Evaluation of Chiyoda Thoroughbred 121 FGD Process and Gypsum Stacking

Volume 3: Testing the Feasibility of Stacking FGD Gypsum

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Prepared by
Ardaman & Associates, Inc.
Orlando, Florida

ELECTRIC POWER RESEARCH INSTITUTE

Evaluation of Chiyoda Thoroughbred 121 FGD Process and Gypsum Stacking
Volume 3: Testing the Feasibility of Stacking FGD Gypsum

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Research Project 536-3

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ABSTRACT

Forced-oxidation flue gas desulfurization (FGD) scrubbers can produce significant quantities of waste gypsum, which, if not utilized, require safe and economical disposal. Gypsum is also a waste product of the phosphate fertilizer industry, which has successfully utilized stacking methods of waste disposal for more than 20 years. Results from geotechnical laboratory testing of Chiyoda Thoroughbred 121 (CT-121) FGD gypsum are presented. These results indicate CT-121 FGD gypsum has settling, dewatering, and structural characteristics similar to and, in some instances, more favorable than phosphate gypsum, making stacking methods of waste disposal a possible option for disposing of FGD gypsum. The construction and nine-month operation of a one-half acre, 12-foot-high prototype CT-121 FGD gypsum stack at the Scholz plant is also discussed. The success of this installation further confirms the feasibility of utilizing stacking for disposal of FGD gypsum. Basic concepts concerning the design and management of gypsum stacks in the phosphate industry are presented to illustrate the stacking method as it may be adopted by the utility industry for stacking FGD gypsum.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This is Volume 3 of EPRI Final Report CS-1579. All three volumes describe flue gas desulfurization (FGD) research efforts performed with Southern Company Services, Inc., since 1978. Volume 1 details the results of an eight-month evaluation of a 23-MW Chiyoda Thoroughbred 121 (CT-121) scrubbing system at Gulf Power Company's Scholz plant near Sneads, Florida. Volume 2 contains the appendixes that support the system evaluation efforts defined in Volume 1. This Volume 3 summarizes the results of RP536-3, which evaluated the feasibility of disposing of FGD gypsum by-product by stacking rather than by ponding or landfilling. Stacking the gypsum by-product offers the utility industry a disposal option that is consistent with the trend toward scrubbing systems that produce gypsum rather than sludge. Proper design, operation, and construction of a gypsum stack can eliminate the need for a thickener, thereby reducing the capital investment and size of a scrubbing system. The CT-121 evaluation (RP536-4) offered an opportunity to test a waste disposal method that has been practiced for years by the phosphate fertilizer industry. Therefore, RP536-3 was pursued in parallel with the evaluation of the CT-121 scrubber--a gypsum-producing process.

PROJECT OBJECTIVE

The objective was to determine the technical and environmental feasibility of stacking FGD gypsum by-product using existing phosphate fertilizer industry stacking techniques.

PROJECT RESULTS

The completed stack, approximately one-half acre (2000 m^2) and 12 feet (4 m) high, was generally constructed and operated using the design concepts and operation practices utilized by the phosphate fertilizer industry. The construction of a prototype FGD gypsum stack at the Scholz Electric Generating Station of the Gulf Power Company confirmed the feasibility of utilizing stacking for disposal of an FGD gypsum by-product.

The gypsum stack evaluation showed that the addition of fly ash to the gypsum by-product produced a mixture that does not stack as well as pure gypsum--that is, the settled gypsum-fly ash mixture has a lower solids content, lower density, and lower permeability. Thus fly ash contamination is a factor that a utility must consider when designing a gypsum stack.

This report is for utilities that are considering a lime-limestone scrubber producing an oxidized by-product (gypsum), do not have an established market for the gypsum, and have limited space for disposal. The report defines, for the utility engineer, detailed results of the gypsum stacking experience obtained at the Scholz Electric Generating Station and the design and operation concepts that a utility must address when constructing a gypsum stack.

No follow-on effort is presently planned; however, if a utility decides to incorporate a gypsum stack into a full-scale scrubbing system, EPRI would seriously consider the possibility of characterizing it.

Thomas M. Morasky, Project Manager
Coal Combustion Systems Division

ACKNOWLEDGMENTS

The successful completion of the CT-121 FGD gypsum stacking experiment at Plant Scholz and the results presented within this report represent the efforts of many individuals. The authors particularly wish to acknowledge the following individuals for their contributions in varying capacities to the success of this research program: Lamar Larrimore, Randall E. Rush, and David P. Burford of Southern Company Services, Inc. for their overall assistance and project management throughout the program; Greg P. Behrens and O. W. Hargrove of Radian Corporation for their assistance in the groundwater monitoring and sampling phases of the project; D. D. Clasen, M. Noguchi, and Y. Kameoka of Chiyoda International Corporation for their contributions to the on-site management of the gypsum stack; and W. T. Lyford and G. O. Layman of Gulf Power Company for their assistance in the selection and use of on-site areas for construction of the gypsum stack. In addition to their contributions during the test program, we also wish to thank these individuals for their valuable suggestions, and critiques of various sections of this report.

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Additional Ardaman & Associates, Inc. personnel that have contributed in varying capacities to the success of this project include A. E. Z. Wissa, M. Varner and H. Hooper.

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SUMMARY

The use of forced oxidation scrubbers for flue gas desulfurization (FGD) produces a waste by-product of essentially pure gypsum which, if not utilized, requires safe and economical disposal. Gypsum is also a waste by-product of the phosphate fertilizer industry. Stacking methods of waste disposal have been successfully utilized by the phosphate industry for permanent disposal of waste gypsum for more than 20 years. In the State of Florida, where the greatest United States concentration of phosphate mining exists, over 21 million tons of gypsum is produced and stacked each year. Currently (1980), there is approximately 300 million tons of waste gypsum which has been disposed by stacking in Florida alone.

Although stacking methods of waste disposal have been successfully utilized by the phosphate industry for disposal of gypsum, no information or experience exists on the stacking characteristics of FGD gypsum. The purpose of this research, therefore, was to assess the feasibility of stacking for disposing FGD gypsum. Two methods of evaluation were used to assess the stacking characteristics of FGD gypsum. First, detailed geotechnical laboratory testing was conducted on Chiyoda Thoroughbred 121 (CT-121) FGD gypsum from the Chiyoda pilot plant in Japan and the Scholz Electric Generating Station (Scholz) of Gulf Power Company in Sneads, Florida. The tests were performed to assess the gypsum's physical and chemical properties, sedimentation-consolidation behavior, permeability characteristics, and shear strength characteristics relevant to stacking for disposal. Test data from this investigation were compared with similar data from numerous phosphate gypsums. The laboratory comparison indicated CT-121 FGD gypsum has settling, dewatering, and structural characteristics similar to and, in some instances, more favorable than phosphate gypsum, making stacking methods of waste disposal a possible option for disposing of CT-121 FGD gypsum.

Secondly, a prototype FGD gypsum stack was constructed and operated for a nine-month test period at Scholz during operation of the CT-121 FGD system.

The completed stack was approximately one-half acre (2000 m^2) and 12 feet (4m) high. Successful operation of the stack indicated CT-121 FGD gypsum can be stacked with a dragline using the upstream method of construction as typically accomplished in the phosphate industry. Based upon results of both the laboratory investigation and short term field study, the only significant stacking characteristic not observed in CT-121 FGD gypsum was the gradual development of some cohesion in the stack slopes from cementation. Although the self-cementation process is a desirable characteristic, the absence of cementation does not preclude the use of stacking.

If stacking methods are selected by utilities for the disposal of FGD gypsum, the upstream method of construction using a dragline as practiced in the phosphate industry appears to be feasible. Basic design and operation concepts which have been developed over the years in the phosphate industry may largely be adopted, without modification, by the utility industry for stacking FGD gypsum.

The effect of fly ash addition on the stacking characteristics of CT-121 FGD gypsum was also briefly investigated, since in some cases the potential exists for the simultaneous disposal of fly ash and gypsum. Detailed assessment of the stackability of fly ash/gypsum mixtures was originally not part of the research program for RP536-3, but some geotechnical laboratory testing was performed as significant interest developed in the topic. Laboratory investigations of the effect of fly ash addition on the permeability, sedimentation-consolidation, and shear strength characterisitics of CT-121 FGD gypsum all indicate that stacking gypsum/fly ash mixtures would be more difficult than stacking pure CT-121 gypsum. However, additional research is certainly required to assess potential stacking methods for simultaneous disposal of gypsum fly ash.

Section 1

INTRODUCTION

PROJECT HISTORY

Currently, and for the past several years, three alternatives have been available to electric utilities to meet federal new source performance standards (NSPS) for coal-fired electric generating stations: (1) burning a coal whose combustion products complied with these regulations, (2) cleaning the combustion gases from noncomplying coal, or (3) cleaning noncomplying coal prior to combustion. The Clean Air Act Amendments of 1977 (Public Law 95-95) have effectively eliminated the first option and placed further constraints on the latter two. Because of this, the development of alternative technologies for postcombustion cleaning of flue gases and precombustion cleaning of coal has taken on a new importance.

Since 1972, Southern Company Services, Inc. (SCS) has been extensively evaluating postcombustion cleaning of flue gas at the Scholz Electric Generating Station (Scholz) of Gulf Power Company in Sneads, Florida (1). As a continuing part of the evaluation program at Scholz, Chiyoda International Corporation installed and operated a 20 MW prototype of their Thoroughbred 121 (CT-121) forced-oxidation direct limestone flue gas desulfurization system (2).

The evaluation of the CT-121 system, sponsored by The Southern Company* and the Electric Power Research Institute (EPRI), included an overall process evaluation by Radian Corporation (RP536-4) and the evaluation presented herein of the feasibility of utilizing stacking for waste disposal of CT-121 FGD gypsum by Ardaman & Associates, Inc. (RP536-3).

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* The Southern Company is an electric utility holding company in the Southeast and is the parent firm of Alabama Power Company, Georgia Power Company, Gulf Power Company, Mississippi Power Company, and Southern Company Services, Inc.

PROJECT PURPOSE

The application of forced oxidation for converting calcium sulfite sludge to calcium sulfate (gypsum) in flue gas desulfurization (FGD) sludge processing and disposal has recently received increased attention. The mineralogy, crystal geometry, and particle size of waste gypsum typically provide settling, dewatering, and structural characteristics which allow easier and more efficient methods of waste disposal than with calcium sulfite sludges.

Gypsum is also a waste product of the phosphate fertilizer industry, which produces in excess of 21 million tons (1.9×10^{10} kg) of gypsum per year in Florida alone. Stacking methods of waste disposal have been economically utilized by the phosphate industry in Florida for gypsum disposal for more than 20 years. These gypsum stacks are typically large (50 to 300 acres), structurally stable stockpiles reaching heights of 100 feet (30.5 m). A typical phosphate industry gypsum stack located near Bartow, Florida is shown in Figure 1-1.

Although gypsum stacking has been successfully utilized by the phosphate fertilizer industry for waste disposal, no experience exists on the stacking behavior and engineering characteristics of waste gypsum produced by FGD scrubbers. The purpose of this project, therefore, was to study the geotechnical and environmental feasibility of: (1) utilizing stacking methods of waste disposal for CT-121 FGD gypsum, and (2) transferring existing phosphate industry waste disposal technology to the utility industry for FGD gypsum stacking and disposal.

BACKGROUND OF FGD BY-PRODUCT GYPSUM

The potential for utilizing "stacking" methods of waste disposal for FGD gypsum was recognized during operation of the Chiyoda Thoroughbred 101 (CT-101) scrubber at the Scholz Electric Generating Station (Scholz) of Gulf Power Company in Sneads, Florida (1). The CT-101 FGD system produced an essentially pure gypsum which could be dewatered by centrifuge to 80 to 88 percent solids. The dewatered CT-101 FGD gypsum was hauled by dump truck to a lined, above-ground storage pond for disposal. Although the applicability of gypsum stacking, as carried out by the phosphate industry, was recognized as a possible method of waste disposal, no stacking experiments were included in the CT-101 process evaluations.

Figure 1-1. Phosphate Fertilizer Plant Gypsum Stack
Near Bartow, Florida

Engineering properties of the centrifuged CT-101 FGD gypsum were determined by the University of Louisville as part of the waste disposal and utilization evaluation of the CT-101 process (1, 3). The test program included grain size analyses, Standard Proctor compaction tests, consolidation tests, and drained triaxial compression tests. These tests were largely performed to evaluate the structural performance of compacted CT-101 FGD gypsum for landfill applications.

Prior to the CT-121 process installation at Scholz, the engineering characteristics of CT-121 FGD gypsum from a Chiyoda pilot plant in Japan were evaluated by Ardaman & Associates, Inc. (4). Laboratory tests were conducted to determine the engineering properties of CT-121 FGD gypsum relevant to the stacking method of disposal, and for comparison to the properties of typical phosphate gypsums, which have been successfully stacked. This study indicated that the pilot plant CT-121 FGD gypsum had engineering properties similar to phosphate gypsums and that a prototype stack could probably be constructed without difficulty. Test results from this initial laboratory study are included in Section 2 of this report.

During subsequent installation and operation of the Chiyoda Thoroughbred 121 (CT-121) Scrubber at Plant Scholz, a unique opportunity was offered to construct and study the performance of a prototype FGD gypsum stack. The CT-121 process is similar to that of conventional limestone scrubbing processes, but different in that SO_2 is completely oxidized to calcium sulfate (gypsum), leaving only trace amounts of calcium sulfite. A schematic process flow diagram of the CT-121 process is shown in Figure 1-2 (2). Flue gas from the plant,after quenching, is introduced directly into the Jet Bubbling Reactor, where it is then sparged into the absorbent through an array of vertical spargers, generating a jet bubbling layer. Sulfur dioxide (SO_2) is absorbed in the jet bubbling layer producing calcium sulfite which is oxidized completely to calcium sulfate. The cleaned flue gas then flows from the reactor, through a mist eliminator, and out the stack.

Limestone slurry is pumped directly to the Jet Bubbling Reactor to precipitate sulfates as gypsum. The crystallized gypsum is discharged from the reactor to a gypsum slurry tank. The slurry is then pumped to the gypsum stack. The gypsum settles from the slurry by gravity and the process liquor is pumped back to the process.

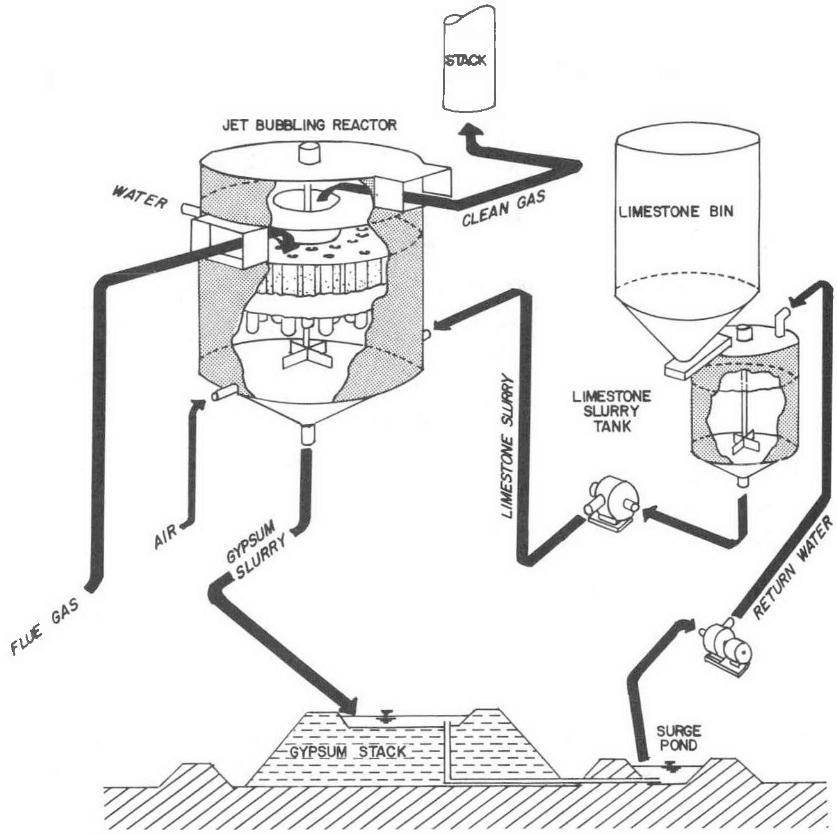

Figure 1-2. CT-121 Process Flow Diagram (Source: Proceedings of the Fourth EPA FGD Symposium, November 1977.)

The prototype stack was constructed and operated over a nine-month test period from October 1978 to June 1979. During this time, every effort was made to construct and operate the stack as typically accomplished in the phosphate fertilizer industry. Although the prototype stack was relatively small (i.e., one-half acre (2023 m^2) and 12 feet (3.7 m) high), the study did allow a comparison of laboratory tests of geotechnical engineering properties relevant to stacking with actual field behavior and a comparison of the overall stacking performance of CT-121 FGD gypsum with gypsum produced in the phosphate industry.

Typical central Florida phosphate fertilizer plants each produce between 2,700 to 5,500 tons (2.4×10^6 to 5.0×10^6 kg) of waste gypsum per day. A rough rule of thumb, using the CT-121 prototype FGD scrubbers, and assuming 2% sulfur coal, is to expect one ton of waste gypsum per day for every megawatt of generation capacity. Conventional coal-fired power plants generally vary from 200 to 3,000 megawatts, indicating a potential waste gypsum production from forced oxidation FGD scrubbers in the range of 200 to 3,000 tons per day (1.8×10^5 to 1.7×10^6 kg/day). Although this rate is less than phosphate fertilizer plants, the quantity is sufficient to pose a significant waste disposal problem.

PROJECT SCOPE

Recognizing the potential for significant production of waste gypsum from FGD scrubbers, the prototype stack at Plant Scholz was constructed to demonstrate the feasibility of stacking CT-121 FGD gypsum and to provide general design and construction guidelines for use throughout the utility industry. The results obtained from the Plant Scholz study are presented in this report and address four major items: (1) an engineering evaluation of the geotechnical properties of CT-121 FGD gypsum, (2) a presentation of general guidelines and methods applicable to designing, constructing, and operating gypsum stacks which have proven successsful in the stacking of phosphate gypsum, (3) a summary of the site specific geotechnical conditions, stacking operations, stack performance, and impact of leachate on groundwater quality at Plant Scholz, and (4) an overall appraisal of the feasibility of utilizing stacking for disposal of FGD gypsum.

Geotechnical engineering properties of CT-121 FGD gypsum relevant to stacking methods of waste disposal are discussed in Section 2. A comparison of CT-121 FGD gypsum and several phosphate gypsums, as well as a brief discussion on the effect of fly ash addition on the engineering behavior of CT-121 FGD gypsum, is also included in Section 2. The performance of the prototype stack at Plant Scholz is discussed in detail and illustrated in Section 3. Specific information and techniques utilized in the design, construction, and management of waste gypsum stacks in the phosphate fertilizer industry (which may be adapted by utilities for stacking FGD gypsum) are presented in Section 4. Finally, significant conclusions and recommendations concerning the geotechnical and environmental feasibility of stacking CT-121 FGD gypsum are discussed in Section 5.

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Section 2

CHARACTERISTICS OF CT-121 FGD WASTE GYPSUM

INTRODUCTION

This section presents the results of detailed geotechnical laboratory and field testing of Chiyoda Thoroughbred 121 (CT-121) FGD waste gypsum. Research emphasis was on assessing the physical and chemical properties, sedimentation-consolidation behavior, permeability characteristics, and shear strength characteristics of CT-121 FGD gypsum relevant to stacking methods of waste disposal. Results from gypsum produced at both the Chiyoda pilot plant in Japan and the prototype plant at Plant Scholz in Sneads, Florida are discussed and compared with the laboratory and field behavior of several phosphate gypsums. The effect of fly ash addition on the engineering behavior of CT-121 FGD gypsum is also briefly discussed.

PHYSICAL AND CHEMICAL PROPERTIES

Mineralogical Analysis

X-ray diffraction data from a sample of pilot plant CT-121 FGD gypsum indicated that gypsum ($CaSO_4 \cdot 2H_2O$) was the only crystalline phase present. The X-ray diffraction trace was virtually identical to a trace obtained from analytical reagent grade gypsum and also agreed with gypsum diffractometer data from the ASTM X-ray powder diffraction file.

The morphology (crystal structure and form) of pilot plant CT-121 FGD gypsum crystals are illustrated by scanning electron photomicrographs in Figure 2-1. The gypsum crystals are generally elongated with sharp, regular edges. The crystals vary in length from 0.05 to 0.15 mm with an average of 0.10 mm, and vary in width from 0.03 to 0.05 mm. The length to width ratio of the crystals ranges from 1.7 to 3.3 and averages 2.5.

X-ray diffraction data from a sample of Plant Scholz CT-121 FGD gypsum indicated gypsum was the only crystalline phase present. Relative peak amplitudes of the Plant Scholz and pilot plant gypsums were essentially identical.

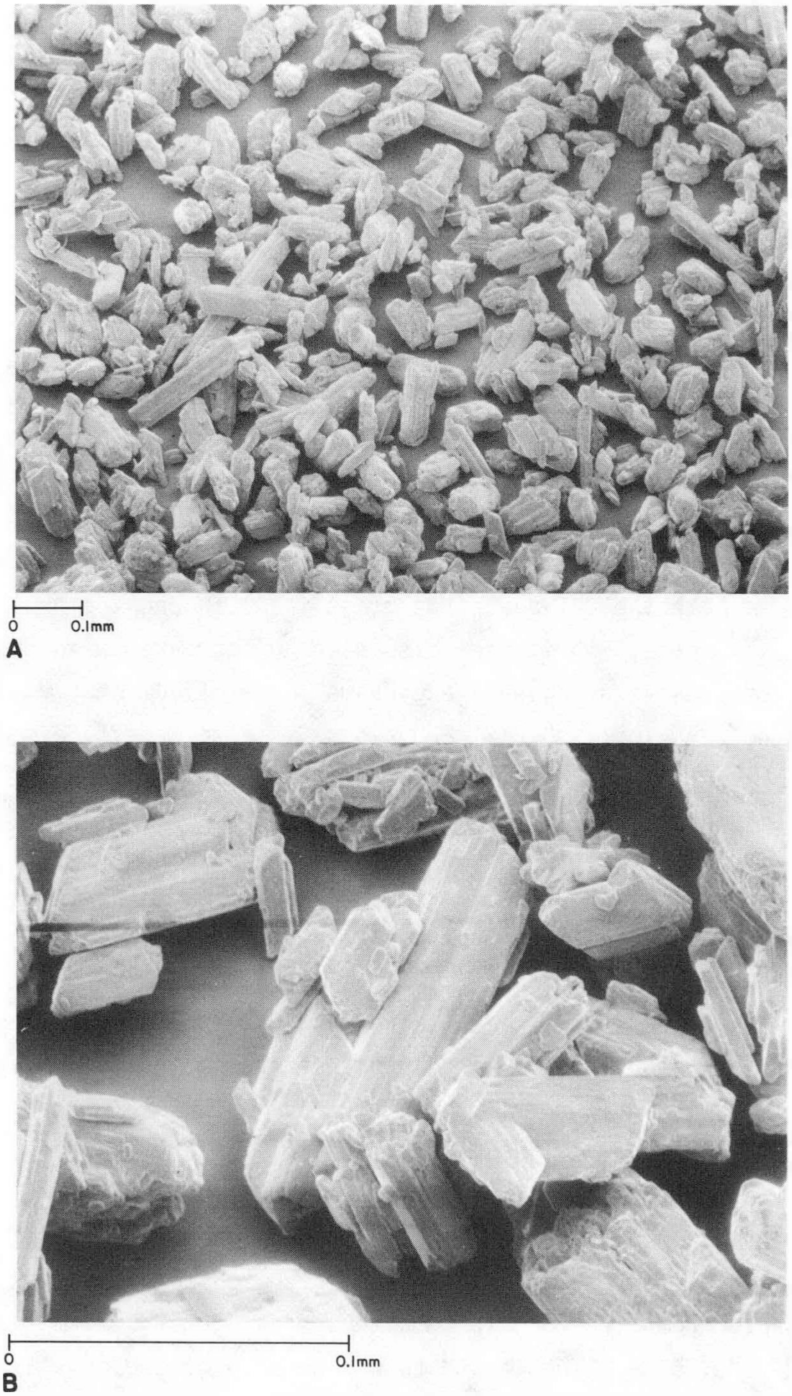


Figure 2-1. Scanning Electron Photomicrographs of Pilot Plant CT-121 FGD Gypsum

The morphology of Plant Scholz CT-121 FGD gypsum is illustrated by scanning electron photomicrographs in Figure 2-2. The most striking feature of the morphology is the tiny crystallites composing each particle. The crystallites are well illustrated in Figure 2-2B which is further magnified in Figure 2-2C. The numerous crystallites in each gypsum particle suggest numerous nucleation sites and/or very rapid crystal growth. The surface roughness produced from the numerous crystallites per crystal in the Plant Scholz gypsum is a marked contrast to the relatively smooth surface of the pilot plant gypsum.

The crystals of Plant Scholz gypsum vary in length from 0.05 to 0.25 mm with an average of 0.13 mm, and vary in width from 0.04 to 0.06 mm. The length to width ratio of the crystals ranges from 1.0 to 3.8 and averages 2.7. The crystal dimensions of the pilot plant and Plant Scholz gypsum, therefore, are similar.

Some minor evidence of penetration twinning is shown in Figure 2-1B. Rosette formation (for an example of a rosette formation see Figure 2-17C), typically observed in many phosphate gypsums, however, was not observed in either the pilot plant or Plant Scholz CT-121 FGD gypsum.

Solubility

Gypsum is soluble in water. No laboratory tests were conducted on CT-121 FGD gypsum, however, to determine the solubility in water. Since gypsum was the only crystalline phase detected during X-ray diffraction analyses, the solubility of CT-121 FGD gypsum in water can be taken as 2,440 to 2,640 mg/l at 10° to 30°C as reported for gypsum. Since gypsum is soluble in water, gypsum saturated solutions should be used to prevent the dissolution of gypsum crystals during testing.

Grain Size Distribution

Results from sieve and hydrometer analyses indicate the particle size distribution of CT-121 FGD gypsum as presented in Figure 2-3. As shown, CT-121 FGD gypsum predominantly consists of non-plastic, poorly-graded coarse silt size particles with a fines content of 100 percent (i.e., percent by dry weight passing the U.S. No. 200 sieve). Based on hydrometer analyses the calculated particle diameter ranges from 0.007 to 0.07 mm with an average (50 percent finer by weight) of 0.06 mm, which corresponds roughly to the equivalent particle diameter calculated from average crystal lengths and widths observed in the scanning electron photomicrographs.

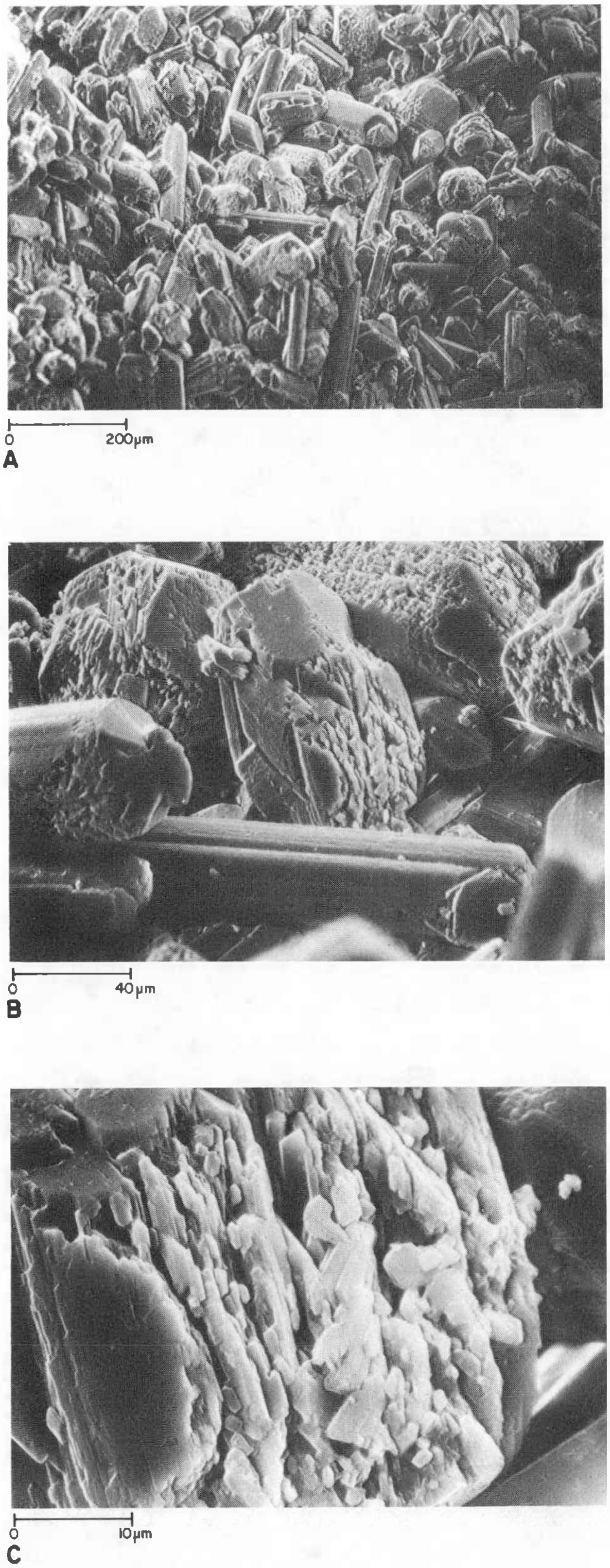


Figure 2-2. Scanning Electron Photomicrographs of Plant Scholz CT-121 FGD Gypsum

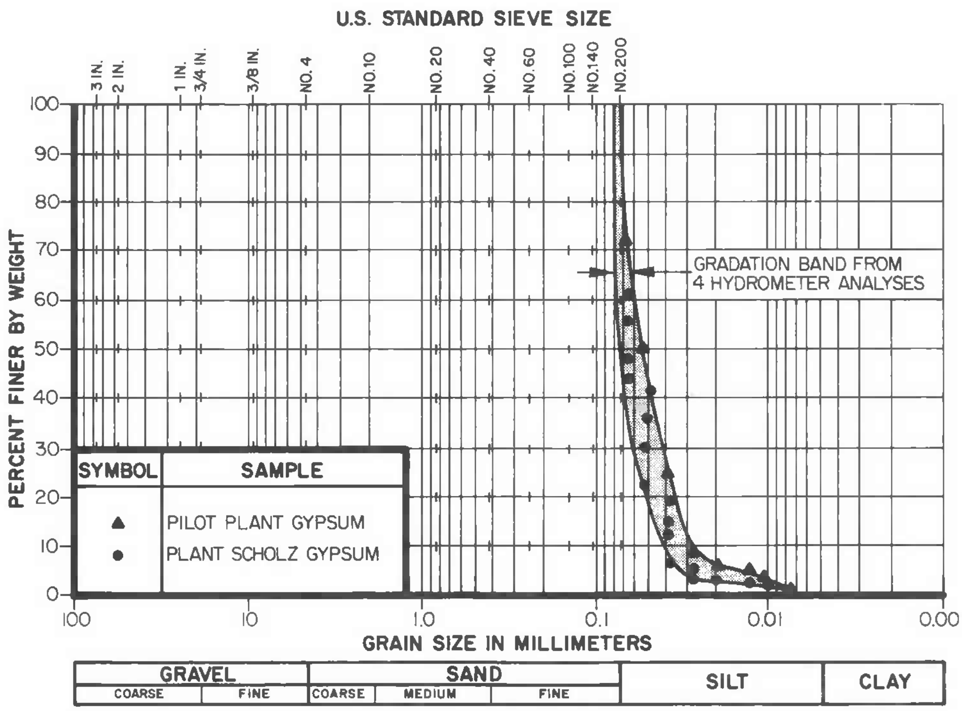


Figure 2-3. Grain Size Distribution of CT-121 FGD Gypsum

Specific Gravity

The specific gravity of CT-121 FGD gypsum varies from 2.27 to 2.44 with an average of 2.34. Since gypsum was the only crystalline phase detected during X-ray diffraction analyses, this value is expected and agrees with the known specific gravity of gypsum of 2.33.

