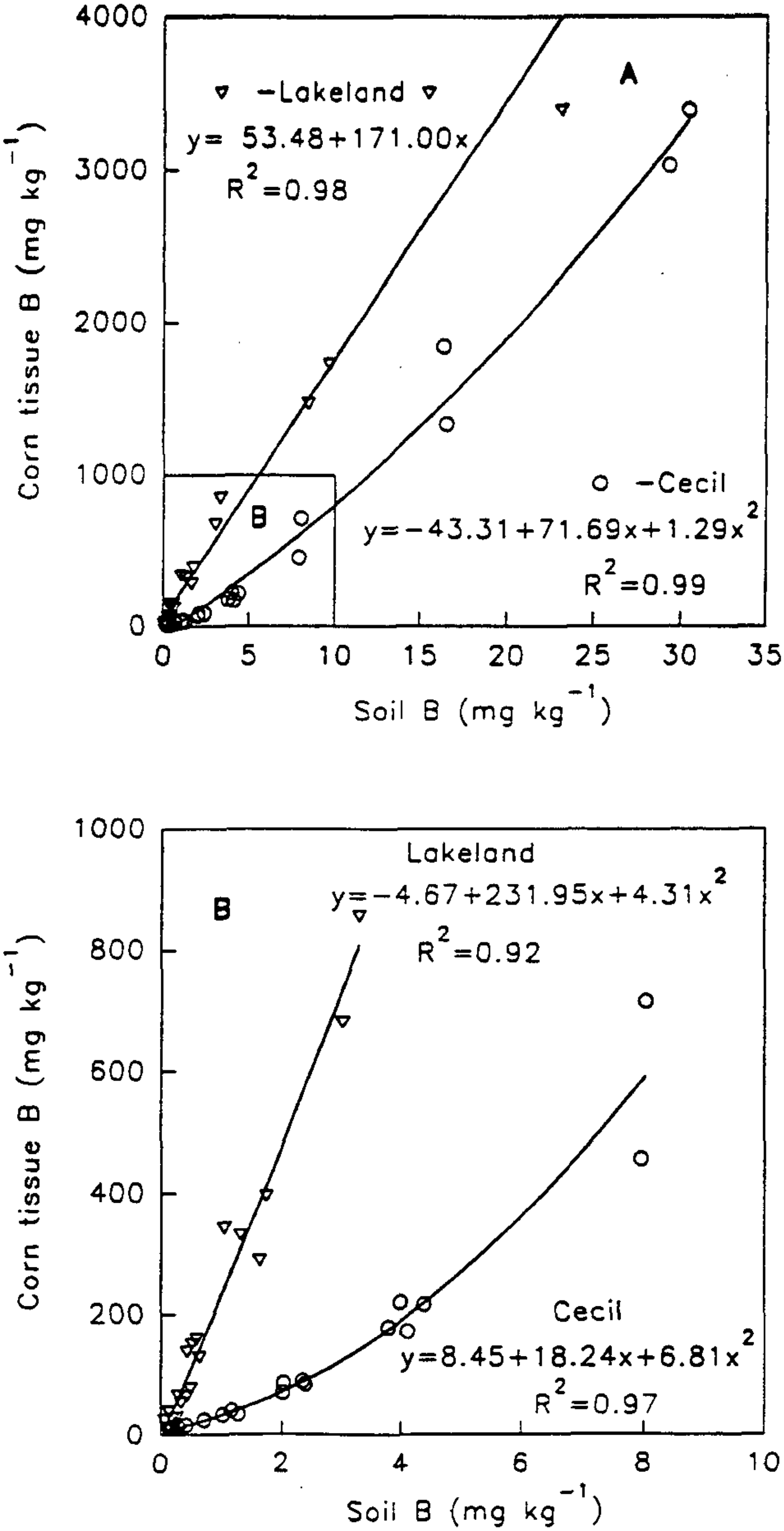


Figure 3-58. Relationship between Hot Water Extractable Soil Boron and Corn Tissue Boron in Leaves and Stems

Both fly ashes increased plant available soil B and its concentration in plants. Boron is likely to be the major limiting factor in the application of Yates fly ash to soil because toxicity symptoms and high B concentrations in plant tissue at application rates 6-12 g/kg are possible. However, these experiments were conducted under closed-pot greenhouse conditions, and therefore did not permit the leaching of soluble materials. Under field conditions, substantial quantities of B would be leached below the root zone. However B leaching poses little threat to ground water as it is not toxic to animals.

3.3.1.2.3.3 Spinach Studies

A further greenhouse experiment with Cecil soil and spinach (Spinacia oleracea L.) Bloomsdale variety as a test plant was conducted to establish whether FGD and Ca amendments would affect plant B uptake from a high B fly ash (fresh Yates). The treatments were: Yates fly ash at rates of 0, 0.5, 1, 2, 4, and 8 g/kg FGD at the same rates and a 1:1 fly ash:FGD mixture at rates of 0, 1, 2, 4, 8, and 16 g/kg. Soil received two levels of lime (0.8 and 2.4 mt/ha) applied as $Ca(OH)_2$ in combination with the above treatments in a split-split pot arrangement. A basal fertilizer was applied at 100 kg N/ha as NH_4NO_3, 200 kg K/ha as KCl and 195 kg P/ha as triple superphosphate. Spinach (5 plants /pot) was grown for 45 days. All other experimental details and post harvest handling were as described for the corn experiment.

Data from both greenhouse experiments were analyzed using analysis of variance. The least significant difference mean separation was performed for chosen data (SAS,1988). Prediction quality of HWSB in soil amended with coal combustion by-products was evaluated using Willmott's D-index (Willmott, 1981).

The rates of Yates fly ash and FGD applied in this experiment were too low to alter soil pH. Lime application was the only factor significantly ($P < 0.0002$) influencing soil pH. Calcium hydroxide rates of 1.48 and 4.44 mt $Ca(OH)_2$/ha resulted in soil pH average values of 5.26 and 6.39, respectively. Plant dry matter (data not shown) was not affected by any of the factors. All coal combustion by-product treatments significantly ($P < 0.0001$) increased HWSB level in soil with no significant difference caused by $Ca(OH)_2$ amendments (Table 3-44). Low rates of FGD decreased soil HWSB in comparison to the control with only the highest rates increasing soil HWSB over control. No explanation of this effect can be provided. Application of increasing fly ash rates caused a consistent increase of HWSB. The result of joint fly ash and FGD applications can be better evaluated by comparing with the equivalent fly ash-FGD mixture (for example 0.5 g/kg fly ash compared with 1.0 g/kg of the mixture). There was no suppressive effect of the FGD on soil HWSB level when applied together with fly ash. Soil amended with the fly ash-FGD mixture had the highest level of HWSB due to the additive effect of the two B sources.

TABLE 3-44
HOT WATER SOLUBLE B (HWSB) IN CECIL SOIL AMENDED WITH DIFFERENT RATES OF YATES FLY ASH, FGD AND 1:1 MIXTURE OF FLY ASH AND FGD

Rate (g/kg)	Hot Water Soluble Boron (mg/kg)		
	Fly ash	FGD	Fly ash/FGD
0.0	0.27[a]	0.27	0.27
0.5	0.38	0.16	-
1.0	0.52	0.18	0.45
2.0	0.84	0.25	0.59
4.0	1.45	0.30	0.94
8.0	2.79	0.47	1.56
16.0	-	-	3.01
$LSD_{0.05}$	0.41	0.10	0.68

[a] Data are average values for both 1.48 and 4.44 mt/ha (0.74 and 2.22 g/kg) $Ca(OH)_2$ rates because there was no statistically significant difference in HWSB between $Ca(OH)_2$ treatments.

Despite similar HWSB levels in soil , the B concentration in spinach leaves was strongly (P <0.005) depressed by $Ca(OH)_2$ application (Figure 3-59). The FGD did not significantly affect B uptake from fly ash suggesting that the pH increase, not the Ca^{2+} cation itself, is probably the factor responsible for decreasing the B availability to plants. Decreased B concentration in corn tissue at higher soil pH may be an effect of lower B concentration in the soil solution due to increased B sorption by soil clay minerals and Al and Fe hydroxides (Keren and Gast, 1983; Mezuman and Keren, 1981). Higher soil pH should also decrease B release from fly ash;

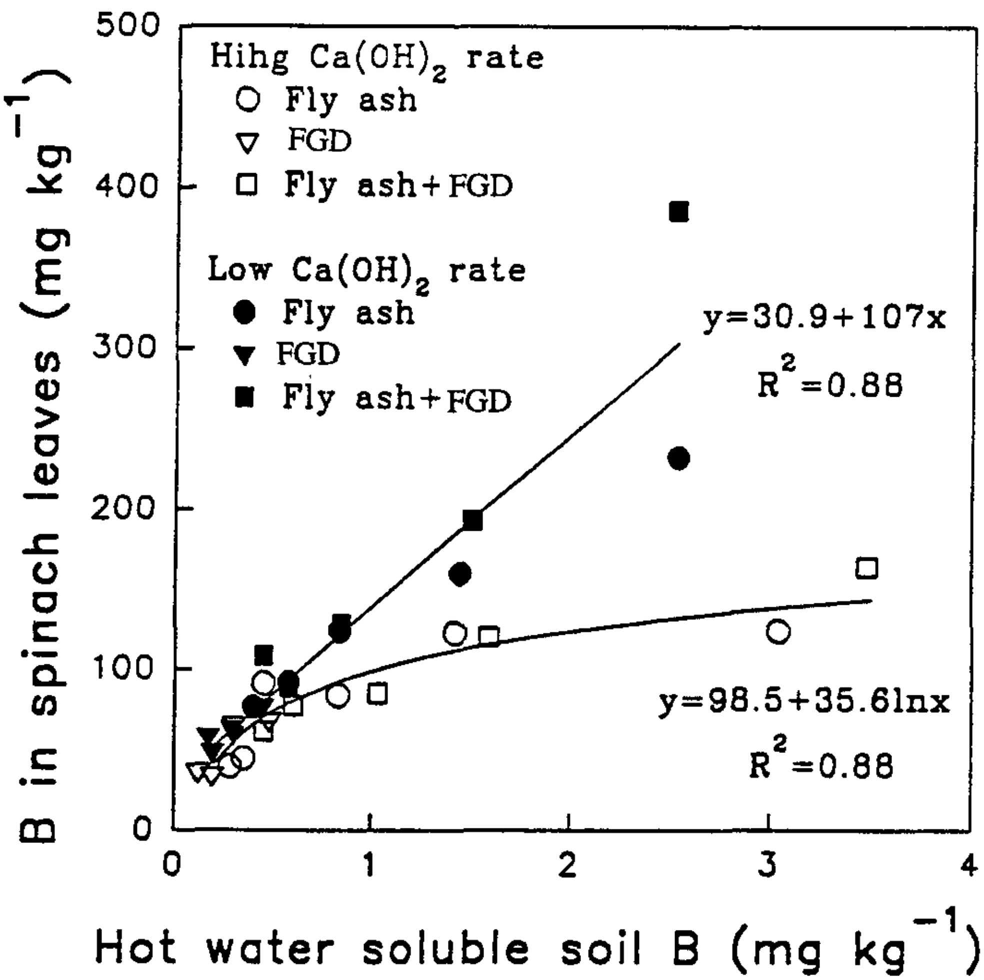


Figure 3-59. Influence of Calcium Hydroxide Level on B Concentration in Spinach Leave Grown in Soil Amended with Different Rates of High Boron Yates Fly Ash, FGD and 1:1 Mixture of Fly Ash and FGD

however, HWSB did not reflect this tendency. According to Oertli and Grgurevic (1975), B uptake by plant roots is largely regulated by diffusion of undissociated boric acid (H_3BO_3) through the root membrane. This form dominates in solution at pH values below 6.0. As solution pH increases, a variety of polyanions appears (Ingri,1963), and B uptake is depressed (Oertli and Grgurevic,1975).On the other hand, Gupta and MacLeod (1977) reported the opposite effect where B added with $CaCO_3$ resulted in higher tissue B content than when added with $CaSO_4$, despite a pH increase of about 1.5 units in the soil amended with $CaCO_3$.

The results of spinach experiment show some limitations of the predictive value of the HWSB test but at the same time, provide a way of avoiding enhanced B uptake by plants from fly ash amended soil.

3.3.1.2.4 Metal Uptake and Mobility: Field Studies

The field experiment phase of the project, described previously under section 3.3.1.1, was used to assess environmental impact as well as agronomic response to CCB additions; the environmental phase of these experiments involved analyses of selected plant tissues samples harvested from both the forage (alfalfa) and row crop plots for trace metal contaminants, and soil analyses to determine if elevated levels of trace metals existed in the soils at various depths from the surface.

3.3.1.2.4.1 Alfalfa Studies

Alfalfa tissue samples harvested from the field plots from the first full year of the study (1994) have been analyzed, and data are available for the multiple cuttings at the three locations. Samples for 1995 were not analyzed because metal levels in the sampled tissues at the end of the 1994 season were uniformly low, and showed no treatment effects due to CCB additions (see discussion below).

Nitric acid digests of the tissue samples were analyzed by a combination of colorimetric (azomethine, for B), graphite furnace (for As), and inductively coupled plasma-mass spectrometry

(ICP-MS; for other elements) techniques. Results for several elements were consistently less than the detection limits for the above methodologies for all samples analyzed: Pb (<0.05 ppm), As (<0.08 ppm), and Se (<0.15 ppm) were in this category, and data are not presented for these elements, and it can be concluded that CCB additions do not affect alfalfa tissue levels for these metals.

Boron levels (Table 3-45) were generally higher at Tifton and Calhoun sites, and overall higher for earlier harvests during the season. Higher rates of fly ash and FGD significantly increased tissue B levels at Athens, where control levels were low, but did not consistently affect tissue B at the other two locations. The experiment at Tifton grew poorly during 1995 (see section 3.3.1.1.2), and the low levels for the June 30 cutting are likely due to overall poor growth. The spring harvest here showed the highest levels of B recorded, probably due to the sandy textured soil occurring at this site. Normal tissue B levels for alfalfa fall in the 40-80 mg/kg range, and thus all of these values must be considered typical; no evidence of B toxicity was ever recorded on forage field plots at any location.

TABLE 3-45
BORON CONCENTRATIONS IN ALFALFA TISSUE -- 1994 HARVESTS AT THREE LOCATIONS

Treatment	Rate (mt/ha)	Athens site (Piedmont)				Tifton site (Coastal Plain)		Calhoun (Mountain Site)		
		Apr. 26	Jun 14	Aug 2	Sep 21	Apr. 21	Jun 30	Apr. 24	Jun 30	Oct. 11
		mg/kg								
Control	0	46.2a	33.2a	22.2a	37.8ab	66.9a	29.9	60.5a	44.8	39.4
Control	0	45.3a	32.8a	23.6a	38.1ab	67.2a	29.4	61.8a	45.3	39.9
FGD	5	56.8ab	45.7ab	24.3a	33.7a	82.4b	28.2	75.5b	48.4	37.9
FGD	20	72.7b	54.7b	27.6a	48.5ab	84.1b	34.2	92.1c	53.4	40.5
FA + FGD	2.5 + 2.5	73.3b	57.7b	26.8a	42.9ab	94.4c	35.2	76.9b	47.9	38.9
FA + FGD	10 + 10	91.5c	33.0a	31.2	53.5b	97.5c	35.7	85.4bc	47.7	44.9
LSD :		16.68				8.74	NS	11.53	NS	NS

Copper measured in forage tissue (Table 3-46) was differentially affected by CCB treatment: Cu content increased with fly ash or FGD additions for the first and third cuttings at Athens, but were lower for the last (September) cutting. Levels were also lower for the first cutting at Tifton, but were unaffected by treatment. Molybdenum analysis has not been completed at this time, but will

TABLE 3-46
COPPER CONCENTRATIONS IN ALFALFA TISSUE -- 1994 HARVEST AT THREE LOCATIONS

Treatment	Rate (mt/ha)	Athens (Piedmont site)				Tifton (Coastal Plain Site)		Calhoun (Mountain site)		
		Apr. 26	Jun 14	Aug 2	Sep 21	Apr. 21	Jun 30	Apr. 24	Jun 30	Oct. 11
		mg/kg								
Control	0	6.71a	6.20a	6.65a	5.80b	5.71c	3.74b	6.28	6.06	3.80
Control	0	6.82a	6.21a	6.67a	5.82b	5.68c	3.67b	6.35	6.10	3.94
FGD	5	8.17b	6.20a	7.52b	5.35a	4.74b	3.42b	6.41	6.44	4.08
FGD	20	8.25b	6.39a	7.36b	6.43b	4.25b	3.05a	9.41	5.36	4.07
FA + FGD	2.5 + 2.5	8.52b	6.49a	7.73b	4.91a	4.39b	2.74a	7.67	4.15	3.74
FA + FGD	10 + 10	8.86b	6.53a	8.49c	5.27a	3.32a	2.76a	7.17	5.63	3.99
LSD =		0.639				0.623	NS	NS	NS	NS

Values within a column with the same letter are not significantly different (p=0.05)

be performed and reported at a later date, in order to assess Cu:Mo ratio and the potential for molybdenosis problems in this forage.

Nickel (Ni) increased in the first two cuttings of alfalfa at the Athens locations by applications of CCB; levels approximately doubled for the highest rate of fly ash + FGD mixture on the Cecil soil at this site (Table 3-47). Fly ash was the major source of this Ni, as FGD only treatments were uniformly similar to controls. However, levels < 1 mg/kg, as found here, do not constitute an environmental hazard for forages. No other significant effects were detected, although similar increases were observed in the Tifton site for the spring cutting.

Analyses for Mo in selected forage samples from high CCB-amended plots using a colorimetric method showed <0.20 ppm Mo in the tissues, very close to the detection limit of the measurement. Earlier concerns of low Cu:Mo ratios raised in greenhouse studies were not borne out in the alfalfa field trials, since Cu levels remained in the normal 5-10 ppm range, giving Cu:Mo ratios significantly greater than 10, which is considered acceptable.

TABLE 3-47
NICKEL CONCENTRATIONS IN ALFALFA TISSUE -- 1994 HARVEST AT THREE LOCATIONS

Treatment	Rate (mt/ha)	Athens (Piedmont site)				Tifton (Coastal Plain site)		Calhoun (Mountain Site)		
		Apr. 26	Jun 14	Aug 2	Sep 21	Apr. 21	Jun 30	Apr. 24	Jun 30	Oct. 11
		mg/kg								
Control	0	0.415a	0.365a	0.315	0.642	0.646	0.357	1.033	1.006	0.726
Control	0	0.419a	0.370a	0.319	0.638	0.644	0.355	1.046	1.027	0.731
FGD	5	0.555ab	0.451a	0.394	0.614	0.947	0.404	1.183	1.061	0.748
FGD	20	0.464a	0.406a	0.359	0.646	0.998	0.440	1.246	1.091	0.746
FA + FGD	2.5 + 2.5	0.722bc	0.629b	0.475	0.658	0.955	0.526	1.261	1.100	0.746
FA + FGD	10 + 10	0.985c	0.957c	0.519	0.611	1.005	0.695	1.513	1.396	0.950
LSD :		0.253		NS	NS	NS	NS	NS	NS	NS

Values within a column with same letter are not significantly different at p=0.05

Conclusions from these measurements are that no environmentally significant increase in contaminant metals results from application of moderate rates (< 20 mt/ha) of fly ash or fly ash-FGD mixtures on forage alfalfa grown on the soils studied here.

3.3.1.2.4.2 Row Crop Studies

Analyses for metal concentrations in harvestable portions of row crops are available for soybeans (Athens, 1993; Calhoun, 1993 and 1994; and Tifton, 1993 and 1994), wheat (Athens, 1994-5; Tifton, 1993-4 and 1994-5), barley (Calhoun, 1993-4), corn (Athens, 1994; Calhoun, 1995), and sorghum (Athens, 1995; Tifton, 1995). Standard digestion (hot nitric acid) and analysis (graphite furnace AA and ICP-MS) methods were used for all samples analyzed.

For the five soybean crops grown at the three locations (Tables 3-48 through 3-52), several treatment effects on metal levels were apparent. For As, tissue levels did increase at Tifton and at Calhoun (1994) with CCB additions above control levels; however the maximum value reached, 0.018 ppm (18 ppb) at Tifton, is still quite low, and only roughly double the control value, and well below food safety guidelines. Boron fairly consistently increased with FGD and ash additions at all sites and both years; agronomically, however, these increases are not

TABLE 3-48
METAL CONCENTRATIONS IN SOYBEANS AT CALHOUN IN 1993

		Metal concentration (mg/kg)							
	Rate mt/ha	Arsenic	Boron	Copper	Lead	Molybdenum	Nickel	Selenium	Zinc
Control	0	0.0104	50.35b	15.67ab	0.065	0.067d	6.22	0.21	45.89 a
FGD	5	0.0088	48.62b	16.74ab	0.068	0.086d	6.36	0.21	46.38 a
FGD	10	0.0108	48.56b	15.86ab	0.081	0.178cd	5.78	0.21	45.74 a
FGD	20	0.0085	60.90a	17.80a	0.051	0.251c	5.77	0.21	46.26 a
FA+FGD	2.5+2.5	0.0090	53.92ab	14.50ab	0.059	0.266c	5.77	0.21	43.19 ab
FA+FGD	5+5	0.0098	55.14ab	13.85b	0.068	0.683b	5.57	0.21	40.19 b
FA+FGD	10+10	0.0108	52.73b	14.96ab	0.066	0.887a	5.92	0.21	42.66 ab
LSD (0.05)		NS	7.117	3.797	NS	0.158	NS	NS	4.85

Values in a column followed by different letters are significantly different at p=0.05

TABLE 3-49
METAL CONCENTRATIONS IN SOYBEANS AT CALHOUN IN 1994

		Metal concentration (mg/kg)							
	Rate mt/ha	Arsenic	Boron	Copper	Lead	Molybdenum	Nickel	Selenium	Zinc
Control	0	0.0035	48.61b	18.75abc	0.145	0.241c	3.60abc	0.21	71.51abc
FGD	5	0.0073ab	55.94ab	20.07a	0.172	0.235c	4.49a	0.21	76.59ab
FGD	10	0.0068ab	56.96a	17.16cd	0.185	0.329c	3.58abc	0.21	84.68a
FGD	20	0.0087a	54.40ab	17.74bcd	0.170	0.381bc	3.01c	0.21	70.03abc
FA+FGD	2.5+2.5	0.0066ab	50.81ab	16.79cd	01.52	0.495bc	2.76c	0.21	63.46bc
FA+FGD	5+5	0.0072ab	57.27a	17.31bcd	0.122	0.780b	3.15bc	0.21	64.31bc
FA+FGD	10 + 10	0.0067ab	56.73a	16.79cd	0.150	2.247a	3.22b	0.21	57.65c
LSD		0.005	7.91	2.13	NS	0.401	0.935	NS	16.72

Values in a column followed by different letters are significantly different at p=0.05

TABLE 3-50
METAL CONCENTRATIONS IN SOYBEANS AT OCONEE CO. (PIEDMONT) IN 1993

		Metal concentration (mg/kg)						
Treatment	Rate mt/ha	Arsenic	Boron	Copper	Lead	Nickel	Selenium	Zinc
Control	0	0.0040	45.55b	12.50d	0.092	0.810ab	<0.21	43.33
FGD	5	0.0042	49.68b	11.94d	0.097	1.120a	<0.21	44.15
FGD	10	0.0067	52.20ab	12.98cd	0.097	0.842ab	<0.21	41.70
FGD	20	0.0050	59.41a	15.04a	0.087	0.817ab	<0.21	40.73
FA+FGD	2.5+2.5	0.0040	53.11ab	13.75bc	0.085	0.810ab	<0.21	45.09
FA+FGD	5+5	0.0040	53.10ab	12.13d	0.092	0.997ab	<0.21	42.71
FA+FGD	10+10	0.0047	52.91ab	13.03cd	0.080	.0920ab	<0.21	41.93
LSD		NS	8.10	1.19	NS	0.3248	Ns	NS

Values in a column followed by different letters are significantly different at p=0.05

TABLE 3-51
METAL CONCENTRATIONS IN SOYBEANS AT TIFTON IN 1993

		Metal concentration (mg/kg)							
Treatment	Rate mt/ha	Arsenic	Boron	Copper	Lead	Molybdenum	Nickel	Selenium	Zinc
CON	0	0.0072c	64.97b	3.77	0.15	1.95d	0.87	<0.21	46.95ab
FGD	5	0.0067c	73.30ab	3.48	0.10	2.48d	0.97	<0.21	46.34ab
FGD	10	0.0090bc	71.16ab	3.55	0.14	2.39d	1.06	<0.21	46.78ab
FGD	20	0.0095bc	70.12ab	3.56	0.18	2.23d	0.99	<0.21	46.09ab
FA+FGD	2.5+2.5	0.0082c	10.11ab	4.43	0.11	5.66cd	0.88	<0.21	44.05b
FA+FGD	5+5	0.0100ab	67.50ab	4.36	0.10	8.70c	1.10	<0.21	47.01ab
FA+FGD	10 + 10	0.0175ab	79.43a	3.18	0.11	17.43c	0.95	<0.21	50.22ab
FA	20	0.0185a	78.64a	4.10	0.08	31.05a	0.81	<0.21	52.69a
LSD		0.008	12.04	NS	NS	4.47	NS	<0.21	8.085

Values in a column followed by different letters are significantly different at p=0.05

TABLE 3-52
METAL CONCENTRATIONS IN SOYBEANS AT TIFTON IN 1994

		Metal concentration (mg/kg)							
	Rate mt/ha	Arsenic	Boron	Copper	Lead	Molybdenum	Nickel	Selenium	Zinc
Control	0	0.0074ab	31.18b	3.34cd	0.147a	3.11d	1.02	<0.21	91.9ab
FGD	5	0.0032b	35.83ab	3.98bc	0.120a	3.46d	1.41	<0.21	79.4b
FGD	10	0.0058ab	31.36b	3.14d	0.110b	3.11d	1.21	<0.21	80.9ab
FGD	20	0.0040b	36.76ab	2.75d	0.107b	3.88d	1.11	<0.21	106.4a
FA+FGD	2.5+2.5	0.0071ab	34.54ab	4.45ab	0.090b	5.40cd	1.24	<0.21	89.5ab
FA+FGD	5+5	0.0055ab	38.74ab	3.00d	0.107b	8.73c	1.60	<0.21	107.3a
FA+FGD	10+10	0.0096a	39.48a	2.82d	0.087b	13.89b	1.34	<0.21	81.5ab
FA	20	0.0051b	41.80a	4.74a	0.087b	18.60a	1.21	<0.21	85.9ab
LSD		0.00430	7.92	0.738	0.0345	3.5026	NS	<0.21	26.904

Values in a column followed by different letters are significantly different at $p=0.05$

significant, typically amounting to only 20% higher values in CCB-amended plots, and uniformly less than 100 ppm. Copper, Pb, Ni, and Zn levels typically were not consistently affected by FGDG or ash additions; Pb and Zn often declined in treated plots due to the higher pH and Ca levels associated with CCB applications, which inhibit metal uptake. Nickel and Cu varied slightly with amendment at the different locations, but again, within narrow ranges which are of questionable agronomic significance. Selenium was uniformly below the method detection limit; however, Mo showed consistent increases with CCBP amendment, particularly on the very sandy soil at Tifton. These increases were limited to higher rates of fly ash addition; at 10-20 mt/ha of ash Mo levels increased to >15 ppm, which was five times the control level. On the finer textured soil at Calhoun, Mo also increased, but levels were < 2 ppm in the forage tissue.