Drying Curve Characteristics

Gypsum contains both chemically bonded and free water. The amount of chemically bonded water expelled during drying increases with increased drying temperature. To determine the correct drying temperature for evaluating gypsum moisture content and dry density, measurements of moisture content versus drying temperature were made for the pilot plant and Plant Scholz CT-121 FGD gypsum as well as for an analytical reagent grade gypsum (Figure 2-4).

During drying, gypsum ($CaSO_4 \cdot 2H_2O$) converts to hemihydrate ($CaSO_4 \cdot 1/2H_2O$) and then anhydrite ($CaSO_4$). Drying at the elevated temperature of 105°C commonly used for moisture content determinations of soils, therefore, is not appropriate. Drying samples of CT-121 FGD gypsum over the temperature range of 25°C to 240°C indicates similar drying curve shapes for all test samples. A drying temperature of less than 60°C should be used for measuring the correct gypsum moisture content, since at temperatures greater than 60°C, CT-121 FGD gypsum begins to expel chemically bonded water, yielding incorrect moisture contents. Accordingly, the moisture content of CT-121 FGD gypsum should be evaluated at temperatures less than 60°C, with a temperature of 50°C recommended.

ENGINEERING PROPERTIES

Sedimentation and Consolidation

The sedimentation-consolidation behavior of CT-121 FGD gypsum was measured in a standard consolidometer modified with a sedimentation column to allow simulation of the complete stress path from initial sedimentation through eventual consolidation under several tens of feet of gypsum. Gypsum was mixed into a slurry and poured into the sedimentation column of the consolidometer. Several layers were allowed to sediment and consolidate under their own weight to form the test sample. The effective consolidation stress was increased from an initial stress of approximately 0.001 kg/cm^2 to 16.0 kg/cm^2 (0.098 kPa to 1570 kPa) in 10 increments. The effect of pore fluid characteristics on the initial void ratio was

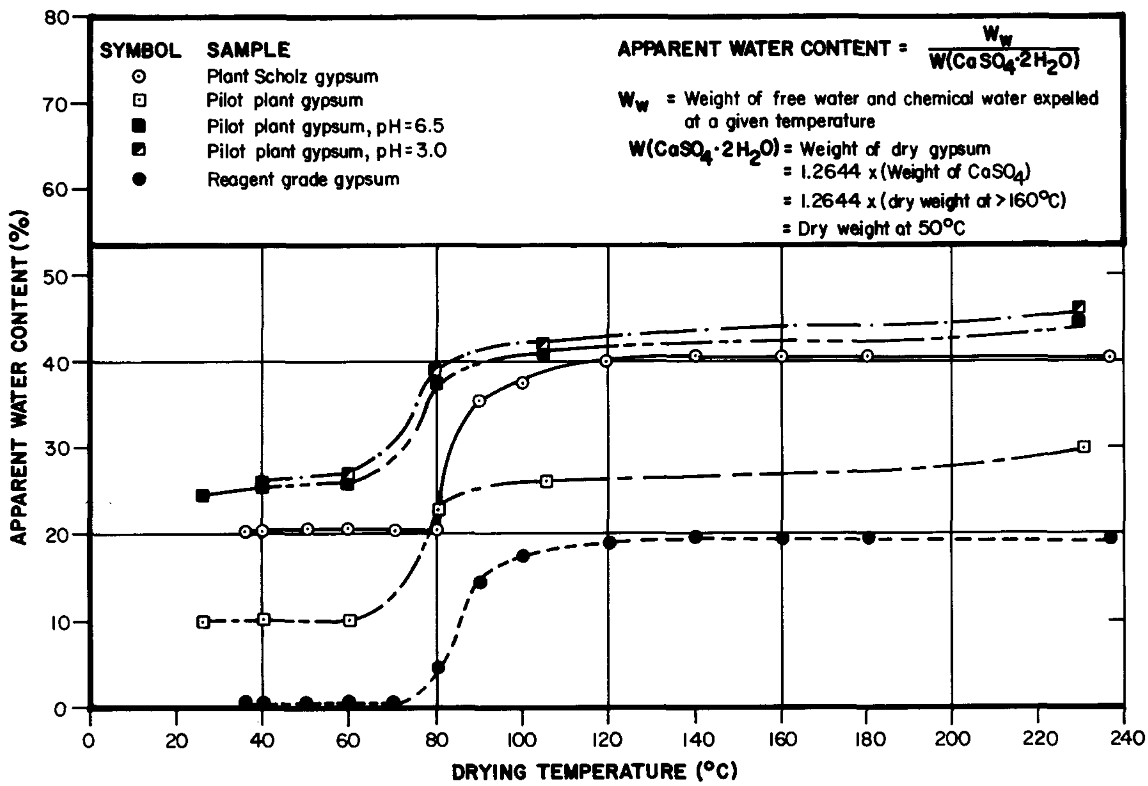


Figure 2-4. Drying Curve Characteristics

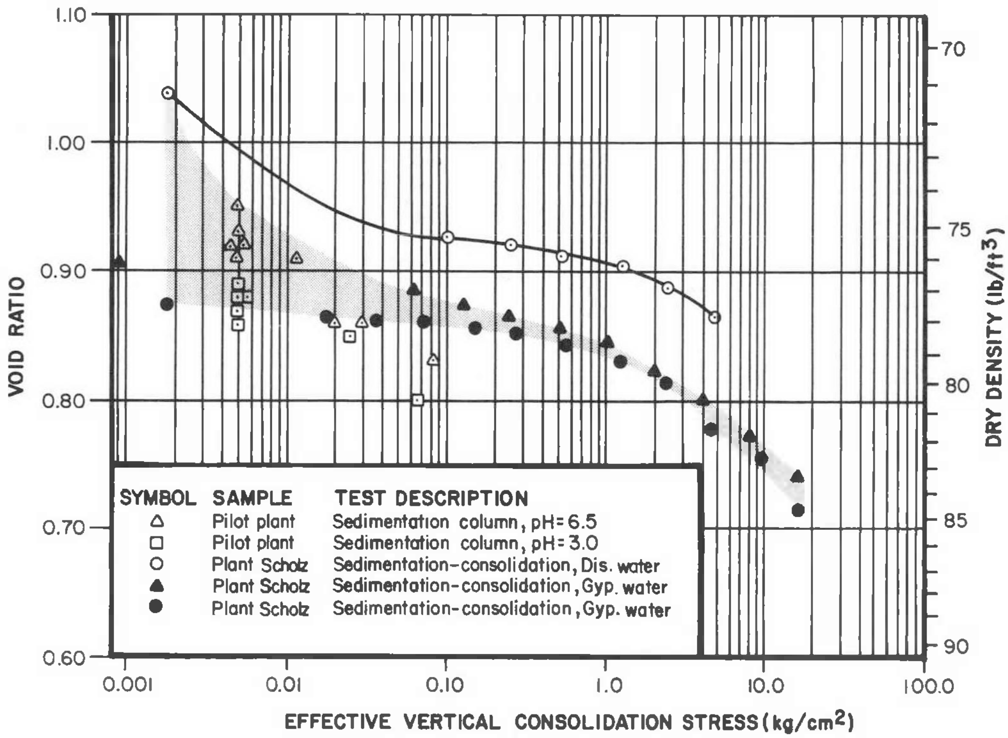
evaluated with: distilled water, as normally accomplished for soils; and with gypsum-saturated water from the Plant Scholz gypsum stack to simulate the actual depositional environment of the gypsum and to prevent the dissolution of gypsum crystals.

Figure 2-5 summarizes the sedimentation-consolidation behavior of three CT-121 FGD gypsum test samples. Two samples were sedimented in gypsum saturated water from the Plant Scholz gypsum stack and one sample in distilled water. The range in initial void ratio and dry density for samples sedimented in gypsum-saturated water were 0.88 to 0.91 and 78.0 to 75.0 lb/ft^3 (71 to 73 percent solids), respectively. Gypsum sedimented in distilled water yielded a slightly higher initial void ratio of 1.04 and corresponding lower dry density of 71.2 lb/ft^3 (69 percent solids).

Results from two sedimentation column tests performed at low stresses on pilot plant gypsum are also included in Figure 2-5. Untreated and neutralized gypsum-saturated pore fluids with pH values of 3.0 and 6.5 were used in the column tests. Five layers of gypsum, each with equal amounts of dry gypsum, were sedimented into a 7.62-cm diameter Plexiglas column to produce an initial sample height of approximately 19 cm. Effective vertical consolidation stresses during the test varied from an initial value of 0.005 kg/cm^2 (0.49 kPa) to a maximum value of 0.08 kg/cm^2 (7.8 kPa). The initial void ratio for gypsum sedimented in pH 6.5 pore fluid varied from 0.91 to 0.95 with corresponding dry densities of 76.1 to 74.6 lb/ft^3 (11.9 to 11.7 kN/m^3). The initial void ratio for gypsum sedimented in pH 3.0 pore fluid was slightly lower (5-7%), and varied from 0.86 to 0.89 with slightly greater (3%) dry densities of 78.2 to 76.9 lb/ft^3 (12.3 to 12.1 kN/m^3).

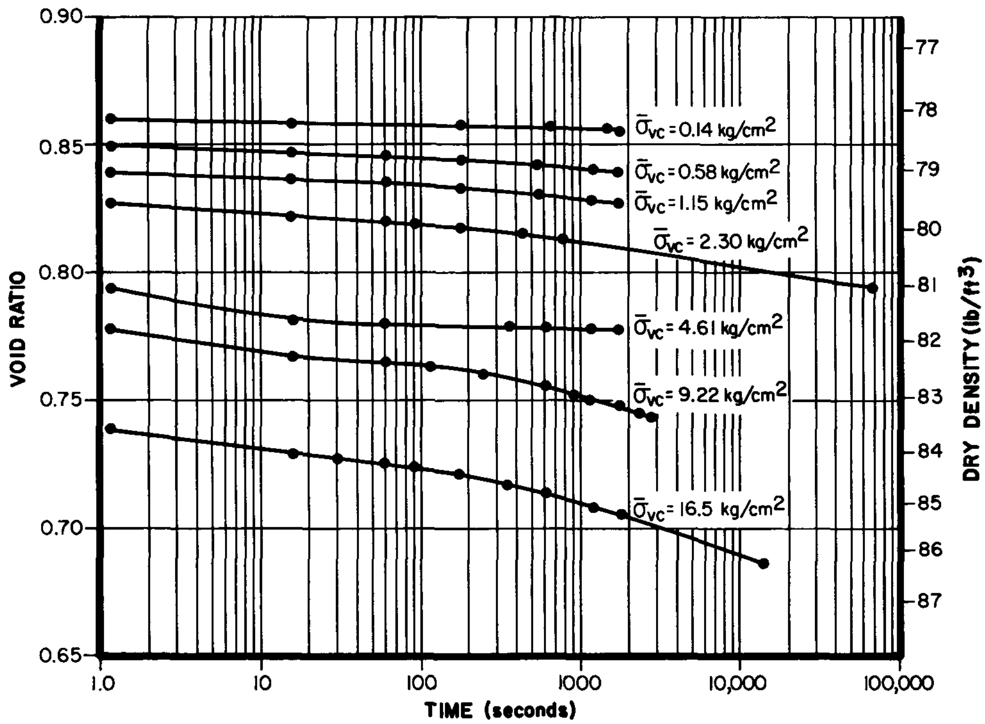
The practical implication for the initial void ratio and dry density of sedimented gypsum at low consolidation stresses is that CT-121 FGD gypsum will initially sediment by gravity to a dry density of 75 to 77 lb/ft^3 (71 to 72 percent solids) before consolidation under subsequent layers of sedimented gypsum. The pore fluid pH will have some effect on the initial sedimented void ratio and dry density, but will be relatively minor.

The void ratio verus effective vertical consolidation stress curves exhibit similar behavior for both test samples sedimented in gypsum-saturated water. Following sedimentation, the gypsum is already relatively stiff and exhibits little



1.0 lb/ft^3 = 0.157 kN/m^3
1.0 kg/cm^2 = 98.1 kPa

Figure 2-5. Sedimentation-Consolidation Behavior



1.0 lb/ft^3 = 0.157 kN/m^3

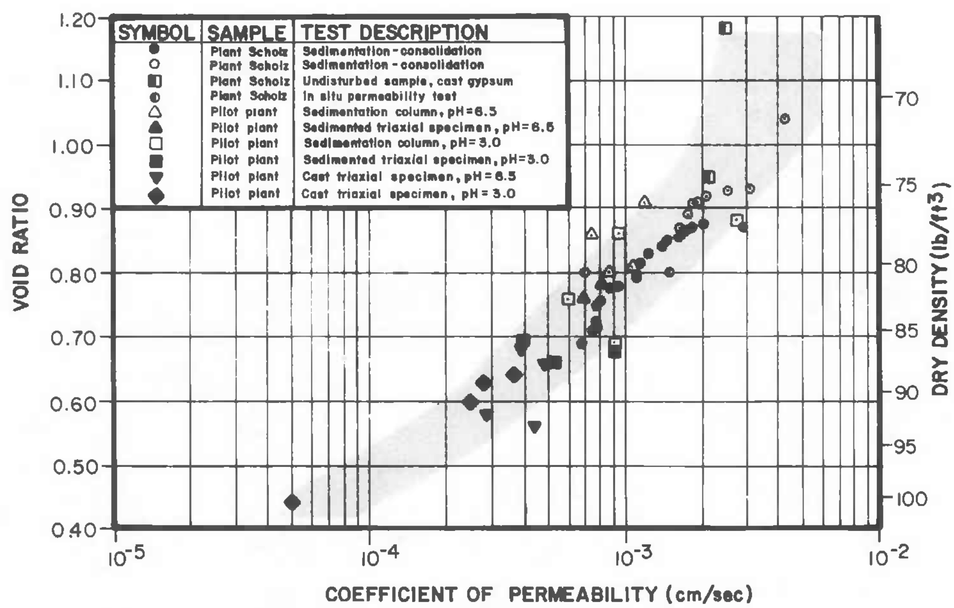
Figure 2-6. Void Ratio Versus Time Consolidation Curves consolidation for stresses below 1.0 kg/cm^2 (98.1 kPa). The compression ratio at these low stress levels is approximately 0.01. Above a stress of 1.0 kg/cm^2 (98.1 kPa), the compression ratio increases to about 0.05. Comparatively, these values are similar to those expected for a loosely-packed sand.

Void ratio versus time consolidation curves for several stress levels for Plant Scholz CT-121 FGD gypsum sedimented in gypsum-saturated water are shown in Figure 2-6. These data indicate primary consolidation occurs quickly followed by secondary compression. Coefficients of consolidation calculated from compressibility and permeability parameters for each load increment indicate values ranging from 10 cm^2/sec at a stress of 0.01 kg/cm^2 (0.98 kPa) to greater than 200 cm^2/sec at stresses of 1.0 kg/cm^2 (98.1 kPa) and higher. Since primary consolidation occurs rapidly, the void ratio versus effective vertical consolidation stress curves (Figure 2-5) were plotted for an arbitrary reference time of ten minutes. All deformation occurring after ten minutes was considered secondary compression. The practical conclusion from these data is that CT-121 FGD gypsum has a rapid rate of primary consolidation, but undergoes some secondary compression.

For CT-121 FGD gypsum, like phosphate gypsums, the coefficient of secondary compression increases with increasing effective vertical consolidation stress. The coefficient of secondary compression generally increased from 0.2 percent per log cycle at a stress of 1.0 kg/cm^2 (98.1 kPa) to about 1.0 percent per log cycle at a stress of 10.0 kg/cm^2 (981 kPa). For these two rates, 1-year of secondary compression will increase the dry density of sedimented gypsum by approximately 1 to 5 lb/ft^3 (0.16 to 0.79 kN/m^3), respectively. These increases are relatively small, and therefore, can generally be neglected in design.

Based upon this study of the sedimentation and consolidation behavior of CT-121 FGD gypsum,the following conclusions can be summarized relevant to gypsum stacking:

- CT-121 FGD gypsum settles rapidly. For the average crystal size of 0.06 mm equivalent diameter (see Figure 2-3), the settling velocity is 20 cm/min.



1.0 lb/ft^3 = 0.157 kN/m^3

Figure 2-7. Void Ratio Versus Coefficient of Permeability

- After initial sedimentation or settling in gypsum-saturated liquor, to a dry density of 75 to 77 lb/ft^3 (71 to 72 percent solids), CT-121 FGD gypsum does not consolidate considerably under additional imposed loads or with time due to secondary compression. Depending on the height and age of the stack, the dry density of sedimented gypsum within the stack may increase an additional 5 to 15 lb/ft^3 (0.79 to 2.4 kN/m^3) to 80 to 90 lb/ft^3 (12.6 to 14.1 kN/m^3).

- The pH of the gypsum-saturated liquor has little effect on the sedimentation and consolidation behavior of CT-121 FGD gypsum.

Permeability

Constant head permeability tests were performed on the sedimentation-consolidation test samples discussed above after each increment of load was applied for approximately ten minutes. Figure 2-7 summarizes these results. Test results from: (1) constant head permeability tests on sedimentation column samples at low stress levels, (2) constant head permeability tests on cast and sedimented triaxial test specimens, (3) falling head permeability tests on undisturbed samples of cast gypsum, and (4) in situ falling head permeability tests on sedimented gypsum are also presented. Laboratory sedimented gypsum samples were prepared to simulate sedimented gypsum within the stack. Cast gypsum samples were prepared to simulate the casting of gypsum by a dragline during construction of the stack perimeter dike.

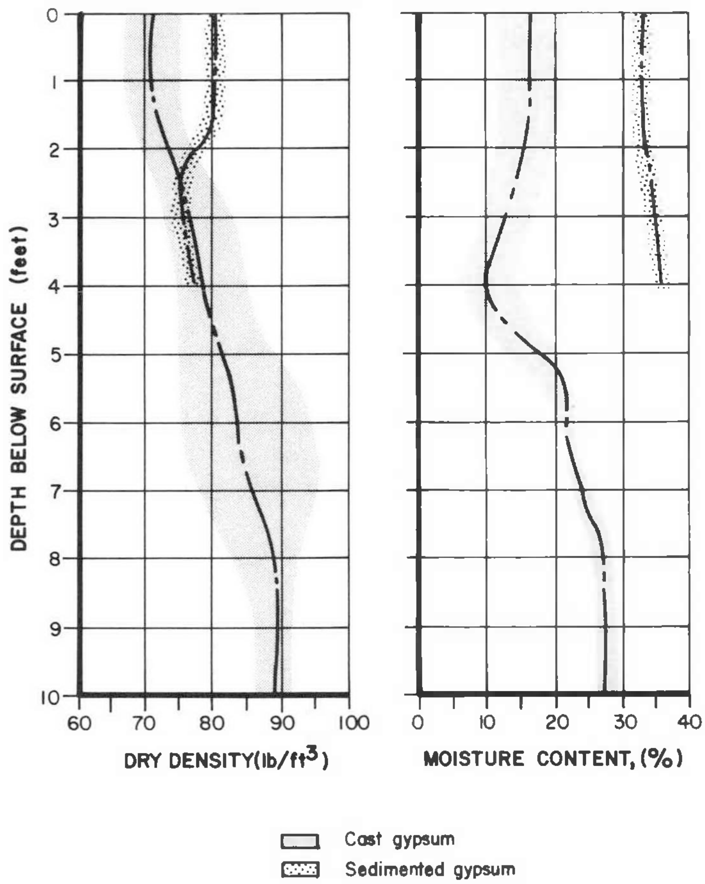
The effect of dry density and void ratio on the coefficient of permeability of sedimented CT-121 FGD gypsum is illustrated in Figure 2-7. At consolidation stresses less than 2.0 kg/cm^2 (196 kPa) and corresponding dry densities less than 80 lb/ft^3 (12.6 kN/m^3), the coefficient of permeability for intact sedimented gypsum ranges from $1.0x10^{-3}$ to $3.0x10^{-3}$ cm/sec. For consolidation stresses approaching 16.0 kg/cm^2 (1570 kPa) the dry density increases to 85 lb/ft^3 (13.3 kN/m^3) and the coefficient of permeability for sedimented gypsum decreases to $6.0x10^{-4}$ cm/sec. Pore fluid pH was found to have no measurable effect on the coefficient of permeability for CT-121 FGD gypsum.

The in situ coefficient of permeability for sedimented gypsum versus depth for a typical 100-foot (30.5 m) high gypsum stack was calculated from the sedimentation-consolidation and permeability data presented above. Since the coefficient of permeability varies with dry density, and since dry density is a function of the effective vertical consolidation stress, two possible cases for the effective vertical consolidation stress were considered. One case considers the water surface within the gypsum stack to be at the top of the stack with pore water pressures increasing linearly with depth. The second case considers the effective stresses occurring when the stack is drained, but 100 percent saturated. For these two conditions, which are believed to represent the range of stresses within a typical stack, the dry density increases from approximately 78 lb/ft^3 (12.2 kN/m^3) near the surface of the stack to 85 lb/ft^3 (13.3 kN/m^3) at a depth of 100 feet (30.5 m). The coefficient of permeability varies slightly from $1.5x10^{-3}$cm/sec to $6.0x10^{-4}$ cm/sec over the 100 foot (30.5 m) depth. For practical purposes, however, an average design coefficient of permeability and dry density for intact sedimented gypsum of $1.0x10^{-3}$ cm/sec and 80 lb/ft^3 (12.6 kN/m^3), respectively, are equally appropriate.

The coefficient of permeability of cast gypsum from triaxial test specimens are also shown in Figure 2-7. The cast gypsum samples generally have a lower void ratio than the sedimented gypsum samples, due to preparation technique, and corresponding lower coefficients of permeability. The dry density of cast gypsum from the laboratory tests varies in the range of 85 to 95 lb/ft^3 (13.3 to 14.9 kN/m^3) with coefficients of permeability in the range of $2.0x10^{-4}$ to $5.0x10^{-4}$ cm/sec.

Permeability tests on undisturbed samples of cast gypsum from the stack at Plant Scholz are shown in Figure 2-7. The dry densities of both samples were less than 75 lb/ft^3 (11.8 kN/m^3) with corresponding coefficients of permeability greater than 10^{-3} cm/sec. These lower dry densities and higher coefficients of permeability, in comparison to values measured on laboratory cast samples, result because the gypsum cast on the dike was relatively dry and loose. Measurements of dry density and moisture content versus depth in the cast gypsum dike are presented in Figure 2-8. As shown, the cast gypsum dry density did not exceed 80 lb/ft^3 (12.6 kN/m^3) except in the lower 4 to 5 feet (1.2 to 1.5 m) of the dike and did not exceed 85 lb/ft^3 (13.3 kN/m^3) except in the lower 2 feet (0.6 m) of the dike. For the cast gypsum dike at Plant Scholz, therefore, the coefficient of permeability of the dike and sedimented gypsum was similar. Depending on construction procedures used to cast gypsum and the condition of sedimented gypsum prior to casting, cast gypsum dikes in larger stacks may have slightly higher dry densities and slightly lower coefficients of permeability than sedimented gypsum.

Measurements of seepage through the gypsum stack into the surrounding perimeter ditch indicated an overall coefficient of permeability for the stack of $1x10^{-3}$



1.0 lb/ft^3 = 0.157 kN/m^3

1.0 foot = 0.3 m

Figure 2-8. In-Situ Dry Density And Moisture Content Determinations to $3x10^{-3}$ cm/sec. These values agree with laboratory measured coefficients of permeability on undisturbed samples of cast gypsum and with the estimated coefficient of permeability for sedimented gypsum within the stack of $2x10^{-3}$ cm/sec. The estimated coefficient of permeability of sedimented gypsum is based upon a stack height of 12 feet (3.7 m), average effective vertical consolidation stress of 0.04 kg/cm^2 (3.9 kPa), and an average dry density of 77 lb/ft^3 (12.1 kN/m^3).

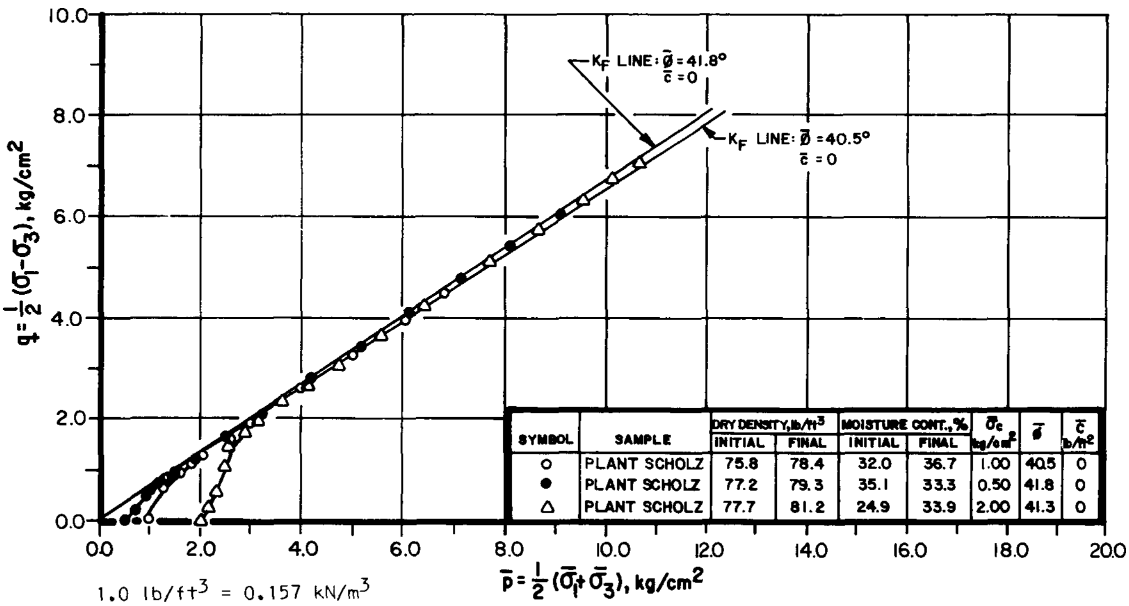
Shear Strength

The objectives of the laboratory investigation of the shear strength characteristics of CT-121 FGD gypsum were to determine:

- The relationship between dry density (or void ratio) and the effective friction angle.
- The relationship between stress, strain, and strength to allow a thorough geotechnical understanding and evaluation of the shear strength behavior or CT-121 FGD gypsum.
- The effect of the pore fluid pH of gypsum-saturated liquor on the shear strength.
- The nature and magnitude of cohesion, if any, developing from cementation.

Consolidated undrained triaxial compression tests with pore pressure measurements ($\overline{CIUC}$) were used to evaluate the shear strength characteristics of CT-121 FGD gypsum. Three types of samples were tested: (1) laboratory sedimented gypsum to simulate the sedimentation of gypsum within the gypsum stack, (2) laboratory cast gypsum to simulate the casting of gypsum by a dragline during construction of the stack perimeter dike, and (3) undisturbed samples of cast gypsum from the Plant Scholz gypsum stack perimeter dike. The effect of pore fluid on shear strength was also investigated with pH 3.0 and 6.5 gypsum-saturated water, corresponding to untreated and neutralized gypsum slurry, respectively.