For the 1993-94 wheat and barley crops at Tifton and Calhoun, B, As, and Pb were determined in grain harvested from the treated and control plots (Tables 3-53 and 3-54). Again, no significant treatment effects due to CCB application were observed using analysis of variance statistical procedures. Grain B was about 70 mg/kg. Pb levels were about 60-90 µg/kg at Tifton on the sandy soil there, and lower on the silty Calhoun soil (20-60 µg/kg), with no effect of treatment. Arsenic determined in wheat at Tifton was within the range of 30-60 µg/kg, with no evidence of higher levels in the fly ash or FGD treatments (Table 3-53).

TABLE 3-53
CONTAMINANT METAL LEVELS IN WHEAT GROWN AT TIFTON IN 1993-1994 SEASON

Treatment	Rate (mt/ha)	Boron	Arsenic	Lead
		mg/kg	μg/kg	
Control		68.5	60.4	96.5
Fly ash only	10	60.0	38.5	86.7
FGD	5	62.4	42.5	76.3
	10	48.8	37.5	85.5
	20	65.7	30.0	74.2
Fly ash + FGD	5	76.1	30.0	77.9
	10	75.6	36.3	95.0
	20	70.0	35.0	61.7
LSD (p=0.05)		NS	NS	NS

TABLE 3-54
BORON AND LEAD CONTENTS OF BARLEY GRAIN GROWN ON CCB-AMENDED SOILS AT CALHOUN DURING 1993-1994

Treatment	Rate (mt/ha)	Boron	Lead
		mg/kg	μg/kg
Control	--	68.8	59.0
FGD only	5	77.6	29.2
	10	69.9	21.5
	20	75.0	53.4
Fly ash + FGD	5	77.9	38.2
	10	64.5	27.0
	20	86.0	36.4
LSD (p=0.05)		NS	NS

The second wheat crop grown at Tifton and Athens showed very similar results to the previous year (Table 3-55): B was 50-60 mg/kg in wheat grain, and largely unaffected by CCB treatment. As was uniformly <90 μg/kg, and Pb <150 μg/kg. Pb levels were variable, and some significant differences were noted, but comparing CCB treatments to control (untreated) plots, there were no elevated Pb levels due to amendments used.

TABLE 3-55
CONTAMINANT METALS IN WHEAT GRAIN AT TIFTON AND ATHENS FOR 1994-95 CROP

Treatment	Rate	Boron	Arsenic	Lead
	(mt/ha)	(mg/kg)	(μg/kg)	(μg/kg)
		Tifton		
Control	0	54.9	<90	117 ab
FGD	5	61.1	<90	121 ab
FGD	10	62.7	<90	nd
FGD	20	62.1	<90	124 ab
FA + FGD	5	62.8	<90	105 b
FA + FGD	10	57.2	<90	nd
FA + FGD	20	47.9	<90	140 ab
FA	10	57.5	<90	145 a
LSD		18.6	NS	37
		Athens		
Control	0	59.8 abc	<90	157 abc
FGD	5	64.1 ab	<90	122 bc
FGD	10	64.1 ab	<90	nd
FGD	20	67.3 a	<90	106 c
FA + FGD	5	61.2 abc	<90	202 a
FA + FGD	10	51.1 c	<90	nd
FA + FGD	20	55.2 bc	<90	170 abc
FA	10	61.0 abc	<90	185 ab
LSD		10.3	NS	64

Different letters within a column indicate significant differences at $p= 0.05$.
nd = not determined

The corn crop at Athens in 1994 was analyzed for As, B, and Pb, both in the corn grain and in the chopped stalks and leaves (silage) that might be used as a cattle feed. Significant differences were found in this data set (Table 3-56). In the fly ash only treatment (10 mt/ha),) As increased from 6 in the control grain to 18 μg/kg , and from 26 in control silage to 99 μg/kg in fly ash only treatment. FGD applied alone at all rates did not affect As in corn, but fly ash alone or in the mixture did have an effect. The FA+FGD material, however, only increased As at the highest rate (20 mt/ha), up to 60 μg/kg. It appears that in this case the presence of the FGD depressed As uptake, compared to the fly ash only treatment where the same mass of fly ash was added. Boron (B) was only elevated above control levels in one treatment, that being the 20 mt/ha FA+FGD , in corn grain, and to a very modest 40 mg/kg. For lead (Pb), concentrations were very low in both grain and silage, and were not affected by applied CCB treatments.

TABLE 3-56
METAL CONTENT OF CORN GRAIN AND SILAGE AT ATHENS FOR 1994 CROP

Treatment	Rate (mt/ha)	Arsenic		Boron		Lead	
		Grain	Silage	Grain	Silage	Grain	Silage
		mg/kg					
Control	---	5.8b	26.3c	33.0b	232a	2.40a	207a
FGD	5	9.6ab	40.0bc	32.1b	263a	4.57a	160ab
	10	10.4ab	34.2bc	39.5ab	313a	5.40a	154b
	20	7.1b	27.9c	32.9b	282a	5.42a	151b
FA+FGD	5	9.6ab	49.1bc	32.6b	330a	2.50a	161ab
	10	7.9b	48.3bc	35.4ab	250a	4.58a	154b
	20	8.3b	60.4b	41.4a	265a	4.19a	202ab
FA only	10	17.9a	98.8a	37.2ab	262a	2.55a	167ab

Dissimilar letters within the same column indicate significant differences at p=0.05.

A corn-for-silage crop was also grown at Calhoun during the 1995 season, but was planted too late to give a reasonable yield estimate; tissue samples were taken, however, and analyzed for metals in the stalks and leaves. The results (Table 3-57) showed quite normal levels of all metallic elements, with only As being statistically affected by FGD or ash amendment; As increased slightly in the higher FGD treatment, but was still < 0.01 ppm. All other metals were low, and not affected by treatment.

TABLE 3-57
METAL CONCENTRATIONS IN MAIZE AT CALHOUN IN 1995

		Metal concentration (mg/kg)							
	Rate mt/ha	Arsenic	Boron	Copper	Lead	Molybdenum	Nickel	Selenium	Zinc
Control	0	0.0069ab	16.92	3.17	0.167	0.180ab	0.627	<0.21	42.82
FGD	5	0.0066ab	18.00	3.57	0.175	0.105b	0.605	<0.21	34.97
FGD	20	0.0089a	20.44	3.96	0.173	0.145ab	0.442	<0.21	39.30
FA+FGD	2.5+2.5	0.0060b	20.92	3.22	1.178	0.160ab	0.385	<0.21	35.12
FA+FGD	10+10	0.0046b	18.64	3.19	0.114	0.212a	0.302	<0.21	35.07
LSD		0.0028	NS	NS	NS	NS	NS	<0.21	NS

Values in a column followed by different letters are significantly different at p=0.05

Grain sorghum metal levels for the 1995 crop at Tifton (Table 3-58) showed no effect of CCB application on B, Cu, Ni, Pb, or As concentrations; all levels were within those considered normal or average for grains. Pb was somewhat higher overall than the corn grain discussed above, while

TABLE 3-58
METAL CONCENTRATIONS IN GRAIN SORGHUM TISSUE AT TIFTON FOR 1995 CROP

			Metal concentration (mg/kg)				
Treatment	**Rate (mt/ha)**	**Boron**	**Copper**	**Nickel**	**Lead**	**Arsenic**	**Selenium**
Control	0	11.87	2.33	0.27	0.09	0.005	0.10ab
FGD	5	8.85	2.2	0.36	0.09	0.006	0.14a
FGD	10	10.29	2.6	0.41	0.14	0.007	0.11ab
FGD	20	11.28	2.65	0.31	0.2	0.006	0.08b
FA +FGD	2.5 + 2.5	9.19	2.37	0.35	0.19	0.004	0.07b
FA +FGD	5 + 5	9.95	3	0.24	0.1	0.007	0.10ab
FA+ FGD	10 + 10	10.79	2.52	0.23	0.11	0.012	0.10ab
FA	20	11.67	2.51	0.2	0.11	0.007	0.10ab
LSD		NS	NS	NS	NS	NS	0.0571

Values within a column with the same letter are not significantly different

As was quite similar at 4-12 µg/kg. Selenium (Se) was about 0.1 mg/kg in these grain samples, and was depressed by additions of FGD; this is an unexpected result, although the low levels of Se found in the ashes (described previously) indicate that very little Se was added to the soil in the FA or FGD treatments. FGD may have inhibited Se uptake by sulfate competition at root surfaces for uptake sites. At the Athens site, sorghum grain showed depressed uptake of B at the highest FGD rates, while being unaffected by FA additions (Table 3-59). Copper uptake was very slightly increased by several treatments (from 2 to 3 mg/kg), although it is difficult to see a rationale for this, as Cu contents of the CCBs were not very high (Table 3-21). Lead uptake on control plots was very low, and was irregularly increased by amendments containing both FGD and fly ash. The highest Pb levels in grain, about 0.14 mg/kg, were similar to those found in corn silage (Table 3-56), but higher than corn grain or sorghum at Tifton. Arsenic was apparently somewhat higher overall at Athens, but not affected by treatment; Se was low, and similarly did not differ with treatment.

TABLE 3-59
METAL CONCENTRATIONS IN GRAIN SORGHUM AT ATHENS (PIEDMONT SITE) FOR 1995 CROP

			Metal concentration (mg/kg)				
Treatment	**Rate (mt/ha)**	**Boron**	**Copper**	**Nickel**	**Lead**	**Arsenic**	**Selenium**
Control	0	14.38a	2.13b	<0.5	.0007b	0.08	0.09
FGD	5	11.56ab	2.35b	<0.5	.0007b	0.08	0.08
FGD	10	12.30ab	3.35a	<0.5	.1398a	0.03	0.08
FGD	20	7.59b	2.22b	<0.5	.0177b	0.01	0.13
FA+FGD	2.5 + 2.5	12.10ab	1.96b	<0.5	.1258a	0.03	0.11
FA+FGD	5 + 5	10.65ab	2.95a	<0.5	.1258a	0.09	0.07
FA+FGD	10 + 10	16.54a	2.04b	<0.5	.0025b	0.03	0.10
FA	20	10.81ab	2.00b	<0.5	.0116b	0.02	0.15
LSD		6.487	0.568	NS	0.0309	NS	NS

Values within a column with the same letter are not significantly different

To put the above concentrations into perspective, guidelines (used in the absence of Federal or state regulations) for maximum metal contents (mg/kg) of foodstuffs in the U.S. are approximately as follows: Cd 0.5, Pb 10, As 2. In Europe and Australia, these values may be lower by a factor of 10. No limits are set for Cu, B, or Se, but conservatively might be estimated at 10 mg/kg. In no case in the present study was any value found which even approached these limits. Even though occasional increases in metals were found on CCB-treated plots, in all cases these increases were still far below levels that might trigger alarm in terms of food chain contamination or human health effects. It might be recalled that in the greenhouse experiments plant tissue concentrations approached levels of 2 mg/kg As; this high value was obtained under conditions where roots were restricted to growth in small volumes of soil amended with high rates (50-200 mt/ha) of high-As fly ash. It seems quite unlikely that such conditions would occur in field soils, and the field plot results bear out this fact.

3.3.1.2.4.3 Soil Metal Levels in Field Plots

The low levels of metals found in the field-grown plant tissues were evaluated in terms of levels of metals found in the amended soils. Soil samples taken from the field plots for soil fertility analyses (described in 3.3.1.1.4) were extracted with dilute acid (pH 2.5; Mehlich's reagent) commonly used to assess plant-available nutrients in soils. It was assumed that metals extracted with this reagent would represent "labile" metals that might be available for plant uptake or potentially for leaching to groundwater. The deep sampling (to 1 m) also allowed an examination of subsoil metal levels that may have already been moved from the topsoil to deeper soil layers by water movement. Currently data for As and Se are available for these extracts; only selected treatment levels, usually the highest levels of CCB addition, were analyzed.

The results for As at Athens and Tifton field plots (Table 3-60) show that CCB amendment did result in some changes in extractable soil As. At Athens, all the plots had high (250 μg/kg) levels of As, probably due to arsenical pesticide applications to cotton over the years. Thus, no increase in soil As was observed due to the high As content of fly ash added. Extractable As was decreased, however, in subsurface soil layers by FGD application: in both the fly ash +FGD and FGD only treatments, As at depths from 20-70 cm was significantly decreased relative to controls. This is undoubtedly due to displacement of adsorbed AsO_4 by SO_4 added in the FGD. At Tifton, topsoil As was lower, and subsoil levels much higher, than at Athens; arsenicals had also probably been used here, and it appears from the control plots that much of that As had already been leached into the subsoil. Fly ash amendment did increase As in the 0-20 cm layer, from 100 to 150 μg/kg; at the 60-70 cm depth, FA + FGD appeared to increase As, while FGD only decreased it, relative to the control. Otherwise, there were no consistent trends in As distribution on this soil due to treatment. At Calhoun (Table 3-61), arsenicals had not been extensively used, and control As levels were more uniformly low; here, while topsoil As in several treatments appeared somewhat elevated relative to controls (90 vs. 120-130 μg/kg), no significant differences at any depth were discovered due to CCB amendment.

For Se, fly ash at the 20 mt/ha rate increased extractable Se relative to control at the Tifton site (Table 3-62); the increase was modest, however, from 7 to 17 μg/kg. Extractable Se levels were quite low here, and no other significant effects were observed, other than a lower value in FGD treatment at 60-70 cm. At the Athens site, extractable Se was higher, and increased with depth to 40 μg/kg on the control plots; CCB did not significantly affect extract Se on the treated plots

TABLE 3-60
EXTRACTABLE ARSENIC BY BRAY I EXTRACTANT FOR SELECTED TREATMENTS FROM FIELD PLOT SOILS AT ATHENS AND TIFTON (µG/KG SOIL)

DEPTH	Fly ash only 20 mt/ha	Fly ash-gyp 20 mt/ha	Gypsum only 20 mt/ha	Control	$LSD_{0.05}$
Oconee					
0-20 cm	262.0 a	275.3 a	379.4 a	263.4 a	210.8
20-30 cm	81.7 a	59.5 b	77.2 ab	88.2 a	18.4
30-40 cm	79.1 a	44.6 b	45.3 b	71.9 a	17.3
40-50 cm	68.1 a	38.3 b	42.2 b	69.5 a	18.3
50-60 cm	73.5 a	45.5 b	41.1 b	69.3 a	15.2
60-70 cm	75.8 a	49.5 b	49.5 b	75.8 a	18.5
Tifton					
0-20 cm	158.7 a	150.7 a	94.5 b	98 .0 b	44.1
20-30 cm	156.6 a	112.9 a	140.5 a	137.2 a	86.2
30-40 cm	156.8 a	147.5 a	180.4 a	157.3 a	93.9
40-50 cm	132.3 a	105.9 a	122.5 a	121.6 a	51.7
50-60 cm	107.8 a	96.6 a	102.2 a	108.3 a	37.02
60-70 cm	117.6 ab	124.1 a	84.0 b	114.8 b	35.1
70-80 cm	115.5 a	120.2 a	95.2 a	114.1 a	25.3

Values within a column with the same letter are not significantly different

TABLE 3-61
EXTRACTABLE ARSENIC BY BRAY I EXTRACTANT FROM FIELD PLOT SOILS AT CALHOUN (µG/KG SOIL)

Depth	Fly ash+FGD (20 mt/ha)	FGD (20 mt/ha)	Control	LSD(0.05)
0-20 cm	121.1a	123.0 a	96.6 a	40.1
20-30 cm	80.5 a	78.2 a	70.8 a	51.1
30-40 cm	79.1 a	78.2 a	71.5 a	47.5
40-50 cm	87.0 a	82.1 a	77.5 a	64.5
50-60 cm	76.3 a	92.6 a	83.8 a	43.1
60-70 cm	87.3 a	80.0 a	77.7 a	34.1
70-80 cm	78.6 a	81.4 a	79.1 a	31.1
Depth	**Fly ash- gyp (10 mt/ha)**	**Gypsum only (10 mt/ha)**	**Fly ash-gyp (5 mt/ha)**	**Gypsum only (5 mt/ha)**
0-20 cm	125.5	132.8	116.2	127.6
20-30 cm	76.8	80.7	69.5	68.6
30-40 cm	73.0	76.8	70.5	62.8
40-50 cm	72.6	72.8	73.0	63.5
50-60 cm	83.1	69.8	66.5	57.4
60-70 cm	78.4	68.1	66.3	48.8
70-80 cm	80.0	60.0	74.7	60.2

Means within a row followed by the same letter are not significantly different at $P<0.05$

TABLE 3-62
EXTRACTABLE SELENIUM (BY BRAY I REAGENT)
IN TIFTON FIELD PLOT SOILS (µG/KG SOIL)

Depth	Fly ash only (20 mt/ha)	Fly ash-gyp (20 mt/ha)	Gypsum only (20 mt/ha)	Control	$LSD_{0.05}$
0-20 cm	16.8 a	12.1 ab	6.8 b	7.7 b	7.2
20-30 cm	21.0 a	12.4 a	15.2 a	16.8 a	13.2
30-40 cm	17.7 a	23.1 a	18.9 a	16.8 a	12.5
40-50 cm	12.8 a	14.0 a	11.2 a	11.7 a	10.1
50-60 cm	9.3 a	8.2 a	6.5 a	9.3 a	7.9
60-70 cm	12.4 a	9.1 ab	4.7 b	7.0 ab	6.8
70-80 cm	8.9 a	13.5 a	8.6 a	7.9 a	14.3

Means within row followed by the same letter are not significantly different at $p<0.05$ (Table 3-63). A similar result was obtained at Calhoun (Table 3-64), where background Se was again higher (up to 50 µg/kg), but neither the 20 mt/ha rate of FGD or fly ash+FGD affected extractable Se levels.

TABLE 3-63
EXTRACTABLE SELENIUM (BY BRAY I REAGENT)
IN ATHENS FIELD PLOT SOILS (µG/KG SOIL)

Depth	Fly ash only (20 mt/ha)	Fly ash-gyp (20 mt/ha)	Gypsum only (20 mt/ha)	Control
0-20 cm	38.5	41.3	23.8	22.6
20-30 cm	29.9	35.2	24.3	20.8
30-40 cm	36.6	33.8	16.3	28.7
40-50 cm	42.2	29.4	24.3	24.0
50-60 cm	48.8	41.8	35.7	37.6
60-70 cm	60.7	50.2	40.1	40.1

TABLE 3-64
EXTRACTABLE SELENIUM (BY BRAY I REAGENT)
IN CALHOUN FIELD PLOT SOILS (μG/KG SOIL)

Depth	Fly ash-gyp (20 mt/ha)	Gypsum only (20 mt/ha)	Control
0-20 cm	51.8	48.8	50.4
20-30 cm	41.1	38.5	38.0
30-40 cm	39.0	42.9	41.1
40-50 cm	41.1	40.8	40.4
50-60 cm	43.9	44.6	40.1
60-70 cm	51.1	47.4	43.2
70-80 cm	51.8	42.9	46.0

3.3.1.2.5 Conclusions

The following are the important environmental conclusions to be drawn from the work completed under this project:

- Based on the range of ashes and FGD materials studied, fly ash is a mineralogically complex aluminosilicate material containing appreciable quantities of metal ions that may potentially contaminate amended soils; FGD is a much more simple gypsum material with considerably lesser amounts of contamination.

- The contaminants of most concern are arsenic (As) and boron (B), the former from a human perspective, the latter from its effect on plants. One of the five ashes had As levels > 100 mg/kg, which in greenhouse studies caused plant uptake of As to levels > 2 mg/kg in tissue. Boron caused considerable plant toxicity in greenhouse testing, and is much more soluble in the ash material than As. Molybdenum may present a problem on soils low in Cu if forages grown on amended soils are fed to livestock; further analyses of field samples is needed to evaluate this.

- Boron was readily leached from amended soils, within the equivalent of 100-150 mm of rainfall, and thus toxicities in leached field soils would be expected to be much less than in greenhouse experiments. Arsenic was immobile in the soil, unless adsorbed by mobile clay particles, which is not common under field conditions.

- Boron solubility can be predicted from analyses of the ash material, and ashes likely to cause plant toxicities in the field can be managed by allowing an adequate leaching period prior to planting. The ash from Plant Yates was in this high B category; the Yates FGD was much lower in total B.

- Despite occasional high levels of metals in foliage and yield reductions on CCB-amended soils in greenhouse trials, no significant effect of 20 mt/ha CCB additions on plant tissue metal levels was detected in field experiments over three years of trials on either perennial or annual crops. Metals added did not accumulate to potentially dangerous levels in soils, and are not anticipated to present either a leaching or crop uptake hazard.

3.3.1.3 Soil/Water Relations

Application of CCBs including FGD and fly ash have the potential to change soil properties that may be important in both agronomic productivity and environmental impacts of amended soils. Such applications may directly affect the particle size distribution, and thus properties such as water-holding capacity, depending on application rates, as well as indirect effects on the rate of water infiltration under rainfall. These properties determine the amounts of plant-available water held in soils, and therefore the yield potential, given the typical limitation of moisture in yield in the Southeastern U.S. In addition, CCB amendment may influence soil erosion, either favorably reducing the tendency of soils to crust and erode under rainfall (as has previously been found for other by-product gypsums), or exacerbating erosion problems, as has been suggested for fly ash applications to soils. The objective of this task, therefore, was to document changes in soil-water relations caused by applications of FGD and mixed fly ash-FGD on Southeastern U.S. soils.

3.3.1.3.1 Soil Water-Holding Capacity

Water holding capacity of soils is defined as the mass ratio of water to dry soil at a specified tension at which the water is held (against the force of an applied vacuum or suction). Water available to plants is defined as that held more tightly than 0.3 bar (33 kPa) tension, but less than 15 bar (1500 kPa) tension. On coarse-textured (sandy) soils, additions of ash have been suggested at high rates in order to add fine particles (since ash is largely silt-sized), and thereby increase water-holding capacity. It should be noted that FGD will not have such an effect, since it will dissolve over a period of weeks or months and not affect soil particle size distribution.

Particle size and moisture retention data were presented previously for the range of five ashes studied (Table 3-15). These data confirm that the ashes are largely silt-sized (2-50 mm diameter), although some ashes have larger percentages of sand-sized (> 50 mm) particles; clay (< 2 mm) is uniformly low. Water-holding capacities at 33 and 1500 kPa (corresponding to 0.3 bar, field capacity, and 15 bar, permanent wilting point, measured on a pressure plate apparatus) are rather variable: excluding the $Yates_{lag}$ sample, field capacity averages about 30% (expressed as g water held per 100 g dry ash) and wilting point (excluding Gaston) about 6%. Average "plant-available" water content is, therefore, about 25% (the difference between these two values).

A range of particle sizes and moisture holding characteristics for topsoils found in the Southeastern U.S. Piedmont and Coastal Plain is shown in Table 3-65. Topsoils are typically sandy, with 70-80 % sand and 10-15% each of silt and clay; moisture holding characteristics are such that about 10% plant-available water is held by these soils. This is a relatively low value, and partially explains why drought stress is so common for field crops in this region.

TABLE 3-65
PARTICLE SIZE AND WATER-HOLDING CHARACTERISTICS OF TYPICAL PIEDMONT AND COASTAL PLAIN TOPSOILS.

Soil	Sand	Silt	Clay	33 kPa H_2O	1500 kPa H_2O	Avail. H_2O
	% of soil mass			g H_2O / 100 g dry soil		
Appling	73	17	10	0.16	0.06	0.10
Worsham	63	24	13	0.19	0.07	0.12
Cecil	74	20	6	0.18	0.06	0.12
Cecil	78	15	7	0.14	0.05	0.09
Pelham	71	15	14	0.16	0.08	0.08
Tifton	79	13	8	0.15	0.05	0.10

Particle size and available water for a "typical" topsoil and a typical fly ash are shown in Table 3-66, along with two mixtures of soil+ash, at rates equivalent to 60 mt/ha (which is roughly equivalent to a 97% soil: 3% ash mix) and 200 mt/ha (equivalent to 90% soil : 10% ash). While the average ash has over twice the water-holding capacity of the soil material, it is clear that such rates have only a minor effect on soil particle size distribution and on water-holding capacity. Even at 200 mt/ha, which would be a considerable application rate even if applied over a period of years, particle size is not drastically changed, and available water is increased only about 15% compared to the untreated soil. While this increase might amount to an extra 1-2 day supply of

TABLE 3-66

PARTICLE SIZE AND AVAILABLE WATER-HOLDING CAPACITY OF TYPICAL SOUTHEASTERN U.S. TOPSOILS AND TYPICAL FLY ASH, AND OF MIXTURES OF SOIL + FLY ASH AT DIFFERENT APPLICATION RATES

Soil	Fly ash	Equiv. Rate	Sand	Silt	Clay	Avail. H_2O
% by wt.		mt/ha	% by wt.			% H_2O
100	0	--	75	15	10	10
0	100	--	25	70	5	25
Mixes:						
97	3	60	73.5	16.7	9.8	10.5
90	10	200	70.0	20.8	9.5	11.5

moisture to a field crop under high evapotranspiration conditions, it is not highly significant. It appears that the potential problems associated with such high rates of application (environmental and economic) would not justify ash additions at rates that would significantly increase water-holding capacities of agricultural field soils.

3.3.1.3.2 <u>Water Infiltration and Runoff Water Quality</u>

The objective of this study was to determine the effect of fly ash and FGD, applied alone and in combination either on the soil surface or incorporated, on the infiltration of rainfall on a typical Georgia soil. Additional objectives included the determination of heavy metal and toxic element (B, Pb, As) concentration in runoff and the relative percentage of added ameliorant in sediment eroded from a one hour rainfall event. The experiment was also used to determine soil erosion rates of CCB-amended soils (see next section).

Cecil sandy loam topsoil was collected from the UGA Plant Science Farm. These samples were dried, crushed and sieved to less than 2 mm. The soil was then packed into 20 x 40 x 10 cm pans, overlying 7 cm of coarse sand. Surface applied treatments (10 or 30 mt/ha equivalent - Yates fly ash and/or FGD) were spread evenly over the soil surface in the packed pans. The incorporated treatment (30 mt/ha) was premixed with the soil at a 15 g material /kg ratio (equivalent to mixing to a 15 cm depth of soil) and then packed into the runoff pans. The pans were then exposed to one hour of rainfall at an intensity of 55 mm/hr. During the rainfall event, runoff was collected in 5 min increments. The runoff bottle from each 5 minute increment was weighed to determine volume, and aliquots for heavy metal analysis were collected and filtered at 0.45 mm. Arsenic and Pb were analyzed in the runoff water from replicate 3 using the Perkin-Elmer graphite furnace atomic adsorption spectrophotometer. Samples from the three treatments analyzed for As were diluted 1:5 in order to lower their concentrations to the linear range for As on the graphite furnace. The Pb analysis and none of the controls required dilution.

The experimental data were analyzed using SAS as a complete factorial experiment. The main effects were: RATE (10 mt/ha. 30 mt/ha, 30 mt/ha incorp.); PAN or "treatment" (Fly-Ash, Gypsum, Fly-Ash + Gypsum, Control); BOTTLE or "time" (1-12 or 0-60 minutes in 5 min. increments); REPLICATE (1,2,3,4). All main effects, except for bottle were subjected to ANOVA. BOTTLE was not analyzed because it is a quantitative variable and its effect was known. The effect of BOTTLE was determined by graphical analysis. The soil loss and infiltration data were summed over the entire simulator run to determine if significant differences existed among treatments.

Infiltration curves for the three treatments (means of three replicates) are shown in Figures 3-60, 3-61, and 3-62; individual control pans were run for each treatment set, and these are shown on each graph. Surface applied ash, FGD , or ash+FGD increased infiltration rates above untreated controls in all cases, although there were no differences from inspection of the curves between the three CCB treatments. Both 10 and 30 mt/ha had similar effects, and were similar in the shapes of their curves and their final infiltration rates (10-20 mm/h, compared to 2-5 mm/h for controls). The incorporated treatments, however, had much less effect on infiltration curves, and final infiltration rates were the same as untreated pans, in the range of 2-5 mm/h. Total infiltration in mm and as a percentage of rainfall is given in Table 3-67. Control pans had about 10 mm infiltrated, or 16-20%; surface-applied CCB at 10 mt/ha increased this to 22-27 mm (40-50%), and 30 mt/ha was higher at 30-35 mm (55-60%). Incorporated treatments , however, were similar to controls, although the incorporated FGD treatment at 14 mm was slightly higher.

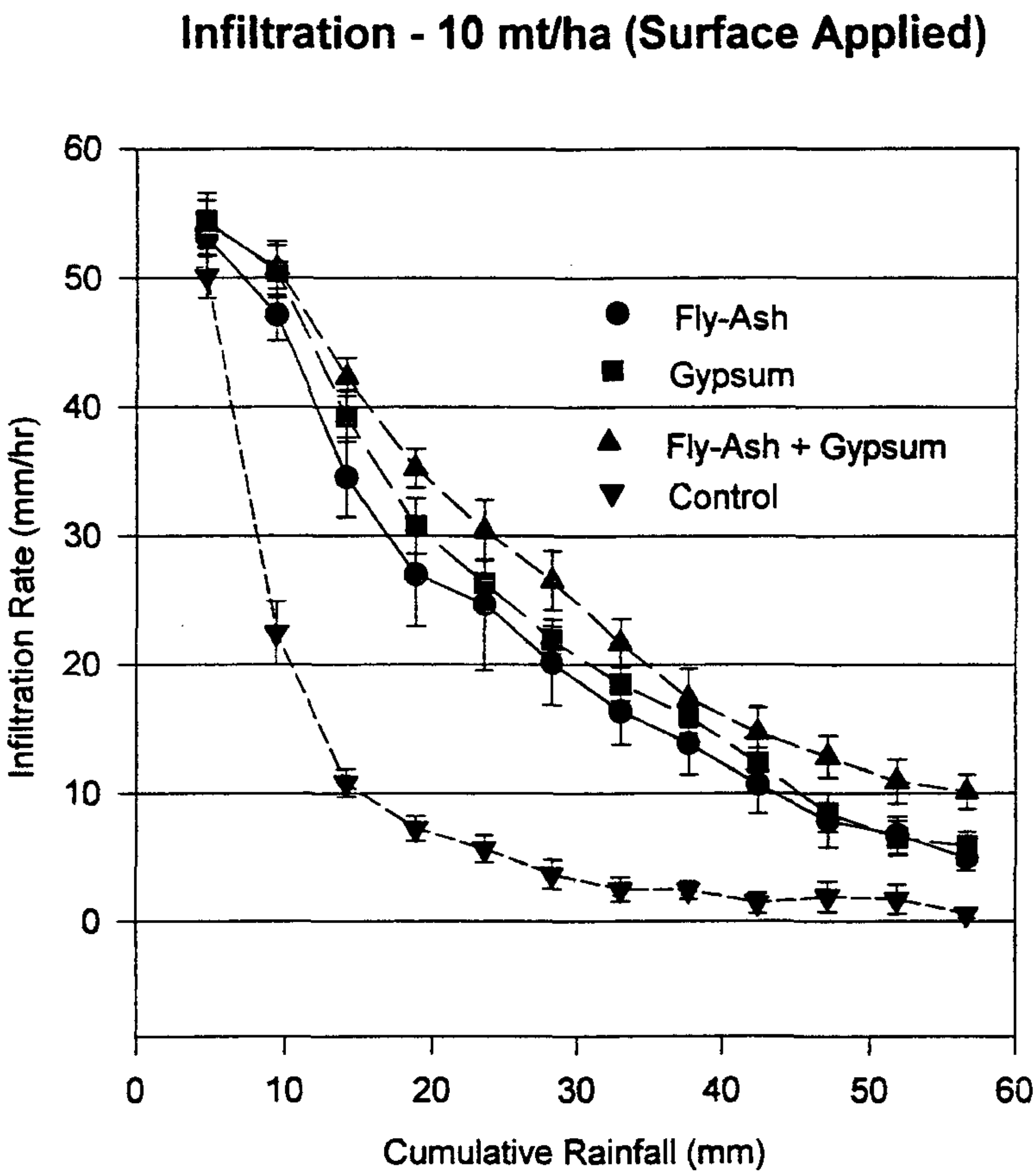


Figure 3-60. Infiltration Curves for Cecil Soil with 10 mt/ha Surface-Applied CCB

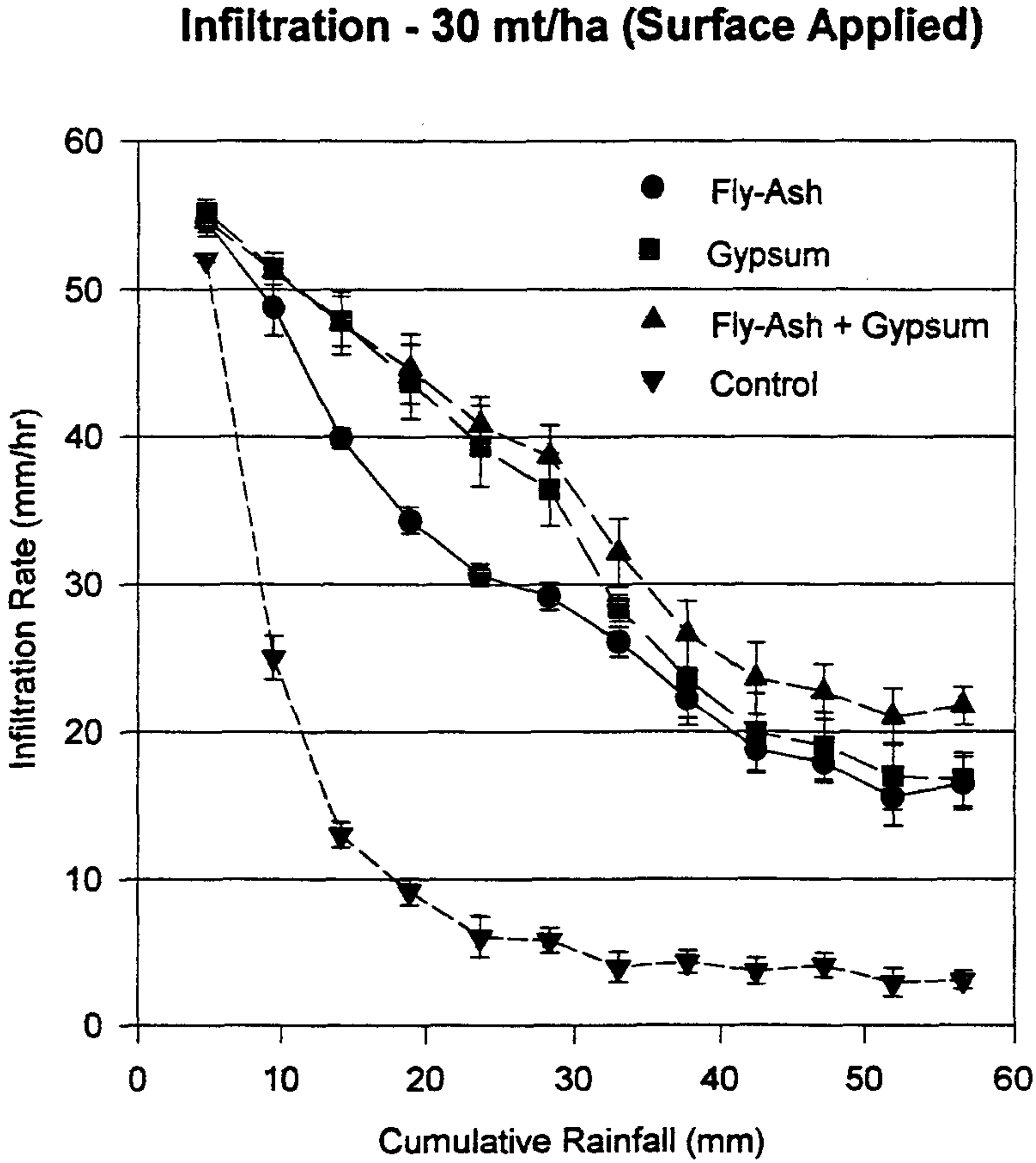


Figure 3-61. Infiltration Curves for Cecil Soil with 30 mt/ha Surface-Applied CCB

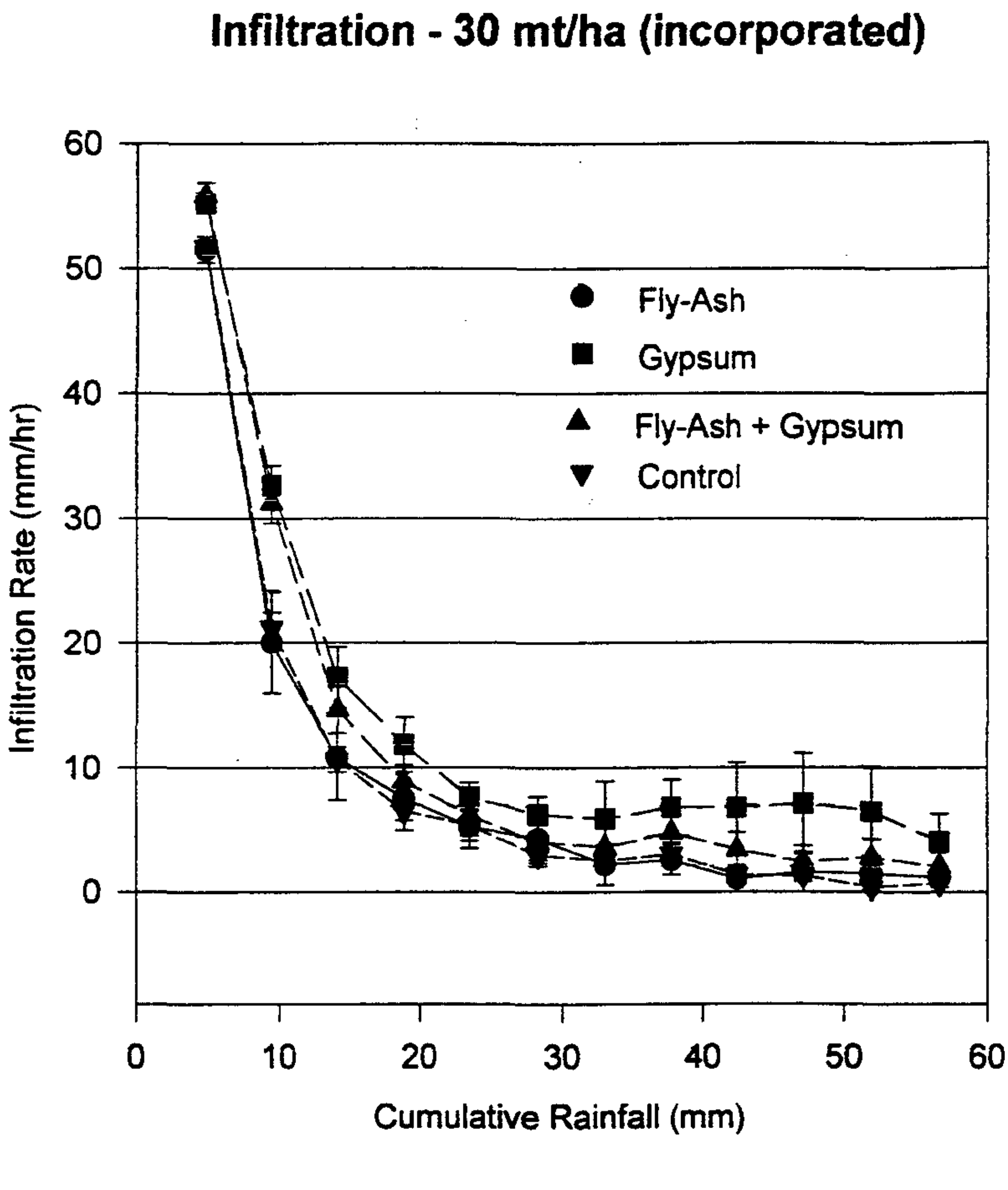


Figure 3-62. Infiltration Curves for Cecil Soil with 30 mt/ha Incorporated CCB

TABLE 3-67
TOTAL INFILTRATION (MM) AND PERCENTAGE ( ) INFILTRATION OF RAINFALL AS AFFECTED BY FLY-ASH AND GYPSUM TREATMENTS

Rates	Fly-Ash	Gypsum	Fly-Ash + Gyp.	Control
10 mt/ha	22.3 e1	24.2 de	27.3 cd	9.2 g
(Surface)	(40.5)	(44.0)	(49.6)	(16.7)
30 mt/ha	29.6 bc	33.2 ab	35.6 a	11.1 gf
(Surface)	(53.8)	(60.4)	(65.0)	(20.2)
30 mt/ha	9.1 g	14.0 f	11.7 fg	9.0 g
(Incorp.)	(16.5)	(25.5)	(21.3)	(16.4)

1 Values followed by different letters are significant by DMRT at alpha=0.05.
Values are the mean of four replications of simulated rainfall events.
Values are subtended by % infiltration of 1 hour of rainfall at 55 mm/hr (italics).

Thus, applications of surface-applied, although not incorporated, CCBs increase water infiltration significantly--doubling infiltration from a 55 mm storm at rates of 10 mt/ha, and nearly tripling if for 30 mt/ha. FGD was expected to have this result, as it releases electrolytes to the runoff water during rainfall, which reduces crust formation and maintains higher surface permeability. The effect of fly ash in this regard is surprising, since its low salt release and high pH was hypothesized to actually promote soil sealing and therefore runoff. The fly ash effect may be more of a physical effect, absorbing raindrop impact and protecting the underlying soil from dispersion.

Contaminant concentrations in the runoff water were measured at 10-minute intervals during the rainfall event; the data for lead are shown in Table 3-68. Lead levels were quite low overall due to the low solubility of Pb in the control soil and CCBs generally. These levels, 1-5 μg/L, were near the detection limit of the graphite furnace instrument, and do not show a clear effect of CCB treatment compared to control. Drinking water limits for Pb are in the range 50-100 μg/L, and thus these levels are not of concern. Arsenic levels in runoff water were more clearly affected by CCB amendment (Table 3-69); while control levels were at the detection limit of the instrument (1 μg/L), surface-applied fly ash resulted in 200-300 μg/L average in the runoff water, while fly ash+FGD mixes gave 50-100 μg/L. In general concentrations of As increased over time of

TABLE 3-68
LEAD CONCENTRATIONS IN RUNOFF WATER FROM PANS EXPOSED TO ONE HOUR OF SIMULATED RAINFALL (55 MM/HR)

Time into	10 mt/ha (surface)			30 mt/ha (surface)			30 mt/ha (incorp.)			Control
Run, min.	Fly-Ash	FGD	FA + FGD.	Fly-Ash	FGD	FA + FGD	Fly-Ash	FGD	FA + FGD	
					μg/L					
10	2	7	3	2	<1	3	<1	<1	2	2
20	1	5	2	3	<1	<1	<1	<1	2	2
30	1	2	2	4	<1	<1	<1	<1	1	2
40	3.5	2	2	6	<1	<1	<1	1	1	2
50	2	2	2	8	<1	<1	<1	1	1	2
60	1	2	3	9	<1	<1	<1	1	1	2
Means	1.75	3.33	2.33	5.33	<1	0.5	<1	0.5	1.33	2

TABLE 3-69
ARSENIC CONCENTRATIONS IN RUNOFF WATER FROM PANS EXPOSED TO ONE HOUR OF SIMULATED RAINFALL (55 MM/HR)

Time into	10 mt/ha (surface)			30 mt/ha (surface)			30 mt/ha (incorp.)			Control
Run, min.	Fly Ash	Gypsum	FA + Gyp.	Fly Ash	Gypsum	FA + Gyp.	Fly Ash	Gypsum	FA + Gyp.	
	μg / L									
5	79	15	48	109	6	36	17	3	19	1
10	201	12	55	183	5	71	11	1	7	1
15	192	14	56	222	4	110	7	2	6	1
20	221	0	58	255	4	111	6	1	6	1
25	215	8	61	245	2	100	6	1	5	1
30	197	7	54	232	1	97	6	2	4	1
35	192	11	60	229	5	115	8	1	4	1
40	206	7	56	290	2	119	7	2	3	1
45	208	10	56	399	3	126	8	1	3	1
50	208	0	48	330	4	136	9	1	5	1
55	212	14	41	343	4	135	10	1	5	1
60	210	4	42	389	4	139	9	1	4	1
Means	195	8.5	52.1	268	3.66	107	8.66	1.41	5.9	1

rainfall, for fly ash treatments, suggesting As is being slowly released from the surface applied materials. With As drinking water levels at 50 μg/L, these levels would be judged potentially unacceptable. Surface-applied FGD resulted in much lower As levels, 4-8 μg/L. Incorporated CCBs, however, released much less As to runoff waters (< 10 μg/L), and while still higher than control levels, are in an acceptable range.

The conclusion from this part of this study is that CCBs have the potential to increase water infiltration when applied on the surface at rates of 10 mt/ha; however, for ashes with considerable As (such as Yates at 35-49 μg/g), water quality may be degraded by the solubility of As in the runoff, and surface applications should be avoided. FGD surface applied did not release As in significant amounts to surface water, nor did fly ash or fly ash+FGD mixes when incorporated into the soil prior to rainfall.

3.3.1.3.3 Soil and CCB Erosion

The infiltration studies described above were also used to measure sediment production, in order to determine the effect of CCBs on soil erodibility; in addition, loss of CCBs through runoff was measured in the solids eroded from the surface of the erosion pans. The collected runoff was siphoned off from the bottles used to collect runoff and the solids transferred to tared beakers; these were dried and weighed for determination of soil loss. The sediment in the dried beakers was then collected and combined into 20 minute increments for content analysis (% soil, fly ash, and FGD).

Eroded sediment was sieved through 80 mesh screen and analyzed for percentage fly ash by preparing known mixtures of fly ash and soil as standards and using comparative X-ray diffraction analysis at 2-theta ranges (32-34) and (40-42) which correspond to peaks for mullite. Peak area for each standard was regressed over the known % fly ash standards. The regression model was then used to predict the amount of fly ash in the unknown 20 min increment sediment samples. Each sample was run three times through the diffractometer for the above ranges.

Percent FGD in each solid was estimated by the Ca content in the sediment samples determined by acetylene flame atomic absorption spectrophotometry using a Perkin-Elmer model 5000. Aliquot preparation for FGD analysis was as follows: sediment samples from the gypsum only treatments were shaken overnight with 0.05% $LaCl_2$ solution and then centrifuged. Where sediments contained both gypsum and fly ash, samples were shaken overnight in 0.1 M EDTA solution and then centrifuged. This supernatant was then diluted with 0.01% $LaCl_2$ for the final sample. Measured Ca contents were converted to % gypsum using the formula weight; corrections were made for the dissolution of Ca from untreated soil (containing no FGD). The remaining sample after extraction with EDTA was dried and mounted for X-ray diffraction for percent fly ash prediction as indicated above.