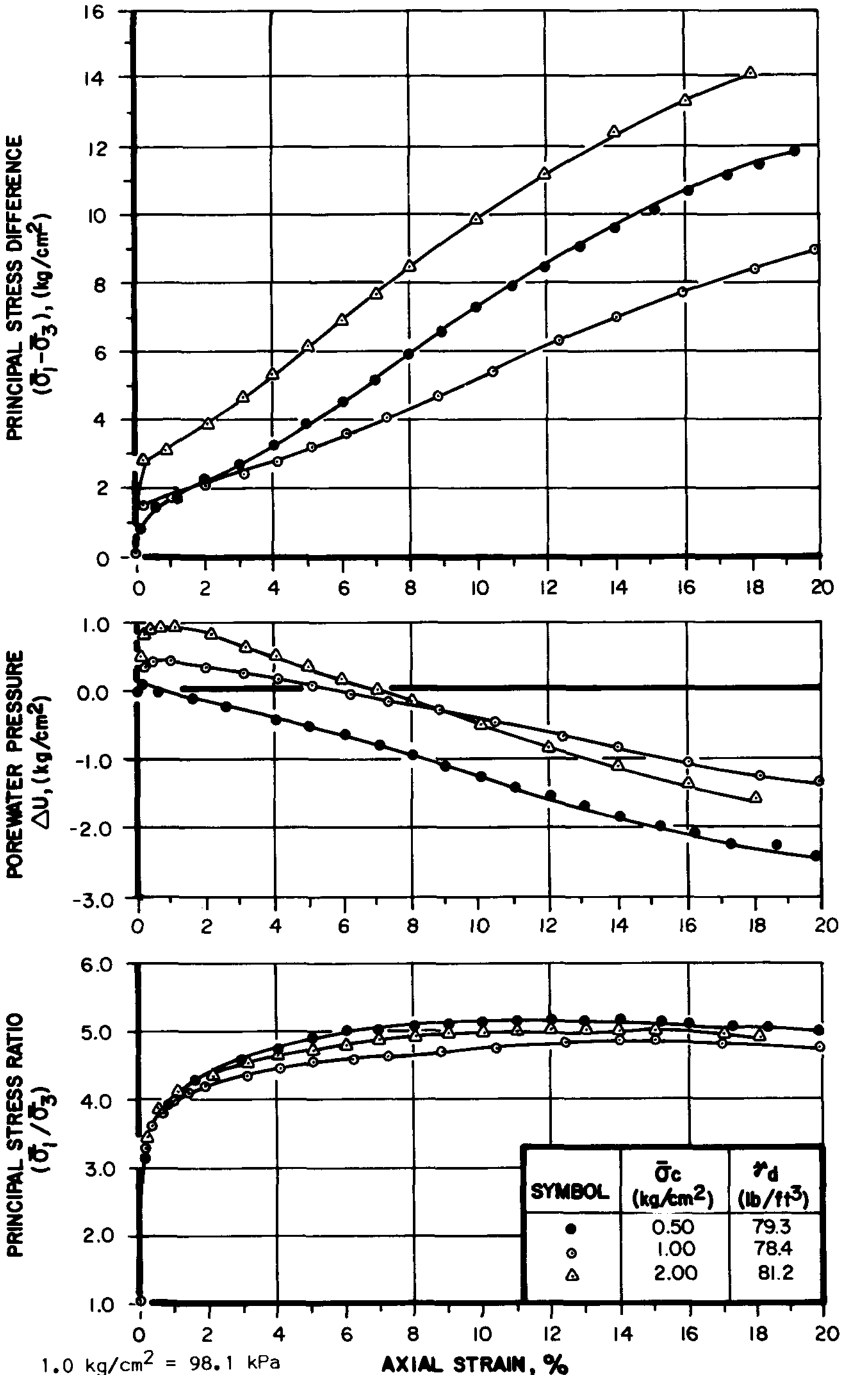
Typical Mohr-Coulomb effective stress paths and undrained stress-strain behavior for sedimented laboratory samples of Plant Scholz CT-121 FGD gypsum are shown in Figures 2-9 and 2-10. Dry densities of the three test samples ranged from 78.4 to 81.2 lb/ft^3 (12.3 to 12.7 kN/m^3) and indicated effective friction angles of 40.5° to 41.8° with zero cohesion. This range in dry density corresponds to dry densities obtained for sedimented gypsum with effective vertical consolidation stresses in the range of 0.50 to 5.0 kg/cm^2 (see Figure 2-5).



SYMBOL	SAMPLE	DRY DENSITY, lb/ft³		MOISTURE CONT., %		$\bar{\sigma}_c$ kg/cm²	$\bar{\phi}$	$\bar{c}$ lb/ft²
		INITIAL	FINAL	INITIAL	FINAL			
○	PLANT SCHOLZ	75.8	78.4	32.0	36.7	1.00	40.5	0
●	PLANT SCHOLZ	77.2	79.3	35.1	33.3	0.50	41.8	0
△	PLANT SCHOLZ	77.7	81.2	24.9	33.9	2.00	41.3	0

1.0 lb/ft^3 = 0.157 kN/m^3
1.0 kg/cm^2 = 98.1 kPa
1.0 lb/ft^2 = 47.9 Pa

Figure 2-9. Mohr-Coulomb Effective Stress Paths For Sedimented Gypsum Samples



1.0 kg/cm^2 = 98.1 kPa
1.0 lb/ft^3 = 0.157 kN/m^3

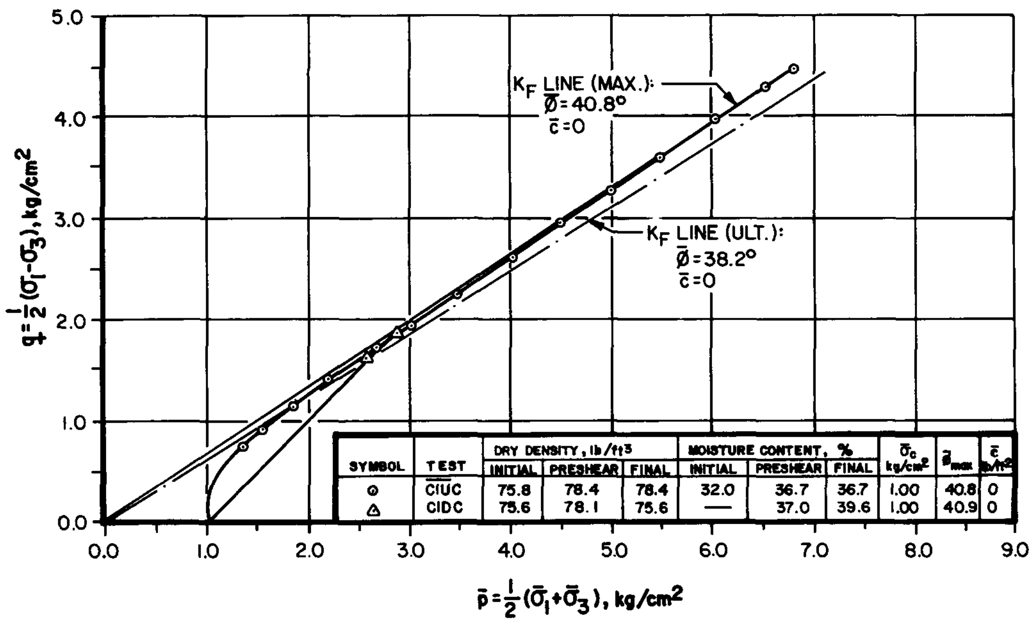
Figure 2-10. Typical Undrained Stress-Strain Behavior For Sedimented Samples

For all three tests,the full effective friction angle is mobilized early in the loading as indicated by the effective stress paths reaching the failure line (K_F line) early in the test. The shear resistance continues to increase, however, because the pore pressures become negative and lead to increased effective stresses. The negative pore pressures develop because,although the sample is compressing during shear, there is a tendency for the sample to attempt to increase in volume to overcome particle interlocking.

Figure 2-11 and 2-12 compare the Mohr-Coulomb effective stress paths and stress-strain behavior for drained (CIDC) and undrained ($\overline{\text{CIUC}}$) triaxial tests on sedimented laboratory samples of Plant Scholz CT-121 FGD gypsum. The principal stress difference ($\bar{\sigma}_1-\bar{\sigma}_3$) for the undrained test continues to increase after 20 percent strain, whereas the drained test reaches a maximum principal stress difference at 10 percent strain and then decreases slightly. The shear resistance in undrained shear continues to increase, as shown by the effective stress path increasing along the $K_F$line, because the pore pressures become negative and lead to increased effective confining stresses. In the drained triaxial test,this behavior is indicated by an increase in volume during shear as the sample increases in volume to overcome particle interlocking.

A comparison of the principal stress difference, volume change, and pore pressure versus axial strain for the drained and undrained tests shows that at 6 percent strain the two tests yield essentially the same shear resistance and an effective friction angle of 40.8°. After 6 percent strain the undrained test begins to develop negative pore pressures which allows the effective stress path to increase along the K_F line. The effective stress path for the drained test, however, remains at the K_F line or decreases slightly to the ultimate shear resistance and effective friction angle of 38.2°.

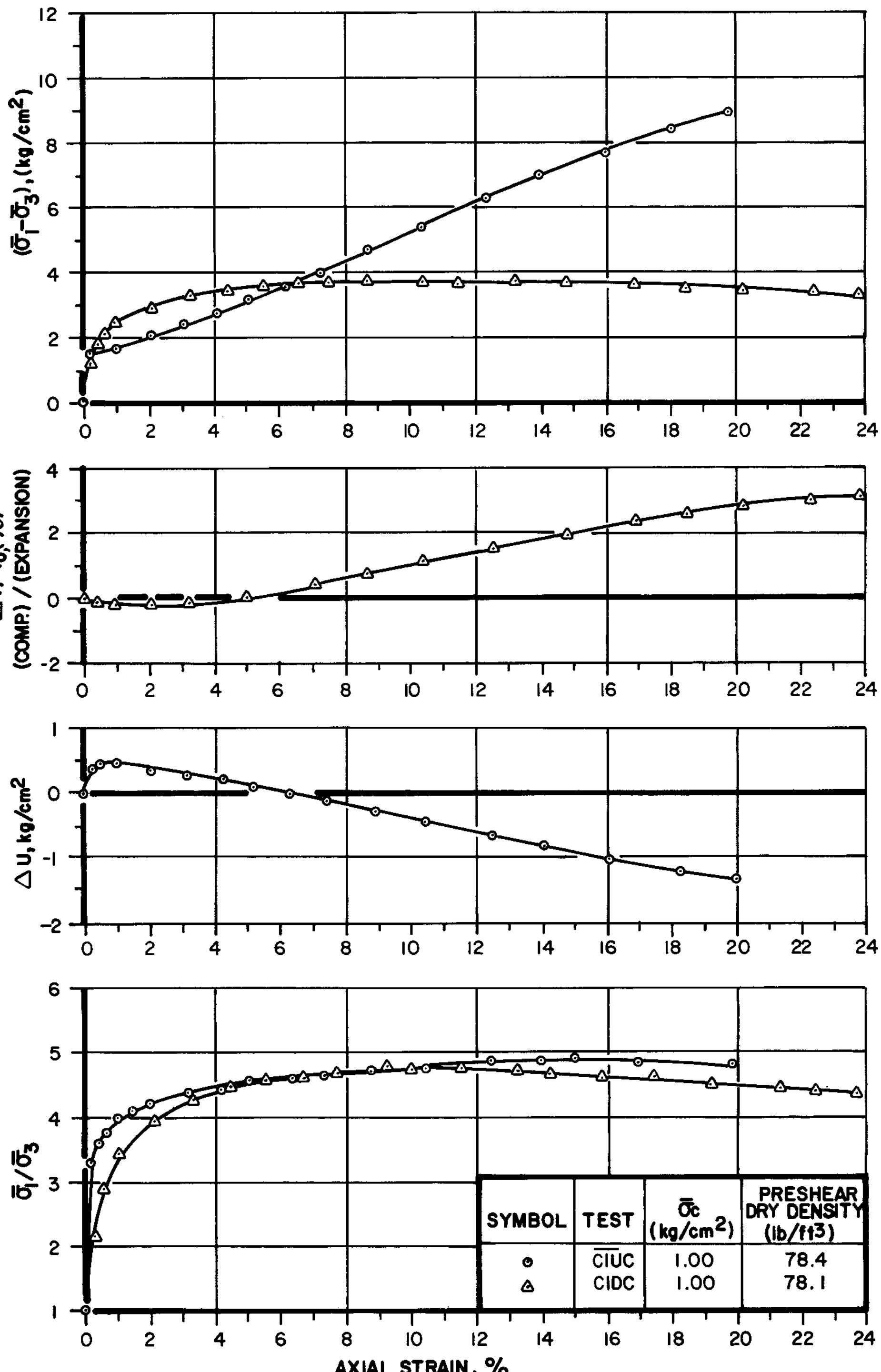
Typical Mohr-Coulomb effective stress paths and undrained stress-strain behavior for laboratory simulated and undisturbed cast gypsum samples of pilot plant and Plant Scholz CT-121 FGD gypsum are shown in Figures 2-13 and 2-14. Over a range of dry densities from 87 to 105 lb/ft^3 (13.7 to 16.5 kN/m^3),the effective friction angle for cast gypsum typically varied from 41.5° to 47.0° with zero cohesion. The stress-strain behavior of the cast samples is similar to the laboratory sedimented samples indicating mobilization of the full effective friction angle early in the test and development of negative or small positive pore pressures during shear.



SYMBOL	TEST	DRY DENSITY, lb/ft³			MOISTURE CONTENT, %			$\bar{\sigma}_c$ kg/cm²	$\bar{\phi}_{max}$	$\bar{c}$ lb/ft²
		INITIAL	PRESHEAR	FINAL	INITIAL	PRESHEAR	FINAL			
⊙	CIUC	75.8	78.4	78.4	32.0	36.7	36.7	1.00	40.8	0
△	CIDC	75.6	78.1	75.6	—	37.0	39.6	1.00	40.9	0

1.0 lb/ft^3 = 0.157 kN/m^3
1.0 kg/cm^2 = 98.1 kPa
1.0 lb/ft^2 = 47.9 Pa

Figure 2-11. Comparison of Drained And Undrained Mohr-Coulomb Effective Stress Paths For Sedimented Gypsum

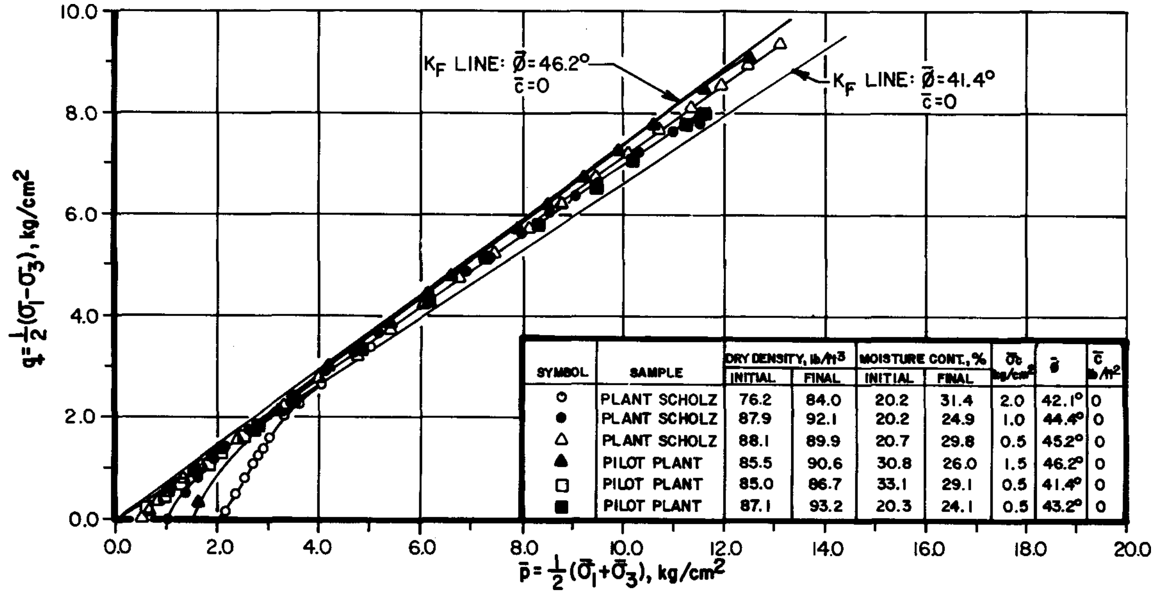


SYMBOL	TEST	$\bar{\sigma}_c$ (kg/cm²)	PRESHEAR DRY DENSITY (lb/ft³)
⊙	$\overline{\text{CIU}}$C	1.00	78.4
△	CIDC	1.00	78.1

1.0 kg/cm² = 98.1 kPa

1.0 lb/ft³ = 0.157 kN/m³

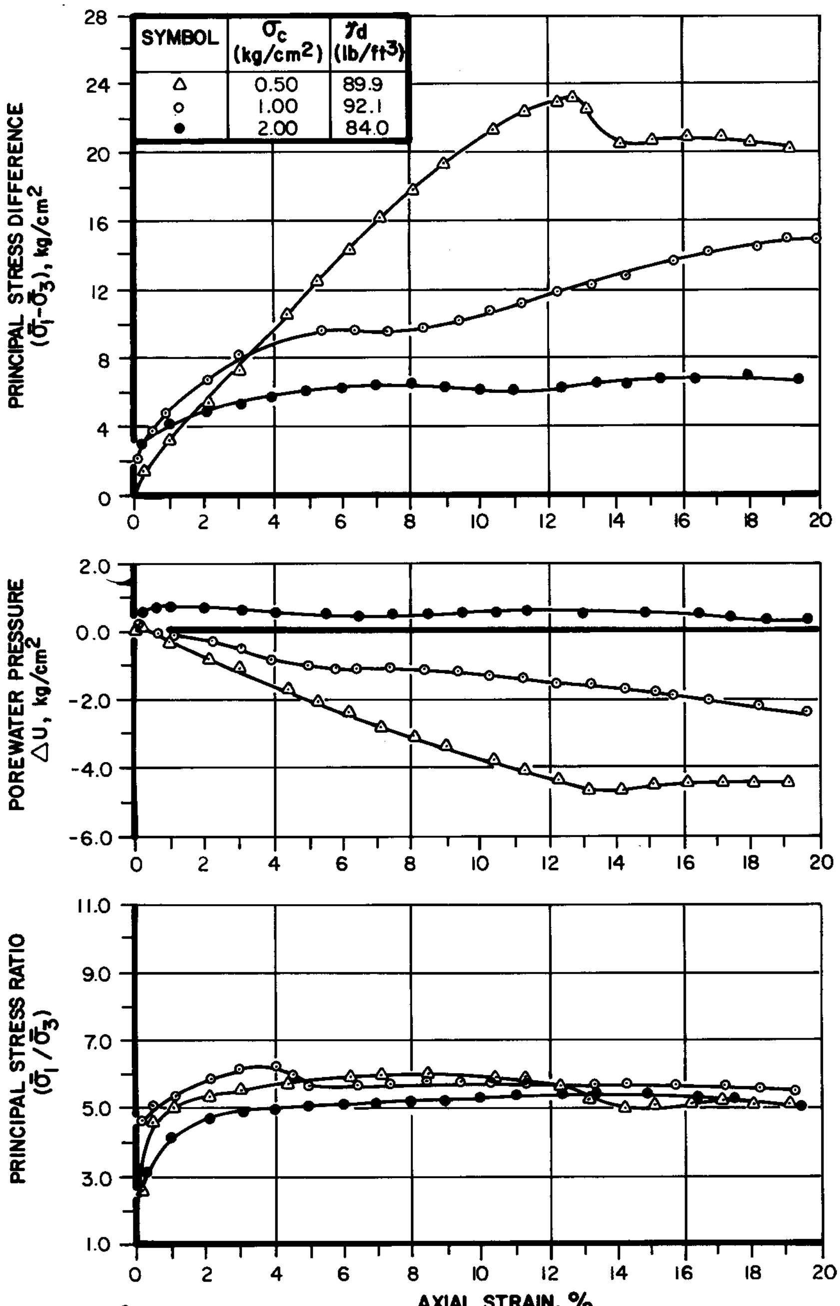
Figure 2-12. Comparison of Drained And Undrained Stress-Strain Behavior For Sedimented Gypsum



SYMBOL	SAMPLE	DRY DENSITY, lb/ft³		MOISTURE CONT., %		$\bar{\sigma}_c$ kg/cm²	$\bar{\phi}$	$\bar{c}$ lb/ft²
		INITIAL	FINAL	INITIAL	FINAL			
○	PLANT SCHOLZ	76.2	84.0	20.2	31.4	2.0	42.1°	0
●	PLANT SCHOLZ	87.9	92.1	20.2	24.9	1.0	44.4°	0
△	PLANT SCHOLZ	88.1	89.9	20.7	29.8	0.5	45.2°	0
▲	PILOT PLANT	85.5	90.6	30.8	26.0	1.5	46.2°	0
□	PILOT PLANT	85.0	86.7	33.1	29.1	0.5	41.4°	0
■	PILOT PLANT	87.1	93.2	20.3	24.1	0.5	43.2°	0

1.0 kg/cm^2 = 98.1 kPa
1.0 lb/ft^3 = 0.157 kN/m^3
1.0 lb/ft^2 = 47.9 Pa

Figure 2-13. Mohr-Coulomb Effective Stress Paths For Cast Gypsum Samples



1.0 kg/cm^2 = 98.1 kPa
1.0 lb/ft^3 = 0.157 kN/m^3

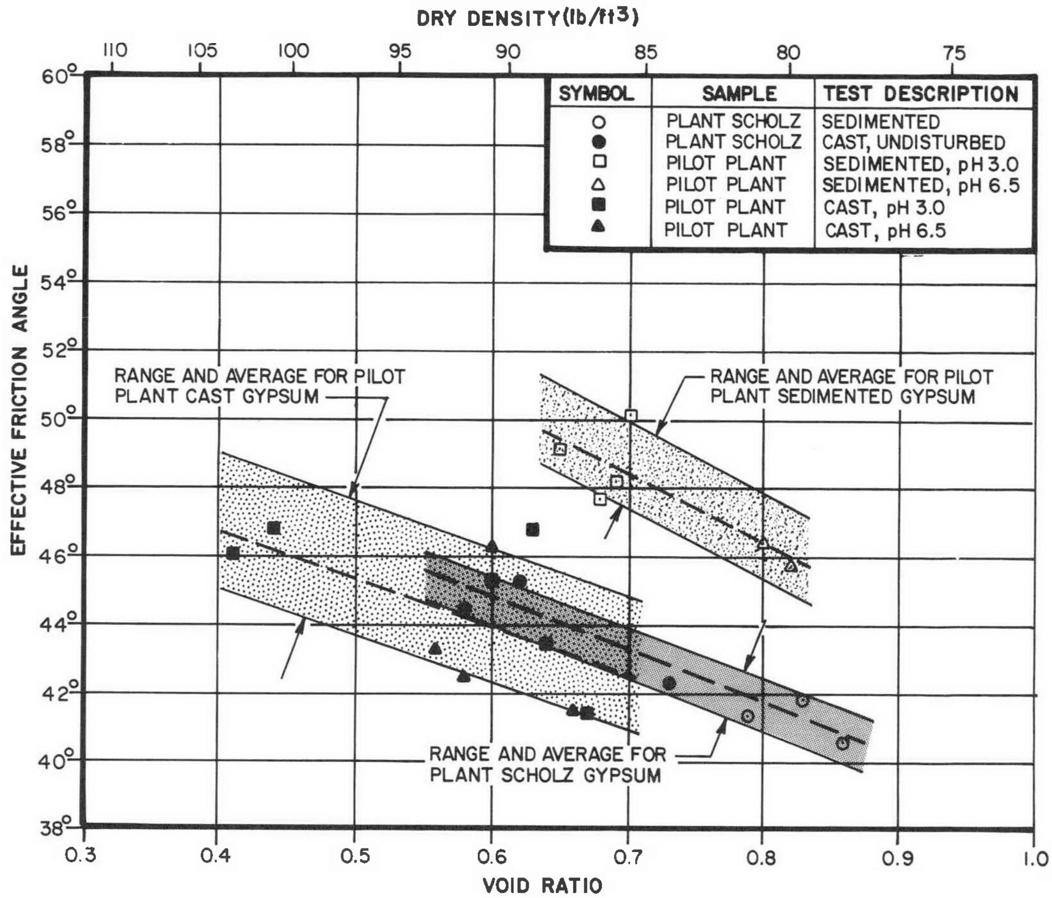
Figure 2-14. Typical Undrained Stress-Strain Behavior For Cast Gypsum Samples

Figure 2-15 summarizes the effective friction angle versus void ratio and dry density for all test samples. Plant Scholz CT-121 FGD gypsum samples consist of laboratory sedimented samples and undisturbed cast samples from the stack perimeter dike. Pilot plant CT-121 FGD gypsum samples consist of laboratory sedimented and cast samples with pore fluid pH of 3.0 or 6.5. Three trends are noticable in these data. The range and trend for both cast and sedimented Plant Scholz CT-121 FGD gypsum agree with the range and trend for the pilot plant laboratory cast samples. These two sets of data indicate a friction angle increasing from 40.5° at a dry density of 78 lb/ft^3 (12.1 kN/m^3) to 46.5° at a dry density of 103 lb/ft^3 (16.2 kN/m^3). The range in dry density from 78 to 103 lb/ft^3 (12.2 to 16.2 kN/m^3) covers most densities likely to occur in a gypsum stack except for loose, initially sedimented gypsum at very low consolidation stresses.

The range and average curves of dry density versus effective friction angle for laboratory sedimented pilot plant gypsum is 4° to 5° above the trend for the cast pilot plant gypsum samples. One possible explanation for this difference may be the particle shape of the gypsums. The larger the length to width ratio of the crystals, the greater the particle interlocking, and the greater the friction angle. During preparation of the laboratory cast samples,the friable gypsum particles may have broken into smaller lengths which could possibly result in the lower measured friction angles. Alternatively, the non-homogeneous nature of the laboratory cast samples may also produce the lower friction angles. The dry density for the laboratory cast samples is an average of the denser portions of the sample and loose zones with voids which occur due to preparation procedure. The loose zones and voids produce planes of weakness within the sample, which during shear could cause lower measured friction angles. For design purposes, however, the combined trend for Plant Scholz cast and sedimented gypsum and pilot plant cast gypsum is believed representative of reasonable strength parameters for CT-121 FGD gypsum.

Pore fluid pH was found to have no measurable effect on the shear strength of cast or sedimented gypsum. At similar void ratios, samples of CT-121 FGD gypsum with pH 3.0 and pH 6.5 pore fluid displayed essentially identical stress-strain-strength behavior.

An important strength characteristic of typical phosphate gypsums relevant to stacking is the development of true cohesion from cementation. The cementation is believed to develop because of the solubility of gypsum in acid or rain water



$1.0\ lb/ft^3 = 0.157\ kN/m^3$

Figure 2-15. Void Ratio Versus Effective Friction Angle allowing dissolution and subsequent recrystallization as a result of seepage and evapotranspiration. Chemical constituents of the process acid waters are also believed to be a significant factor affecting cementation. These field conditions causing cementation, however, could not be simulated in the laboratory. Laboratory cast samples of pilot plant gypsum were allowed to dry under varying conditions in an attempt to simulate the drying which occurs in the perimeter dike. No true cohesion from cementation, however, was observed for any of these specimens upon resaturation and subsequent shearing in undrained triaxial compression tests.

Phosphate gypsums which develop cementation in the field often exhibit a true cohesion upon drying at elevated temperatures. Several samples of CT-121 FGD gypsum were statically compacted to dry densities of 74 to 80 lb/ft^3 (11.6 to 12.6 kN/m^3) and dried at 50°C for 48 hours. After drying, the samples were partially immersed in gypsum saturated water to check for cementation. All of the samples disintegrated and sloughed almost immediately after immersion indicating no true cohesion from cementation. Based upon laboratory triaxial strength tests, visual observation of laboratory test samples, and short-term observations of the gypsum stack at Plant Scholz, no true cohesion from cementation has been found to develop for CT-121 FGD gypsum.

In summary, the following conclusions can be advanced concerning the shear strength of CT-121 FGD gypsum relevant to stacking:

- The shear strength characteristics of CT-121 FGD gypsum are acceptable for stacking methods of waste disposal. The effective friction angle was generally found to increase from 40.5° at a dry density of 78 lb/ft^3 (12.2 kN/m^3) to 46.5° at a dry density of 103 lb/ft^3 (16.2 kN/m^3).
- The pH of the gypsum-saturated liquor has little effect on the shear strength of CT-121 FGD gypsum.
- No cohesion from cementation has been found to develop for CT-121 FGD gypsum for the laboratory and field conditions investigated during this study.