The sediment analysis showed that total solid eroded from CCB-treated pans was greater than control pans, consistently for surface-applied treatments (Table 3-70). However, much of the eroded sediment was actual CCB material, either fly ash or gypsum. At the 10 mt/ha rate, actual loss of soil was similar between the treatments, but in fly ash treatments, nearly as much ash as soil was eroded from the pan surfaces. This amount doubled in the 30 mt/ha treatment. FGD was lost as a solid in the sediment to a lesser extent. This result is undoubtedly due to the fine particle size and therefore ready transportability of the CCB particles in runoff water, even though there was less volume of runoff in the CCB treatments. Incorporated treatments lost almost no CCB, and soil loss was similar to the control soils, although the incorporated fly ash only treatment appeared to be somewhat elevated relative to the control.

The results of the sediment analysis indicate clearly that surface applications of CCBs will produce off-site transport of these materials as eroded particles, and in the case of fly ash particularly, this is an undesirable result. FGD amendment did not reduce soil loss when surface-applied, as has been found for other by-product gypsums; the reasons for this are not known, and are under investigation. Lacking a clear rationale for surface application, and given the documented environmental impacts of runoff and sediment contamination from fly ash in surface-applied

TABLE 3-70
TOTAL SOIL AND/OR AMELIORANT LOSS (KG/HA)
FROM ONE HOUR OF SIMULATED RAINFALL AS AFFECTED
BY FLY ASH AND GYPSUM TREATMENTS

Rates		**Fly-Ash**	**Gypsum (FGD)**	**Fly Ash + Gyp.**	**Control**
10 mt/ha	Soil Loss	2259	2812	2375	2620
(Surface)	Ameliorant loss	2734	564	2114	
	Total:	4994 b1	3376 cde	4490 bc	2620 de
30 mt/ha	Soil Loss	1597	1820	1353	2134
(Surface)	Ameliorant loss	5244	1858	3678	
	Total:	6841 a	3678 bcd	5031 b	2134 e
30 mt/ha	Soil Loss	4315	2587	2363	3354
(Incorp.)	Ameliorant loss	75	3	26.3	
	Total:	4390 bc	2590 de	2389 de	3354 cde

1 Values followed by different letters are significant by DMRT at alpha=0.05. Values are the mean of four replications of simulated rainfall events.

CCBs, it is clear than CCBs should be incorporated into the soil. When this is done, runoff water and sediment quality are not impaired, and soil erodibility does not seem to be affected.

3.3.1.4 Crop Rotation and Deep Rooting

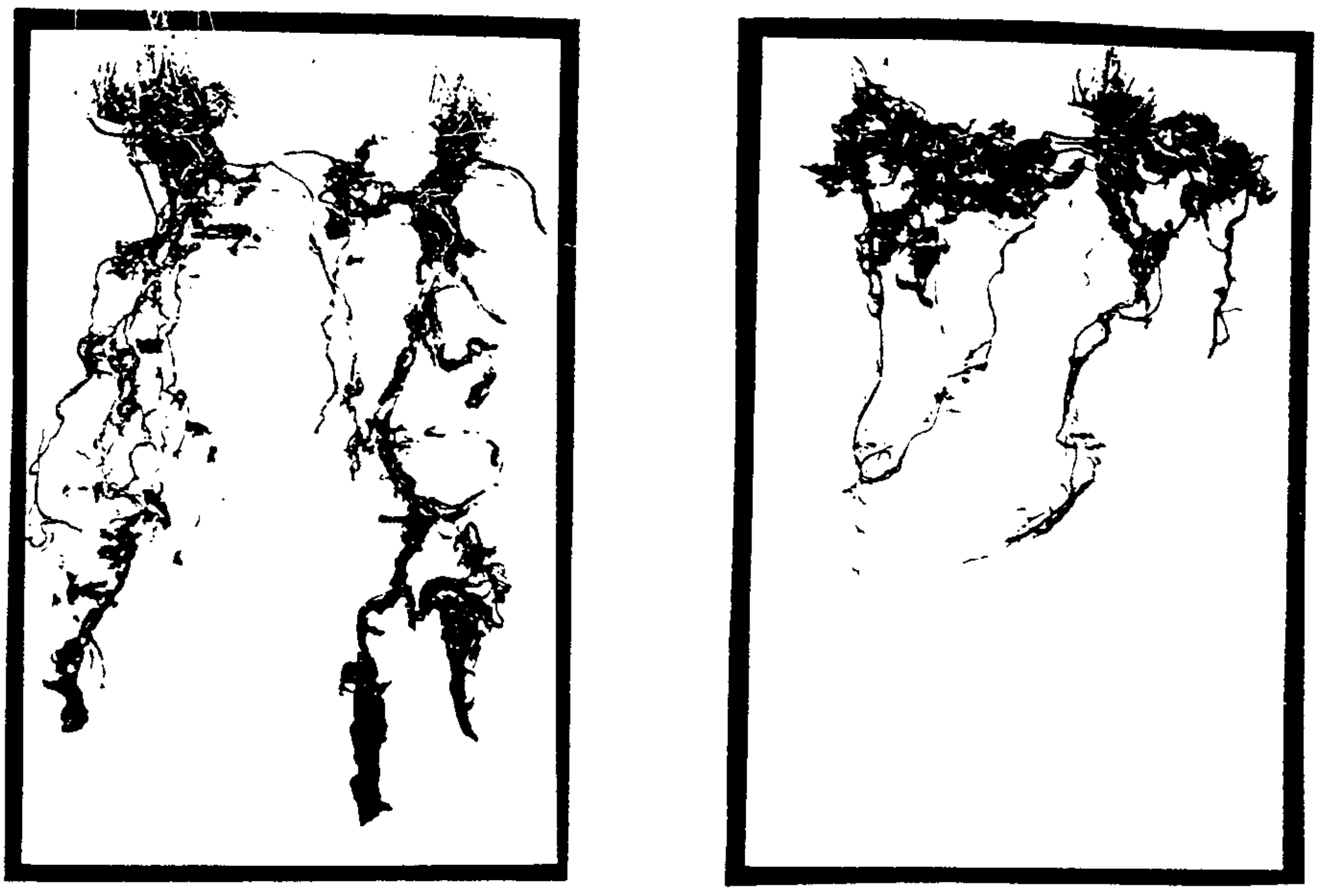
The objective of this task was to demonstrate that FGD applied on the surface of soil which has dense subsoil layers with high penetration resistance together with a deep rooting crop results in reduced penetration resistance. Previously, Sumner (1990) demonstrated this effect with phosphogypsum.

3.3.1.4.1 Field Experiments

The alfalfa experiment described in Section 3.3.1.1.2 was used for this purpose. Penetrometer resistance measurements (Cone Index) were made using a tractor-mounted hydraulically driven penetrometer (Clark and Reid, 1984) on all replications of the control and 20 mt/ha FGD treatments in December 1994 (2 years after establishment of the experiment). The penetrometer drives a standard American Society of Agricultural Engineers (ASAE) cone (0.02 m base diameter) into the soil in accordance with ASAE standard S313.2 and records the force required, which when divided by the cross-sectional area of the base of the cone gives the cone index (CI) in units of pressure (MPa). A microcomputer recorded CI for each 0.0025 m of probe depth from the surface, from which the average CI for each 0.025 m depth increment was calculated. Fifteen separate CI measurements with depth were made on each treatment.

Because mechanical impedance increases with decreasing soil moisture content, soil water contents were measured on each treatment immediately after penetrometer measurements had been completed. This was accomplished by taking 10 cores per plot to a depth of 0.7 m with a core sampler. These cores were divided into 0.15 m depth increments and bulked by depth for gravimetric moisture determination. No significant differences in moisture content between treatments were recorded, which means that the measured CI values truly reflected the mechanical impedance likely to be experienced by roots.

Mean cone index values with depth for the control and FGD treatments are presented in Figure 3-63. At depths less than 0.2 m, CI values were not different which is to be expected as the soil had been tilled to this depth. Below 0.2 m, the CI values in the FGD treatment began to deviate from those in the control and the difference became significant at depths below 0.37 m. Values for CI above 2 MPa have been shown to inhibit root growth (Taylor et al., 1966). In this experiment, CI values in the control treatment were well above 3 MPA particularly below 0.4 m. FGD reduced these values to the non-limiting range between 0.25 and 0.4 m but below this depth the values, while considerably reduced, increased from 2 to 4 MPa which would have still been limiting as far as root penetration is concerned. These results confirm the results previously reported by Radcliffe et al. (1986) who first demonstrated this effect. They found that the beneficial effect of gypsum on penetration resistance continued with time and the differences between control and gypsum treatments continued to increase. In the present experiment, the beneficial effect of FGD is likely to continue with time but because the CI values at depth were still likely to be limiting



a) b)

Figure 3-63. Root Response of Alfalfa in a Cecil Soil to (a) Gypsum and (b) Control

root growth in both treatments, no significant yield differences were observed. In the Radcliffe, et al. (1986) experiment where CI values became non-limiting in the subsoil, considerable improvements in alfalfa yields and rooting patterns were observed between control and gypsum treatments. Presumably with time, a similar improved rooting pattern will evolve in the current experiment when the CI values become non-limiting.

3.3.1.4.2 Conclusions

The data collected under this task show that FGD behaves in the same way in terms of reducing penetration resistance in the B horizon of Ultisols as other sources of gypsum (phospho- and mined) tested in the past (Sumner, 1990). Subsequent crops planted on such ameliorated fields should also exhibit improved rooting in the subsoil. The Ca leaching data presented previously (appendix tables, and 3.3.1.1.4) support the contention that movement of Ca into subsoils is responsible for this effect. However, this is a long-term improvement that even a project of 6 year duration such as the current one cannot fully document. The indications of improvements in subsurface horizons are evident, none-the-less, and should be a continued benefit of FGD applications to croplands.

3.3.1.5 Revegetation of Gypsum Stack

The objective of this task was to develop the technology required to grow a permanent vegetative cover on the waste FGD and fly ash+FGD stacks. The initial phase involved greenhouse testing of the growth of various plant species at various fertilizer rates, and the second phase testing of the best prospects in the field on the actual FGD stack at Plant Yates.

3.3.1.5.1 Greenhouse Experiments

Because of delays in the construction and commissioning of the flue gas desulfurization unit at Plant Yates, it was not possible to obtain gypsum on schedule. Therefore, a preliminary set of experiments using gypsum from other sources as surrogates for the Yates material were conducted to establish the requirements for plant growth on by-product gypsum materials. In an initial experiment, flue gas desulfurization gypsums from Illinois (Chiyoda Process) (FGD -IL) and Florida (FGD -FL) having the chemical and physical properties presented earlier were used. Particle size was determined by the pipet method using a saturated gypsum solution instead of water (Gee and Bander, 1986). Hydraulic conductivity was measured by the constant head method using a saturated gypsum solution in place of water (Klute and Dirksen, 1986). Water content at field capacity (-0.01 MPa) was determined using a pressure plate apparatus (Richards, 1954). Saturation extracts were prepared by vacuum filtration (Richards, 1954). Electrical conductivity (EC), pH, SO_4, Cl and B contents were determined according to Rhoades (1982) and Si, Ca, Mg, Na and K by inductively coupled plasma (ICP) spectroscopy.

From the analyses in Tables 3-71 and 3-72, the only properties of these materials which might adversely affect plant growth are the low hydraulic conductivity of the Florida material due to the finer particle size and the high salt content (EC) of the Illinois material which is due to the high $MgSO_4$ content arising from the use of a dolomitic limestone in the desulfurization process. The first attempt at growing plants directly on these materials resulted in complete failure in FGD-IL due to the high salt content (EC = 9.8 dS/m) and very poor growth in FGD -FL due to high Cl content. As a result, the materials were first leached with water to remove these impurities, which resulted in both materials having similar EC values (2.42 and 2.51 dS/m) which would not inhibit growth.

The main greenhouse experiment consisted of a 2 gypsum (FGD -IL and FGD -FL, previously leached) x 2 crops (weeping lovegrass [*Eragrostis curvula*] and lespedeza *[Sericia lespedeza]*) x 15 N-P-K nutrient rates (mg/kg) and combinations (0-50-150, 50-50-150, 100-50-150, 200-50-150, 250-50-150, 100-0-1500, 100-12.5-150, 100-25-150, 100-50-150, 100-100-150, 100-50-0, 100-50-50, 100-50-150, 100-50-250, 100-50-300) factorial in a completely randomized design with 3 replications. The other nutrients were applied as follows (mg/kg): Mg 12.5, Mn 5, Fe 2.5, Cu 1.2, B 1.0, Zn 1.0, and Mo 0.1. Solutions of all nutrients were prepared and thoroughly mixed with the by-product gypsums. Weeping lovegrass and lespedeza which was inoculated,

TABLE 3-71

SOME PHYSICAL AND CHEMICAL PROPERTIES OF BY-PRODUCT GYPSUMS

Gypsum source	pH	Size class and particle diameter (mm)			Water Content -0.1 bar	Hydr. Cond.
		Sand	Silt	Clay		
		2-0.05	0.05-0.002	<0.002		
		%			%	cm/h
FGD (Florida)	7.5	22.50	74.05	3.45	27.4	1.68
FGD (Illinois)	8.7	75.56	23.20	1.24	16.2	7.24

TABLE 3-72

SATURATION EXTRACT COMPOSITION FROM BY-PRODUCT GYPSUMS

Gypsum source	Cations ($mmol_c$/L)				Anions ($mmol_c$/L)				EC
	Ca	Mg	Na	K	SO_4	Si	B	Cl	dS/m
FGD (Florida)	31.8	3.77	0.77	0.15	31.53	0.14	0.20	3.98	3.21
FGD (Illinois)	20.5	57.10	2.25	0.18	62.81	0.04	2.04	13.89	9.80

were selected as they were likely to grow well on waste materials. Pots which contained 2 kg of FGD were watered to -0.01 MPa and then seeds were spread on top of each pot and covered with a thin layer of each material. Tops were harvested after 45 days and yields were determined.

The results of N-P-K combination rates on top growth of weeping lovegrass and lespedeza are presented in Tables 3-73 and 3-74. The best growth for both gypsum materials and for both species, was obtained with application of 100-50-150 mg N-P-K/kg. Nutrient applications above and below this level tended to reduce dry weight of both crops but the magnitude of the reduction differed with nutrient and gypsum source. These results indicate that the balance between N, P and K is important in promoting growth on these types of materials. By comparison, Giordano et al. (1984) established a vigorous cover of bermuda grass on FGD with 13-13-13 fertilizer at a rate

TABLE 3-73
EFFECT OF N-P-K TREATMENTS ON TOP GROWTH OF WEEPING LOVEGRASS ON VARIOUS BY-PRODUCT GYPSUM MATERIALS

Treatment			Dry weight of tops	
N	P	K	FGD-FL	FGD-IL
mg/kg			g/pot	
50	50	150	5.69	5.25
100	50	150	6.88	6.34
200	50	150	6.54	6.05
250	50	150	6.22	6.00
100	12.5	150	6.12	5.47
100	25	150	6.85	5.82
100	100	150	6.35	5.63
100	50	50	6.18	6.05
100	50	250	5.45	5.14
100	50	300	5.50	5.08
$LSD_{0.05}$			0.54	0.59

TABLE 3-74
EFFECT OF N-P-K TREATMENTS ON TOP GROWTH OF LESPEDEZA ON VARIOUS BY-PRODUCT GYPSUM MATERIALS

Treatment			Weight of tops	
N	P	K	FGD-FL	FGD-IL
mg/kg			g/pot	
50	50	150	2.42	1.90
100	50	150	3.11	2.25
200	50	150	2.73	2.05
250	50	150	2.66	2.00
100	12.5	150	2.25	1.80
100	25	150	2.65	1.93
100	100	150	2.60	1.49
100	50	50	2.06	1.70
100	50	250	2.35	1.75
100	50	300	2.15	1.49
$LSD_{0.05}$			0.25	0.29

of 550 kg/ha with N being the most limiting element. The N was split applied as ammonium nitrate at 336 kg/ha. In the context of the present experiment, these rates would be equivalent to approximately 180 mg N, 60 mg P and 120 mg K/kg which are not very different from the results presented here. Vegetative growth of lovegrass was greater than that of lespedeza regardless of by-product gypsum sources. Lespedeza, despite inoculation, did not nodulate and responded more to N and K than P.

A second greenhouse experiment was conducted to examine more plant species and improved fertilization on the actual Yates FGD . The FGD being produced at Yates is contaminated with high levels of soluble salts (EC > 70 dS/m as a result of the recycling of process water. Because this level of salts would totally inhibit germination and growth, the material was leached with tap water to remove the excess salinity before commencing the greenhouse experiment. In order to determine how much rainfall would be required to remove salts in the field, a column leaching experiment was conducted by leaching a column of FGD with deionized water. After leaching with approximately 170 mm of water, the EC of the material in the top 25 cm had been reduced to acceptable levels. Based on the experience gained in the initial phase of greenhouse experimentation, a modified type of experiment was designed to test the FGD material from Yates. The experiment consisted of 3 replications of a completely randomized design with 4 plant species (alfalfa [*Medicago sativa*], johnsongrass [*Sorghum halepense*], bermudagrass [*Cynodon dactylon*] and weeping lovegrass) and 6 N-P-K fertilizer rates in mg/kg (0-50-100, 0-100-200, 50-25-50, 100-50-100, 200-100-200, and 300-100-300) in factorial combination with split plots for minor elements (Mg 12.5, Mn 5, Fe 2.5, Cu, 1.2, Zn 1.0, Mo 0.1). Management of the pots which contained FGD, and analytical methods, were as indicated in the initial experiment. Plants were harvested periodically and their dry weight determined.

Of all the species grown, bermudagrass was the most vigorous (Table 3-75). The best N-P-K fertilizer treatment combination proved to be 300-100-300 for all species, with yield responses being recorded when minor elements were applied in all cases. These results suggest that high rates of fertilizer as well as applications of minor elements will be necessary to successfully establish vegetative cover on the stacks in the field.

TABLE 3-75
EFFECT OF FERTILIZER RATES ON THE CUMULATIVE YIELD OF PLANTS AFTER THE NUMBER OF CUTS INDICATED GROWN ON YATES FLUE GAS DESULFURIZATION GYPSUM

N-P-K mg/kg	Yields (g/pot)							
	Alfalfa (4 cuts)		Johnson grass (3 cuts)		Bermuda grass (3 cuts)		Weeping love grass (3 cuts)	
	– ME	+ ME	– ME	+ ME	– ME	+ ME	– ME	+ ME
0-50-100	4.21	6.45	0	0	0	0	0	0
0-100-200	5.67	9.11	0	0	0	0	0	0
50-25-50	3.69	4.56	2.72	3.32	4.37	3.48	2.86	3.26
100-50-100	5.03	5.41	5.60	7.81	7.46	8.18	6.51	7.25
200-100-200	5.57	6.21	10.65	13.40	11.38	13.68	8.38	11.27
300-100-300	7.20	10.04	11.33	13.53	17.13	21.27	11.65	14.83
$LSD_{0.05}$	2.27	2.76	2.96	3.25	1.95	0.89	1.81	0.95

In general, the problems associated with the establishment of vegetation on by-product gypsums are the same as the physical and chemical limitations found on other mine waste materials (Hossner and Shahandeh, 1991). The main chemical problems are nutrient deficiency, especially N,P and K, and ion toxicity and salinity on some of FGD materials. The main physical problem is associated with the texture of by-product gypsum especially in disposal areas where it could limit nutrient and water availability. The success of direct seeding on the gypsum waste materials will be primarily dependent on these limitations. The addition of a complete fertilizer at normal agricultural rates substantially improves the growth of plants on by-product gypsums. In the event of the problem being associated with excess salts or toxic ions, pre-irrigation (leaching) will be necessary prior to seeding any vegetation. The results of the current and other experiments indicate that it should be possible to eliminate the covering of waste stacks with topsoil and allow direct seeding, which would significantly reduce the reclamation cost.

3.3.1.5.2 Field Experiment on Gypsum Stack

Prior to establishing experimental plots on the pure gypsum stack at Yates, samples were taken to establish whether sufficient rainfall had fallen on the stack to leach soluble salts out of the rooting zone. The results (Table 3-76) indicate that, at all sampling sites, the EC was low enough to permit good root growth in the top 20 cm of the material and, at most sites, in the top 30 cm of material. The very high rainfall received during the months of June, July and August 1994 after establishment would have completed the leaching process.

TABLE 3-76
EC VALUES WITH DEPTH AT SITES ON YATES GYPSUM STACK BEFORE PLANTING OF VEGETATION

Depth (cm)	Site 1		Site 2		Site 3		Site 4		Site 5	
	EC	pH	EC	PH	EC	PH	EC	pH	EC	pH
0-10	2.13	7.30	2.27	7.30	2.94	7.24	2.35	7.24	2.19	7.43
10-20	2.26	7.23	2.36	7.22	3.18	7.30	2.94	7.37	2.19	7.41
20-30	2.28	7.30	2.94	7.22	4.17	7.43	3.03	7.44	2.27	7.50
30-40	2.52	7.30	8.00	7.25	7.18	7.40	3.8	7.45	2.72	7.53

The experiment was laid out on flat and sloping portions of the stack. Because of the limited area available for experimentation on the stack, small plots (1 x 1 m) were laid out on May 17, 1994. The experiment consisted of 6 replications of 4 plant species (weeping lovegrass, bermudagrass, johnsongrass and bahiagrass) seeded at 0.6, 1.0, 5.0 and 4.2 g seed/m, respectively. The plots were covered with hay after seeding to reduce evaporation. The following fertilizer treatment was applied to all plots before planting and incorporated (kg/ha): 200 N as $(NH_4)NO_3$, 200 P as triple superphosphate, 200 K as KCl, 70 Mg as $MgSO_4.7H_2O$, 5 Fe as $FeSO_4.7H_2O$, 10 Mn as $MnSO_4.5H_2O$, 2.4 Cu as $CuSO_4.5H_2O$, 2 Zn as $ZnSO_4.7H_2O$ and 0.2 Mo as $Na_2MoO_4.2H_2O$. On July 1, 1994, a topdressing of 100 N as NH_4NO_3 and 100 K as KCl was made. Irrigation was applied in order to achieve good germination (6.3 and 9.5 mm on May 17 and May 21, respectively).

Good germination was achieved on all plots. All grasses with the exception of bahiagrass have grown well. However on the replications set out on the old roadway, growth has been slow and rather poor probably due to compaction of the material. No yields of the various grasses were taken because such comparisons would have little meaning. Visual rates, however, indicated that growth was excellent the first year where the FGD material was not excessively compacted (as in the roadway).

There is no doubt that vegetative cover can be established on waste gypsum stacks. However the longevity of the stands will probably depend on continued management, at least for several years until full nutrient cycling is established. In the second season, a topdressing of 360 lb N/ac was applied to all plots on the Yates stack. Growth during the second year (1995) was still poor due to the harsh environmental conditions (low water availability, large temperature variations and extremes). Weeping lovegrass was the most vigorous species in the second year. It is hypothesized that once an organic layer forms beneath the growing vegetation (which may require several years), continued management will be unnecessary, and the stack should have fully self-supporting vegetation. Longer-term studies will be necessary to establish how long this process takes, however.

3.3.2 Wallboard and Cement

As described in Sections 2.4.2.2 and 3.1 the planned gypsum processing plus wallboard and cement manufacturing demonstrations did not take place due to unavailability of a portion of funding. However, a shipment of approximately 1000 tons of Yates gypsum provided to a local portland cement manufacturer should result in a manufacturing and handling trial in 1997. The plan is that the manufacturer will use a blended gypsum (FGD + mined gypsum), gradually increasing the FGD component until handling problems are encountered.

Regarding these two applications, where moisture and chloride levels are particular concerns, in situ samples were taken from the gypsum stack to check the changes which would take place without mechanical washing and dewatering equipment. The west and south dikes (centerline position) were sampled at 3, 13, and 29 months since process slurry was diverted to the other stack. Retrieval depths were at least 6 feet in each case. After the initial check at 3 months, when chloride levels were above 5000 ppm, there was a dramatic decline to values below 100 ppm in succeeding tests at 13 and 29 months. Moisture levels remained at marginally useable levels at the 13 and 29-month intervals.

Thus, it is possible that the desirable material characteristics (<100 ppm chloride and <10% free moisture) could be achieved by operating a stack with multiple compartments to allow washing by natural rainfall in the inactive compartment. Perhaps moisture levels could be reduced by excavating and stockpiling gypsum to allow for air drying prior to utilization of the gypsum.