COMPARISON OF CT-121 FGD AND PHOSPHATE GYPSUMS

Mineralogical Analysis

The crystal habit and morphology of pilot plant CT-121 FGD gypsum is compared with three phosphate gypsums in Figures 2-16 and 2-17. Differences in crystal

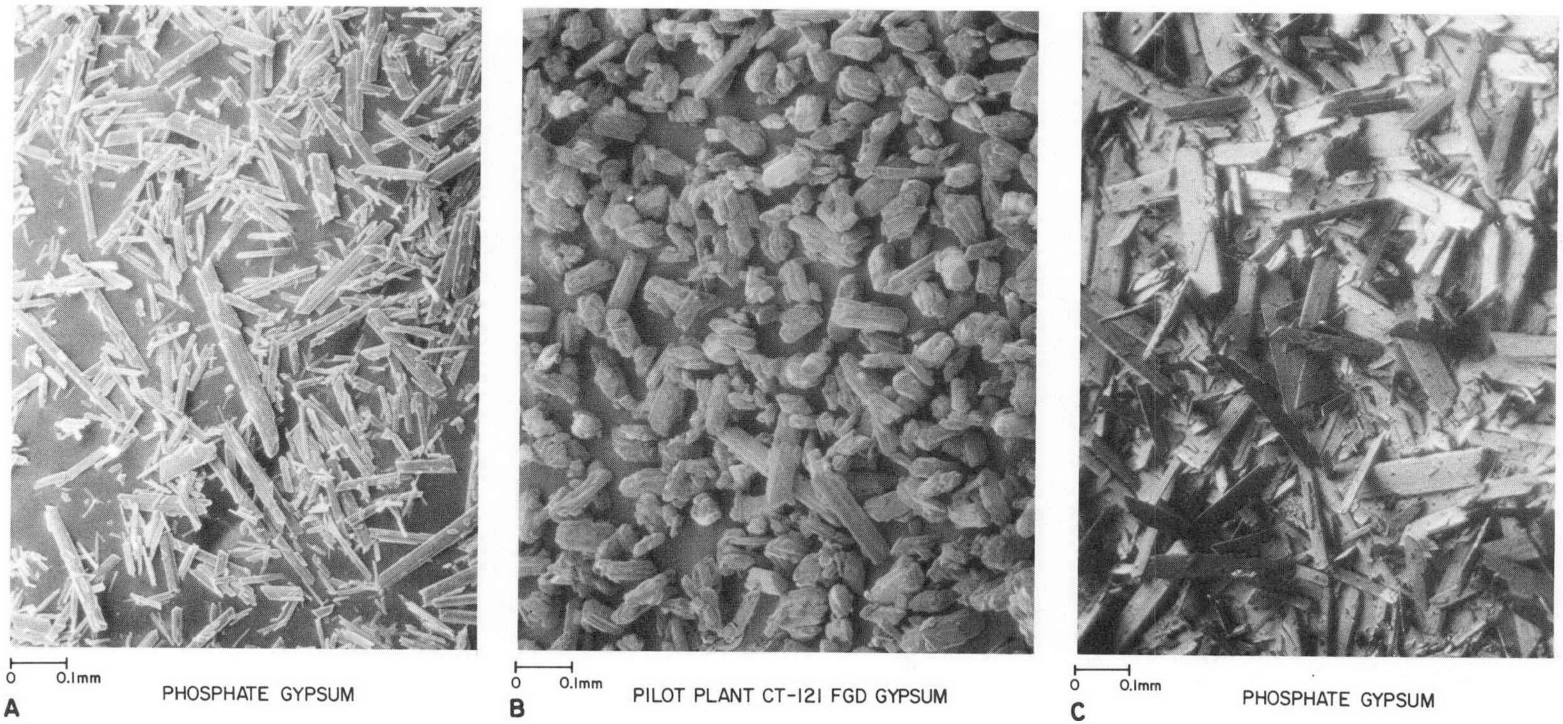
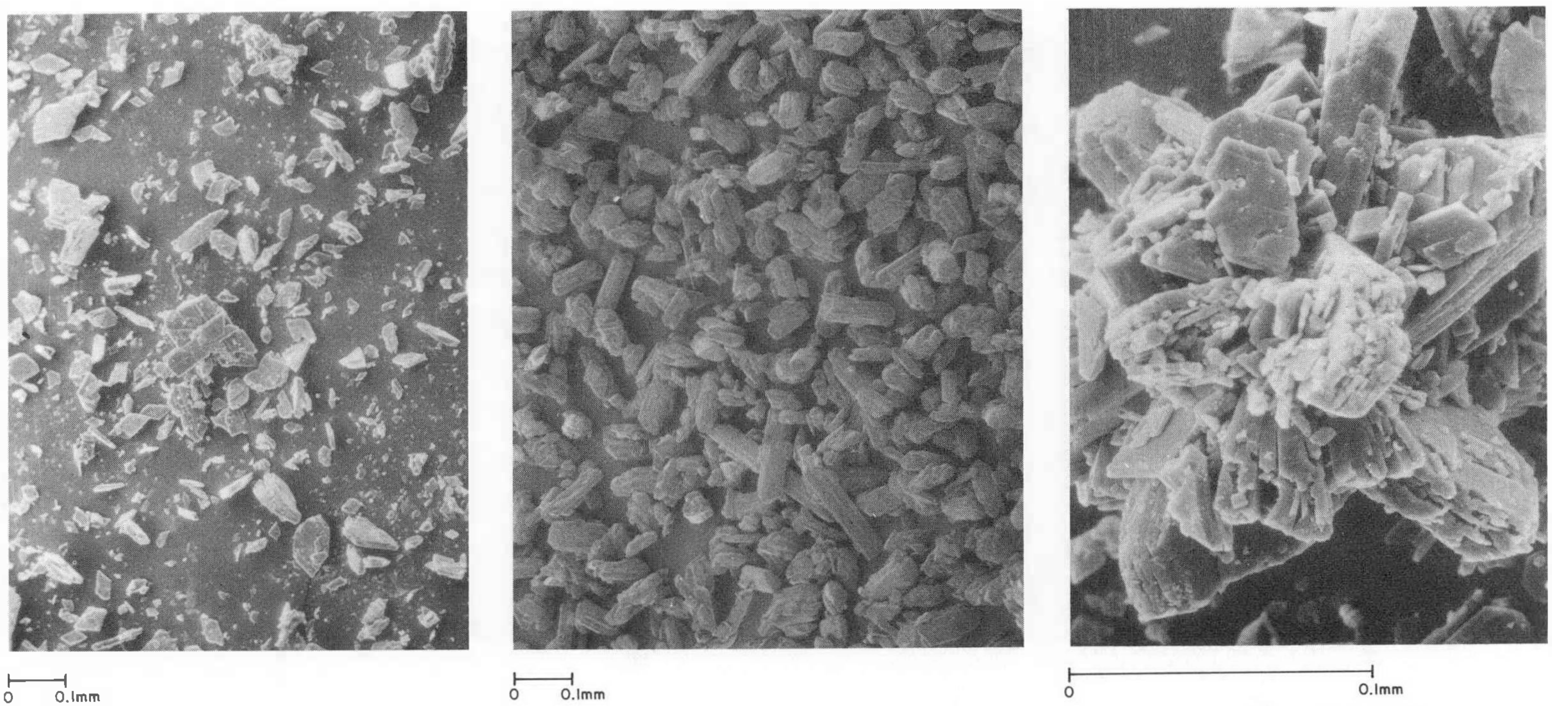


Figure 2-16. Scanning Electron Photomicrographs of Three Gypsums



A PHOSPHATE GYPSUM

B PILOT PLANT CT-121 FGD GYPSUM

C PHOSPHATE GYPSUM

Figure 2-17. Scanning Electron Photomicrographs of Two Gypsums size are apparent as illustrated by comparison of the three photomicrographs in Figure 2-16. Rosette formation, typically observed in many phosphate gypsums as shown in Figure 2-17C, was not observed in CT-121 FGD gypsum.

Grain Size Distribution

The grain size distribution for CT-121 FGD gypsum and the three phosphate gypsums shown in Figures 2-16 and 2-17 are compared in Figure 2-18. CT-121 FGD gypsum is predominately a poorly-graded, coarse silt size material with 100 percent passing the U.S. No. 200 sieve. Phosphate gypsums, however, tend to be slightly more well-graded with a wider range of coarse to fine silt size particles. Depending on the settling techniques used within phosphate gypsum stacks, the percent passing the U.S. No. 200 sieve can vary from 50 to 95 percent.

Specific Gravity

The specific gravity of CT-121 FGD gypsum was determined to vary from 2.27 to 2.44 with an average of 2.34. Specific gravities of phosphate gypsums typically vary over a similar range of 2.27 to 2.42. Since gypsum is typically the predominate or only crystalline phase present in both phosphate or CT-121 FGD gypsums, the measured specific gravity should be close to the known specific gravity of gypsum of 2.33.

Sedimentation and Consolidation

The sedimentation-consolidation behavior of CT-121 FGD gypsum and three phosphate gypsums are compared in Figure 2-19. As shown, CT-121 FGD gypsum sediments to a denser initial dry density at low consolidation stresses than typical phosphate gypsums. Following initial sedimentation, the compressibility of CT-121 FGD gypsum is considerably less than that of typical phosphate gypsums. The higher initial dry density and lower compressibility of CT-121 FGD gypsum are both favorable characteristics for waste disposal by stacking since the greater the sedimented dry density the larger the quantity of gypsum that can be stored in a given volume. Differences in the initial sedimented dry density and compressibility of the various gypsums are probably attributable to crystal geometry. Long needle-like crystals apparently yield the lowest initial dry density and highest compressibility, while relatively equidimensional crystals yield the highest initial dry density and lowest compressibility.

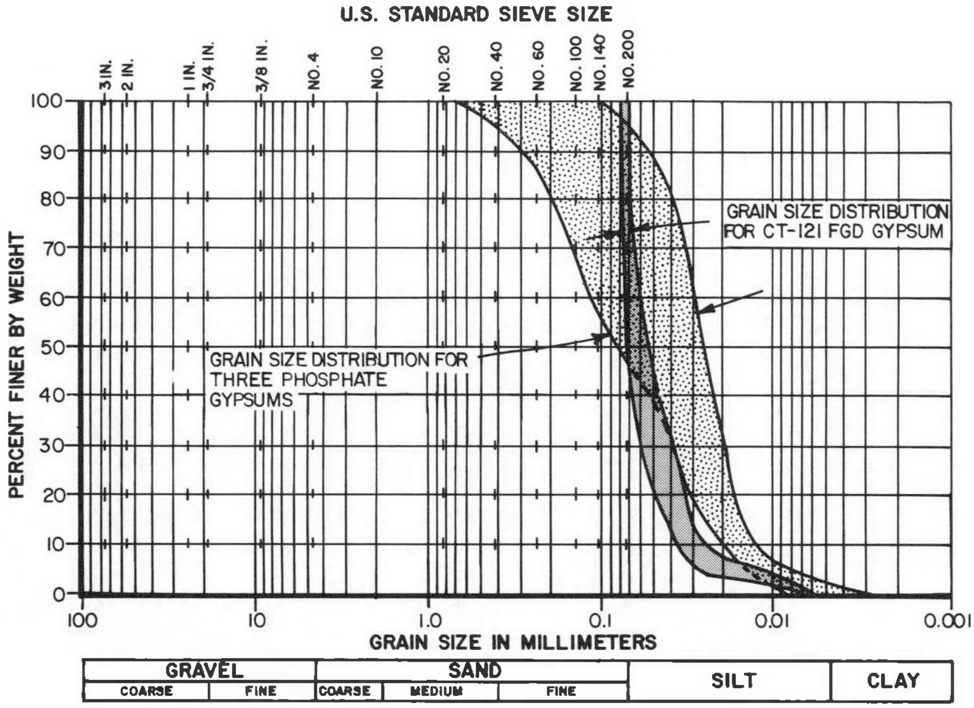
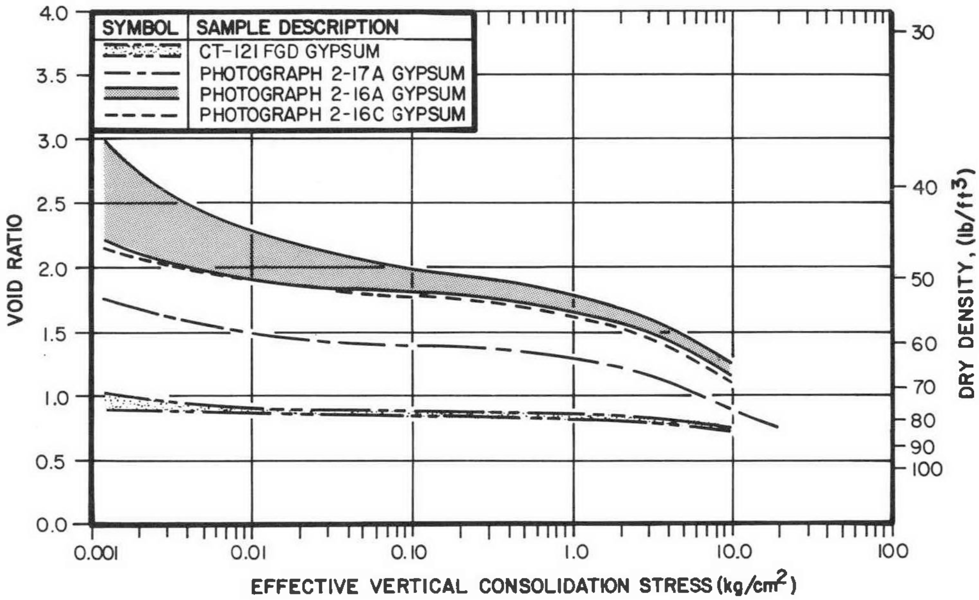
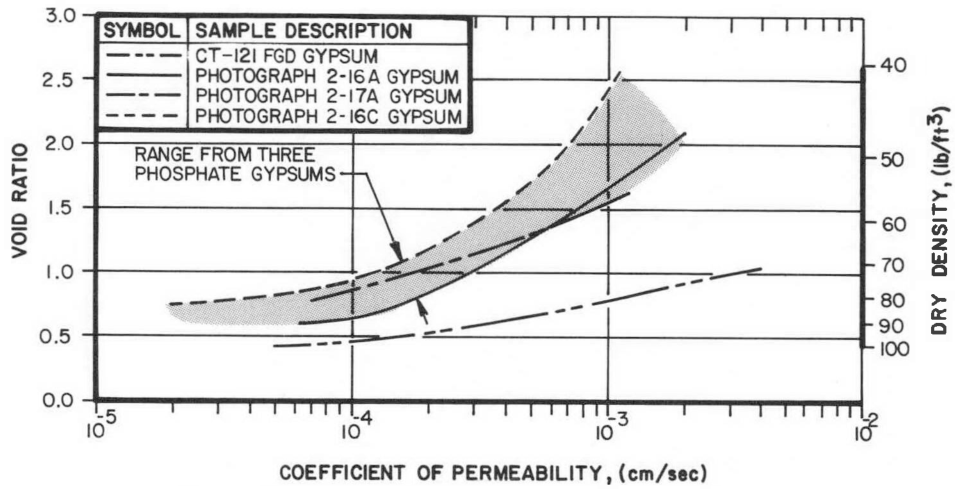


Figure 2-18. Comparison of Grain Size Distributions From Four Gypsums



1.0 lb/ft^3 = 0.157 kN/m^3
1.0 kg/cm^2 = 98.1 kPa

Figure 2-19. Comparison of Sedimentation-Consolidation Behavior From Four Gypsums



1.0 lb/ft^3 = 0.157 kN/m^3

Figure 2-20. Void Ratio Versus Coefficient of Permeability From Four Gypsums

Permeability

Figure 2-20 compares the permeability characteristics of CT-121 FGD gypsum with three phosphate gypsums. Due to variations in grain size distributions and crystal geometries the coefficient of permeability for gypsum has been found to vary by over one order of magnitude at equal void ratios or dry densities. As shown by Figure 2-20, CT-121 FGD gypsum is relatively pervious in comparison to typical phosphate gypsums. The higher permeability of CT-121 FGD gypsum is a favorable characteristic for raising the perimeter containment dikes by casting since the gypsum drains very rapidly and is easily handled as a construction material. The disadvantage of the relatively high permeability of CT-121 FGD gypsum is the increased quantity of seepage through the gypsum stack. Overall, however, the higher permeability of CT-121 FGD gypsum in comparison to typical phosphate gypsums does not adversely effect stacking performance.

Shear Strength

Typical phosphate gypsums usually have effective friction angles measured on laboratory samples in undrained triaxial compression tests ranging from 45° to 50° with zero effective cohesion. Values ranging from as low as 31° to as high as 57° have been measured, however, depending on sample preparation technique and interpretation of test results. Although field experience indicates some cohesion typically develops from cementation, no consistent measurements of cohesion have been made on laboratory prepared gypsum samples. The relationship between dry density and effective friction angle shown in Figure 2-15 for CT-121 FGD gypsum is similar to the strength behavior measured for some phosphate gypsums, and generally lies between the lower bound and average for the range of strengths measured on phosphate gypsum. The undrained stress-strain-strength behavior measured on CT-121 FGD gypsum, particularly the development of negative pore pressures during shear, is also similar to many phosphate gypsums.

Field experience indicates phosphate gypsums typically develop some cohesion from cementation. Chemical constituents of the process acid waters are believed to be a significant factor affecting the cementation process. No true cohesion from cementation, however, has been found to develop for CT-121 FGD gypsum as produced at Plant Scholz.

EFFECT OF FLY ASH ADDITION ON CT-121 FGD WASTE GYPSUM CHARACTERISTICS

During one phase of the Chiyoda test program at Plant Scholz, fly ash was collected at the same time as CT-121 FGD gypsum. This occurred during particulate tests which allowed venturi liquor containing the fly ash to enter the Jet-Bubbling Reactor (JBR). The resulting slurry was piped to the stacking area as normally accomplished with gypsum alone. Since the potential exists for FGD systems to simultaneously require the disposal of fly ash and gypsum, the effect of fly ash addition on the stacking behavior of CT-121 FGD gypsum is of interest. Although geotechnical testing of fly ash was not included as part of the original RP536-3 research program, some laboratory testing was performed to attempt to quantify the effect of fly ash addition on the engineering behavior of CT-121 FGD gypsum.

Samples of the fly ash-gypsum mixture which sedimented within the gypsum stack during the particulate tests, and were subsequently used for laboratory testing, were collected from the stack on June 6, 1979.

Mineralogical Analysis

Chemical analysis of a typical sedimented fly ash-gypsum mixture taken from the stack and used in the laboratory testing indicated the following composition (percent of dry weight):

Silica, SiO_2	66.8%
Calcium, CaO	1.0%
Aluminum, Al_2O_3	6.3%
Iron, Fe_2O_3	5.7%
Magnesium, MgO	0.1%

These five chemical constituents, which comprise the significant portion of typical bituminous fly ashes, account for 80 percent of the composition of the mixture. The remaining 20 percent of the sample may consist of other chemical constituents such as potassium, sodium, carbon, and sulfate. Gypsum is also probably contained within the sample.

Scanning electron photomicrographs of the fly ash-gypsum mixture taken from the gypsum stack are shown in Figures 2-21 through 2-23. Three distinct morphologies are apparent in these photographs as clearly illustrated in Figure 2-21: (1) gypsum crystals, (2) spherical particles with smooth surfaces, and (3) porous particles of irregular shape with rough surface texture.

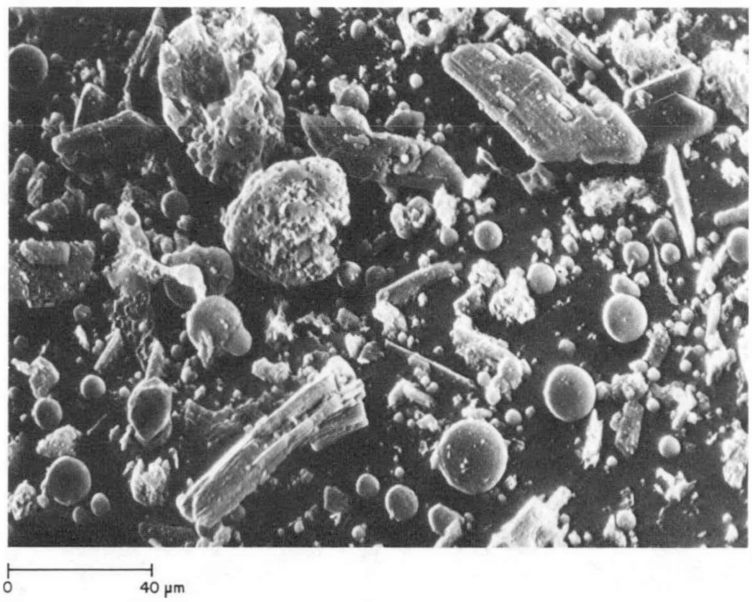


Figure 2-21. Scanning Electron Photomicrograph of Plant Scholz Fly Ash-Gypsum Mixture

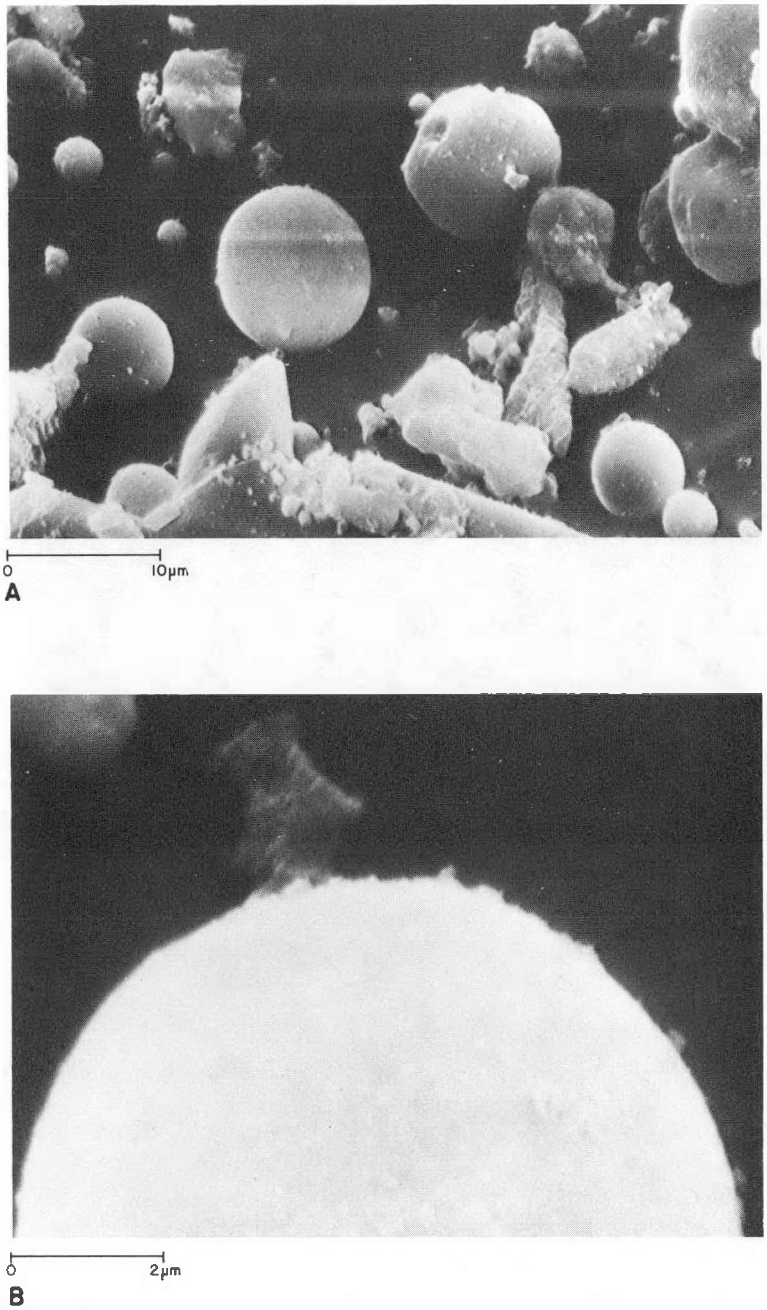


Figure 2-22. Scanning Electron Photomicrographs of Spherical Particles in Plant Scholz Fly Ash-Gypsum Mixture

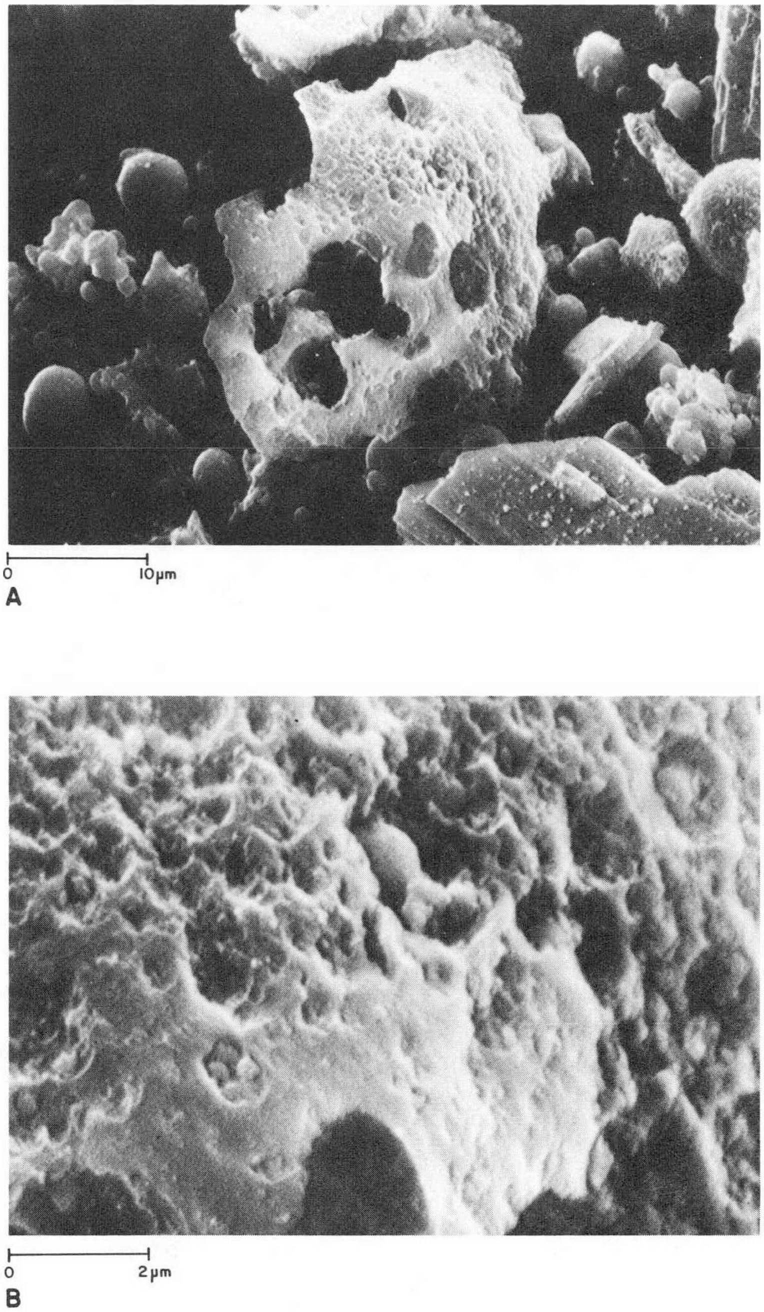


Figure 2-23. Scanning Electron Photomicrographs of Porous Particles in Plant Scholz Fly Ash-Gypsum Mixture

The spherical particles range in diameter from 0.001 to 0.02 mm. The well sintered nature of the spherical particles is illustrated by the smooth surface texture shown in Figure 2-22B. The composition of the spherical particles determined from energy dispersive X-ray emission spectroscopy (EDAX) indicated an aluminum silicate compound containing some potassium and iron. X-ray diffraction data suggests this compound is probably sillimanite (Al_2OSiO_5).

The irregular shaped porous particles range in overall diameter from 0.0025 to 0.06 mm. These poorly sintered particles, shown in Figure 2-23, had basically the same inorganic composition as the spherical particles but the proportion of each element was significantly less, probably from dilution due to the presence of unburned carbon. Carbon, however, cannot be detected with the EDAX method used to determine composition so this hypothesis cannot be confirmed.

X-ray diffraction of a sample of the fly ash-gypsum mixture used in the laboratory testing indicated a gypsum content of 20 to 25 percent. EDAX data indicated a similar gypsum content of about 25 percent. Based upon chemical analysis, X-ray diffraction and EDAX data, the fly ash-gypsum mixture obtained from the stack is largely composed of fly ash with about 20 to 25 percent gypsum.

Grain Size Distribution

Results from three sieve and hydrometer analyses on the fly ash-gypsum mixture are presented in Figure 2-24. As shown, the mixture is poorly-graded and largely composed of silt sized particles with a fines content of 100 percent. The particle diameter largely ranges from 0.01 mm to 0.07 mm with an average (50 percent finer by weight) of 0.013 to 0.026 mm. This average particle size is 2 to 5 times smaller than the average particle size of CT-121 FGD gypsum. Typical grain size distributions reported for two bituminous fly ashes are also shown in Figure 2-24. These gradations indicate bituminous fly ashes are typically slightly sandy to sandy silts with a fines content of 60 to 90 percent. The gradation of the mixture sampled at the gypsum stack, therefore, is slightly finer than reported for typical bituminous fly ashes (1, 2).

Specific Gravity

The specific gravity of the fly ash-gypsum mixture was in the range of 2.45 to 2.47. These values are near the upper bound of specific gravities reported for bituminous fly ashes which typically vary from 1.9 to 2.4 (2).