4.0 RECOMMENDATIONS

4.1 Stacking

As stated above, it has been demonstrated at Plant Yates that CT-121 FGD gypsum and gypsum-fly ash can successfully be stored/disposed by wet-stacking using upstream construction methods. The following sections present recommendations, based primarily on field evaluation of the demonstration project, to improve stackability and operational efficiency for future projects, and, in particular, for modifying and implementing design elements of the small-scale test facility to future full-scale byproduct disposal.

4.1.1 Design and Construction

The wet-stacking disposal facility at Plant Yates for the demonstration project was designed to provide adequate storage for the projected byproduct volumes and result in stack heights that would allow for use of full-scale procedures and field evaluation of stackability. Accordingly, the area encompassed by the stacks was minimized. In addition to byproduct storage requirements, the basic design of future full-scale facilities should consider incorporating:

- A significantly larger perimeter seepage/runoff collection ditch to minimize flow velocities to reduce erosion, to provide storage in the event of minor spills, and to allow for optional use for decant water conveyance.
- Larger perimeter dike heights above the internal base to provide more freeboard during casting operations associated with initial upstream dike raising.
- Site selection or basic site grading for construction of disposal ponds at level grades so that flow gradients of the perimeter ditches can be minimized to prevent erosion and provide additional surge capacity, or incorporate drop structures in relatively level ditches around the stack(s) at sloping sites.

Gypsum stack underdrains, consisting of a perforated collection pipe in non-reactive gravel completely wrapped in filter fabric, are typically installed within gypsum to prevent clogging of the fabric by gypsum fines that might otherwise be deposited in direct contact with the drain.

However, the Plant Yates gypsum and gypsum-fly ash stack drains were installed directly upon the synthetic liner because no FGD gypsum was available for use as a construction material at the time (see Details A and B on Figure A4 in Appendix A). Based on observed seepage at the face of the gypsum stack slope, it appears that sedimented fines may have been deposited in direct contact with the drain resulting in increased head losses for flow into the drain and correspondingly elevated water levels in the stack. Stability of the lower portion of the gypsum slope where seepage was occurring required that side slopes flatter than the design slope be implemented in raising the stack.

The apparent partial clogging of the filter fabric by gypsum fines was likely further caused by the initial use of the drains for decanting clarified supernatant water to the surge pond. Underdrains associated with future facilities should not be used in this capacity, and should be provided with stop-valves that could restrict flow into the drains until after a uniform sedimented gypsum cover is established.

The basic design of future, full-scale facilities should consider incorporating drains at the base that are either installed within FGD gypsum (sedimented or mechanically placed) or a multiple graded filter system compatible with the finer fraction of the byproduct material. Full-scale stack designs should also incorporate stack slope drains that would be periodically installed within the gypsum upstream of the outer slope as the stack is raised to prevent seepage from exiting of the slope and thus allow for steeper growth slopes (and would further allow vegetation of the slopes as the stack is raised).

In order to maximize efficiency of the gypsum and gypsum-fly ash stack underdrains, the invert elevation at the discharge of the outlet pipes in the surge pond was minimized (i.e., just above the normal operating depth in the surge pond). The result was that the outlet discharges were seldom visible and that the outlet flows could not readily be measured. Drain outlets for future facilities should be designed to allow for routine visual inspection and flow measurement.

4.1.2 Liners

The composite liner used for the wet-stacking demonstration project, consisting of 12 inches of compacted clayey soil and a 60-mil high density polyethylene (HDPE) liner, was successful in protecting groundwater resources as evidenced by water quality testing results for samples taken from the compliance monitor wells located around the site.

The upper horizon soils at the site provided borrow sources for clayey soils that, when adequately compacted, could achieve a coefficient of permeability less than $1x10^{-7}$ cm/sec. However, the upper horizon soils of the residual soil profile at the site display a few characteristics that may not be favorable from a construction cost standpoint, including: (i) a tendency to erode which results in the need for considerable surface maintenance prior to deployment of the HDPE liner; (ii) a particle size distribution that contains a relatively high fraction of large gravel sizes that must be removed from the surface prior to placement of the HDPE liner; and (iii) a fairly wide range of clay-sized particle fraction which requires a significant effort to thoroughly mix and homogenize the fill in order to construct a uniform clay liner. Alternative composite liner components should be evaluated during the basic design phase of a full-scale wet-stacking facility.

The surge pond liner design incorporated smooth HDPE on the inboard dike slopes since not soil cover was used. To enhanced the safety of future facilities, textured liner sheets should be considered for all lined slopes. Furthermore, gypsum or soil cover to protect the liner should be considered in the basic design for long-term applications related to full-scale operations.

4.1.3 Water Management

Due to the limited size of the gypsum and gypsum-fly ash disposal areas at Plant Yates, and considering that development of elevated rim ditches was not fully realized, water management was somewhat difficult. In particular, maintenance of a central pond with sufficient size and depth for clarification of the slurry was very sensitive to the slurry flow rate, discharge location and decant operation. In general, water management for a larger, full-scale facility should be expected to be significantly less intensive.

Operation of a full-scale wet-stacking disposal facility should incorporate moveable-type decant systems rather than the fixed-type decant structures used in test facilities. The vertical risers associated with the fixed-type decant are not expected to be compatible with the large downdrag forces that will develop as greater gypsum thicknesses consolidate. Further, moveable decants similar to the one shown in Figure 2-13 will provide for greater operational flexibility for management of the size and depth of the internal settling pond for efficient clarification of the slurry.

4.1.4 Operation Procedures

Efficient operation of a full-scale wet-stacking facility for FGD byproducts will likely require successful implementation of the elevated rim-ditch concepts described in Section 2.4.1. Use of elevated rim-ditches will enhance stackability by providing more coarse and better dewatered gypsum for upstream cast dike raising, improve control of slurry distribution within the impoundment, and improve both the safety of and operational control over the clarification pond within the interior of the stack. Detailed operation guidelines and more comprehensive equipment operator training should be provided during initial stages of full-scale operation.

Full-scale facilities should be large enough to permit operation of two or more separate compartments within the disposal facility. This will allow operation of an active compartment for slurry deposition and an inactive compartment for upstream construction (and perhaps an inactive compartment of surge). Furthermore, elevated rim ditches can be constructed and slurry flows routed used such that deposition into a portion of the active compartment will not interfere with excavation and casting dewatered gypsum along the remainder of the perimeter.

4.1.5 Closure

The design sideslopes of 2.0H to 1.0V for the gypsum and gypsum-fly ash stacks at Plant Yates were selected based on stability considerations and to demonstrate stackability at relatively steep slopes. However, design sideslopes for future full-scale stacks should consider final slope geometries relative to closure requirements and costs. For instance, a final 2.0H to 1.0V may not be compatible with the required top cover design thus resulting in substantial grading and earthwork costs to prepare the stack for closure.

The basic design of full-scale facilities might also consider incorporating incremental closure and reclamation of the lower slopes in order to minimize impacted runoff catchment areas and improve the overall water balance of the facility. For instance, if stack drains are installed periodically as the stack is raised to prevent seepage from exiting the lower slope, then a portion of the lower slope may be capped and vegetated to allow removing a portion of the rainfall runoff from the closed-circuit water system.

4.2 Agriculture

4.2.1 Yield Response of Crops

Two complete years of yield data are available for the field studies using alfalfa grown for forages, and for a number of row crops. Given that the potential positive effect of gypsum is dependent upon leaching of Ca to the subsoil, which occurs only over a period of several years, these results must still be considered as preliminary and probably conservative in terms of the magnitude of response that may occur in successive years. Previous studies with gypsum materials such as phosphogypusm (Sumner, 1990) have shown that substantial yield responses are more likely in the second and subsequent years following gypsum application.

The fact that positive yield responses were obtained at all three locations in both years (Sections 3.3.1.1.2 and 3.3.1.1.3) indicates that the same or even a better pattern response to gypsum as has been obtained in the past is highly likely to occur with CCBP materials. At the Calhoun site, in particular, where the subsoil was the most acid of all but one site (Athens, unlimed), substantial yield responses of between 1,500 and 2,300 lb/ac of alfalfa hay were obtained at the high rate of addition for both FGD and FGD+FA. The size of this response was much greater than that obtained on a similar soil in the first year of the previous study (Sumner, 1990). This suggests that the yield response at this site is likely to continue in the future. In the previous study, yields continued to increase each year for the first 10 years without the need for reapplication of gypsum. The data for changes in the Calhoun soil composition where levels of Al have deceased as a result of gypsum application (sec 3.3.1.1.4), support the contention that yields are likely to continue to increase in the future.

A yield response in alfalfa was also observed at Tifton, but the harsh environmental conditions on the very sandy soil resulted in overall low yield levels. At the limed Athens site, no yield responses were obtained as the soil profile contained no exchangeable Al, a requirement for previous yield increases to gypsum applications (Sumner, 1990). This lack of yield response is in line with expectations. At the unlimed Athens site, a substantial yield response was obtained to gypsum application, but because the topsoil had not been limed, overall yields were low as expected. Nevertheless, the pattern of behavior is consistent with continued responses to gypsum.

The alfalfa yield results obtained indicate similar response patterns for treatments containing fly ash as compared to those with FGD only; crop response was mostly likely due to Ca additions, but at Calhoun there is a trend for FA treatments to yield better, and this may be due to micronutrients (e.g., B and Mo) supplied in the FA. There was no evidence of any deleterious effect of fly ash on yields, other than initial transient B toxicity the year of application. Thus, mixed FGD+FA material produced when the electrostatic precipitators are off would still be suitable for use in agriculture, and although having a lower FGD content, appears to be similar in promoting yield increases over several years' duration.

As to rates giving the best yield responses, the highest application used (20 mt/ha) was clearly superior to the lower rates used, particularly on the poorer soils of the Athens unlimed trial and at

Calhoun. There seems to be every reason to recommend a single high rate of application of CCB to forage crops.

Row crop yield increases due to CCB were sporadic, and previous experiments have confirmed that annual crops do not consistently respond to gypsum amendment, due to their limited rooting depth and variations in water availability due to weather conditions. While many of the experiments did not show statistically significant yield increases, several crops (Athens corn, 1994; wheat at Tifton, 1993 and Athens, 1994; both sorghum crops) show trends of increasing yield with higher rates of addition of both FGD and mixed FGD+FA. Again, there is no simple way to make rate recommendations from such data given its variability, but an attempt will be made to summarize this data in the Economics section (Section 5.0) that follows.

All the data at hand, and observations made of field plots at the beginning of 1996 (year 3 after application), support the contention that alfalfa yield responses will continue to be observed in future years at sites where the subsoil is acid and contains appreciable levels of exchangeable Al. Thus the most beneficial use for gypsum will be on such soils which comprise a substantial acreage in North Georgia.

4.2.2 Application Methods

Because gypsum is water-soluble, it can be directly broadcast applied to the surface of a newly planted alfalfa field or applied to existing stands as a topdressing. There is no need to incorporate the material mechanically into the soil. It will then dissolve over a period of several weeks, and move into subsoil horizons. Such an application technology in the case of established stands removes the need to till and thereby disrupt the stand.

Surface applications of fly ash or mixed fly ash+FGD, however, have the potential to be substantially lost due to erosion and subsequently to contaminate runoff water with fly ash solids and/or soluble metals. Despite the fact that surface applications decrease runoff volumes, these materials are easily eroded, and management practices need to be adapted to account for runoff and sedimentation. On established forage stands, runoff is commonly low, and should not result in excessive runoff or sediment loss due to the rough soil surface and presence of plant cover; on bare soil at establishment of a forage crop, or on application to row crops at planting, CCBs should be mixed into the soil to prevent loss of material and water quality impacts due to runoff.

4.2.3 Revegetation of Stacks

Greenhouse work has demonstrated that in order to obtain "green" cover on FGD stacks, it is necessary to apply a complete fertilizer comprising both macro- and micro-nutrients. Because FGD contains adequate levels of Ca, S and B, these factors were not varied in the experiments and are not recommended for application. Based on these studies, the recommended fertilizer rates for initial establishment are presented in Table 4-1.

TABLE 4-1
RECOMMENDED RATES OF NUTRIENTS FOR ESTABLISHMENT OF VEGETATIVE COVER ON FLUE GAS DESULFURIZATION GYPSUM STACKS

Nutrient	Optimum Rate	Fertilizer		
	mg element/kg	Element Rate lb/ac	Fertilizer Type	Fertilizer Rate lb/ac
N	200	360	Urea	780
P	200	360	Triple Superphosphate	1720
K	200	360	Muriate of Potash	720
Mg	12.5	23	Magnesium Sulfate	220
Fe	2.5	4.6	Ferrous Sulfate	20
Mn	5.0	9.2	Manganous Sulfate	40
Cu	1.2	2.2	Copper Sulfate	10
Zn	1.0	1.8	Zinc Sulfate	10

The efficacy of these rates was tested in the field at the Yates stack over two growing seasons on areas of the stack that had been exposed to rainfall for more than a year. This allowed the excessive levels of B present in the material to be leached to depth prior to planting, thus precluding any toxicity to the plants sown. Because of the harsh conditions on exposed stacks, a very hardy plant is required to withstand these conditions. Of the many plants tested, the only plant which successfully withstood these conditions was weeping lovegrass (Eragrostis curvula).

In order to obtain a good cover of grass, weeping lovegrass should be seeded at a rate of 10-20 lb seed/ac and the above fertilizer mixture applied and disked in prior to planting. In subsequent seasons, topdressings of N at 200-300 lb N/ac should be applied in the spring. Provided that the grass is never burnt, this fertilizer regimen should ensure a good cover for a number of years.

4.2.4 Environmental Considerations

The major concerns in CCB application center on excessive crop uptake of contaminants and movement of these contaminants to ground or surface water; fly ash is much higher in these contaminants than FGD, so that fly ash + FGD mixtures represent the greatest concern environmentally.

Both FGD and fly ash contain excessive levels of soluble B which can cause toxicity in plants. However because B is highly soluble, it is readily leached from the topsoil during the first two or three storm events. This leached B presents no environmental problems as far as water quality is concerned because the quantities involved are small and it is not toxic to animals or humans. Consequently, crops should not be sown on soils treated with CCBs immediately after application: sufficient time should be allowed for the B to leach to depth. The other elements of environmental concern are As, Pb, and possibly Mo; these elements are present in concentrations of concern only in fly ashes, which vary considerably in their concentrations depending on coal source and burner configuration. Lead is fairly low in concentration and quite insoluble, and no crop uptake or movement in water was detected. Molybdenum may accumulate in forage crops and depress Cu uptake, but this effect was not conclusively shown to be a problem.

Arsenic is by far the most limiting component environmentally in CCBs; while total concentrations are variable, levels above 75 mg/kg represent a general level of regulatory concern. In the ashes examined here, only one of five had such a concentration, and this ash did show enhanced uptake in plant foliage in greenhouse experiments at high application rates, in the range above 1 mg/kg which may constitute a concern for human health. While no movement of As through the soil profile was observed, As did move in soluble form in runoff water under rainfall from a high-As, surface-applied ash, at levels approaching regulatory action. Thus, selection of ash for land application should include screening for total As and As solubility, in order to prevent such occurrences. Field studies did not show potentially dangerous As levels in crops when applied in Yates ash-FGD mixtures at moderate rates (20 mt/ha).

Thus, while some environmental concern will probably always exist in land application of CCBs, the hazards as estimated in this research are relatively low. It is recommended that As levels of applied ash mixes be restricted to less than 75-100 mg/kg total, if possible, and that Mo be monitored in any forages grown on amended soils (until further data are available on this potential hazard). Application rates studies here were in the range of 20-30 mt/ha, which were never found to be a problem in greenhouse studies; rates above 100 mt/ha are more problematic environmentally. If CCBs are applied at reasonable rates as suggested here, and if CCBs containing fly ash are incorporated into the soil prior to seeding, they can be applied to agricultural soils with little risk of environmental consequences.

Regulatory agencies will need to be apprised of these recommendations, and hopefully these data included in their deliberations relative to guidelines or rulings on land application of CCBs. The states of Georgia, Alabama, and South Carolina are currently considering rulings on use of wood ash on cropland, and adoption of EPA rulings on sewage sludge to cover other waste applications to soils. Undoubtedly a dialogue will ensue on the environmental risks of fly ash use on cropland, centering on regulatory metal contamination; it is hoped that the data contained herein can form part of the discussion on the merits of land application of these materials.

5.0 COMPARATIVE ECONOMICS

5.1 Construction

An attempt has been made to derive useful economic projections from available project cost information. Including costs for the surge pond and two stacks, and dividing by the 7.1-acre footprint for the overall byproduct storage area, the construction cost is roughly estimated to be $60,000 per acre. This figure includes factors such as site preparation, earthwork, liners, drains and spillways. Other necessary factors such as pumps, piping, groundwater monitoring, construction supervision (by utility) and other hardware are not included due to difficulty in separation from other process costs or likelihood that the costs are too site-specific to be meaningful in a general sense.

5.2 Operation

The operating cost was approximated as the subcontractor costs for gypsum excavation, stacking and other general upkeep of the FGD gypsum stack. Invoiced amounts through the entire operating period of the gypsum stack were divided by the estimated 25,000 tons of material produced prior to switching to the ash/gypsum stack in March 1994. This value is $5 per ton and applies to the first stack only. It should be noted that this figure would likely be reduced substantially through the economies of scale appropriate for a larger facility.

5.3 Agricultural Markets

In order to evaluate agricultural use of CCBs on an economic basis, the data from alfalfa growth at the Calhoun and Athens sites where responses were expected and obtained will be used. Growth and yields at Tifton were so poor that no meaningful economics can be derived from that experiment. The analysis, assuming a value of $150/t for alfalfa hay, is presented in Table 5-1; the entries show the value of the yield increase associated with CCB additions over the two years of data collection, and the resultant value per ton of the applied CCB, obtained by dividing the value of the increased alfalfa yield by the weight of CCB applied (note units are in U.S. tons per

TABLE 5-1
ECONOMICS OF CCB USE ON ALFALFA AT THREE SITES OVER TWO GROWING SEASONS

Calhoun: FGD								
	1994			**1995**				**Value of**
Rate	**Yield**	**Increase**	**Value**	**Yield**	**Increase**	**Value**	**Sum**	**amendment**
(US t/a)	**lbs/a**	**lbs/a**					**($)**	**($/t)**
0	9752	------	------	6230	------	------	------	------
2.7	10722	970	$73	6793	563	$42	$115	$43
5.4	11270	1518	$114	7847	1617	$121	$235	$44
10.8	11678	1926	$144	8368	2138	$160	$305	$28
Calhoun: FGD+FA								
	1994			1995				Value of
Rate	Yield	Increase	Value	Yield	Increase	Value	Sum	amendment
(US t/a)	**lbs/a**	**lbs/a**					**($)**	**($/t)**
0	9752	-----	-----	6230	-----	-----	-----	------
2.7	11371	1619	$121	7960	1730	$130	$251	$93
5.4	11271	1519	$114	8437	2207	$166	$279	$52
10.8	12036	2284	$171	9246	3016	$226	$398	$37
Athens limed plot: FGD only								
	1994			**1995**				**Value of**
Rate	**Yield**	**Increase**	**Value**	**Yield**	**Increase**	**Value**	**Sum**	**amendment**
(US t/a)	lbs/a	lbs/a					($)	($/t)
0	11660			9460				
2.7	11882	222	$17	9625	165	$12	$29	$11
5.4	12194	534	$40	9731	271	$20	$60	$11
10.8	12718	1058	$79	10549	1089	$82	$161	$15
Athens limed plot: FGD+FA								
	1994			**1995**				**Value of**
Rate	**Yield**	**Increase**	**Value**	**Yield**	**Increase**	**Value**	**Sum**	**amendment**
(US t/a)	lbs/a	lbs/a					($)	($/t)
0	11660			9460				
2.7	12454	794	$60	9557	97	$7	$67	$25
5.4	12934	1274	$96	10153	693	$52	$148	$27
10.8	12430	770	$58	10572	1112	$83	$141	$13
Athens unlimed plot: FGD and FGD+FA: 1994 only								
	FGD only			**Value of**	**FGD+FA**			**Value of**
Rate	**Yield**	**Increase**	**Value**	**amend**	**Yield**	**Increase**	**Value**	**amendment**
(US t/a)	**lbs/a**	**lbs/a**		**($/t)**				**($/t)**
0	110				110			
2.7	1005	895	$67	$25	466	356	$27	$10
5.4	2367	2257	$169	$31	588	478	$36	$7
10.8	5046	4936	$370	$34	2181	2071	$155	$14

Alfalfa valued at $150/US ton — Amendment rates expressed in US tons/acre

acre). This value is the maximum cost a farmer could pay for the CCB material and break even, and would include all costs associated with purchasing, transporting, and applying the material in the field.

For the Calhoun site, it is clear that significant value increases were obtained both years and for both materials (FGD alone and FGD+FA), and the two year totals give an appreciable value to the amendment; of course as application rates increase, value per ton of CCB decreases, as yield increases do not increase proportionately. Values range from \$30-\$90 per US ton (2000 lbs) of material. Yield response to CCB was not as strong at Athens limed site, and two-year values range from \$10-\$30 per ton. Values of CCB computed using the one-year yield increases on the Athens site show substantial values at this site, although very low control yield make this scenario somewhat unrealistic from which to extrapolate to general field conditions.

Previous studies (Sumner, 1990) suggest yield increases will persist and perhaps increase over time in gypsum-amended alfalfa stands, and observations in spring of 1996 indicate continued superior growth of CCBP-amended plots. If one assumes that yields will increases over the next five years in a similar fashion to the initial two years of measured data, the costs of CCB application are amortized over a longer time span, and hence the value of CCB increases. In Table 5-2, the values of CCB additions are computed over such a five-year span, showing that at both sites values are greater than or equal to \$30/ton, and at Calhoun significantly higher. Current costs for gypsum application (purchasing and application) are about \$25-30 per ton; thus, the computed values of CCB are in the range of gypsum products currently being applied (to peanuts) in the state. Lower rates of application appear to be more profitable in this analysis, as significant yield responses are obtained even at lower rates; however, other evidence indicates that while the 5 t/acre (10 mt/ha) rate may last 5+ years, the higher (10 t/acre, or 20 mt/ha) rate may give yield increases up to 10 years. The economic data of Sumner (1990) using a single 10 mt/ha (5 ton/acre) application of phosphogypsum or mined gypsum over 4- and 5-year periods, respectively are presented in Table 5-3. From this analysis, the resultant values of the gypsum sources are much higher than in the present study, illustrating the benefits to be derived in the second and subsequent years after gypsum application. Based on the current data, however, we would recommend 5 t/acre as a rate that would give an optimal response over a hypothetical 5-year period of alfalfa culture.

TABLE 5-2
CALCULATION OF CCB VALUE ON ALFALFA AFTER FIVE YEARS

Site+CCB Rate (mt/ha)		Value of 2-Year Yield Increase	Avg. Annual Value of Yield Increase ($/yr)	5-Yr Value of Yield Increase	CCB Value ($/ton)
Calhoun:	**FGD Only**				
2.7		$115	$57	$287	$106
5.4		$235	$118	$588	$109
10.8		$305	$152	$762	$71
Calhoun: FGD+FA					
2.7		$251	$126	$628	$233
5.4		$279	$140	$699	$129
10.8		$398	$199	$994	$92
Athens--limed plot: FGD only					
2.7		$29	$15	$73	$27
5.4		$60	$30	$151	$28
10.8		$161	$81	$403	$37
Athens limed plot—FGD+FA					
2.7		$67	$33	$167	$62
5.4		$148	$74	$369	$68
10.8		$141	$71	$353	$33

Assumes continued yield increases similar to two-year field data.

TABLE 5-3
ECONOMIC ANALYSIS OF APPLYING PHOSPHOGYPSUM OR MINED GYPSUM ON ALFALFA PRODUCTION AT TWO SITES IN GEORGIA (SUMNER, 1990)

Soil	No. of Years	Gypsum Rate	Cumulative Alfalfa Yield Increase	Value of Yield Increase	Resultant Value of Gypsum Over the Given Period
		t/ha (lb/ac)	lb/ac	$	$/t
Appling	5	10 (8900)	22267	1519	375
Dyke	4	5 (4450)	12100	825	408

Of the three sites tested, the soil at the Calhoun site was the most acidic, with higher levels of exchangeable Al, followed by Athens unlimed site, Athens limed, and Tifton. The data collected here and elsewhere in the literature supports the contention that higher subsoil acidity will enhance the effect of CCB on yields, and thus sites proposed for amendment should be screened for subsoil acidity to predict potential yield responses. In general, where pH values of the Bt horizon (measured in salt solution such as KCl or $CaCl_2$) are less than 4.7, Al will be soluble to toxic concentrations, and a significant response to CCB may be expected. This would include a major portion of agricultural soils in the southeast, although no specific data are available to indicate the total acreage of such soils.

A similar economic analysis was performed on row crop yields for the three locations over the three growing seasons (Table 5-4). The data are somewhat incomplete due to crop failures at several locations at various times. However, despite some irregularities in the computed values of yield increases due to yield declines, over all highly significant values for the CCB ($/ton) were apparent, particularly at Tifton. Again, lower rates of application were more profitable generally, and values of $70-$100/ton at the 2.7 t/acre rate were obtained at Tifton. No statistical analyses of this data is possible, but the overall trends suggest a positive value to both CCB materials, particularly at rates of 3-5 t/acre.

In conclusion, it is clear that CCB should be marketable for forage production based on multi-year yield responses, and should be expected to last up to 5 years at a medium (5 t/acre) application rate. For row crop use, economic return on investment is less certain, but in intensively row-cropped areas, even marginal annual increases result in a significant return on CCB application over several years. Equivalent values of >$100/t for the material over a 5 year period are fairly conservative, based on the current and projected data. This value would allow transport over a fairly wide geographical area; even at $0.20/mile for transport, distances of 100-200 miles would still allow considerable margin for return. Other sources of gypsum are priced considerably higher: mined gypsum available in southern Georgia is $100-$140/t, and

TABLE 5-4
ECONOMICS OF CCB USE ON ROW CROPS OVER THREE YEARS AT THREE GEORGIA LOCATIONS

		Yields (kg/ha, or lbs/acre)						Value of yield increase ($/acre)						
Athens:		**1993**	**1994**	**1994-95**	**1995**			**1993**	**1994**	**94-95**	**1995**	**Overall**	**Value**	
	Rate	**soybeans**	**Corn**	**wheat**	**sorghum**			**soybeans**	**corn**	**wheat**	**sorghum**	**sum**	**($/t)**	
Control	0	503	12,269	1811	2756									
FGD	2.7	572	12,769	2082	3232			$10	$25	$27	$56	$118	$44	
	5.4	694	14,652	2353	3305			$29	$119	$54	$64	$266	$49	
	10.8	523	13,593	2355	3415			$3	$66	$54	$77	$200	$19	
FA+FGD:	2.7	678	10,857	1944	2902			$26	($71)	$13	$17	($14)	($5)	
	5.4	635	11,151	1828	3524			$20	($56)	$2	$90	$55	$10	
	10.8	672	13,416	2536	3439			$25	$57	$73	$80	$235	$22	
FA only:	5.4	175	14,299	1896	3317			($49)	$102	$9	$65	$126	$23	
Tifton:		**1993**	**1993-94**	**1994**	**1994-95**	**1995**		**1993**	**1993-94**	**1994**	**1994-95**	**1995**	**Overall**	**Value**
	Rate	**soybeans**	**Wheat**	**soybean**	**wheat**	**sorghum**		**soybeans**	**wheat**	**soybeans**	**wheat**	**sorghum**	**sum**	**($/t)**
Control	0	1302	893	2328	400	2229								
FGD:	2.7	2041	1859	2319	444	2268		$111	$81	($1)	$4	$5	$198	$73
	5.4	1974	1915	2134	381	3122		$101	$85	($29)	($2)	$104	$259	$48
	10.8	1519	1575	1854	463	2463		$33	$57	($71)	$5	$27	$51	$5
FA+FGD:	2.7	1750	1679	2742	450	2992		$67	$66	$62	$4	$89	$288	$107
	5.4	1799	2071	2115	399	2130		$75	$98	($32)	($0)	($12)	$129	$24
	10.8	1231	2075	2155	455	3496		($11)	$99	($26)	$5	$148	$214	$20
FA only:	5.4	1398	1166	2903	407	2610		$14	$23	$86	$1	$44	$168	$31
Calhoun:		**1993**	**1993-94**	**1994**				**1993**	**1993-94**	**1994**	**Overall**	**Value**		
	Rate	**soybean**	**Barley**	**soybean**				**soybean**	**barley**	**soybean**	**sum**	**($/t)**		
Control	0	579	2486	2990										
FGD:	2.7	671	2338	3134				$14	($15)	$22	$21	$8		
	5.4	519	3462	2717				($9)	$98	($41)	$48	$9		
	10.8	680	2901	2621				$15	$42	($55)	$1	$0		
FA+FGD:	2.7	709	2817	3132				$20	$33	$21	$74	$27		
	5.4	834	2153	3519				$38	($33)	$79	$84	$16		
	10.8	560	2891	3108				($3)	$41	$18	$55	$5		

Pricing assumptions: Corn silage: $100/t; soybeans: $9/bu; wheat: $5/bu; barley: $6/bu; sorghum: $7/bu; bushel = 60 lbs; values in ( ) are negative (yield declines) phosphogypsum in central Florida is currently unavailable due to EPA restrictions on transport and use. Agricultural operations in the Mountain area (including north Georgia, Alabama, and South Carolina), in the Piedmont of the same states, and on acid sites in the Coastal Plain should all be accessible to power plants producing such materials. Plant Yates, for example, is adjacent to all three of these areas, and should have a large potential market for CCB in the future.

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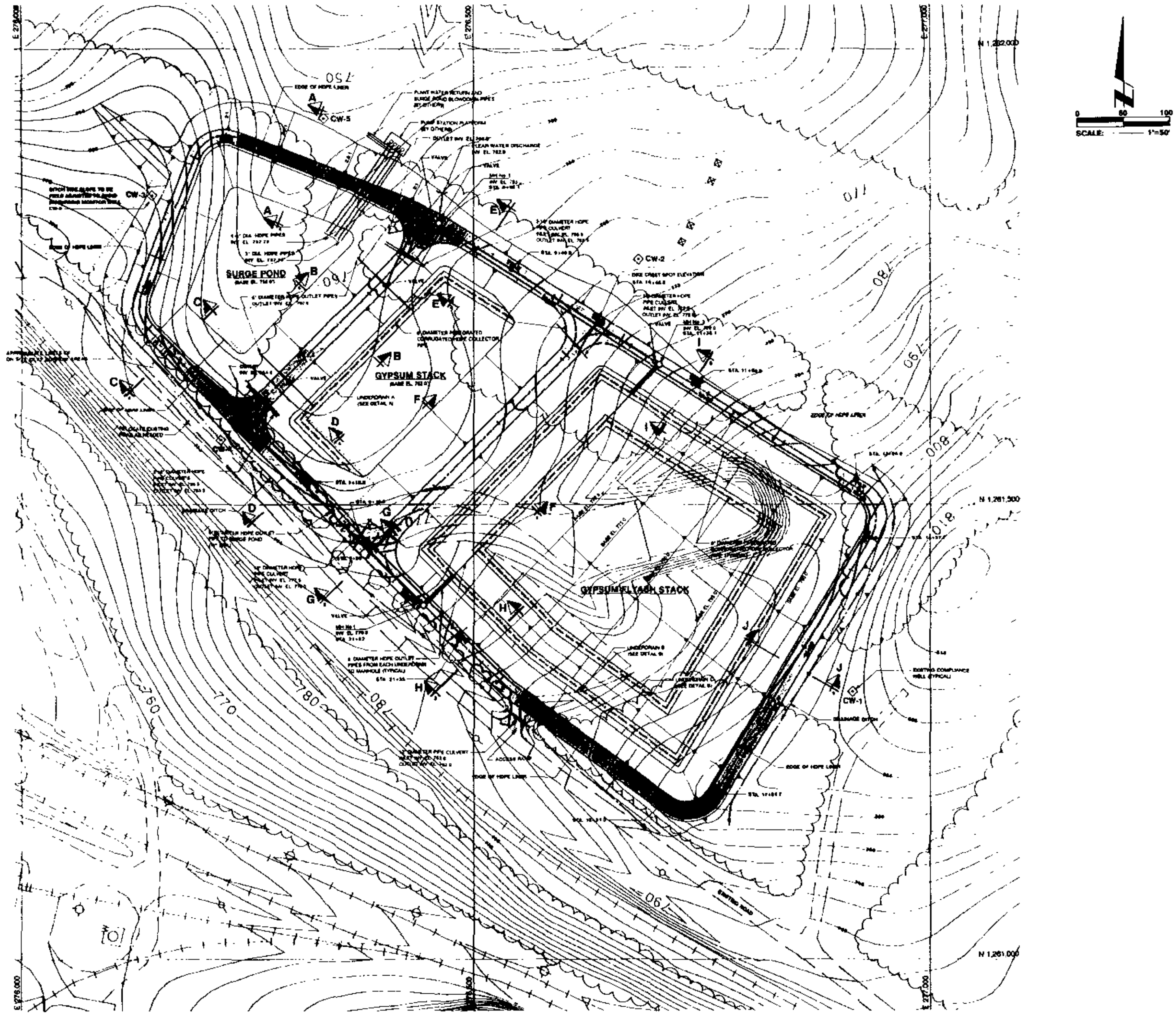
APPENDIX A
CONSTRUCTION DRAWINGS



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SITE PLAN

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FGD GYPSUM & GYPSUM-FLYASH WET-STACKING DISPOSAL FACILITY
GEORGIA POWER COMPANY
PLANT YATES
NEWNAN, GEORGIA

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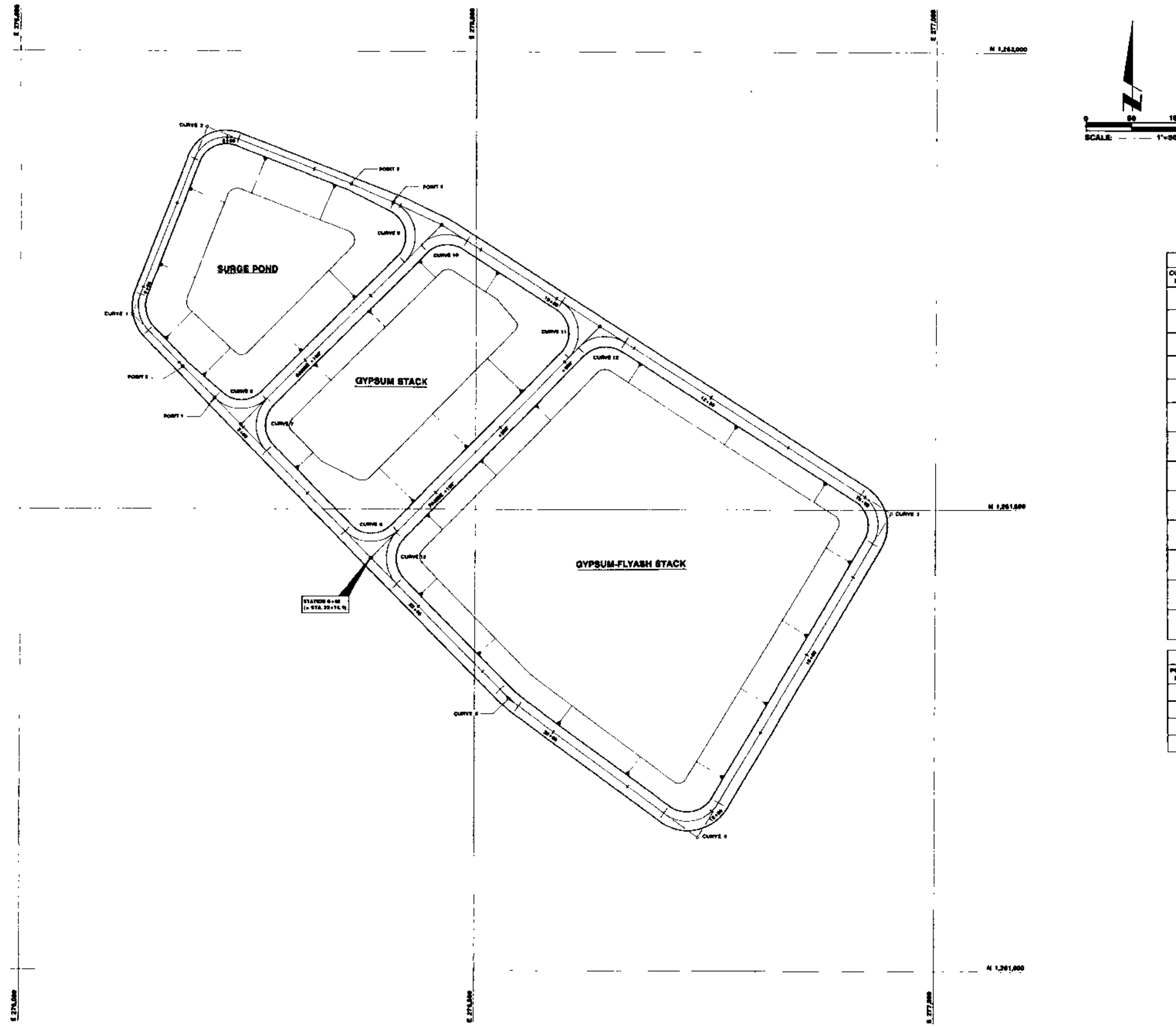

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ALIGNMENT OF DIKE CENTERLINE

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PLANT YATES
NEWNAN, GEORGIA

DRAWN BY KJB	CHECKED BY RJW	DATE 7/3/91
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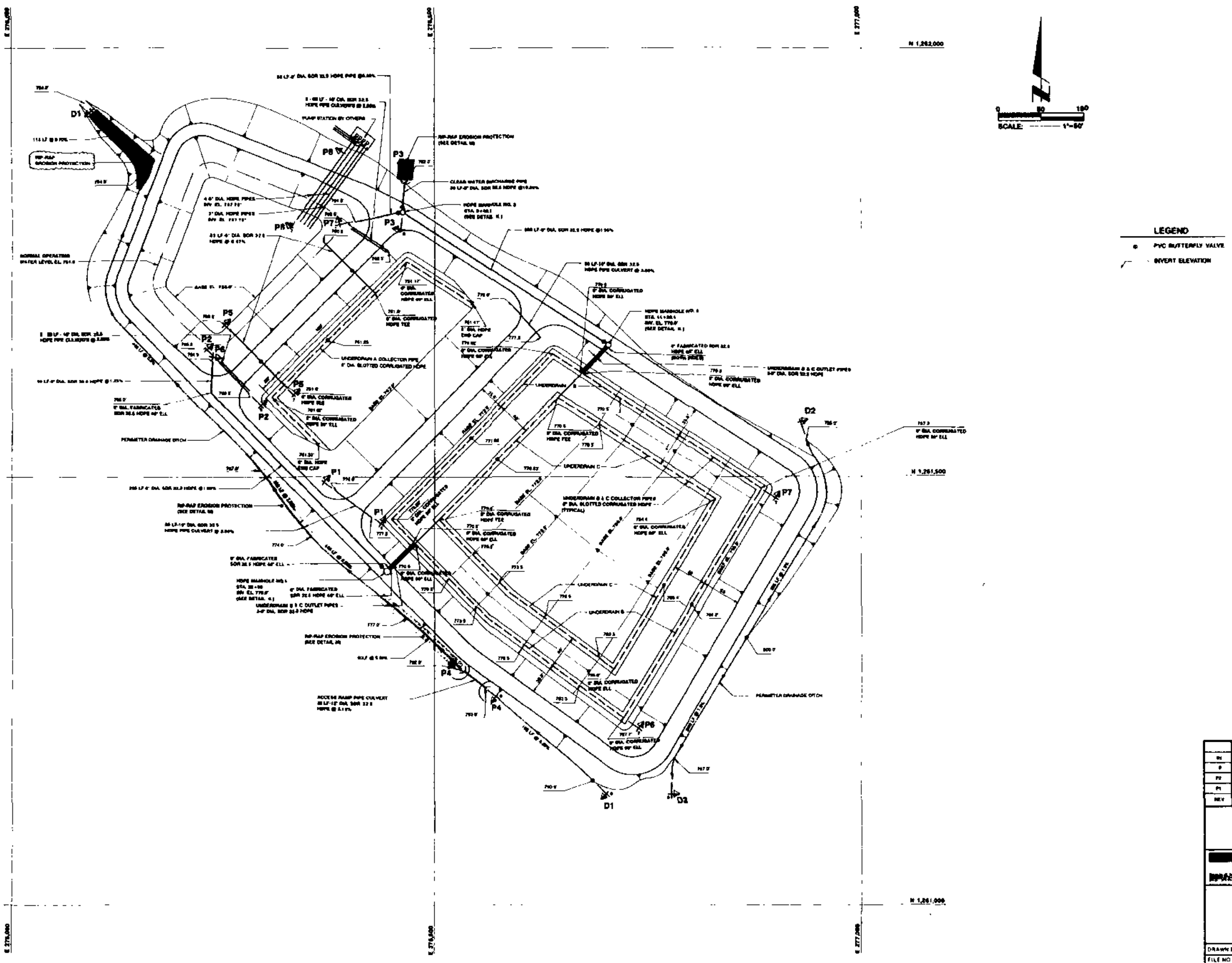

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P1		ISSUED FOR REVIEW/COMMENTS	

PIPING AND DITCH PLAN

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NEWNAN, GEORGIA

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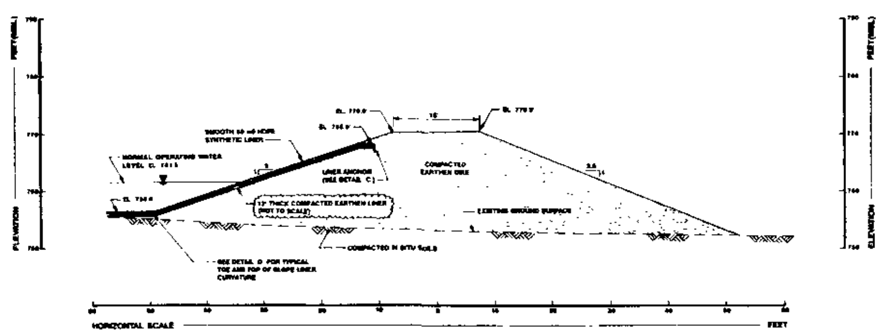

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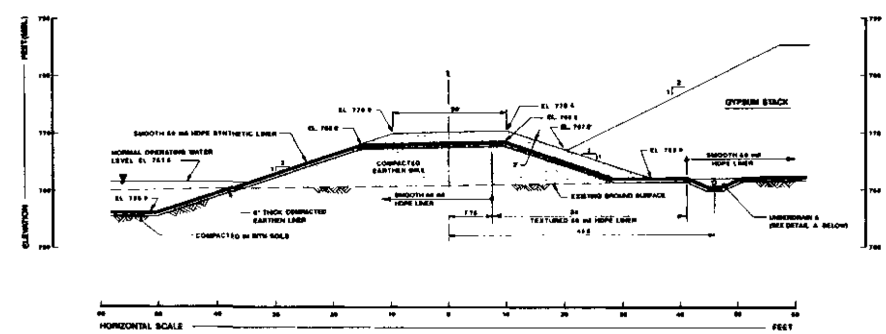

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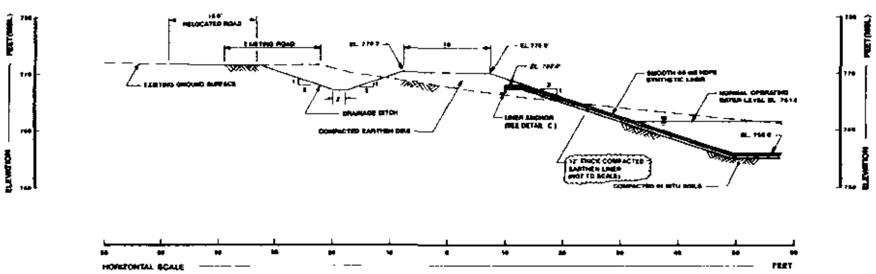

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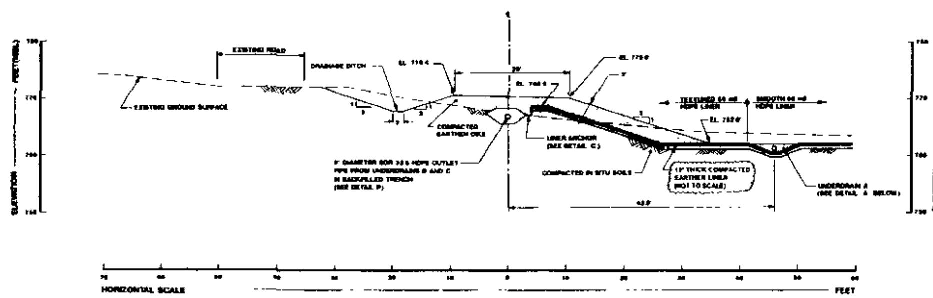

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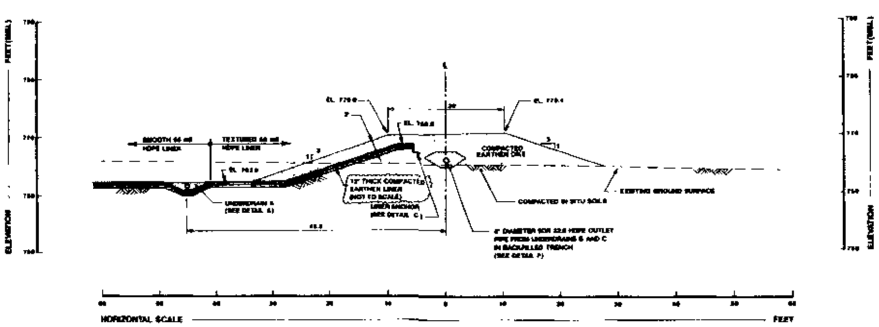

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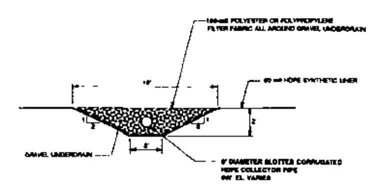
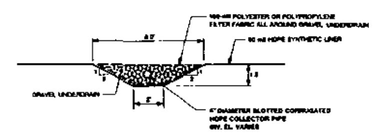