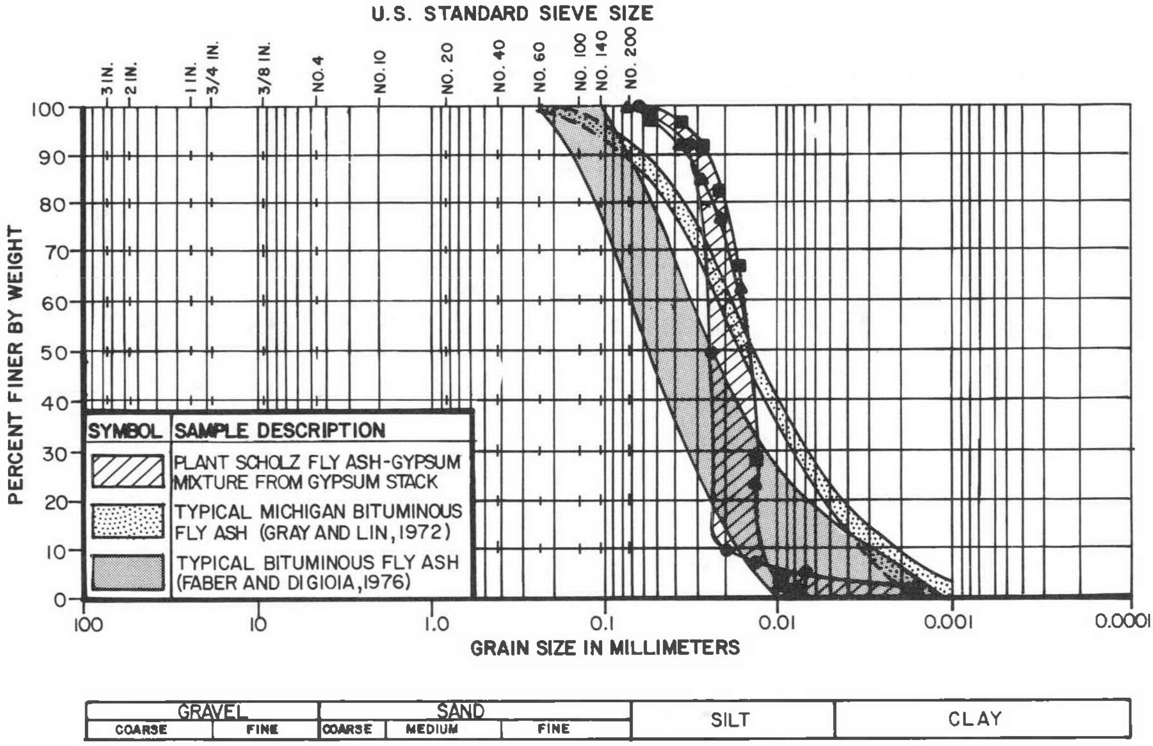
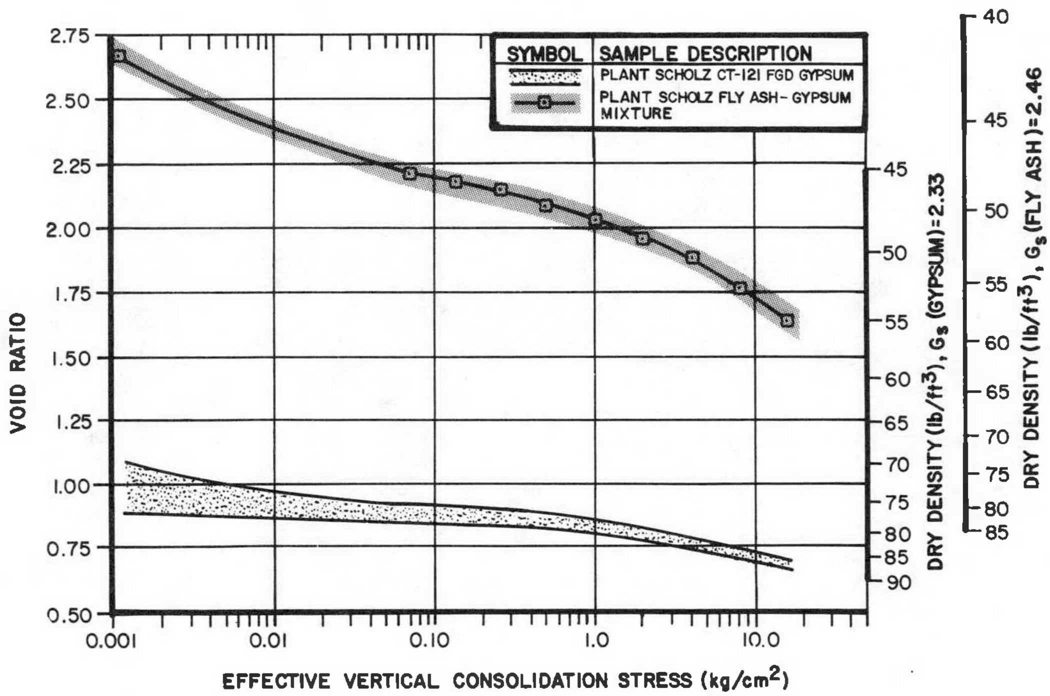


Figure 2-24. Grain Size Distribution of Plant Scholz Fly Ash -Gypsum Mixture



1.0 lb/ft^3 = 0.157 kN/m^3
1.0 kg/cm^2 = 98.1 kPa

Figure 2-25. Comparison of Fly Ash-Gypsum Mixture And Gypsum Sedimentation-Consolidation Behavior

Sedimentation and Consolidation

The sedimentation-consolidation behavior of the fly ash-gypsum mixture and CT-121 FGD gypsum is compared in Figure 2-25. As shown, the fly ash-gypsum mixture sediments to a much higher initial void ratio than CT-121 FGD gypsum. At low effective consolidation stresses, the mixture sediments to a void ratio of 2.65 and corresponding dry density, water content, and percent solids of 42.1 lb/ft^3 (6.6 kN/m^3), 92.8 percent, and 52 percent, respectively. CT-121 FGD gypsum, however, sediments to a lower void ratio of 0.95 and corresponding dry density, water content, and percent solids of 74.6 lb/ft^3 (11.7 kN/m^3), 40.8 percent, and 71 percent, respectively. The much lower inital dry density and higher water content of the sedimented mixture in comparison to CT-121 FGD gypsum is definitely a negative characteristic for stacking methods of waste disposal.

Permeability

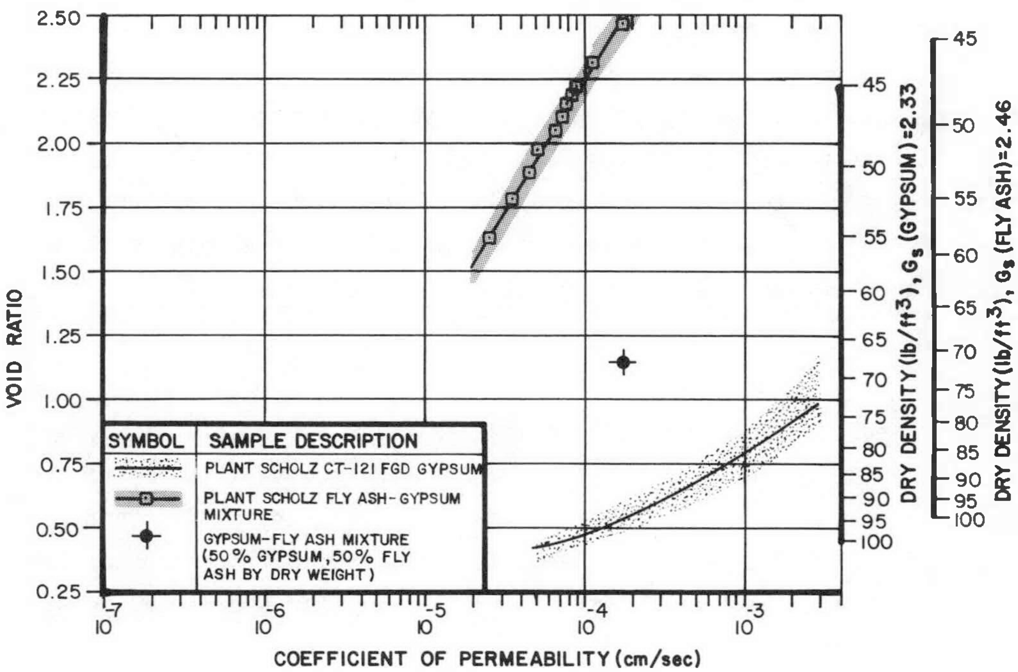
Figure 2-26 compares the permeability characteristics of the fly ash-gypsum mixture and CT-121 FGD gypsum. At equal consolidation stresses, the coefficient of permeability of the mixture is 10 to 20 times less than the coefficient of permeability of CT-121 FGD gypsum. For example, at consolidation stresses less than 2.0 kg/cm^2 (196 kPa), the coefficient of permeability for sedimented gypsum ranges from $1.0x10^{-3}$ to $3.0x10^{-3}$ cm/sec for dry densities from 70 to 80 lb/ft^3 (11.0 to 12.6 kN/m^3), whereas the coefficient of permeability for the sedimented mixture ranges from $5.0x10^{-5}$ to $2.0x10^{-4}$ cm/sec at dry densities from 44 to 52 lb/ft^3 (6.9 to 8.2 kN/m^3).

The coefficient of permeability of a gypsum-fly ash mixture consisting of 50 percent gypsum and 50 percent fly ash by dry weight is also shown in Figure 2-26. The fly ash addition to the gypsum reduced the coefficient of permeability by a factor of 15 from $3.0x10^{-3}$ to $2.0x10^{-4}$ cm/sec at equal void ratios of 1.15.

The low permeability of gypsum-fly ash mixtures is a negative characteristic for stacking since drainage of sedimented and cast material is significantly slower than normally occurs with pure gypsum. The poor drainage characteristics of gypsum-fly ash mixtures also make excavation and casting difficult.

Shear Strength

A comparison of the stress-strain-strength characteristics of the sedimented fly ash-gypsum mixture and CT-121 FGD gypsum from consolidated undrained triaxial



1.0 lb/ft^3 = 0.157 kN/m^3

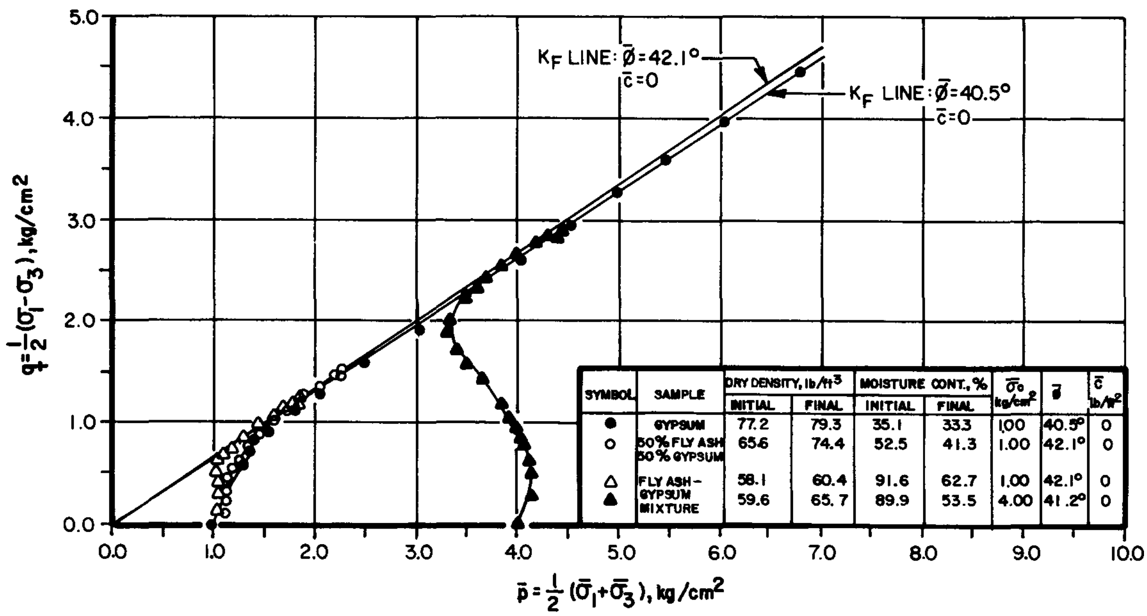
Figure 2-26. Permeability Characteristics of Fly Ash-Gypsum Mixtures compression tests with pore pressure measurements ($\overline{CIU}C$) is shown in Figures 2-27 and 2-28. A mixture of 50 percent gypsum and 50 percent fly ash by dry weight was also tested to indicate whether the strength characteristics of gypsum or fly ash govern the overall strength behavior of gypsum-fly ash mixtures.

Two test samples were prepared by allowing the fly ash-gypsum mixture from the gypsum stack to sediment by gravity through gypsum saturated water and then isotropically consolidating at stresses of 1.0 and 4.0 kg/cm^2 (98.1 to 392 kPa). The Mohr-Coulomb effective stress paths for these two tests, shown in Figure 2-27, indicate effective friction angles of 41° to 42° with zero effective cohesion at dry densities of 60.4 to 65.7 lb/ft^3 (9.5 to 10.3 kN/m^3).

A comparison of the stress-strain behavior of the sedimented fly ash-gypsum mixture and CT-121 FGD gypsum is shown in Figure 2-28. During undrained shear, gypsum typically mobilizes the full effective friction angle at small axial strains and continues to gain shear resistance as pore pressures become increasingly negative. The negative pore pressures develop as the sample attempts to increase in volume to overcome particle interlocking. Since fly ash is typically spherical in shape, there should be much less particle interlocking than occurs with elongate to tabular gypsum crystals and, hence,should display less tendency to increase in volume or develop negative pore pressures. This hypothesis is confirmed by the triaxial tests which indicate positive pore pressures during undrained shear of the sedimented fly ash-gypsum mixture.

The stress-strain-strength characteristics of a 50 percent gypsum and 50 percent fly ash mixture by dry weight is governed by the behavior of the fly ash. As shown in Figures 2-27 and 2-28, the mixture of gypsum and fly ash develops positive pore pressures during shear, displays a definite peak shear resistance, and indicates an effective friction angle of 42.1° with zero cohesion.

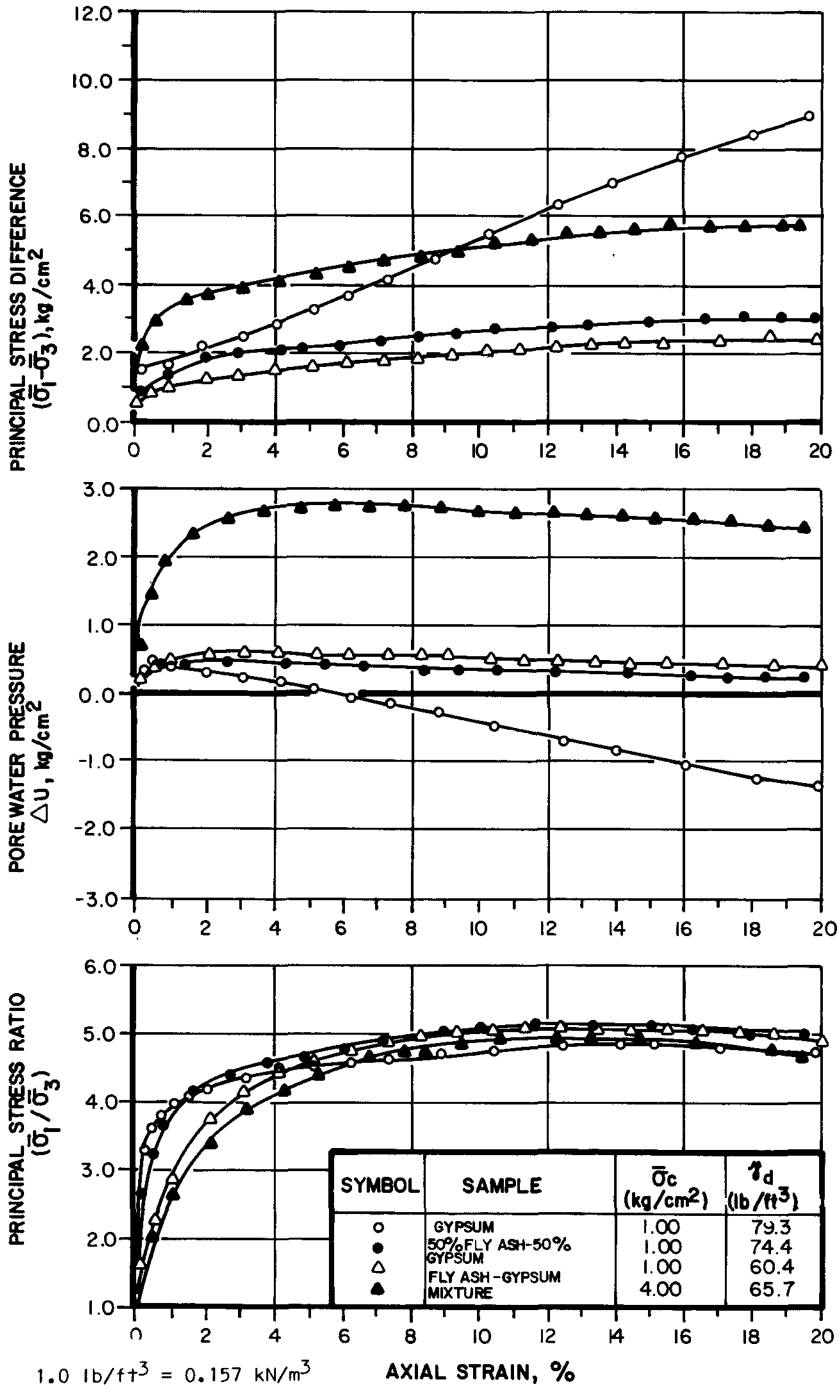
The effective friction angle versus void ratio and dry density for Plant Scholz CT-121 FGD gypsum and the fly ash-gypsum mixture is shown in Figure 2-29. Over the range of dry densities tested for the sedimented fly ash-gypsum mixture, the effective friction angle was found to be reasonably constant between 41° and 42°. This range of effective friction angles is similar to the effective friction angle measured for sedimented CT-121 FGD gypsum and indicates a 41° to 42° effective friction angle may be selected for mixtures of sedimented fly ash and gypsum with dry densities from 60 to 85 lb/ft^3 (9.4 to 13.3 kN/m^3). Based on these data,



SYMBOL	SAMPLE	DRY DENSITY, lb/ft³ INITIAL	DRY DENSITY, lb/ft³ FINAL	MOISTURE CONT., % INITIAL	MOISTURE CONT., % FINAL	$\bar{\sigma}_o$ kg/cm²	$\bar{\phi}$	$\bar{c}$ lb/ft²
●	GYPSUM	77.2	79.3	35.1	33.3	1.00	40.5°	0
○	50% FLY ASH 50% GYPSUM	65.6	74.4	52.5	41.3	1.00	42.1°	0
△	FLY ASH-GYPSUM MIXTURE	58.1	60.4	91.6	62.7	1.00	42.1°	0
▲	FLY ASH-GYPSUM MIXTURE	59.6	65.7	89.9	53.5	4.00	41.2°	0

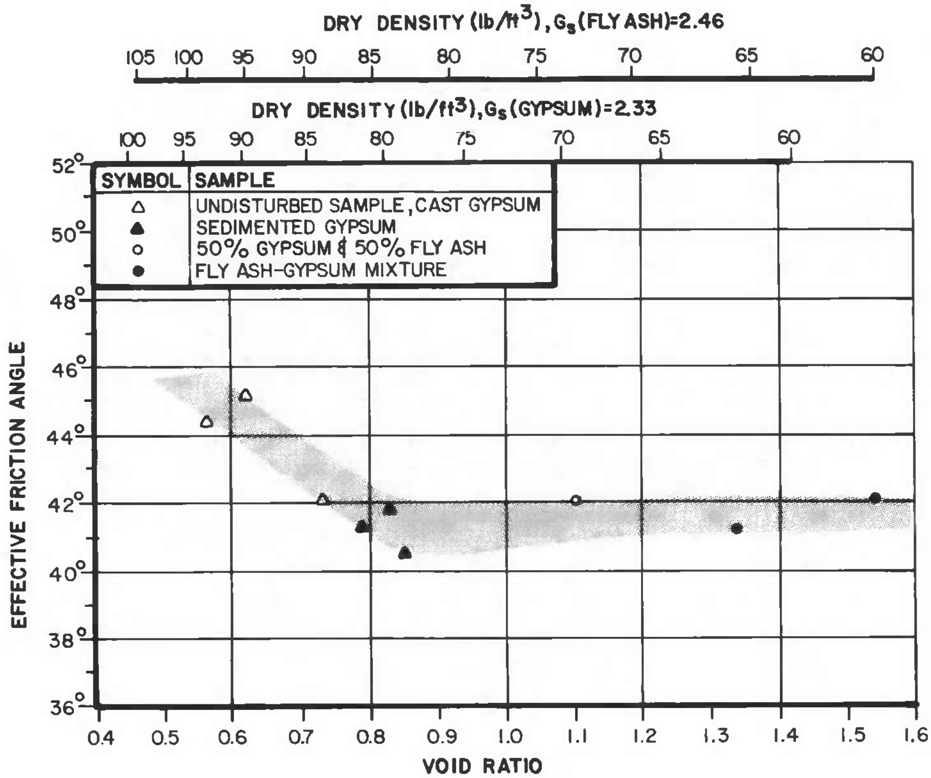
1.0 kg/cm^2 = 98.1 kPa
1.0 lg/ft^3 = 0.157 kN/m^3
1.0 lb/ft^2 = 47.9 Pa

Figure 2-27. Mohr-Coulomb Effective Stress Paths For Fly Ash-Gypsum Mixtures



1.0 lb/ft^3 = 0.157 kN/m^3
1.0 kg/cm^2 = 98.1 kPa

Figure 2-28. Undrained Stress-Strain Behavior For Fly Ash-Gypsum Mixtures



1.0 lb/ft^3 = 0.157 kN/m^3

Figure 2-29. Shear Strength Characteristics of Fly Ash-Gypsum Mixtures the frictional strength characteristics of gypsum-fly ash mixtures are satisfactory for stacking methods of waste disposal provided the mixtures are adequately drained and densified to the dry densities shown in Figure 2-29. However, since fly ash sediments to much lower dry densities and lower percent solids than shown in Figure 2-29, (i.e., see Figure 2-25), the shear strength of sedimented fly ash-gypsum mixtures can generally be expected to be less than the shear strength of sedimented gypsum. Furthermore, the development of positive pore pressures during shear, which could potentially lead to liquifaction-type failures of gypsum-fly ash mixtures, is another negative characteristic for stacking.

In summary, the results of laboratory testing on the effect of fly ash addition on the permeability, sedimentation-consolidation, and shear strength characteristics of CT-121 FGD gypsum all indicate reductions in the favorable stacking characteristics of CT-121 FGD gypsum. Since it was not within the scope of this research to establish the stackability of gypsum-fly ash mixtures, and particularly since no field experience exists on the stackability of such mixtures, no definitive conclusions can be advanced at this time on the potential for successfully stacking gypsum-fly ash mixtures. The laboratory tests, however, do indicate the following conclusions:

- The strength characteristics of gypsum-fly ash mixtures appear satisfactory for stacking methods of waste disposal provided the mixtures are drained and densified.
- The lower dry density, higher water content, and lower coefficient of permeability of gypsum-fly ash mixtures in comparison to pure gypsum will definitely make the excavation of sedimented material and the casting of the perimeter dike more difficult.

Since the addition of fly ash to gypsum produces a material which is not as well suited for stacking as pure gypsum, the stacking of gypsum-fly ash mixtures should be avoided to obtain the greatest benefit and ease of construction from the favorable stacking characteristics of FGD gypsum. Research is certainly necessary, however, to determine if feasible alternatives exist for simultaneous disposal of fly ash and FGD gypsum.

REFERENCES

1. D. H. Gray and Y. K. Lin. "Engineering Properties of Compacted Fly Ash." Journal of the Soil Mechanics and Foundation Division. American Society of Civil Engineers, Volume 98, Number SM4, 1972, pp. 361-380.
2. J. H. Faber and A. M. DiGioia, Jr. "Use of Ash in Embankment Construction." Presented at Annual Meeting, Transportation Research Board, Washington, D. C., 1976.

Section 3

PLANT SCHOLZ CT-121 FGD GYPSUM STACK

INTRODUCTION

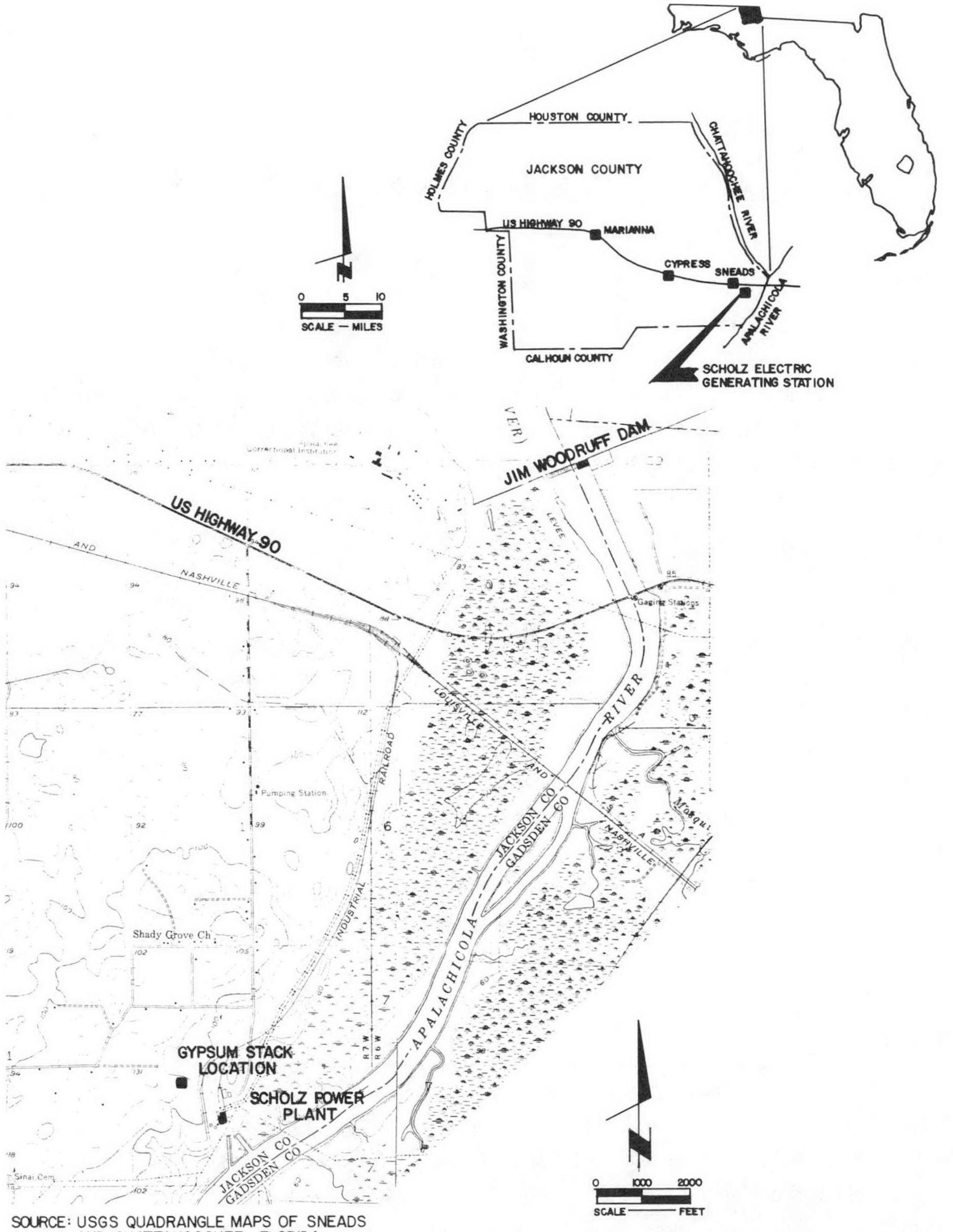
The objective of constructing and operating a prototype FGD waste gypsum stack was to establish the feasibility of disposing of waste gypsum produced by the Chiyoda Thoroughbred 121 (CT-121) Flue Gas Desulfurization process by stacking with a dragline using the upstream method of construction. Although by-product gypsum from the manufacture of phosphate fertilizer has been successfully stacked, no field experience exists on the stacking characteristics of gypsum produced by FGD scrubbers.

Operation of the CT-121 prototype test facility at Plant Scholz offered the unique opportunity to construct and study the stacking performance of a FGD gypsum stack. Both the structural and environmental performance of the stack were monitored over a 9-month test period from October 1978 through June 1979, with additional field investigations and evaluations continuing through June 1980. Although the prototype stack is small (i.e., one-half acre (2023 m^2) and 12 feet (3.7 m) high), the study allowed a comparison of laboratory tests of geotechnical engineering properties relevant to stacking with actual field behavior and a comparison of the stacking performance of CT-121 FGD gypsum with gypsum produced by the phosphate fertilizer industry.

GEOTECHNICAL ASPECTS OF TEST SITE

Site Location

The prototype FGD waste gypsum stack is located at the Scholz Electric Generating Station of Gulf Power Company in Jackson County, Florida. The plant is approximately 1,000 feet (305 m) west of the Apalachicola River, 4 miles (6.4 km) southeast of Sneads, Florida, and 3 miles (4.8 km) south of U.S. Highway 90 within Section 12 of Township 3 North, Range 7 West. Figure 3-1 illustrates the location of the gypsum stack and Scholz Electric Generating Station.



SOURCE: USGS QUADRANGLE MAPS OF SNEADS
AND CHATTAHOOCHEE, FLORIDA

Figure 3-1. Site Location Map

The stacking area is located at the northern end of the plant adjacent to an existing wastewater settling pond (Figure 3-2). The area adjacent to the north side of the existing pond is relatively flat, ranging in elevation from 112 to 118 feet (MSL). Embankments for the wastewater settling pond and ash pond rise 10 to 15 feet (3.1 to 4.6 m) above surrounding ground. A site plan of the one-half acre (2023 m^2) stacking area is shown in Figure 3-3.

Site Conditions

A subsurface investigation was conducted to assess the subsurface soil and groundwater conditions underlying the test site in order to: (1) assess the potential for groundwater contamination from process water leachate and (2) evaluate the overall geotechnical characteristics of the site with regard to construction of the disposal area and earthen starter dikes. The field investigation program included standard penetration test borings and auger borings to determine the subsurface soil conditions, and observation wells and piezometers with collection zones sealed at various depths within the subsurface profile to monitor groundwater quality.

Surficial and Bedrock Geology. The regional stratigraphy for Jackson County, Florida and surrounding areas typically consists of several hundreds of feet of limestone and dolomite overlain by several tens of feet of surficial soils (1, 3, 4). Specifically, the geologic sequence in ascending order from upper Eocene to Recent age consists of upper Eocene Gadsden limestone, lower Oligocene Marianna limestone, upper Oligocene Suwannee limestone, the Miocene age Tampa formation, and Pleistocene to Recent age surficial soils. Figure 3-4 illustrates the regional geology for eastern Jackson County.

The oldest geologic unit of interest with respect to construction of the gypsum disposal area is the Oligocene age Suwannee limestone which is penetrated by two water supply wells of the plant (see Figure 3-2 for these well locations). Suwannee limestone is a tan to white, soft to hard, crystalline, porous, frequently dolomitic, fossiliferous limestone. The top of the formation occurs at a depth of 140 feet (42.7 m) and is approximately 175 feet (53.3 m) thick. At the top of the Suwannee limestone and extending into the overlying Tampa formation are clay deposits occurring as discontinuous layers and irregular masses. The clay deposits often extend 30 feet (9.1 m) into the base of the Tampa formation. These deposits are the result of erosion and weathering of the top of the Suwannee limestone prior to the deposition of Miocene sediments.

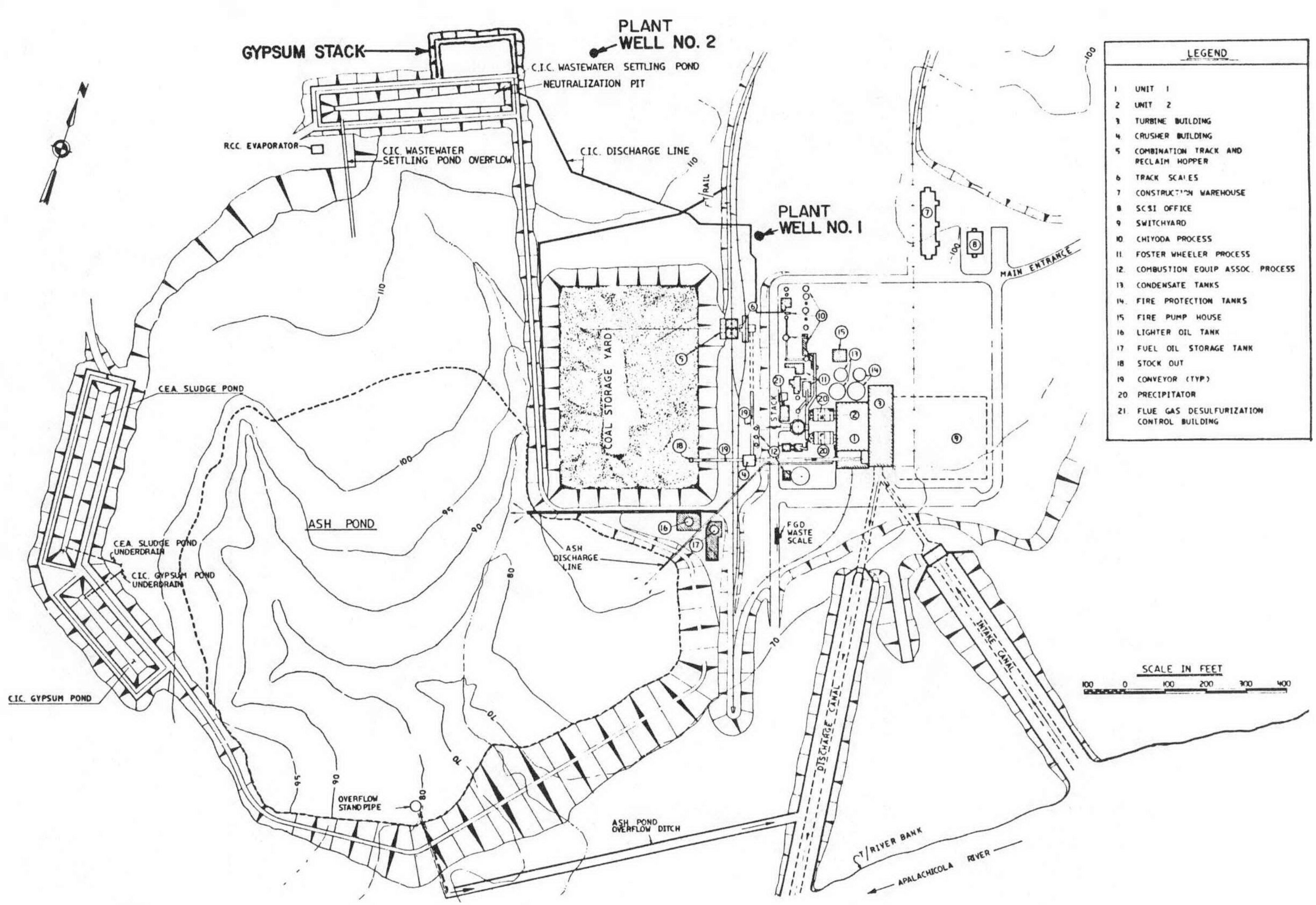


Figure 3-2. Scholz Electric Generating Station Site Plan

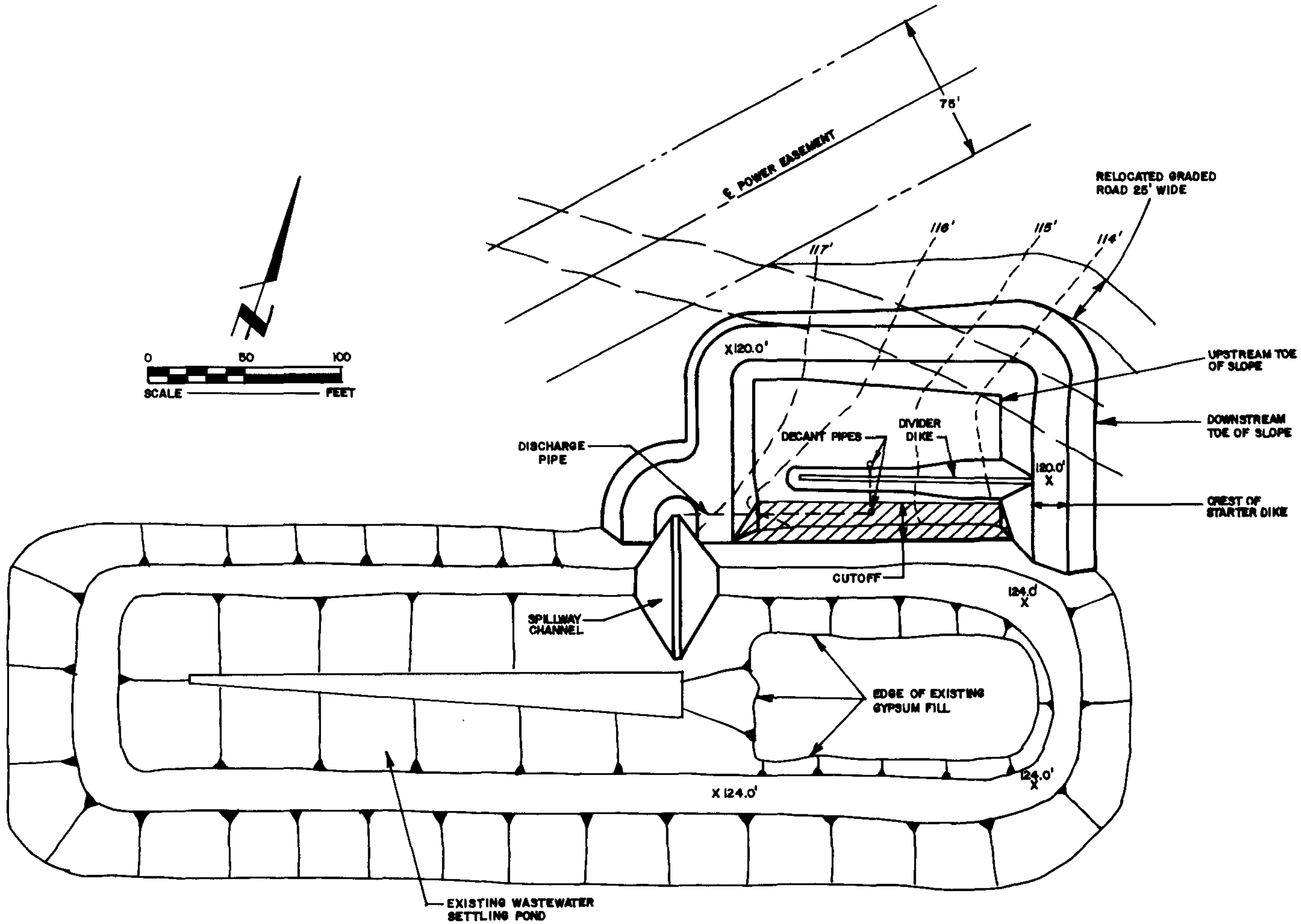


Figure 3-3. Gypsum Stack Site Plan

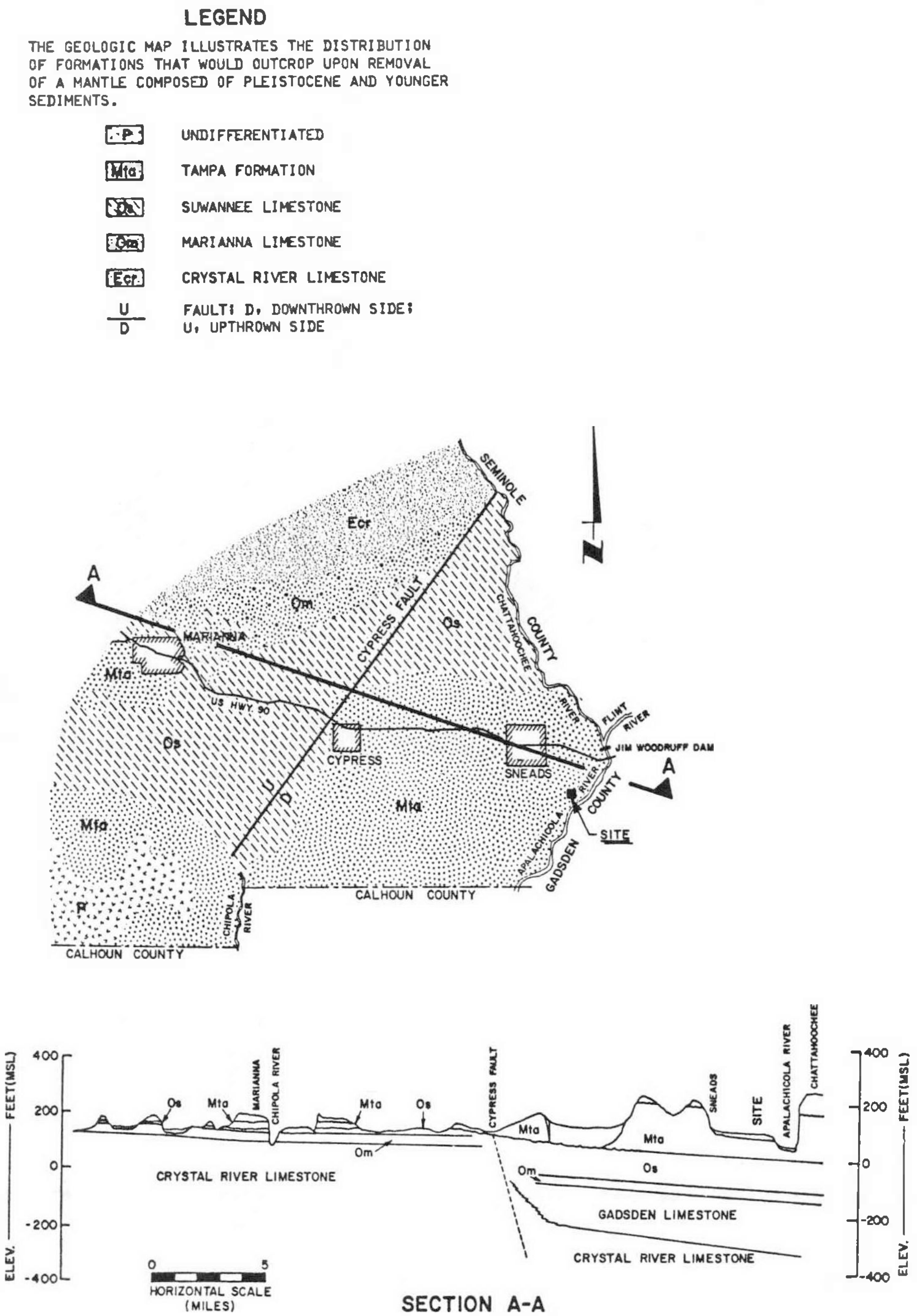


Figure 3-4. Regional Bedrock Geology
(Source: Geological Bulletin No. 37, 1955.)

The Miocene age Tampa formation unconformably overlies the Suwannee limestone. The Tampa formation consists of discontinuous layers of clay within a white to tan, very silty to sandy, chalky to crystalline, soft to hard limestone. Layers of soft plastic clay 1 to 3 feet (0.3 to 0.9 m) thick often occur within the upper 20 to 35 feet (6.1 to 10.7 m) of the formation. The clay layers are residual in nature and result from weathering of underlying calcareous soil and limestone.

The surficial soils and upper 50 feet (15.2 m) of the Tampa formation were investigated in detail during the subsurface investigation. A total of eight standard penetration test borings and seven auger borings were performed at the stacking area and along the crest of the existing wastewater settling pond. The locations of the borings and results of the investigation are presented in Figure 3-5. Laboratory tests performed on undisturbed and split-spoon jar samples are also presented beside the test sample.

Based upon the results of the subsurface investigation, the shallow subsurface stratigraphy can be divided into four strata of interest with regard to design and construction of the disposal area and monitoring of groundwater quality. This sequence consists of a relatively thin layer of silty sands, overlying 3 to 13 feet (0.9 to 4.0 m) of clayey sands, followed by a 3-to 7-foot (0.9 to 2.1 m) thick layer of soft plastic mottled clay, and then by the hard calcareous clays, limestones, and dolomites of the Tampa formation.

The surficial silty medium to fine sands of Stratum 1 vary in thickness from less than 1 foot to 4 feet (0.3 to 1.2m), with an average of 2.5 feet (0.8 m). The standard penetration resistance varies from 2 blows per foot (very loose) to 32 blows per foot (dense) with an average of 10 blows per foot (loose). The sands have a relatively high fines content (i.e., percent passing the U.S. No. 200 sieve) of 14 to 20 percent and a natural moisture content of 10 percent. Stratum 1 is a relatively pervious layer with laboratory measured coefficients of permeability on undisturbed samples of 1×10^{-3} cm/sec to 6×10^{-4} cm/sec.

Stratum 2 consists of light brown to reddish brown clayey medium to fine sands. The thickness of the stratum varies from 3 to 13 feet (0.9 to 4.0 m) and averages 7.5 feet (2.3 m). Standard penetration test values range from 5 blows per foot (loose) to 45 blows per foot (dense) with an average of 16 blows per foot (medium dense). The fines content and natural moisture content average 37 and 15 percent, respectively. Two laboratory constant head permeability tests indicate relatively low coefficients of permeability of $2x10^{-5}$ to $4x10^{-5}$ cm/sec for Stratum 2 soils.

Stratum 3 generally consists of a 3-to 4-foot (0.9 to 1.2 m) thick light brown and gray mottled soft plastic clay. Standard penetration test values typically vary from 3 to 5 blows per foot within the clay layer. The natural moisture content of the clay varies considerably from 40 to 120 percent with a gross average of about 80 percent. Three Atterberg limit determinations yield plasticity indices and liquid limits of 61, 76, and 126, and 83, 98, and 179 percent, respectively, and are all indicative of a highly plastic clay. A laboratory constant head permeability test on an undisturbed sample of Stratum 3 clay indicated a very low coefficient of permeability of $8x10^{-8}$ cm/sec.

The upper Tampa formation, Stratum 4, consists of tan to light gray,hard, indurated, calcareous clays and limerock with lenses of soft plastic clay. Standard penetration test values typically exceed 50 blows for 1 foot of penetration. Intact samples of hard calcareous clay within Stratum 4 displayed a very low degree of permeability with laboratory measured coefficients of permeability of $2x10^{-7}$ to $2x10^{-8}$ cm/sec. The actual mass permeability of the upper Tampa formation may be several orders of magnitude higher than measured on intact samples, however, due to structural discontinuities such as bedding planes, joints, fractures, and solution cavities. The effect of discontinuities on mass permeability is well illustrated by the low permeability of the Tampa formation in piezometers P-2 and P-4 which encountered no water loss during drilling in comparison to zones of much higher permeability encountered in piezometers P-1, P-4A, and P-6 as evidenced by water losses of greater than 30 gallons per minute (0.0019 m^3/sec) during drilling.

Groundwater Hydrology. The subsurface profile may be divided into three hydrologic units: the surficial aquifer, the underlying Floridan aquifer, and the intervening aquiclude.

The surficial aquifer consists of the silty and clayey sands of Pleistocene to Recent age. Figure 3-6, based on the results of our field investigation, indicates that the water level in the shallow aquifer ranges from 2 to 12 feet (0.6 to 3.7 m) below ground surface. The direction of groundwater flow within the surficial aquifer is generally from northwest to southeast.

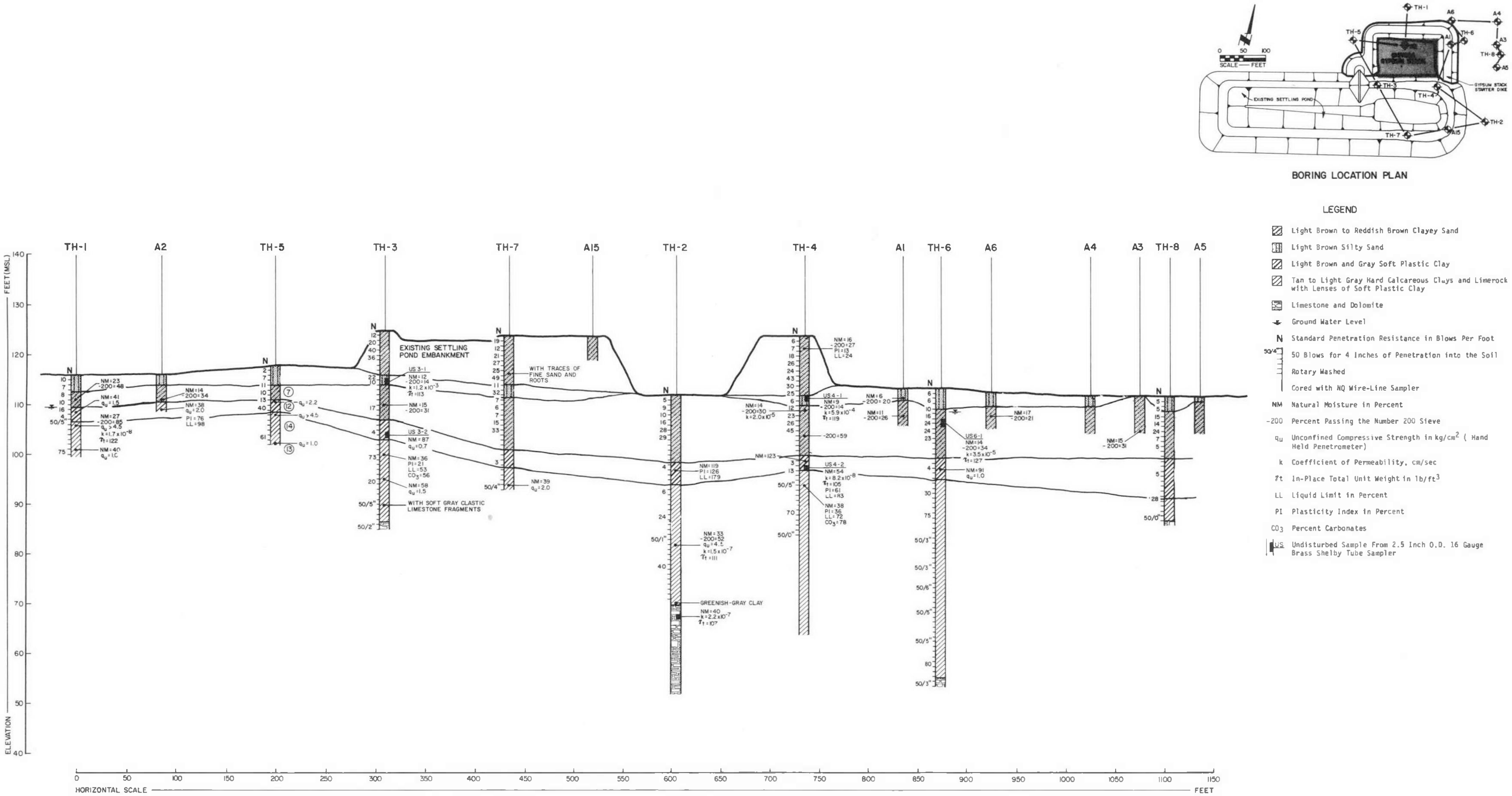


Figure 3-5. Subsurface Profile

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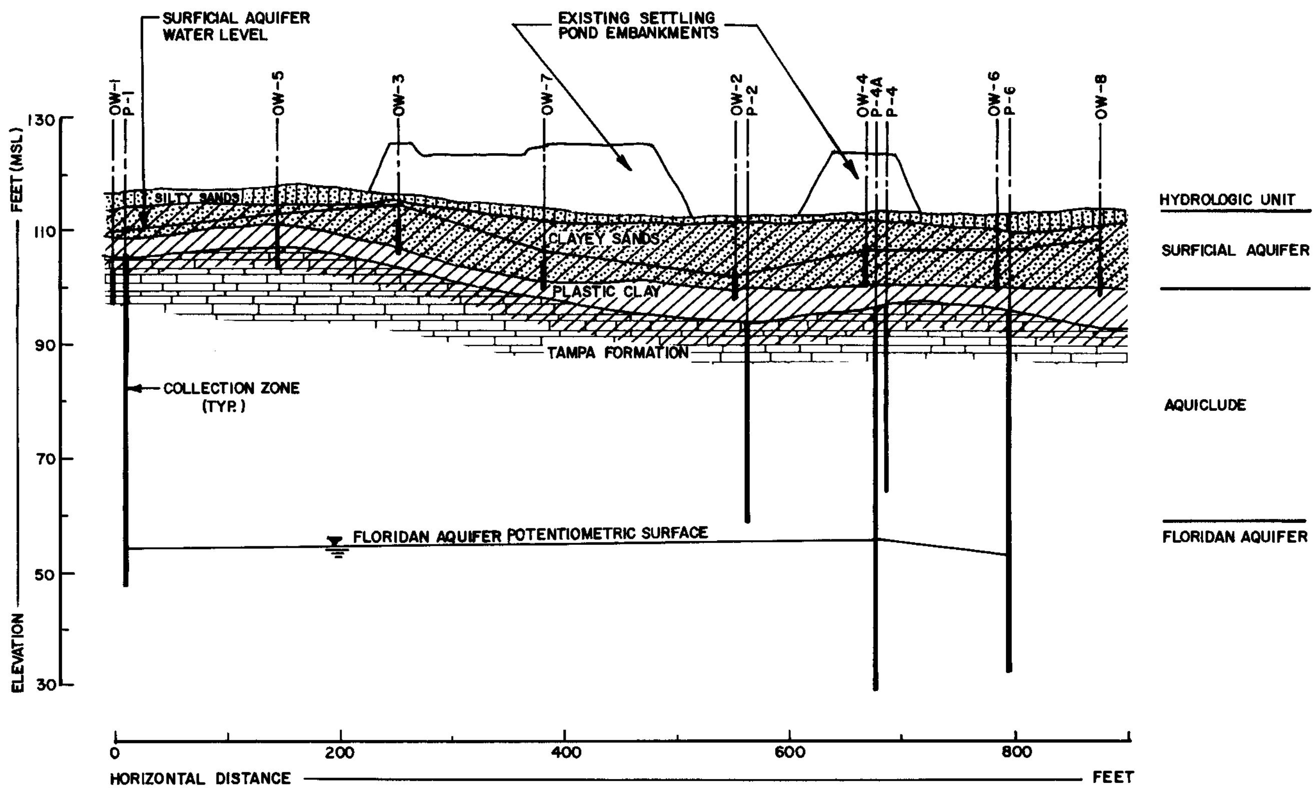


Figure 3-6. Observation Well And Piezometer Collection Zones

The Floridan aquifer underlies the region and supplies most of the water used in the area. The aquifer is composed of several hundreds of feet of limestone from Eocene to Miocene age including the Tampa formation and Suwannee limestone. Two water supply wells for Plant Scholz (Figure 3-2) penetrate the Floridan aquifer with collection zones within the Suwannee limestone. Well No. 2 is 165 feet (50.3 m) deep and is within 200 feet (61.0 m) of the disposal area. Well No. 1 is 185 feet (56.4) deep and is 700 feet (213.4 m) from the disposal area. The collection zone for Well No. 2 occurs within the top of the Suwannee limestone from Elevation -20 feet (MSL) to Elevation -50 feet (MSL).

The potentiometric surface of the Floridan aquifer is measured by three deep piezometers (P-1, P-4A, and P-6). Water level measurements within these piezometers indicate the potentiometric surface of the Floridan aquifer varies from Elevation 50 to 55 feet (MSL), or approximately 60 to 65 feet (18.3 to 19.8 m) below ground surface. These elevations are approximately the same as the normal water level for the Apalachicola River. The regional direction of groundwater flow in the Floridan aquifer is in a northwest to southeast trend toward the Apalachicola River (2). Locally, however, pumping from Plant Well No. 2 will cause groundwater within the Floridan aquifer to flow towards the plant well.

Readings from our observation wells and piezometers indicate that the clay layer and upper 30 to 50 feet (9.1 to 15.2 m) of the Tampa formation form a confining bed (aquiclude) between the surficial and Floridan aquifers. Wells and piezometers with collection zones above Elevation 55 feet (MSL) read the surficial aquifer groundwater table, while deep piezometers P-2, P-4A, and P-6 record the potentiometric surface of the Floridan aquifer.

DESIGN OF GYPSUM STACKING AREA

Although the stacking area is relatively small and was only required to provide 9 months of storage capacity, several aspects of design required consideration similar to large scale gypsum stacks. Design problems requiring consideration included: (1) the size and layout of the disposal area and gypsum stack, (2) construction of the containment area and starter dikes, (3) operation and maintenance of the process water decant and return water system, (4) selection of engineering properties of FGD gypsum relevant to stacking, (5) selection of allowable slopes for raising the gypsum stack, and (6) control of seepage from the disposal area into underlying aquifers.

Layout of Disposal Area

The disposal area and gypsum stack were proportioned for an estimated 9-month gypsum production of 5,500 to 6,500 tons ($5.0x10^6$ to $5.9x10^6$ kg) and a final stack height of 25 feet (7.6 m). Actual gypsum production during the test program, however, required a reduction in the final stack height. The stack geometry was also governed by the minimum dimensions required for: (1) safe operation of the dragline from the perimeter dike of the stack and (2) providing sufficient storage capacity within the center of the stack to sediment gypsum and allow clarification of the process water. For the small quantity of gypsum scheduled to be produced during the 9-month test program, the stack also had to be small in area to allow raising the stack to a sufficient height to observe the stacking behavior of CT-121 FGD gypsum and slope stability of the cast gypsum dikes.

The selected site plan and typical cross section of the disposal area and gypsum stack is shown in Figure 3-7. The stacking area was located adjacent to the north side of the existing settling pond and incorporated the embankment of the settling pond as the south wall of the disposal area. The disposal area encloses approximately 0.5 acres (2023 m^2) within 375 linear feet (114.3 m) of starter dike. The bottom of the stacking area was excavated to an average elevation of 113.5 feet (MSL), 6.5 feet (2.0 m) below the crest of the starter dike.

The starter dike was constructed of compacted clayey sand borrowed from areas adjacent to the stack. The starter dike was keyed 1 foot (0.3 m) into the clayey sands underlying the site, and the surficial silty sand layer was removed from beneath the entire stacking area to reduce seepage from the stacking area into the surficial aquifer. The surficial silty sand layer beneath the adjacent settling pond was also cut off with a compacted clayey sand blanket.

A liner was not installed within the gypsum stacking area because:(1) the underlying soils were thought to be sufficiently impervious to prevent any significant migration of leachate from the stacking area, and (2) the stack was only to be used for a short period of time before retirement and eventual removal.

Process Water Return System

A fixed vertical riser type decant structure was selected for the gypsum stack. The fixed vertical riser type decant structure was selected because of the minimum amount of required maintenance. The disadvantage of the system is that the

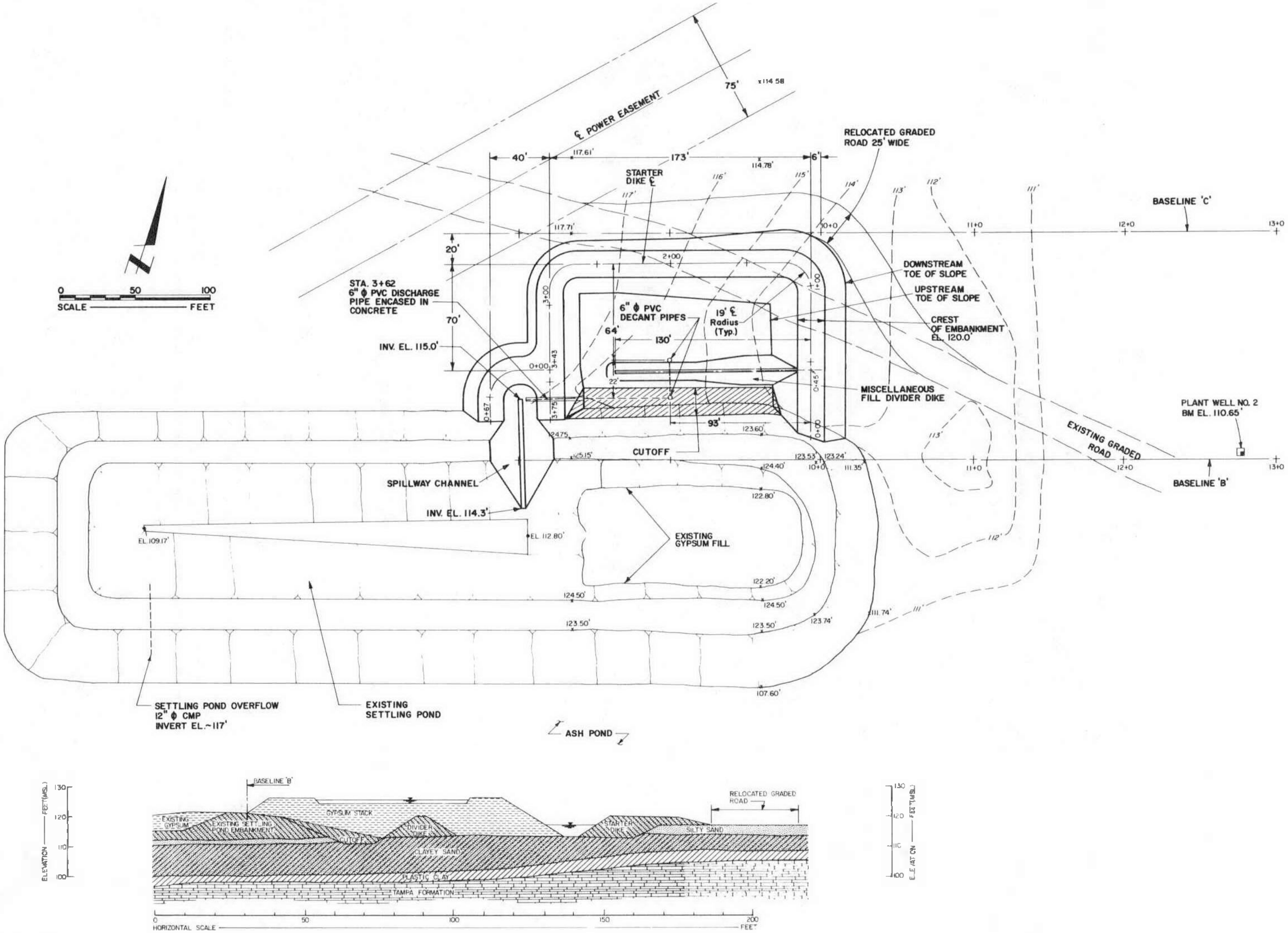


Figure 3-7. Gypsum Stack Site Plan And Cross-Section

spillway must be continuously raised as the surface of the sedimented gypsum rises, requiring frequent access to the spillway.