DETAIL B - UNDERDRAINS B AND C



DETAIL A - UNDERDRAIN A

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CROSS SECTIONS OF PERIMETER DIKES AND DETAILS

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DRAWN BY KJS	CHECKED BY		DATE 12-01-90
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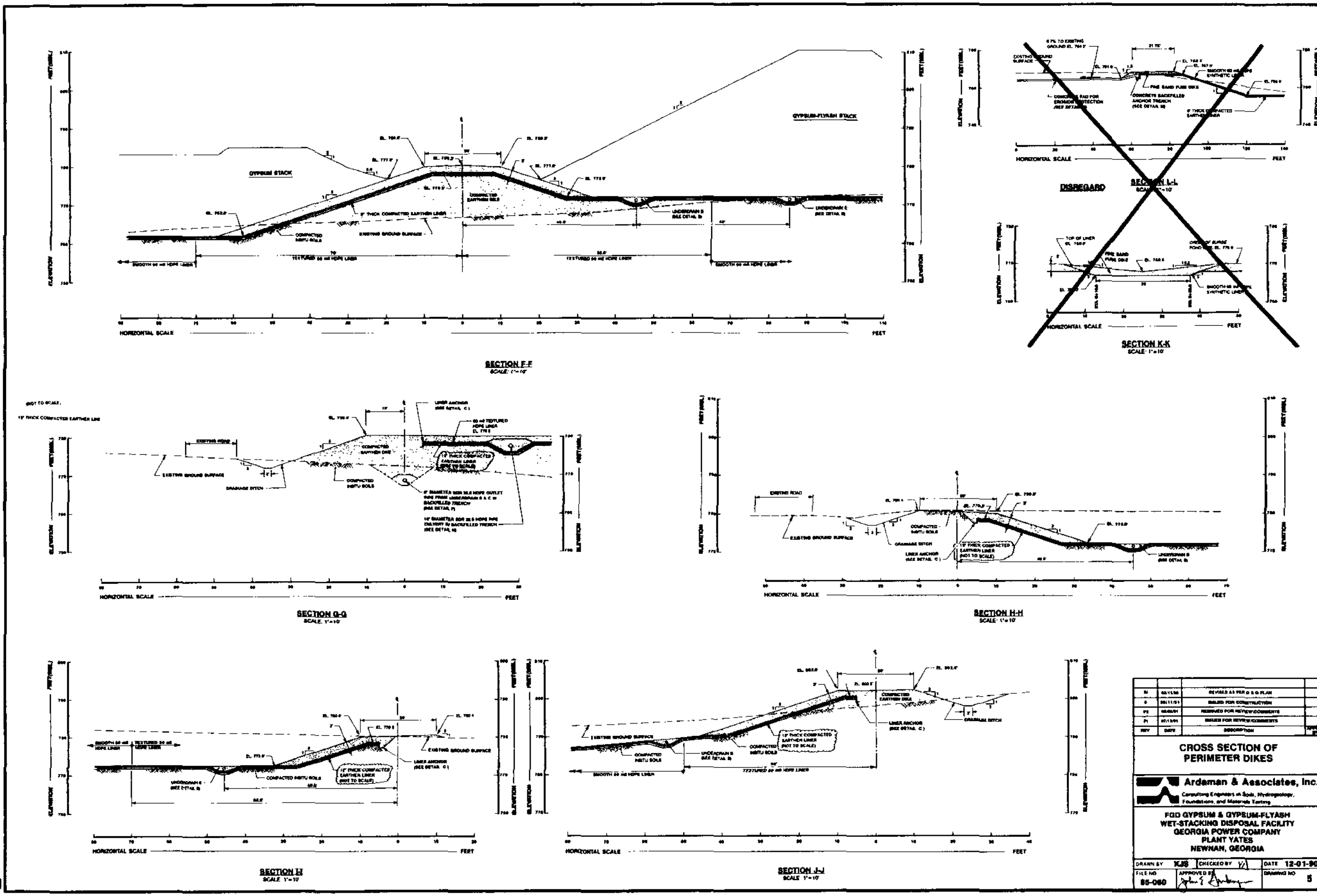
GYPSUM STACK
GYPSUM-FLYASH STACK
SECTION F-F
SECTION G-G
SECTION H-H
SECTION I-I
SECTION J-J
SECTION K-K
SECTION L-L
DISREGARD
HORIZONTAL SCALE
FEET
ELEVATION
CROSS SECTION OF
PERIMETER DIKES
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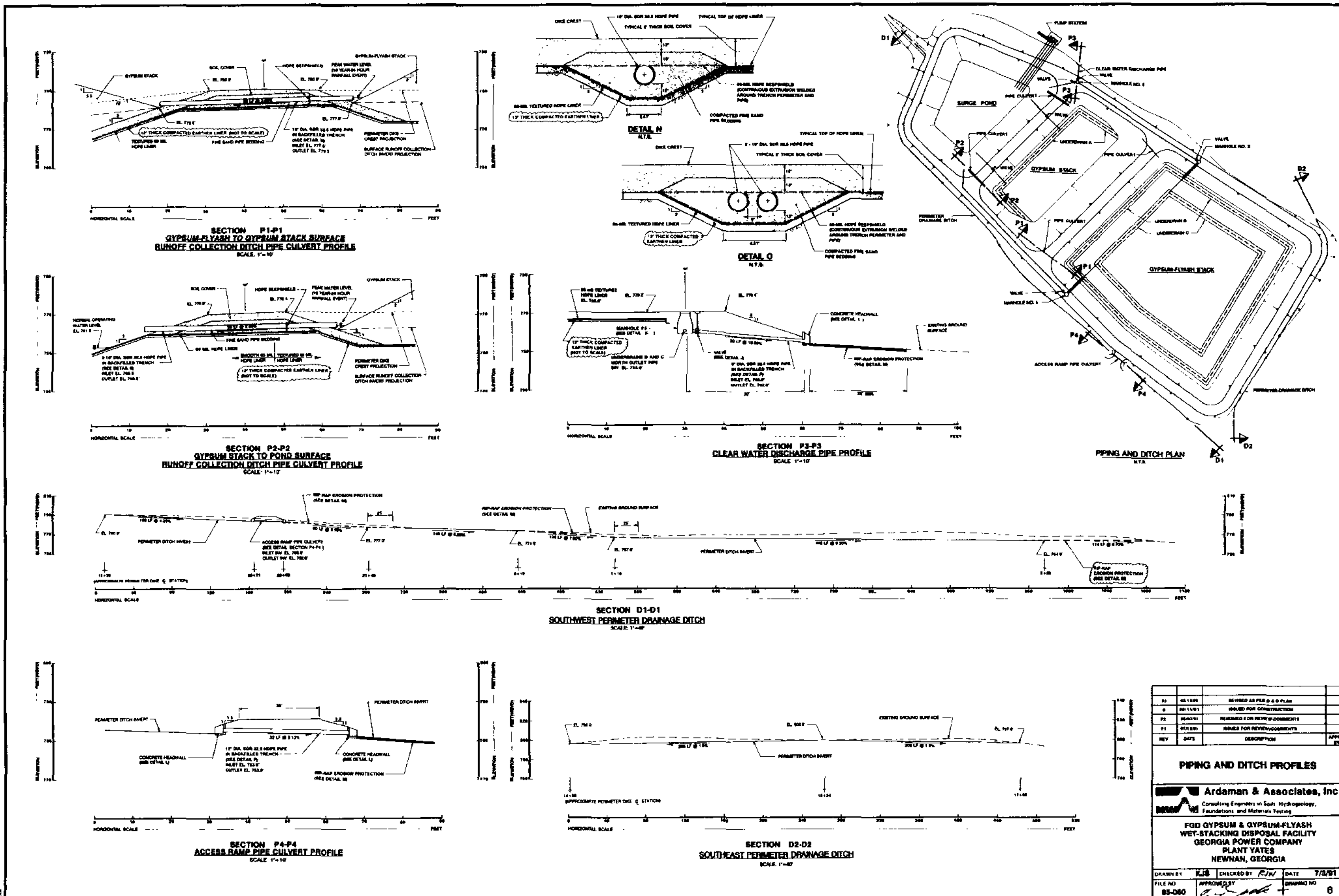
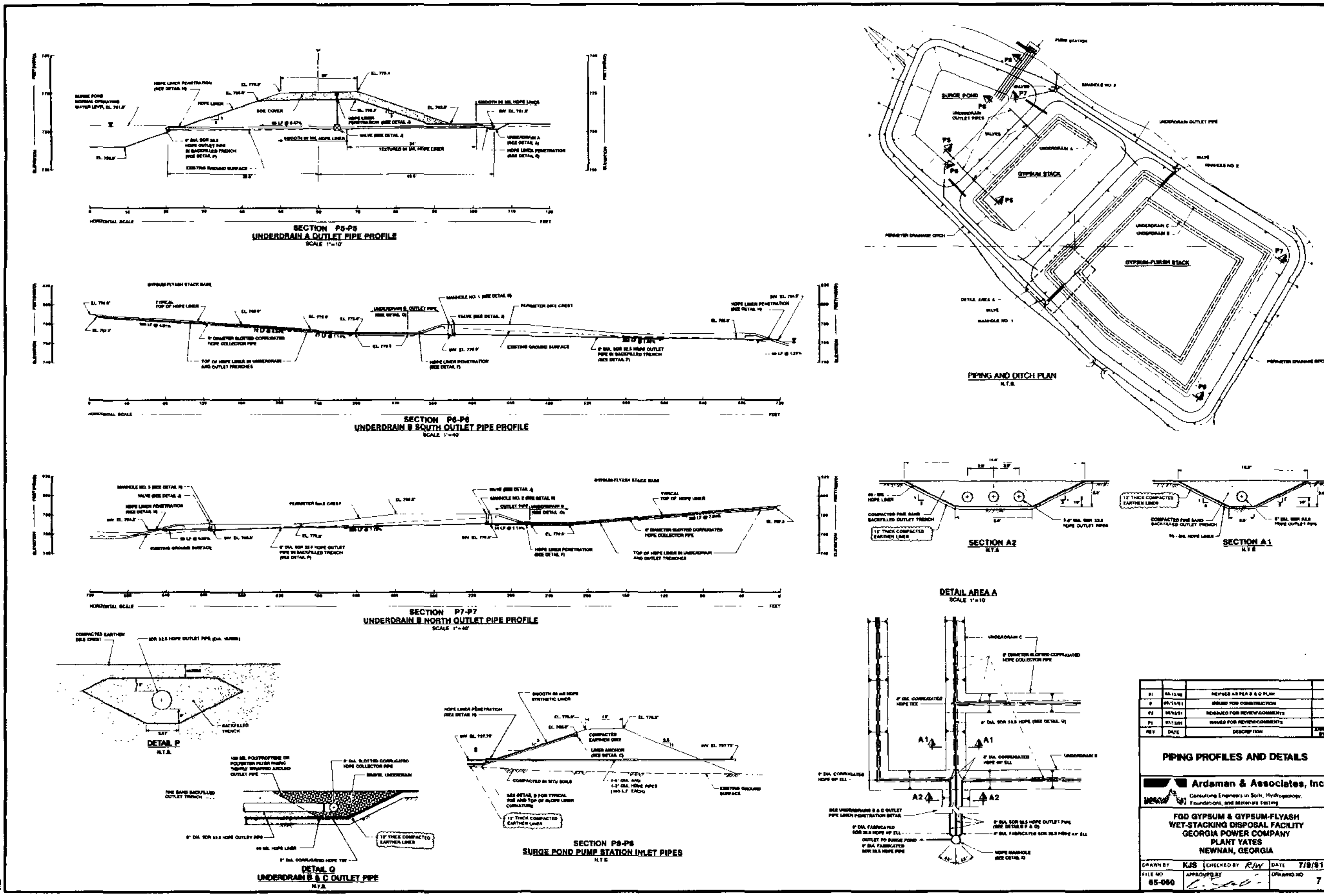
FILE NO 85-060
DRAWING NO 5


SECTION P1-P1
GYPSUM-FLYASH TO GYPSUM STACK SURFACE
RUNOFF COLLECTION DITCH PIPE CULVERT PROFILE
SCALE: 1"=10'
DETAIL N
N.T.S.
DETAIL O
N.T.S.
SURGE POND
GYPSUM STACK
GYPSUM-FLYASH STACK
PIPING AND DITCH PLAN
N.T.S.
SECTION P2-P2
GYPSUM STACK TO POND SURFACE
RUNOFF COLLECTION DITCH PIPE CULVERT PROFILE
SCALE: 1"=10'
SECTION P3-P3
CLEAR WATER DISCHARGE PIPE PROFILE
SCALE: 1"=10'
SECTION D1-D1
SOUTHWEST PERIMETER DRAINAGE DITCH
SECTION P4-P4
ACCESS RAMP PIPE CULVERT PROFILE
SCALE: 1"=10'
SECTION D2-D2
SOUTHEAST PERIMETER DRAINAGE DITCH
PIPING AND DITCH PROFILES
Ardaman & Associates, Inc.
Consulting Engineers in Soil, Hydrogeology, Foundations and Materials Testing
FGD GYPSUM & GYPSUM-FLYASH
WET-STACKING DISPOSAL FACILITY
GEORGIA POWER COMPANY
PLANT YATES
NEWNAN, GEORGIA
DRAWN BY KJS
CHECKED BY
DATE 7/3/91
FILE NO. 85-060
APPROVED BY
DRAWING NO. 6

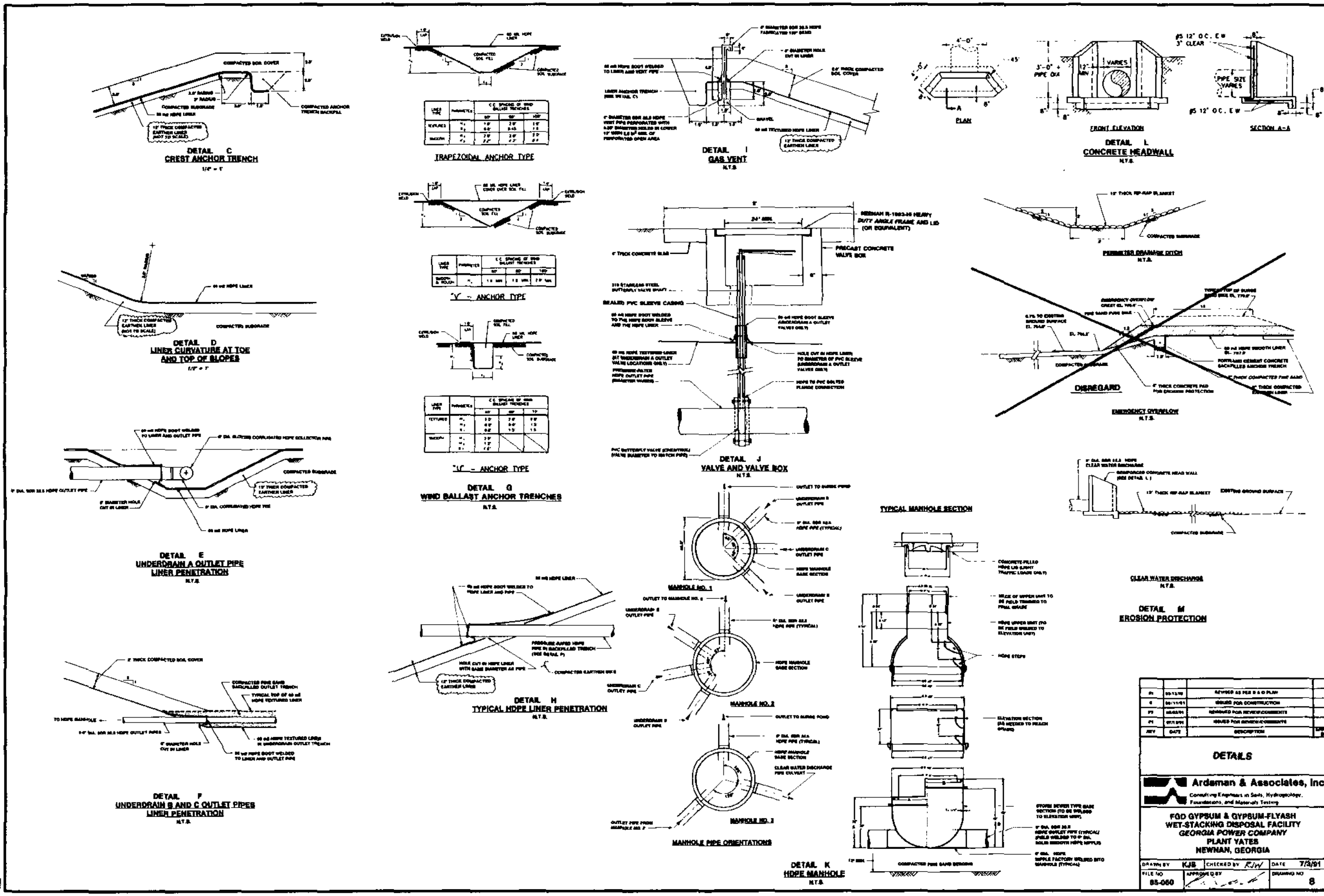


PIPING PROFILES AND DETAILS

Ardaman & Associates, Inc.
Consulting Engineers in Soils, Hydrogeology, Foundations, and Materials Testing

FGD GYPSUM & GYPSUM-FLYASH WET-STACKING DISPOSAL FACILITY
GEORGIA POWER COMPANY
PLANT YATES
NEWNAN, GEORGIA

DRAWN BY KJS	CHECKED BY RJW	DATE 7/9/91
FILE NO 65-060	APPROVED BY	DRAWING NO 7



DETAIL C
CREST ANCHOR TRENCH
1/4" = 1'
TRAPEZOIDAL ANCHOR TYPE
"V" - ANCHOR TYPE
"U" - ANCHOR TYPE
DETAIL G
WIND BALLAST ANCHOR TRENCHES
N.T.S.
DETAIL I
GAS VENT
N.T.S.
PLAN
FRONT ELEVATION
SECTION A-A
DETAIL L
CONCRETE HEADWALL
N.T.S.
DETAIL D
LINER CURVATURE AT TOE
AND TOP OF SLOPES
DETAIL J
VALVE AND VALVE BOX
N.T.S.
PERIMETER DRAINAGE DITCH
N.T.S.
DISREGARD
EMERGENCY OVERFLOW
N.T.S.
DETAIL E
UNDERDRAIN A OUTLET PIPE
LINER PENETRATION
N.T.S.
DETAIL H
TYPICAL HDPE LINER PENETRATION
N.T.S.
MANHOLE NO. 1
MANHOLE NO. 2
MANHOLE NO. 3
MANHOLE PIPE ORIENTATIONS
TYPICAL MANHOLE SECTION
DETAIL K
HDPE MANHOLE
N.T.S.
CLEAR WATER DISCHARGE
N.T.S.
DETAIL M
EROSION PROTECTION
DETAIL F
UNDERDRAIN B AND C OUTLET PIPES
LINER PENETRATION
N.T.S.
DETAILS
Ardaman & Associates, Inc.
Consulting Engineers in Soils, Hydrogeology, Foundations, and Materials Testing
FGD GYPSUM & GYPSUM-FLYASH
WET-STACKING DISPOSAL FACILITY
GEORGIA POWER COMPANY
PLANT YATES
NEWNAN, GEORGIA
DRAWN BY KJB
CHECKED BY RJW
DATE 7/3/91
FILE NO 85-060
APPROVED BY
DRAWING NO 8

APPENDIX B

LABORATORY AND FIELD DATA FOR STACKING

TABLE B-1
SUMMARY OF WATER CONTENT DETERMINATIONS

Sample No.	Date Sampled	Depth (ft)	Fraction of Total Sample [2]	$AWC_{40°C}$ (%)	$AWC_{180°C}$ (%)	$AWC_{240°C}$ (%)	Chemically Bonded Water Content ($AWC_{240°C}$-$AWC_{40°C}$)	Gypsum Content (%) [3]
Bulk Samples Taken From Stack Surface During Operation								
X	12/92		1	20.77	41.17	41.25	20.48	98.0
I-A	3/93		0.33	32.83	-	50.71	17.88	85.6
I-B	3/93	0	0.23	29.93	-	46.35	16.42	78.6
I-C	3/93		0.44	25.70	-	37.93	12.23	58.5
II	3/93		1	197.74	-	212.86	15.12	72.3
Split-Barrel Samples Taken From SPT Test Boring TH-1A (Performed on Completed Stack)								
S1		1.0	1	10.86	30.34	(30.42)	19.56	93.5
S3		4.0	1	15.21	34.92	(35.00)	19.79	94.7
S5		7.0	1	23.11	43.46	(43.54)	20.43	97.8
S7	7/19/94	10.0	1	20.90	39.88	(39.96)	19.06	91.2
S9		13.0	1	23.94	43.03	(43.11)	19.17	91.7
S13		19.0	1	27.56	47.22	(47.30)	19.74	94.4
Split-Barrel Samples Taken From SPT Test Boring TH-2A (Performed on Completed Stack)								
S1		1.0	1	15.30	35.34	(35.42)	20.12	96.3
S3		4.0	1	12.98	32.52	(32.60)	19.62	94.9
S5		7.0	1	18.32	39.22	(39.30)	20.98	100
S7	7/20/94	10.0	1	24.87	44.92	(45.00)	20.13	96.3
S9		13.0	1	18.30	37.98	(38.06)	19.76	94.5
S11		16.0	1	23.87	44.61	(44.69)	20.82	99.6
S13		19.0	1	25.49	45.95	(46.03)	20.54	98.3
Reagent Grade Gypsum							20.9	100

NOTES:
1. Apparent Water Content, AWC = weight of water at a given drying temperature divided by the weight of dry solids at a drying temperature of 40°C
2. Ratio of the subsample dry weight to the total sample dry weight
3. Gypsum content is estimated as the ratio of the chemically bonded water content to the theoretical value of 20.9% for reagent grade gypsum.
4. $AWC_{240°C}$ computed as ($AWC_{180°C}$ + 0.08); based on test results for sample X
5. Subsamples IA, IB and IC separated in the laboratory using a settling column

TABLE B-2
SUMMARY OF CARBONATE CONTENT DETERMINATIONS

Sample No.	Date Sampled	Depth (ft)	Sample Description	Fraction of Total Sample [1]	$CaCO_3$ (%) [2]	(100-$CaCO_3$) (%)
Bulk Samples Taken From Stack Surface During Operation						
I-A	3/93	0	Finest fraction of Sample I	0.33	12.2	87.8
I-B			Intermediate fraction of Sample I	0.23	21.4	78.6
I-C			Coarsest fraction Sample I	0.44	41.8	58.2
I			Light brown gypsum	1	27.3 [3]	72.7
II	3/93	0	Orange-brown gypsum	1	28.6	71.4
III	7/93	0	Light yellowish-brown gypsum	1	7.5	92.5
III-A			Orange-brown fine fraction of III	0.22	12.2	87.8
III-AA			Reddish brown fine fraction of IIIA	0.03	18.4	81.6
Split-Barrel Samples Taken From SPT Test Boring TH-1A (Performed on Completed Stack)						
S1	7/19/94	1.0	Light brown cast gypsum	1	3.4	96.6
S3		4.0	Light brown cast gypsum	1	3.1	96.9
S5		7.0	Light brown cast gypsum	1	3.0	97.0
S7		10.0	Light brown cast gypsum	1	5.8	94.2
S9		13.0	Yellowish-brown sedimented gypsum	1	7.2	92.8
S11		16.0	Orange-brown sedimented gypsum	1	0.9	99.1
S13		19.0	Light brown sedimented gypsum	1	6.4	93.6
Split-Barrel Samples Taken From SPT Test Boring TH-2A (Performed on Completed Stack)						
S1	7/20/94	1.0	Light brown cast gypsum	1	2.0	98.0
S3		4.0	Light brown cast gypsum	1	3.9	96.1
S5		7.0	Light brown cast gypsum	1	2.6	97.4
S7		10.0	Light brown cast gypsum	1	5.9	94.1
S9		13.0	Yellowish-brown sedimented gypsum	1	5.8	94.2
S11		16.0	Yellowish-brown sedimented gypsum	1	0.9	99.1
S13		19.0	Yellowish-brown sedimented gypsum	1	2.2	97.8
Reagent Grade Gypsum					0.02	99.98

NOTES:
1. Ratio of the subsample dry weight to the total sample dry weight
2. Carbonate content by dry weight
3. Computed based on measured carbonate contents for subsamples IA, IB and IC
4. Subsamples IA, IB and IC separated in the laboratory using a settling column
5. Subsample IIIAA separated out of subsample IIIA using a laboratory centrifuge

TABLE B-3
SUMMARY OF LABORATORY SETTLING TEST RESULTS FOR BULK GYPSUM SAMPLES

Sample No.	Date Sampled	Sample Description	Gypsum Content (%)	Initial Condition			Final Condition			Initial Settling Velocity (cm/min)
				Solids Content (%)	Void Ratio	Dry Density (lb/ft^3)	Solids Content (%)	Void Ratio	Dry Density (lb/ft^3)	
X	12/92	Light brown gypsum (Sample IIIB is Sample III less the orange-brown fine fraction IIIA)	98.0	14.0	14.40	9.5	70.2	1.00	73.4	-
I	3/93		72.5	9.7	21.8	6.4	71.3	0.94	75.2	7.5
III-B	7/93		94.4	28.6	5.85	21.4	71.7	0.93	76.1	-
				29.6	5.42	22.9	68.0	0.92	76.2	3.2
				38.3	3.79	30.6	72.0	0.92	75.6	1.6
III	7/93	Yellowish-brown gypsum (mix of light brown and orange-brown gypsum)	92.5	4.8	47.07	3.0	62.6	1.40	61.0	-
				9.5	22.48	6.2	65.8	1.22	66.0	6.9
				9.6	22.00	6.4	64.4	1.30	63.8	-
				14.5	13.80	9.9	63.5	1.35	62.4	4.6
				19.4	9.78	13.6	63.8	1.34	62.8	3.3
				28.6	5.85	21.4	62.7	1.40	61.2	1.3
II	3/93	Orange-brown fine gypsum (IIIA is fine fraction of Sample III)	71.8	4.2	53.60	2.7	23.8	7.53	17.2	-
III-A	7/93		87.8	9.0	23.66	6.0	34.6	4.45	26.9	0.8
III-A	7/93		87.8	28.6	5.85	21.4	33.4	4.68	25.8	-

NOTES:

TABLE B-4
SUMMARY OF PERMEABILITY RESULTS FOR TEST SPECIMENS PREPARED IN THE LABORATORY FROM BULK GYPSUM SAMPLES

Bulk Sample No.	Specimen Type	Mold Type	Initial Conditions				Final Conditions				Test Conditions		k_v (cm/s)
			w_i (%)	γ_d (lb/ft^3)	e_i	S_i (%)	w_f (%)	γ_{df} (lb/ft^3)	e_f	S_f (%)	$\bar{\sigma}_o$ (lb/ft^2)	i (in/in)	
X	R	RW	31.8	83.9	0.746	100	19.8	97.2	0.466	100	865	21	$1.7x10^{-4}$
I	R	RW	31.2	84.6	0.734	99	25.1	92.2	0.591	100	290	19	$6.5x10^{-4}$
III	S	RW	51.5	66.4	1.211	100	36.1	79.4	0.849	100	290	25	$2.2x10^{-4}$
III-AB	R	RW	34.4	77.7	0.871	92	28.7	87.3	0.667	100	290	21	$1.1x10^{-5}$
III-AA	R	FW	223.9	23.9	5.072	104	100.7	43.7	2.328	101	1150	58	$1.2x10^{-7}$
I	S	GR(1)	40.8	75	0.96	100	39.6	76.0	0.93	100		2.5	$9.9x10^{-4}$
I	S	GR(2)					37.4	78.1	0.88	100		2.6	$1.0x10^{-3}$
I	S	GR(3)					39.2	76.3	0.92	100		0.7	$1.5x10^{-3}$

NOTES:

TABLE B-5
SUMMARY OF PERMEABILITY RESULTS FOR TEST SPECIMENS TAKEN FROM THIN-WALLED TUBE GYPSUM SAMPLES

Boring No.	Tube Sample No.	Sample Depth (ft)	Sample Description	Initial Conditions			Final Conditions			$\bar{\sigma}_c$ (lb/ft²)	k_v (cm/s)
				w_i (%)	γ_{di} (lb/ft³)	e_i	w_f (%)	γ_{df} (lb/ft³)	e_f		
TH-1B	PS-1	7.0	Light brown cast	27.4	91.3	0.592	25.8	91.1	0.597	580	5.4×10^{-4}
TH-1B	PS-3	10.5	Uniform light brown sedimented	23.2	98.0	0.483	21.9	96.9	0.500	720	2.7×10^{-4}
TH-1B	PS-6	18.5		25.3	90.2	0.612	24.4	93.4	0.556	1260	3.0×10^{-4}
TH-3	PS-3	15.0		26.9	87.3	0.666	26.2	86.0	0.690	680	1.0×10^{-4}
TH-4	PS-3 B2	16.5	* Top half of B2	27.8	91.7	0.586	24.5	91.6	0.587	580	1.6×10^{-4}
TH-2B	PS-6	17.0	Uniform orange-brown and yellow-brown sedimented	20.6	97.9	0.485	19.0	99.9	0.459	1150	3.6×10^{-5}
TH-3	PS-2	12.0		21.6	96.8	0.502	20.0	98.6	0.474	650	6.2×10^{-6}
TH-3	PS-3	13.0		27.2	88.7	0.639	26.0	95.3	0.526	650	4.6×10^{-5}
TH-4	PS-3 B2	16.5	* Bottom half of B2	26.6	90.5	0.606	25.3	94.9	0.529	580	1.1×10^{-5}
TH-1B	PS-5	15.5	Layered light brown and orange-brown sedimented	27.2	88.3	0.647	25.5	89.6	0.623	580	2.4×10^{-6}
TH-4	PS-3 B2	16.5		27.8	88.5	0.644	26.5	91.5	0.588	720	1.4×10^{-5}
TH-4	PS-3	17.0		24.1	94.3	0.542	23.1	91.6	0.588	720	4.6×10^{-5}

NOTES:

BORING LOG
ARDAMAN & ASSOCIATES, INC.