The decant structure for the prototype stack consisted of two 6-inch (0.15 m) diameter polyvinyl chloride (PVC) vertical riser pipes connected to a 6-inch (0.15 m) diameter PVC discharge pipe emptying into the spillway channel. The size of the riser and discharge pipes was selected to operate at less than 6 inches (0.15 m) of head above the spillway inlet for a design process flow of 45 gal/min (0.0028 m^3/sec) and 0.50 inches (1.3 cm) of rainfall per hour on the 0.5 acre (2023 m^2) stacking area. After the gypsum stack was raised for the first time and the perimeter ditch was formed around the stack (i.e., see Figure 3-12), a 6-inch (0.15 m) diameter PVC pipe was also installed to drain seepage and runoff from the perimeter ditch into the spillway channel.

After clarification within the stacking area, the process water discharged through the decant system and spillway channel to the existing settling pond. The plant return line was located at the west end of the settling pond. Overflow from the settling pond was discharged to the ash pond through a spillway at the west end of the settling pond.

Engineering Properties of Gypsum

The engineering properties of gypsum relevant to sizing the gypsum stack, estimating seepage through the stack, and estimating the stability of the stack slopes are the *in situ* density, coefficient of permeability, and shear strength. Based on preliminary laboratory data from pilot plant CT-121 gypsum presented in Section 2, the following average properties were initially selected for the prototype stack:

Parameter	Sedimented Gypsum	Cast Gypsum
Saturated Unit Weight	109 lb/ft^3	112 lb/ft^3
Water Content	35%	30%
Dry Unit Weight	81 lb/ft^3	86 lb/ft^3
Coefficient of Permeability	$7x10^{-4}$cm/sec	$5x10^{-4}$ cm/sec

The selection of these parameters was based on an average effective vertical consolidation stress in the range of 0.10 to 0.50 kg/cm^2 (9.8 to 49.1 kPa) for sedimented gypsum. Properties for cast gypsum were based on the results of laboratory tests simulating the casting of gypsum.

For an average effective vertical consolidation stress of 0.10 to 0.50 kg/cm^2 (9.8 to 49.1 kPa) and corresponding void ratios of 0.87 to 0.85, sedimented pilot plant CT-121 gypsum displayed an effective friction angle of 44° to 45° with zero cohesion (i.e., see Figure 2-15). For cast gypsum, a friction angle of 43° was selected corresponding to a void ratio in the range of 0.60 to 0.70. Average strength parameters consisting of an effective friction angle of 43° with zero cohesion were selected for design.

Slope Stability

The stability of the gypsum stack slopes was analyzed for the case of a 25-foot (7.6 m) high gypsum stack with a slope of 1.5 Horizontal to 1.0 Vertical as commonly found on phosphate industry gypsum stacks. Figure 3-8A presents results from circular arc stability analyses for gypsum shear strength parameters of $\bar{\phi}$ = 43° and $\bar{c}$ = 0. The location of the phreatic line within the gypsum stack for steady-state seepage is also shown. Failure (i.e., factor of safety less than 1.0) occurs for shallow circular arcs through the toe of slope and either completely within the gypsum stack or slightly within the foundation soils. Circular arcs with the lowest factor of safety are shallow failure surfaces which result because of seepage instability below the springline. Circular arcs deeper within the stack generally have factors of safety between 1.0 to 1.1. Infinite slope solutions for local slope stability below the springline indicate a slope of 3.0 Horizontal to 1.0 Vertical is required for a factor of safety of 1.0.

The circular arc stability analyses were repeated using a small component of cohesion ($\bar{c}$ = 100 lb/ft^2) and the same effective friction angle ($\bar{\phi}$ = 43°). Although no cohesion was measured on laboratory samples, the analysis was repeated using cohesion since field experience indicates most gypsums usually develop some cohesion from cementation. These results are shown in Figure 3-8B. The shallow circular arc factors of safety increase significantly by 30 to 60 percent. For example, the failure surface with the factor of safety of 0.78 increases to 1.23. The factors of safety for deeper circles increase slightly by 8 percent.

Since the most research benefit could be derived by stacking the gypsum as steeply as possible, slopes of 1.5 Horizontal to 1.0 Vertical, corresponding approximately to the angle of repose of cast gypsum, were recommended for construction of the gypsum stack. If no cohesion develops within the cast gypsum, sloughing of the

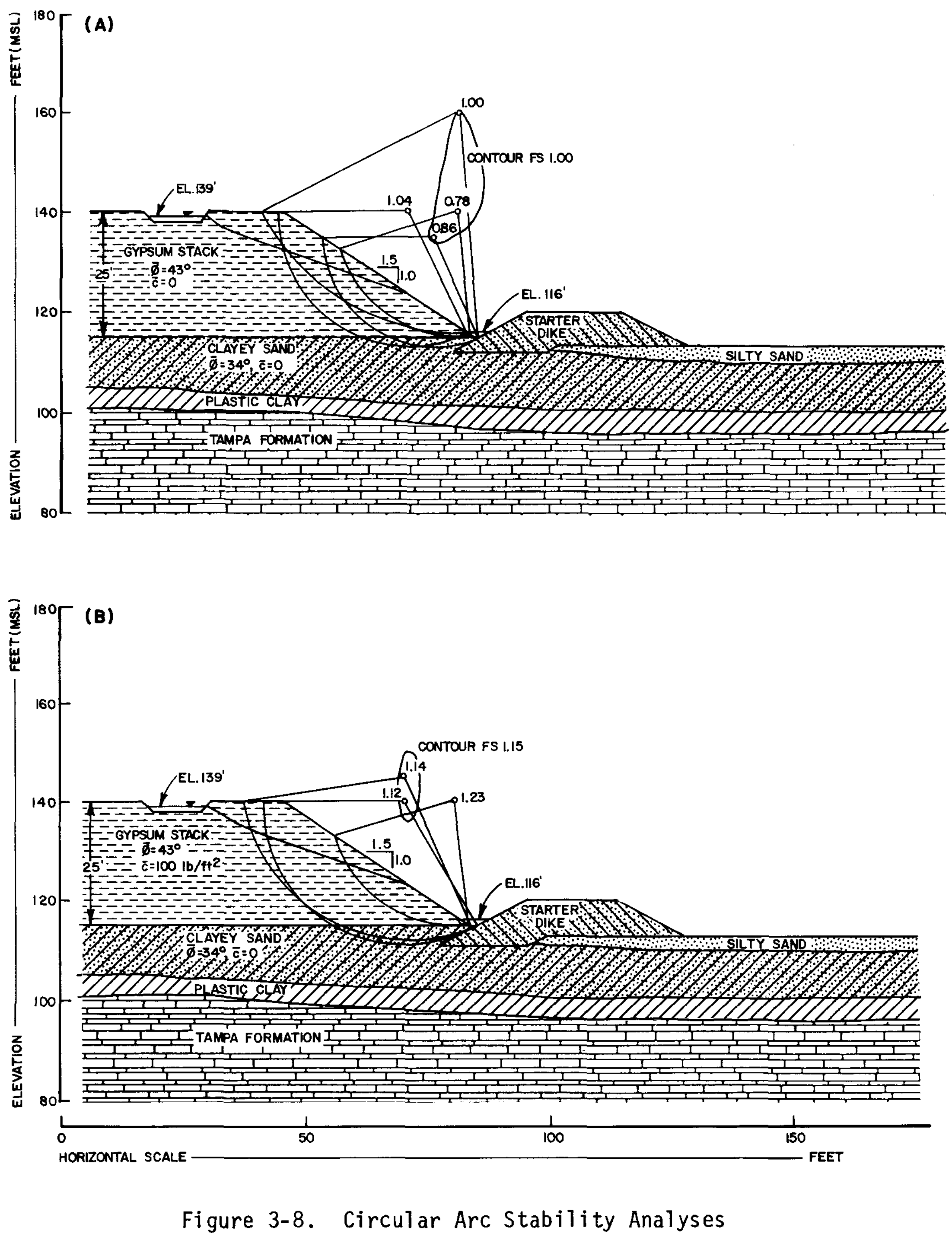


Figure 3-8. Circular Arc Stability Analyses

downstream toe of slope will occur. If sloughing occurs, the lower portion of the downstream slope can be flattened as required.

PROTOTYPE STACK CONSTRUCTION, OPERATION, AND PERFORMANCE

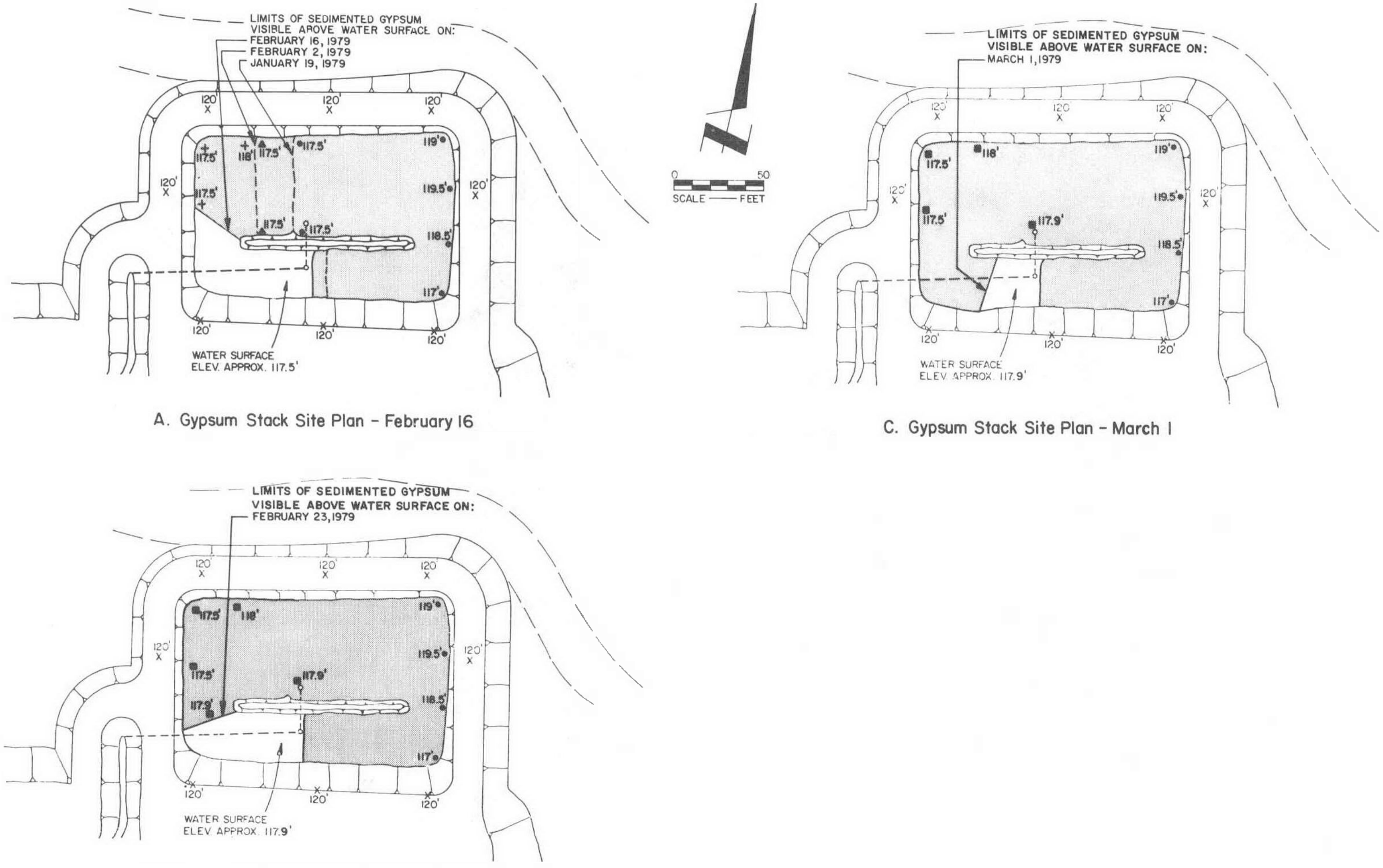
During construction and operation of the prototype stack,efforts were made to construct and operate the stack as typically accomplished in the phosphate industry. However, the relatively small size of the stack and the limited quantity of gypsum available for stacking required some departures from normal stacking procedures. The actual construction sequence and procedures used to raise the gypsum stack are discussed in this section. Problems particular to the prototype stack are also discussed and the overall stacking performance of CT-121 FGD gypsum is evaluated.

Stack Construction and Operation

Gypsum and process water were initially deposited in the stacking area on October 12, 1978. Process water was pumped to the stacking area at rates varying from 30 to 70 gal/min (0.0019 to 0.0028 m^3/sec) and solids contents varying from 5 to 15 percent. Gypsum production varied considerably during the 9-month test program within the range of 12 to 26 tons per day (10,900 to 23,600 kg/day).

The gypsum slurry was initially discharged along the east side of the north compartment and allowed to flow in a westerly direction around the divider dike to the south decant pipe. The south decant pipe was set 1-foot lower than the north decant pipe at Elevation 117 feet (MSL). The purpose of the divider dike and two decant pipes was to: (1) allow filling of the north compartment first using the south decant pipe, (2) allow filling of the south compartment using the north decant pipe, and (3) allow one compartment to drain prior to raising the gypsum stack while one compartment is used for the deposition of gypsum. A breach in the crest of the divider dike and the relatively small areas of the compartments subsequently precluded the use of the divider dike to drain one compartment prior to raising the gypsum stack.

The progression of sedimented gypsum within the stacking area from February through March is shown in Figure 3-9. On March 1, the slurry discharge pipe was relocated to the east side of the south compartment and the south decant pipe raised to Elevation 119 feet (MSL) to allow the slurry to flow in a westerly direction around the divider dike to the north decant pipe. The slurry discharge pipe was



A. Gypsum Stack Site Plan - February 16

C. Gypsum Stack Site Plan - March 1

B. Gypsum Stack Site Plan - February 23

Figure 3-9. Progression of Sedimented Gypsum With Time

Figure 3-10. Stacking Area Prior to Initial Dike Raising

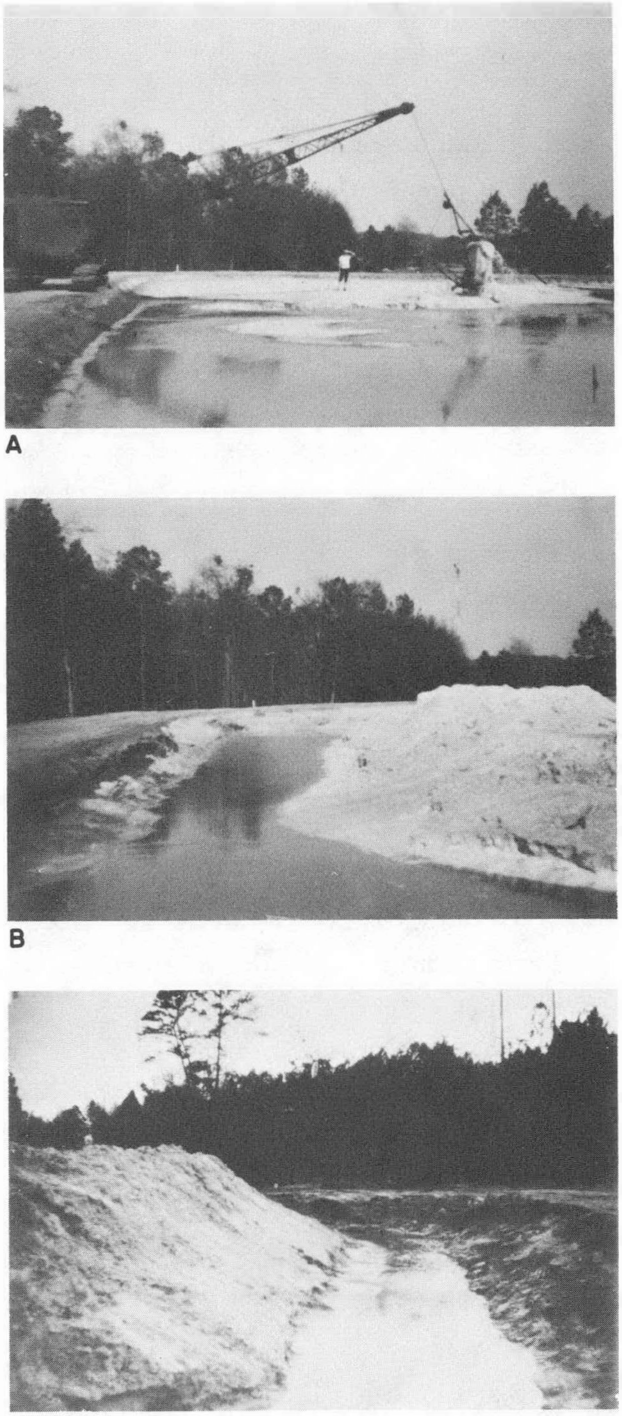
relocated as necessary within the south compartment to uniformly raise the surface of the gypsum to an average elevation of 118 feet (MSL).

On March 19, sufficient gypsum was sedimented within the stacking area to allow raising of the gypsum stack. Figure 3-10 presents photographs of the containment area on March 19 prior to raising the gypsum stack. As shown, the sedimented gypsum can be walked upon at most locations within the containment area except near the slurry outlet where the sedimenting gypsum is still very loose. Initial efforts to cast the sedimented gypsum were difficult due to the high water level within the stacking area and lack of drained sedimented gypsum. Accordingly, the stacking area was dewatered with pumps and incoming gypsum slurry was temporarily discharged into the surge pond. This departure from normal stacking procedures was necessary since the small area of the gypsum stack did not allow draining of one compartment prior to stacking as normally accomplished on large gypsum stacks.

Once the water level within the stacking area had dropped sufficiently to expose the top of the sedimented gypsum and provide a drained surface to cast the gypsum upon, the stacking progressed smoothly. After three days of dewatering and stacking, the north, east and west sides of the dike were complete.

Stacking of saturated gypsum from beneath the water surface was possible provided the gypsum was cast upon a dry surface and sufficient time was allowed for water to drain from the cast material before attempting to pile the gypsum more than 2 to 3 feet (0.6 to 0.9 m) high. Dry gypsum located above the water surface was excavated and cast easily and displayed acceptable stacking behavior. Following several days of draining and drying from exposure to the sun, the cast gypsum dike was in satisfactory condition.

Figure 3-11 presents photographs taken during construction of the north wall of the cast dike and perimeter ditch. As shown, the dragline first excavates gypsum from the containment area adjacent to the starter dike to form the perimeter ditch. The gypsum excavated from the perimeter ditch is then cast to form the perimeter dike of the gypsum stack. Photograph 3-11A shows the dragline removing gypsum from the perimeter ditch and casting the material to form the stack perimeter dike. Photograph 3-11B shows the perimeter ditch and cast dike shortly after construction. At this time, the gypsum was still too wet to cast more than 2 to 3 feet (0.6 to 0.9 m) high without allowing some time for draining and drying.



A

B

C

Figure 3-11. Raising North Wall of Cast Gypsum Dike

After drainage and drying from exposure to the sun, the gypsum was cast much easier and at steeper slopes as shown in Photograph 3-11C.

The site plan and cross sections of the gypsum stack before and after the first raising of the perimeter dike are shown in Figure 3-12. The perimeter dike was raised approximately 5 to 6 feet (1.5 to 1.8 m) above the surface of the sedimented gypsum to Elevation 123.0 to 124.0 feet (MSL). The north, east and west sides of the dike were constructed with an 8-to 10-foot (2.4 to 3.1 m) crest width and exterior slopes of 1.0 Vertical to 1.5 Horizontal. The south side of the perimeter dike was constructed with a 15-foot (4.6 m) crest width from gypsum previously dredged from the surge pond. The perimeter ditch surrounding the north, east and west sides of the stack was excavated to an invert elevation varying from 114.0 to 114.5 feet (MSL) and with a bottom width ranging from 10 to 13 feet (3.1 to 4.0 m).

Existing gypsum from the CT-101 process within the surge pond was used to construct the south dike to allow use of the CT-121 FGD gypsum within the stacking area for construction of the north, east and west dikes. The south dike of the gypsum stack adjoins the embankment of the surge pond and is not of interest in evaluating the stacking behavior of the CT-121 FGD gypsum.

After the first dike raising the gypsum slurry was alternately discharged at the four corners of the stack and allowed to flow toward the south decant pipe at the center of the stacking area. The slurry was discharged at the corners of the stack to provide the longest flow path and, hence,the most efficient clarification of the process water. The north decant pipe, used during the initial filling of the stacking area, was capped and no longer used. Since the stacking area was reduced significantly in size after raising the dikes, complete clarification of the process water became difficult and some gypsum was carried over through the decant pipe. The loss of gypsum, however, was not a major problem. The decant pipe was raised as necessary in approximately 1-foot (0.3 m) increments as gypsum sedimented within the stack.

The sedimentation of gypsum within the stack progressed satisfactorily, except for an initial problem with sloughing along the base of the downstream slope of the perimeter dike below the springline. The seepage induced sloughing resulted from the absence of significant cohesion within the steep outer slope of the gypsum perimeter dike and was aggravated by the relatively thin width of the

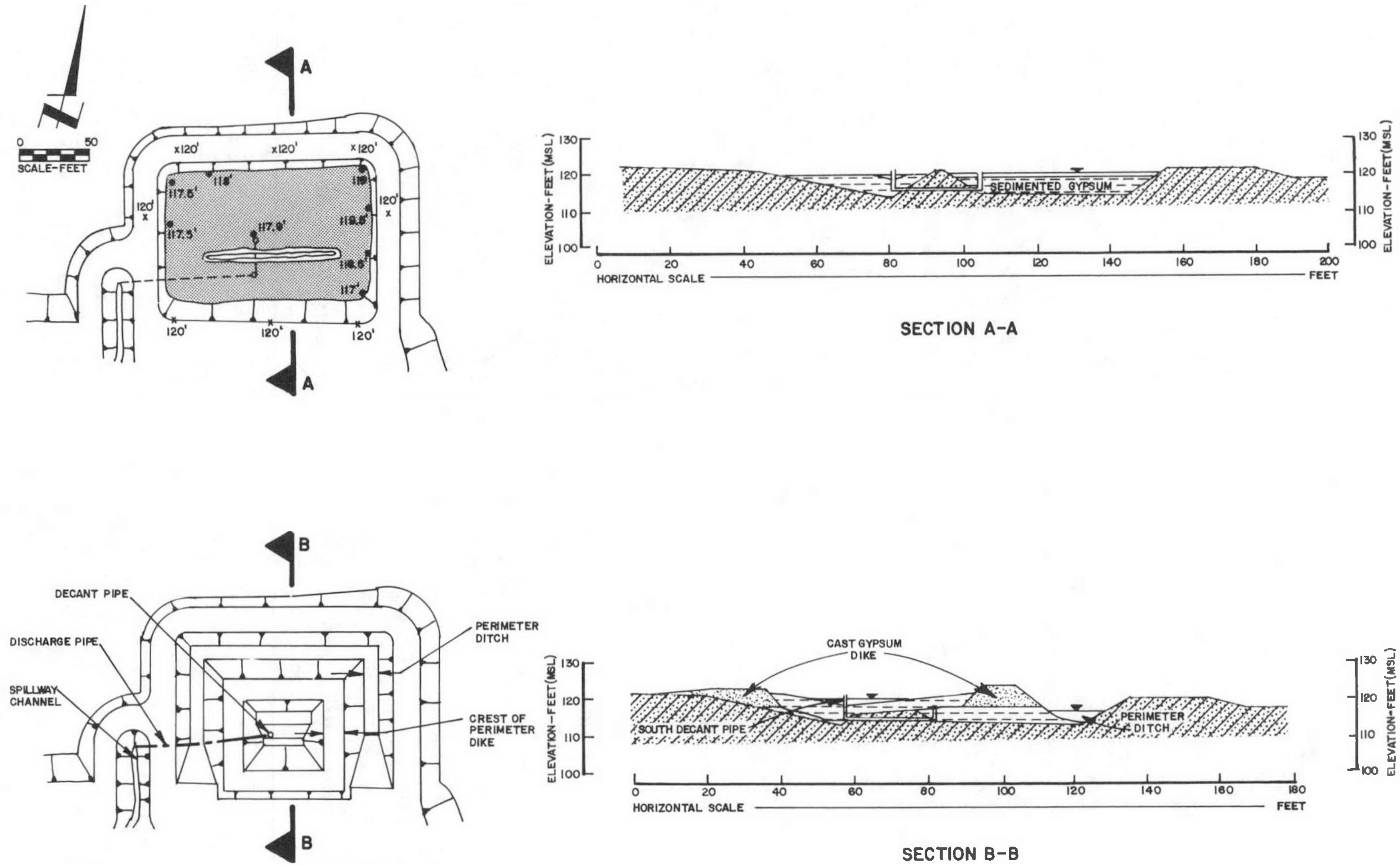


Figure 3-12. Gypsum Stack Site Plan And Cross-Section Before And After Raising Perimeter Dike

perimeter dike in comparison to the head difference across the dike. The sloughing generally extended 2 feet to 3 feet (0.6 to 0.9 m) above the water level in the perimeter ditch.

On April 12, the sloughing became serious enough to require the removal of the slurry discharge pipe from the stack. From April 12 through April 19, the gypsum slurry was discharged into the east end of the perimeter ditch, and the stack was allowed to drain. Figure 3-13 shows the extent of sloughing along the north wall of the gypsum stack. When the perimeter dike was raised for the second time, the downstream slopes were flattened near the base of the stack and the width of the perimeter dike was increased by several feet. No major sloughing occurred after the dike was raised for the second time.

The excavation of sedimented gypsum from within the stack and the raising of the perimeter dikes was repeated for a second and third time on April 19 and 20 and May 3 and 4. Several days prior to raising the stack, however, the gypsum discharge was placed in the perimeter ditch to allow the stack to drain. This procedure made stacking and handling of gypsum by the dragline relatively easy. The crests of the east and west dikes were sufficiently widened during the second raising to allow the dragline to work from both dikes as shown by the photographs in Figure 3-14. The cast gypsum dikes of the stack were sufficiently stable and trafficable to allow the dragline to work from and move upon the dikes with no difficulty. Gypsum deposited in the perimeter ditch during draining and raising of the stack was also excavated and cast on the dikes (Photograph 3-14B). The height of the perimeter dike was increased approximately one foot during the second raising to Elevation 124.0 to 125.0 feet (MSL) and an additional one foot (0.3 m) during the third raising to an average elevation of 125.5 feet (MSL).

The gypsum stack perimeter dike was raised for the fourth time on June 6 and 7. The stack contained approximately 7 feet (2.1 m) of sedimented gypsum which was removed during stacking operations. Much of the gypsum (3 to 4 feet) was contaminated with fly ash due to particulate tests that were conducted as part of the overall CT-121 process evaluation (see Volume I) and was not used to raise the perimeter dike. The high ash content gypsum was cast separately along the exterior of the south perimeter dike. Sufficient uncontaminated gypsum was available to raise the perimeter dike approximately 1 foot (0.3 m) to an average elevation of 126.2 feet (MSL).

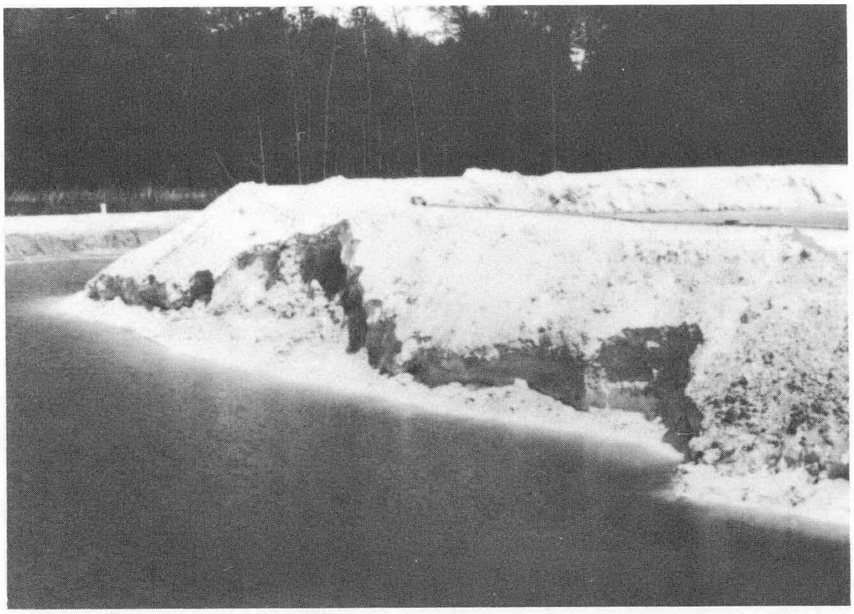
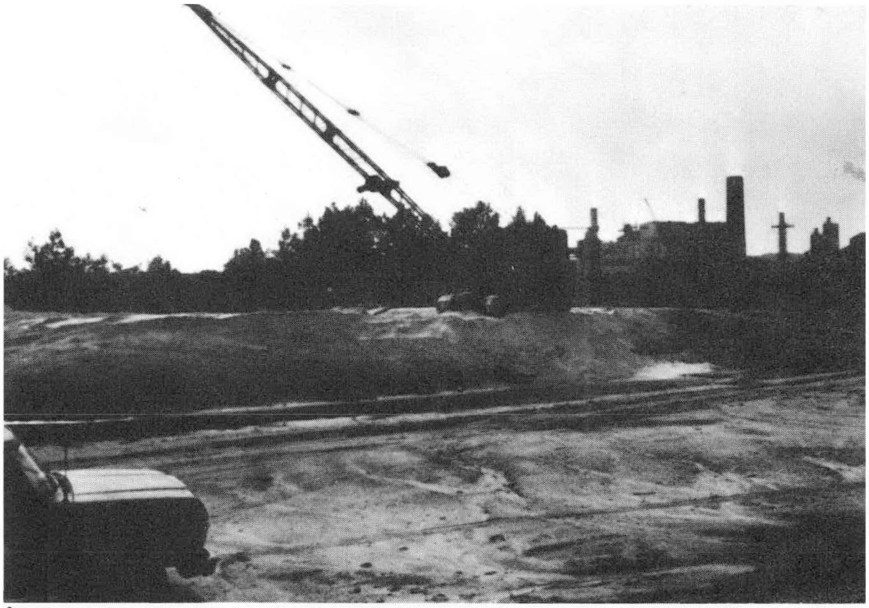


Figure 3-13. Sloughing Along North Wall of Cast Gypsum Dike



A

B

Figure 3-14. Dragline Operation From Crest of Cast Gypsum Dike

Following the fourth dike raising, the gypsum stack was again refilled with gypsum until the process was shut-down on June 26. The final as-built geometry of the gypsum stack is shown in Figure 3-15. The average height of the stack above the invert of the perimeter ditch is approximately 12 feet (3.7 m). The perimeter dike crest width varies from 9 to 15 feet (2.7 to 4.6 m) and the exterior slopes of the stack are generally 1.0 Vertical to 1.5 Horizontal.