BORING NO: TH-1A
TOTAL DEPTH: 21.0 ft
SHEET 1 OF 1

PROJECT BYPRODUCT EVALUATION - FGD CLEAN COAL PROJECT
FILE NO. 85-080D
CLIENT SOUTHERN COMPANY SERVICES
ELEVATION 785 ft (MSL)
BORING LOCATION
BORING TYPE SPT
COUNTY COWETA
STATE GEORGIA
CASING TYPE NONE
DATE STARTED 7/19/94
COMPLETED 7/20/94
DRILLER/RIG McCLUSKEY/CME45
WATER TABLE: 1st depth -- 9.0 ft
DATE -- 7/19/94
TIME --
WATER TABLE: 2nd depth -- 9.5 ft
DATE -- 7/20/94
TIME --
REMARKS Supervision & field classification by John May

Elevation	Depth (ft)	Standard Pen. Test ASTM D-1586: Blows/6 in.	N Value	Sample No.	Lab Test Results: NM 40 C (%)	NM 180 C (%)	$CaCO_3$ (%)	Total Unit Wt. (pcf)	Dry Dens. (pcf)	Descriptions and Remarks	Depth (ft)	Graphic Log
		4-4-2	6	1	10.9	30.3	3.4					
		4-8-16	24	2	12.1							
		12-8-12	20	3	15.2	34.9	3.1			CAST GYPSUM		
-5	5	16-14-16	30	4	17.6							
		13-11-11	22	5	23.1	43.5	3.0					
		15-18-16	34	6	21.5					SEDIMENTED GYPSUM ▽		
-10	10	18-16-18	34	7	20.9	39.9	5.8					
		18-25-29	54	8	20.3					MIXED, DISTURBED GYPSUM		
		24-40-40	80	9	23.9	43.0	7.2					
-15	15	13-30-32	62	10	25.0					SEDIMENTED GYPSUM; LAYERED ORANGE-BROWN & LIGHT BROWN		
		40-45-50/5"	105	11	-		0.9					
		13-25-25	50	12	23.5							
		20-24-17	41	13	27.6	47.2	6.4			UNIFORM SEDIMENTED GYPSUM LIGHT BROWN		
-20	20	20-22-29	51	14	26.3							
										BORING TERMINATED AT 21.0 FT.		
										HDPE LINER (EL. 762 FT)		
-25	25											
-30	30											

BORING LOG
ARDAMAN & ASSOCIATES, INC.

BORING NO: TH-2B
TOTAL DEPTH: ± 17.5 FT
SHEET 1 OF 1

PROJECT BYPRODUCT EVALUATION – FGD CLEAN COAL PROJECT
FILE NO. 85-060D
CLIENT SOUTHERN COMPANY SERVICES
ELEVATION 786 FT (MSL)
BORING LOCATION
BORING TYPE SAMPLING
COUNTY COWETA
STATE GEORGIA
CASING TYPE 6 1/4" DIA. H.S. AUGER
DATE STARTED 7/21/94
COMPLETED 7/21/94
DRILLER/RIG McCLUSKEY/CME45
WATER TABLE: 1st depth -- 9.5'
DATE -- 7/21/94
TIME --
WATER TABLE: 2nd depth --
DATE --
TIME --
REMARKS Supervision & field classification by John May

Elevation	Depth (ft)	Undisturbed Samples ASTM D-1587: Sample No.	Length (in.)	Recovery (%)	Lab Test Results: NM 40 C (%)	NM 180 C (%)	CaCO3 (%)	Total Unit Wt. (pcf)	Dry Dens. (pcf)	Descriptions and Remarks	Depth (ft)	Graphic Log
										LIGHT BROWN AND BROWN CAST GYPSUM DIKE		
-5	5	PS-1	20	83	19			103	87			
		PS-2	16	53	24			106	85			
-10	10	PS-3	21	70	25			115	92	WATER LOSS — BROWN + ORANGE-BROWN DISTURBED SEDIMENTED AND CAST GYPSUM (EXCAVATED)		
										WATER LOSS		
		PS-4	20	67	21			115	95	ORANGE-BROWN SEDIMENTED GYPSUM		
-15	15	PS-5	20	67	20			116	97	LIGHT BROWN SEDIMENTED GYPSUM		
		PS-6	24	80	21			116	96			
										BORING TERMINATED AT 17.5 FT		
-20	20											
-25	25									HDPE LINER (EL. 762 FT)		
-30	30											

BORING LOG
ARDAMAN & ASSOCIATES, INC.

BORING NO: TH-2A
TOTAL DEPTH: ft.
SHEET 1 OF 1

PROJECT BYPRODUCT EVALUATION - FGD CLEAN COAL PROJECT
FILE NO. 85-0600
CLIENT SOUTHERN COMPANY SERVICES
ELEVATION 786 FT
BORING LOCATION
BORING TYPE SPT
COUNTY COWETA
STATE GEORGIA
CASING TYPE 12' - 4" DIA. STEEL (HW)
DATE STARTED 7/20/94
COMPLETED 7/20/94
DRILLER/RIG McCLUSKEY/CME45
WATER TABLE: 1st depth -- 9.0 ft
DATE -- 7/20/94
TIME --
WATER TABLE: 2nd depth --
DATE --
TIME --
REMARKS Supervision & field classification by John May

Elevation	Depth (ft)	Standard Pen. Test ASTM D-1586: Blows/6 in.	N Value	Sample No.	Lab Test Results: NM 40 C (%)	NM 180 C (%)	$CaCO_3$ (%)	Total Unit Wt. (pcf)	Dry Dens. (pcf)	Descriptions and Remarks
		3-3-6	6	1	15.3	35.3	2.0			
		1-2-1	3	2	16.0					
		5-15-13	28	3	13.0	32.5	3.9			LIGHT BROWN CAST GYPSUM DIKE
-5	5	20-17-12	29	4	14.4					
		10-9-9	18	5	18.3	39.2	2.6			
		15-14-14	28	6	20.1					WATER LOSS ▽
-10	10	16-14-13	27	7	24.9	44.9	6.0			BROWN AND ORANGE-BROWN DISTURBED SEDIMENTED & CAST GYPSUM (EXCAVATED)
		12-13-20	33	8	21.7					ORANGE-BROWN SEDIMENTED GYPSUM
		13-34-47	81	9	18.3	38.0	5.8			
		50-50/6"	100	10	23.9					
-15	15									LIGHT BROWN SEDIMENTED GYPSUM
		18-25-50	75	11	23.9	44.6	0.9			
		23-34-39	73	12	23.1					
		13-22-25	47	13	25.5	46.0	2.2			
-20	20	26-40-38	78	14	18.8					
										BORING TERMINATED AT 21.0 FT
-25	25									HDPE LINER (EL. 762 FT)
-30	30									

BORING LOG
ARDAMAN & ASSOCIATES, INC.

BORING NO: TH-1B
TOTAL DEPTH: ±20.0 FT
SHEET 1 OF 1

PROJECT BYPRODUCT EVALUATION - FGD CLEAN COAL PROJECT
FILE NO. 85-080D
CLIENT SOUTHERN COMPANY SERVICES
ELEVATION 785 FT (MSL)
BORING LOCATION
BORING TYPE SAMPLING
COUNTY COWETA **STATE** GEORGIA
CASING TYPE NONE
DATE STARTED 7/19/94 **COMPLETED** 7/19/94
DRILLER/RIG McCLUSKEY/CME45
WATER TABLE: 1st depth -- 9.5' **DATE** -- 7/19/94 **TIME** --
WATER TABLE: 2nd depth -- **DATE** -- **TIME** --
REMARKS Supervision & field classification by John May

Elevation	Depth (ft)	Undisturbed Samples ASTM D-1587: Sample No.	Length (in.)	Recovery (%)	Lab Test Results: NM 40 C (%)	NM 180 C (%)	CaCO3 (%)	Total Unit Wt. (pcf)	Dry Dens. (pcf)	Descriptions and Remarks
		UD-1	24	100	12 / 16			93	82	LIGHT BROWN CAST GYPSUM DIKE
-5	5									
		PS-1	20	67	28			106	83	
		PS-2	19	63	25			115	92	BROWN / ORANGE-BROWN DISTURBED SEDIMENTED AND CAST GYPSUM (EXCAVATED) ▽
-10	10									ORANGE-BROWN SEDIMENTED GYPSUM
		PS-3	26	87	25			115	92	← WATER LOSS; LIGHT BROWN SEDIMENTED GYPSUM
										MIXED LIGHT BROWN / ORANGE-BROWN GYPSUM (DISTURBED SEDIMENTED)
		PS-4	30	100	20			116	97	
-15	15									LIGHT BROWN SEDIMENTED GYPSUM W/TH ORANGE-BROWN SEAMS
		PS-5	28	93	23			112	91	
		PS-6	21	88	27			114	90	LIGHT BROWN SEDIMENTED GYPSUM W/ 3" THICK ORANGE-BROWN LAYER AT 18.75'
-20	20									BORING TERMINATED AT 20.0 FT
										HDPE LINER (EL. 762 FT)
-25	25									
-30	30									

BORING LOG

ARDAMAN & ASSOCIATES, INC.

BORING NO: TH-3
TOTAL DEPTH: ft. 16.5 FT
SHEET 1 OF 1

PROJECT BYPRODUCT EVALUATION - FGD CLEAN COAL PROJECT
FILE NO. 85-0600
CLIENT SOUTHERN COMPANY SERVICES
ELEVATION 782 FT (MSL)
BORING LOCATION
BORING TYPE SAMPLING
COUNTY COWETA
STATE GEORGIA
CASING TYPE 6 1/4" DIA. H.S. AUGER
DATE STARTED 7/22/94
COMPLETED 7/22/94
DRILLER/RIG McCLUSKEY/CME45
WATER TABLE: 1st depth -- 5.5 FT
DATE -- 7/22/94
TIME --
WATER TABLE: 2nd depth --
DATE --
TIME --
REMARKS Supervision & field classification by John May

Elevation	Depth (ft)	Undisturbed Samples ASTM D-1587: Sample No.	Length (in.)	Recovery (%)	Lab Test Results: NM 40 C (%)	NM 180 C (%)	CaCO3 (%)	Total Unit Wt. (pcf)	Dry Dens. (pcf)	Descriptions and Remarks	Depth (ft)	Graphic Log
										LIGHT BROWN CAST GYPSUM DIKE		
-5	5											
										MIXED LIGHT BROWN & ORANGE-BROWN DISTURBED SEDIMENTED GYPSUM (EXCAVATED)		
-10	10	PS-1	18	60	19			120	101	LIGHT BROWN SEDIMENTED GYPSUM		
		PS-2	30	100	21			118	98	MIXED LIGHT BROWN & ORANGE-BROWN GYPSUM (DISTURBED SEDIMENTED)		
-15	15	PS-3	29	97	27			110	87	LIGHT BROWN SEDIMENTED GYPSUM		
										BORING TERMINATED AT 16.5'		
-20	20									HDPE LINER (EL. 762 FT)		
-25	25											
-30	30											

TABLE C-1
EXCHANGEABLE Ca (meq/100g soil) IN CALHOUN SOIL WITH DEPTH

Depth cm	Fly Ash - FGD 1:1 Mixture			FGD Only			Control
	5 t/ha	10 t/ha	20 t/ha	5 t/ha	10 t/ha	20 t/ha	
0-20	1.422	1.437	2.467	1.444	1.941	2.690	1.163
20-30	2.200	1.980	2.417	1.585	2.354	2.376	1.656
30-40	2.414	2.280	2.548	2.213	2.820	2.743	1.923
40-50	2.044	1.913	2.001	1.986	2.253	2.459	1.758
50-60	1.701	1.538	1.561	1.648	1.914	1.944	1.532
60-70	1.449	1.336	1.307	1.367	1.508	1.539	1.307
70-80	1.245	1.100	0.805	1.152	1.178	1.257	1.061

TABLE C-2
EXCHANGEABLE Mg (meq/100g soil) IN CALHOUN SOIL WITH DEPTH

Depth cm	Fly Ash - FGD 1:1 Mixture			FGD Only			Control
	5 t/ha	10 t/ha	20 t/ha	5 t/ha	10 t/ha	20 t/ha	
0-20	0.250	0.171	0.187	0.164	0.125	0.109	0.319
20-30	0.441	0.350	0.373	0.271	0.306	0.263	0.355
30-40	0.528	0.484	0.515	0.449	0.551	0.451	0.438
40-50	0.535	0.509	0.519	0.484	0.553	0.528	0.466
50-60	0.548	0.512	0.479	0.478	0.587	0.533	0.485
60-70	0.529	0.489	0.447	0.448	0.543	0.486	0.471
70-80	0.488	0.440	0.381	0.418	0.463	0.424	0.416

TABLE C-3
EXCHANGEABLE K (meq/100g soil) IN CALHOUN SOIL WITH DEPTH

Depth cm	Fly Ash - FGD 1:1 Mixture			FGD Only			Control
	5 t/ha	10 t/ha	20 t/ha	5 t/ha	10 t/ha	20 t/ha	
0-20	0.246	0.226	0.248	0.271	0.240	0.240	0.260
20-30	0.168	0.181	0.173	0.205	0.191	0.205	0.179
30-40	0.113	0.139	0.133	0.174	0.128	0.167	0.144
40-50	0.085	0.093	0.101	0.119	0.084	0.117	0.105
50-60	0.087	0.090	0.097	0.098	0.091	0.100	0.102
60-70	0.092	0.089	0.093	0.097	0.090	0.096	0.098
70-80	0.093	0.088	0.095	0.141	0.130	0.093	0.099

TABLE C-4
EXCHANGEABLE Ca (meq/100g soil) IN CECIL SOIL AT OCONEE CO. SITE

Depth cm	Fly Ash - FGD 1:1 Mixture			FGD Only			Fly Ash Only	Control
	5 t/ha	10 t/ha	20 t/ha	5 t/ha	10 t/ha	20 t/ha	20 t/ha	
0-20	0.812	1.119	1.516	0.795	1.777	2.495	0.825	0.885
20-30	1.176	1.650	1.577	1.083	2.512	1.884	1.396	1.577
30-40	1.310	1.844	1.684	1.043	2.111	1.417	1.470	1.770
40-50	1.370	1.617	1.530	1.196	1.717	2.091	1.483	1.770
50-60	1.470	1.443	1.570	0.842	1.757	1.797	1.443	1.483
60-70	1.276	1.063	1.303	1.196	1.276	1.036	1.123	1.043

TABLE C-5
EXCHANGEABLE Mg (meq/100g soil) IN CECIL SOIL AT OCONEE CO. SITE

Depth cm	Fly Ash - FGD 1:1 Mixture			FGD Only			Fly Ash Only	Control
	5 t/ha	10 t/ha	20 t/ha	5 t/ha	10 t/ha	20 t/ha	20 t/ha	
0-20	0.120	0.113	0.156	0.081	0.101	0.069	0.214	0.235
20-30	0.372	0.433	0.397	0.297	0.520	0.342	0.457	0.508
30-40	0.410	0.517	0.473	0.319	0.525	0.329	0.460	0.556
40-50	0.397	0.481	0.415	0.364	0.473	0.504	0.438	0.537
50-60	0.391	0.428	0.395	0.249	0.471	0.467	0.395	0.437
60-70	0.317	0.311	0.297	0.329	0.317	0.267	0.290	0.308

TABLE C-6
EXCHANGEABLE K (meq/100g soil) IN CECIL SOIL AT OCONEE CO. SITE

Depth cm	Fly Ash - FGD 1:1 Mixture			FGD Only			Fly Ash Only	Control
	5 t/ha	10 t/ha	20 t/ha	5 t/ha	10 t/ha	20 t/ha	20 t/ha	
0-20	0.190	0.197	0.238	0.157	0.191	0.157	0.225	0.251
20-30	0.367	0.375	0.370	0.271	0.425	0.292	0.375	0.401
30-40	0.372	0.365	0.327	0.288	0.334	0.260	0.306	0.316
40-50	0.225	0.259	0.203	0.219	0.197	0.242	0.194	0.254
50-60	0.164	0.157	0.147	0.135	0.105	0.146	0.126	0.143
60-70	0.100	0.096	0.094	0.119	0.106	0.122	0.112	0.096

TABLE C-7
EXCHANGEABLE Ca (meq/100g soil) IN TIFTON SOIL AT TIFTON SITE

Depth cm	Fly Ash - FGD 1:1 Mixture			FGD Only			Fly Ash Only	Control	LSD
	5 t/ha	10 t/ha	20 t/ha	5 t/ha	10 t/ha	20 t/ha	20 t/ha		
0-20	1.273c	1.543bc	2.023bc	1.472bc	2.249ab	3.154a	1.374bc	1.177c	0.916
20-30	0.537c	0.867bc	1.208ab	0.749bc	1.519a	1.615a	0.873bc	0.690bc	0.596
30-40	0.198c	0.307c	0.561ab	0.313bc	0.783a	0.785a	0.333bc	0.309bc	0.252
40-50	0.182c	0.228bc	0.398ab	0.255bc	0.507a	0.509a	0.277bc	0.234bc	0.189
50-60	0.178d	0.185d	0.358ab	0.211cd	0.465a	0.389ab	0.326bc	0.188d	0.133
60-70	0.208ab	0.245ab	0.223ab	0.258ab	0.387a	0.277ab	0.229ab	0.177b	0.206
70-80	0.269ab	0.256ab	0.153b	0.250ab	0.398a	0.276ab	0.250ab	0.218ab	0.208

Means within the **row** followd by the same latter are not significantlly differnt at $P<0.05$

TABLE C-8
EXCHANGEABLE Mg (meq/100g soil) IN TIFTON SOIL AT TIFTON SITE

Depth cm	Fly Ash - FGD 1:1 Mixture			FGD Only			Fly Ash Only	Control	LSD
	5 t/ha	10 t/ha	20 t/ha	5 t/ha	10 t/ha	20 t/ha	20 t/ha		
0-20	0.212ab	0.081b	0.047b	0.168ab	0.081b	0.042b	0.420a	0.433a	0.300
20-30	0.138ab	0.064b	0.022b	0.188ab	0.119ab	0.041b	0.396a	0.321ab	0.317
30-40	0.065a	0.043a	0.018a	0.098a	0.094a	0.020a	0.167a	0.170a	0.153
40-50	0.083abc	0.047bc	0.025c	0.077bc	0.135ab	0.032c	0.180a	0.141ab	0.100
50-60	0.110ab	0.051b	0.049b	0.066b	0.169a	0.061b	0.194a	0.147ab	0.103
60-70	0.151a	0.150a	0.114a	0.138a	0.250a	0.194a	0.180a	0.158a	0.170
70-80	0.230a	0.235a	0.165a	0.190a	0.313a	0.241a	0.245a	0.172a	0.164

Means within the **row** followd by the same latter are not significantlly differnt at $P<0.05$

TABLE C-9
EXCHANGEABLE K (meq/100g soil) IN TIFTON SOIL AT TIFTON SITE

Depth cm	Fly Ash - FGD 1:1 Mixture			FGD Only			Fly Ash Only	Control	LSD
	5 t/ha	10 t/ha	20 t/ha	5 t/ha	10 t/ha	20 t/ha	20 t/ha		
0-20	0.065ab	0.057ab	0.047bc	0.056ab	0.054ab	0.028c	0.062ab	0.072a	0.021
20-30	0.033bc	0.047abc	0.027c	0.033bc	0.051ab	0.027c	0.052ab	0.062a	0.020
30-40	0.038abc	0.035bc	0.031bc	0.042abc	0.062a	0.028c	0.049abc	0.053ab	0.025
40-50	0.039bc	0.039bc	0.036bc	0.046bc	0.077a	0.027c	0.056ab	0.051abc	0.028
50-60	0.046a	0.046a	0.045a	0.046a	0.070a	0.038a	0.070a	0.056a	0.037
60-70	0.056a	0.071a	0.065a	0.068a	0.083a	0.057a	0.074a	0.058a	0.051
70-80	0.069a	0.071a	0.068	0.077a	0.081a	0.066a	0.074a	0.061a	0.035

Means within the **row** followd by the same latter are not significantlly differnt at $P<0.05$

TABLE C-10
EXCHANGEABLE ALUMINUM AT TIFTON FIELD PLOTS WITH DEPTH

Depth cm	Fly Ash - FGD Mixture (t/a)			FGD Only (t/a)			Fly Ash Only (t/a)	Control
	5	10	20	5	10	20	20 t/ha	
	cmol (c)/kg soil							
0-20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20-30	0.021	0.000	0.000	0.000	0.000	0.000	0.087	0.000
30-40	0.030	0.006	0.000	0.069	0.000	0.000	0.069	0.017
40-50	0.077	0.056	0.065	0.059	0.000	0.007	0.033	0.050
50-60	0.131	0.112	0.135	0.076	0.021	0.075	0.068	0.140
60-70	0.167	0.221	0.210	0.197	0.138	0.181	0.185	0.269
70-80	0.417	0.523	0.537	0.523	0.380	0.434	0.534	0.498

TABLE C-11
EXCHANGEABLE ALUMINUM AT OCONEE (ATHENS) FIELD PLOTS WITH DEPTH

Depth cm	Fly Ash - FGD Mixture (t/a)			FGD Only (t/a)			Fly Ash Only (t/a)	Control
	5	10	20	5	10	20	20 t/ha	
	cmol (c)/kg soil							
0-20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20-30	0.000	0.000	0.000	0.000	0.012	0.000	0.000	0.000
30-40	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.021
40-50	0.020	0.000	0.069	0.013	0.022	0.043	0.061	0.023
50-60	0.122	0.021	0.199	0.047	0.069	0.160	0.114	0.085
60-70	0.379	0.110	0.402	0.149	0.165	0.162	0.183	0.295

TABLE C-12
EXCHANGEABLE ALUMINUM AT CALHOUN FIELD PLOTS WITH DEPTH

Depth cm	Fly Ash - FGD Mixture (t/a)			FGD Only (t/a)			Control
	5 t/ac	10 t/ha	5 t/ha	5 t/ha	10 t/ha	20 t/ha	
	cmol (c)/kg soil						
0-20	0.597	0.668	4.428	0.826	0.453	0.382	0.740
20-30	0.338	0.774	0.791	1.161	0.621	0.764	0.843
30-40	0.561	0.733	0.922	1.087	0.625	0.637	0.915
40-50	1.104	1.373	1.456	1.516	1.202	1.084	1.437
50-60	1.875	1.975	2.035	2.062	1.864	1.748	1.946
60-70	2.334	2.329	2.370	2.512	2.378	2.329	2.434
70-80	2.495	2.640	2.676	2.700	2.627	2.627	2.644