Photographs of the completed gypsum stack are shown in 3-16. Photographs 3-16A and 3-16B show the entire stack and north wall approximately one month after the process shut-down. At this time, process water from the settling pond was being pumped to the stack to maintain seepage through the stack. Seepage was maintained through the stack for a period of approximately one month after process shut-down to further observe the effects of steady-state seepage on slope stability. Photograph 3-16C, taken 5 months after the process shut-down, shows no significant change in the appearance of the north wall after several months of weathering and aging.

Stacking Performance

Stacking of saturated CT-121 FGD gypsum from beneath the water surface of the undrained pond was possible provided the gypsum was cast upon a dry surface and sufficient time was allowed for water to drain from the cast material before attempting to pile the gypsum more than 2 to 3 (0.6 to 0.9 m) feet high. Dry gypsum located above the water surface, which would be similar to gypsum within a drained pond, was excavated and cast easily and displayed acceptable stacking behavior.

Since no cohesion from cementation developed during the test program, sloughing often occurred below the springline for the relatively steep slopes of the cast gypsum dike. The overall stability of the slope, however, was generally not affected by the sloughing. In full-scale FGD gypsum stacks, flat slopes below the springline or internal drains may be required to control seepage instability and sloughing if some cohesion from cementation does not develop.

The fly ash-gypsum mixture deposited in the stack during the particulate tests could be excavated with a dragline, although the process was much more time consuming. The fly ash-gypsum mixture could be cast although the poor drainage characteristics and high water content of the mixture generally produced much

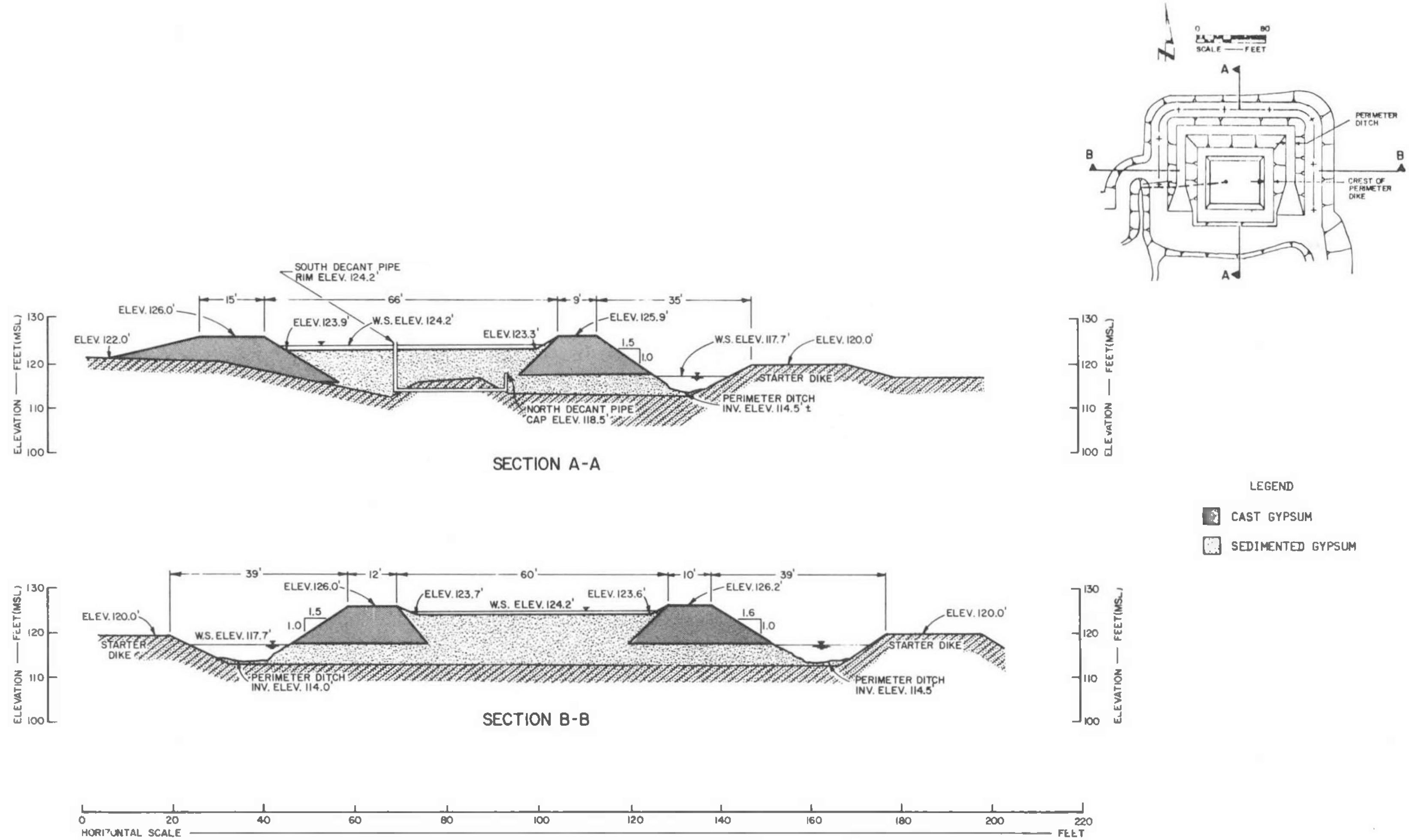
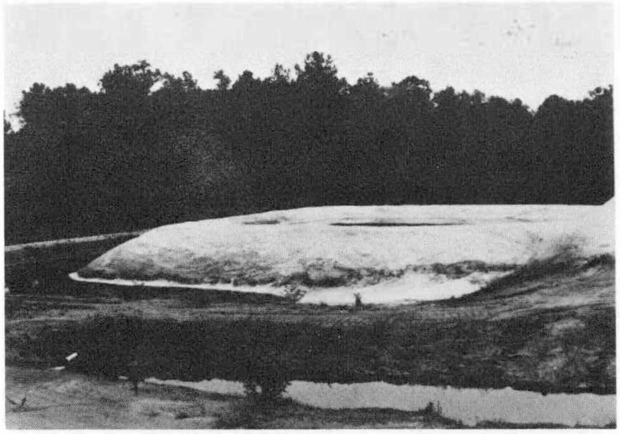


Figure 3-15. Final Gypsum Stack Cross-Sections



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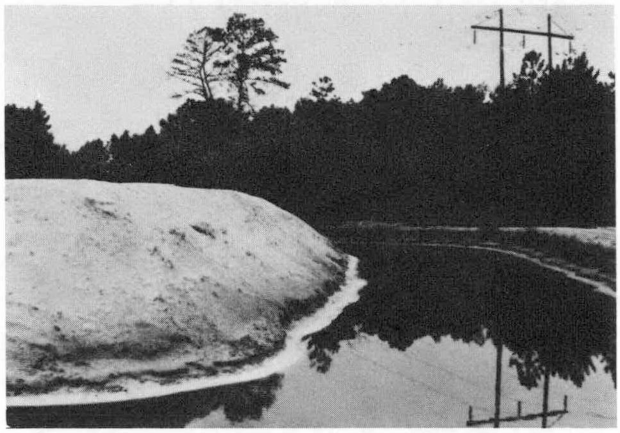

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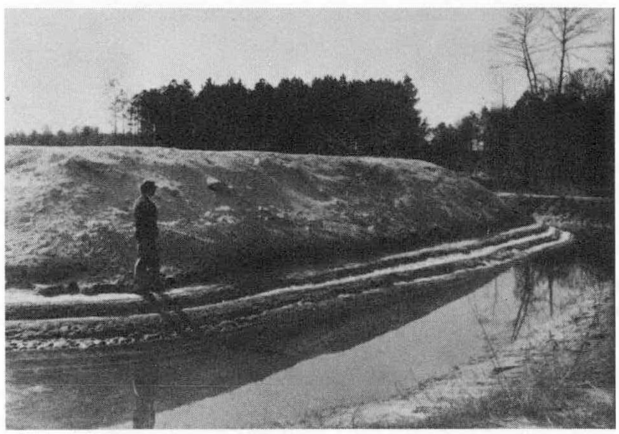


C

Figure 3-16. Completed Gypsum Stack

flatter cast slopes than occur with gypsum. Overall, the field performance indicated the addition of fly ash to CT-121 FGD gypsum significantly reduced the favorable stacking characteristics of CT-121 FGD gypsum. Laboratory tests presented in Section 2 on the effect of fly ash addition on the engineering characteristics of CT-121 FGD gypsum also indicated a general reduction in the favorable stacking characteristics of CT-121 FGD gypsum by the addition of fly ash.

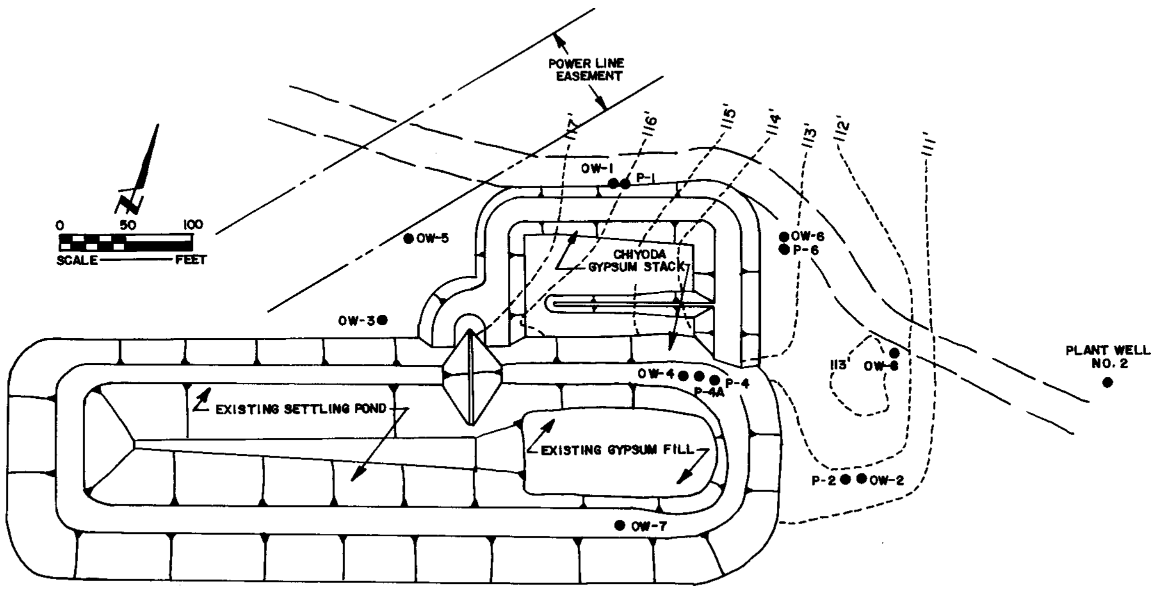
A light brown slightly clayey silt (liquid limit of 58% and plastic limit of 35%) was normally found to sediment within the stack near the spillway outlet. This material was apparently pumped to the stack within the gypsum slurry. Since the quantity of material was very small and occurred as very thin layers, no stacking or operation problems resulted from its presence.

As with phosphate gypsum stacks, the cast CT-121 FGD gypsum dikes and slopes developed a thin, hard drying crust. This crust apparently resulted from the dissolution of gypsum crystals from rainfall and subsequent recrystalization and drying. The slopes displayed essentially no erosion from rainfall. Dusting also was not a problem. Therefore, it is not expected that erosion protection will be required on the outside slope of FGD gypsum stacks.

If long-term maintenance and reclamation require that the slopes be grassed, it may be expedient to flatten the slopes to 2.5 Horizontal to 1.0 Vertical or flatter as the stack is raised. Some small clumps of grass were observed growing on the stack slopes, and grassing with or without a topsoil dressing may be possible, although no research was performed with the CT-121 gypsum stack on this topic.

GROUNDWATER MONITORING

Observation wells and piezometers were installed around the gypsum disposal area to monitor changes in groundwater quality during and after construction and operation of the gypsum stack. Since no "impermeable" liner was installed within the gypsum stacking area, some impact on the aquifers was anticipated. Due to the relatively impervious nature of the underlying soils and temporary nature of the stack, however, the impact was expected to be acceptable and locally isolated immediately below and adjacent to the stack. Accordingly, the observation wells and piezometers were installed close to the stack to detect changes in groundwater quality at the earliest possible time. The locations and formations penetrated by the observation wells and piezometers are shown in Figure 3-17. The locations



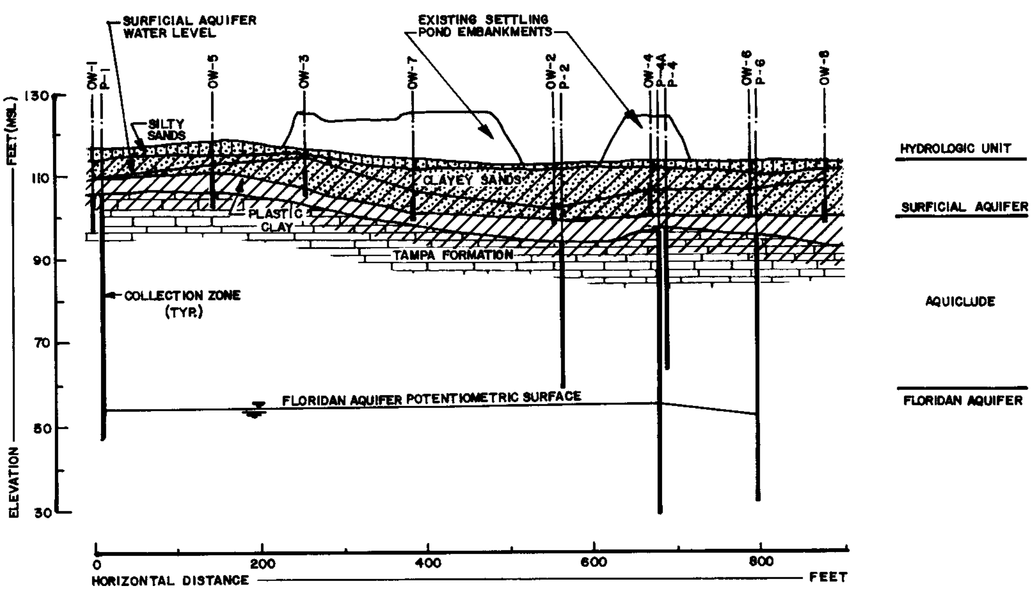


Figure 3-17. Groundwater Monitoring Location Plan And Profile

of the wells and piezometers were selected to monitor the water quality both upstream and downstream of the stack relative to the direction of groundwater flow within both the surficial and Floridan aquifers. Six observation wells (OW-2, OW-3, OW-4, OW-6, OW-7, and OW-8) have collection zones within the silty and clayey soils of the surficial aquifer. Two observation wells (OW-1 and OW-5) and two piezometers (P-2 and P-4) have collection zones within the aquiclude of the upper Tampa formation. Three piezometers (P-1, P-4A, and P-6) have collection zones within the Floridan aquifer within the Tampa formation. Methods used to install and sample the observation wells and piezometers are presented in Appendix B.

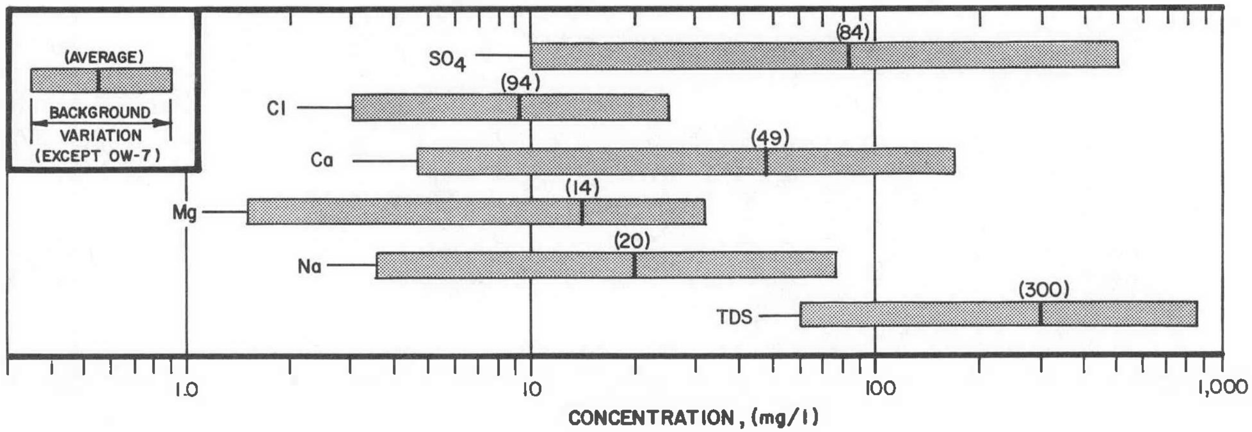
Background water quality samples were collected from each observation well and piezometer on October 4, 1978 prior to the placement of gypsum or process water within the stacking area. Subsequent water quality samples were obtained approximately once per month from each observation well and piezometer during the active life of the stack, and for one year beyond the active life of the stack, on six-month intervals. Test results from the water quality monitoring are summarized in Appendix A and discussed in subsequent sections.

Trace elements within the groundwater, which may have entered the process water from the limestone and/or fly ash removed in the pre-scrubber and Jet-Bubbling Reactor (JBR), were monitored periodically as part of the overall groundwater monitoring program. Observation wells OW-1 and OW-2 and piezometers P-4A and P-6 were used for the periodic trace element determinations. Trace elements were also determined for all observation wells and piezometers during the November 1979 sampling.

All chemical analyses were performed by Radian Corporation. The chemical analyses included major species, pH, total dissolved solids, and conductivity. Trace elements were determined by spark source mass spectroscopy (SSMS) and inductively coupled argon plasma emission spectroscopy (ICAPES). Analyses required by the Florida Department of Environmental Regulation included monthly groundwater sampling for sulfate, calcium, sodium, pH, and conductivity.

Groundwater Background Chemical Composition

As mentioned above, the background chemical composition of groundwater underlying the stacking area was obtained on October 4, 1978. These background water quality



AQUIFER		pH	CONCENTRATION, (mg/l)					
			Ca	Mg	Na	Cl	SO_4	TDS
SURFICIAL AQUIFER	OW-2	7.2	4.7	1.5	22	11	13	61
	OW-3	7.0	170	24	15	19	200	757
	OW-6	8.1	45	11	4.5	5.9	29	235
	OW-7	4.9	100	26	1230	210	2700	3780
	OW-8	6.7	7.1	2.9	20	7.7	25	83
AQUICLUDE	OW-1	8.1	99	32	88	25	510	255
	OW-5	8.4	34	13	9.5	3.0	11	232
	P-2	8.0	26	12	3.5	4.1	10	187
	P-4	8.2	34	18	15	6.1	13	211
FLORIDAN AQUIFER	P-4A	8.3	38	17	15	5.5	22	232
	P-6	8.6	29	10	3.8	6.7	11	158

Figure 3-18. Groundwater Background Chemical Composition

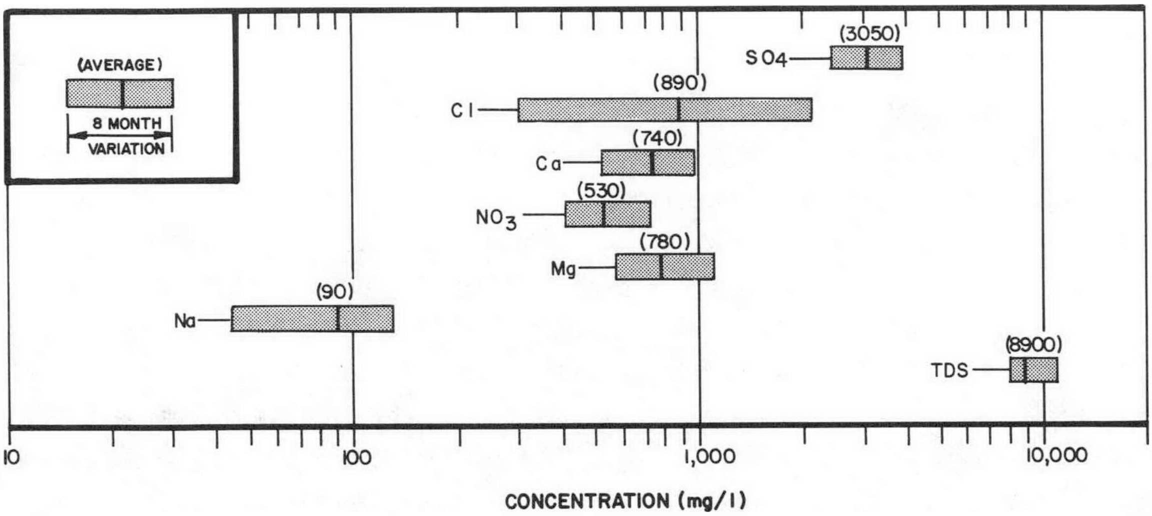
measurements are summarized in Figure 3-18. No major differences in chemical composition between the three hydrologic units (surficial aquifer, aquiclude, and Floridan aquifer) are apparent in the background data.

Observation wells OW-3 and OW-7 indicate local contamination of the surficial aquifer from existing wastes stored in the adjacent settling pond. Observation well OW-3 indicates slightly above normal levels of calcium and sulfate in comparison to observation wells OW-2, OW-6 and OW-8, which are probably the result of leachate from an existing small pile of CT-101 FGD gypsum stockpiled on the settling pond embankment only 50 feet (15.2 m) away from this well. Observation well OW-7 indicates very high levels of sodium and sulfate, which are apparently a result of leachate from the existing settling pond which contains both waste CT-101 FGD gypsum and dual alkali sludge. The background concentrations of measured constituents in OW-1 are also significantly above concentrations measured in wells and piezometers with collection zones installed at similar depths. No explanations for these high concentrations are apparent since this well is located upstream relative to the direction of groundwater flow of all waste disposal areas. Subsequent water quality measurements from OW-1 during stacking operations, however, did indicate significant reductions in all concentrations from the initial set of measurements.

Process Water Chemical Composition

The process water reaching the disposal area was monitored by Radian Corporation on a monthly basis during the life of the gypsum stack. Results from these analyses are summarized in Figure 3-19. The process water is a neutralized gypsum-saturated liquor and therefore contains high concentrations of calcium and sulfate ions. The process water is also high in chloride, magnesium, nitrate, and sodium ions.

Comparing the 8 month average values for chemical composition of the process water with the average groundwater background chemical composition (i.e., compare Figure 3-18 and 3-19) indicates the process waters are approximately 100 times higher in sulfate and chloride concentrations, 50 times higher in magnesium and total dissolved solids concentrations, and 10 to 20 times higher in calcium and sodium concentrations than the groundwater.



SAMPLING DATE	pH	CONCENTRATION, (mg/l)						
		Ca	Mg	Na	Cl	SO_4	TDS	NO_3
11-29-78	7.4	560	580	58	330	3250	—	450
1-16-79	7.6	516	656	44	305	3100	—	422
2-14-79	7.7	668	1090	72	386	3860	9260	445
3-13-79	7.9	712	688	100	566	3260	7712	725
4-12-79	7.2	825	756	121	1000	2910	8710	600
5-18-79	6.5	981	841	130	2050	2570	10900	645
6-26-79	7.6	912	839	101	1590	2430	8110	420

Figure 3-19. Process Water Chemical Composition

Changes In Aquifer Water Quality

Changes in aquifer water quality due to leachate from the gypsum stack were compared to primary drinking water standards of the United States Environmental Protection Agency and the United States Public Health Service (5, 6). A list of recommended and maximum permissible concentration limits for the primary drinking water standards from these agencies is presented in Table 3-1 (7).

The primary drinking water standards were selected for evaluating the impact of leachate from the gypsum stack since: (1) the groundwater within the Floridan aquifer is often locally used as a source of drinking water, (2) groundwater within the aquifers satisfied the drinking water standards at most of the monitoring locations prior to constructing the stack, and (3) the primary drinking water standards are being used by the Environmental Protection Agency in the toxicity tests for identifying hazardous wastes under the RCRA requirements.

Although varying initial groundwater chemical composition, leachate from adjacent waste disposal areas, and anisotropic seepage conditions near the gypsum stack influenced the migration of leachate from the disposal area, five significant observations are apparent in water quality data obtained during the nine-month active life of the stack and five-month period following the process shutdown:

- No consistent increase in trace elements has occurred in either the surficial or Floridan aquifer. Levels of arsenic, chromium, and selenium, the trace elements of major pollution concern, are generally within acceptable primary drinking water standards.
- Observation wells and piezometers within the aquiclude separating the surficial and Floridan aquifers (i.e., P-2 and P-4) show no change in water quality since construction of the gypsum stack.
- Leachate has not affected water quality within deeper units of the Floridan aquifer as evidenced by no change from background conditions at Plant Well No. 2 within the Suwannee limestone.
- Leachate has entered the Floridan aquifer within the upper units of the Tampa formation immediately below the gypsum stack as evidenced by consistent increases in all monitored parameters within piezometers P-4A and P-6.
- The surficial aquifer adjacent to the gypsum stack in the direction of groundwater flow (i.e., southeast of the gypsum stack) shows contamination in observation wells OW-6 and OW-2, as evidenced by increases in all monitored parameters.

Table 3-1

DRINKING WATER STANDARDS

Constituent	Recommended Concentration Limit* EPA (mg/l)	USPHS
Total dissolved solids	500	500
Chloride (Cl)	250	250
Sulfate (SO_4)	250	250
Nitrate (NO_3)***	45	10 (as N)
Iron (Fe)	0.3	0.3
Manganese (Mn)	0.05	0.05
Copper (Cu)	1.0	1.0
Zinc (Zn)	5.0	5.0
Hydrogen sulfide (H_2S)	0.05	None
	Maximum Permissible Concentration EPA (mg/l)**	**USPHS**
Arsenic (As)	0.05	0.05
Barium (Ba)	1.0	1.0
Cadmium (Cd)	0.01	0.01
Chromium (Cr)	0.05	0.05
Selenium (Se)	0.01	0.01
Antimony (Sb)	0.01	None
Lead (Pb)	0.05	0.05
Mercury (Hg)	0.002	None
Silver (Ag)	0.05	0.05
Fluoride (F)	1.4 - 2.4†	1.3

Source: Adapted from Groundwater, 1979, p. 386.

* Recommended concentration limits for these constituents are mainly to provide acceptable esthetic and taste characteristics.

** Maximum permissible limits are set according to health criteria.

*** Limit for NO_3 expressed as N is 10 mg/l.

† Limit depends on air temperature of the region; fluoride is toxic at about 5-10 mg/l if water is consumed over a long period of time.

Floridan Aquifer Water Quality. Water quality versus time within the Floridan aquifer immediately below the gypsum stack is summarized in Figure 3-20. These data, combining the monthly measurements from piezometers P-4A and P-6, indicate leachate from the gypsum stack is entering the Floridan aquifer within the upper units of the Tampa formation. Concentrations of sulfate, calcium, chloride, nitrate, and total dissolved solids are shown to increase above background levels abruptly between December 1978 and January 1979, only 2.5 to 3.5 months after initial deposition of gypsum within the disposal area. At the end of the test program in June 1979, the levels of sulfate, nitrate, and total dissolved solids of 600, 110, and 1200 mg/l, respectively, are above acceptable concentrations for drinking water. Although chloride concentrations increased considerably above the background level of 7 mg/l to 125 mg/l, they remain within the primary drinking water standard of 250 mg/l. Concentrations for all constituents within piezometer P-4A were consistently greater than concentrations within piezometer P-6 which should be expected since piezometer P-4A is slightly closer to the stack.

A comparison (Figure 3-21) of water quality versus depth at monitoring Station 4, consisting of OW-4, P-4, and P-4A, generally indicates that at this location only the Floridan aquifer has been affected by leachate from the gypsum stack. This result suggests leachate is not entering the Floridan aquifer by vertical seepage at this location, but rather reaching piezometer P-4A by horizontal flow within the Floridan aquifer. Leachate entering the Floridan aquifer, therefore, is probably seeping vertically downward beneath the gypsum stack through a sand-filled breach in the clayey sand, plastic clay, and upper unit of the Tampa formation into the Floridan aquifer and then seeping horizontally within the aquifer toward piezometer P-4A.

Water quality within the Floridan aquifer affected by leachate can be expected to improve with time since: (1) water levels within the stack and perimeter ditch are now at lower elevations than existed during the active life of the stack and, hence, have reduced the hydraulic head causing seepage from the stack, and (2) mechanical dispersion and diffusion of the leachate plume within the Floridan aquifer with time will reduce the chemical constituent concentrations.

Plant Well No. 2 is approximately 250 feet (76.2 m) east of the disposal area with a collection zone within the Floridan aquifer in the upper Suwannee limestone approximately 135 to 165 feet (41.2 to 50.3 m) below ground surface. No change in water quality is apparent over the 9 month test period as shown in Figure 3-22.

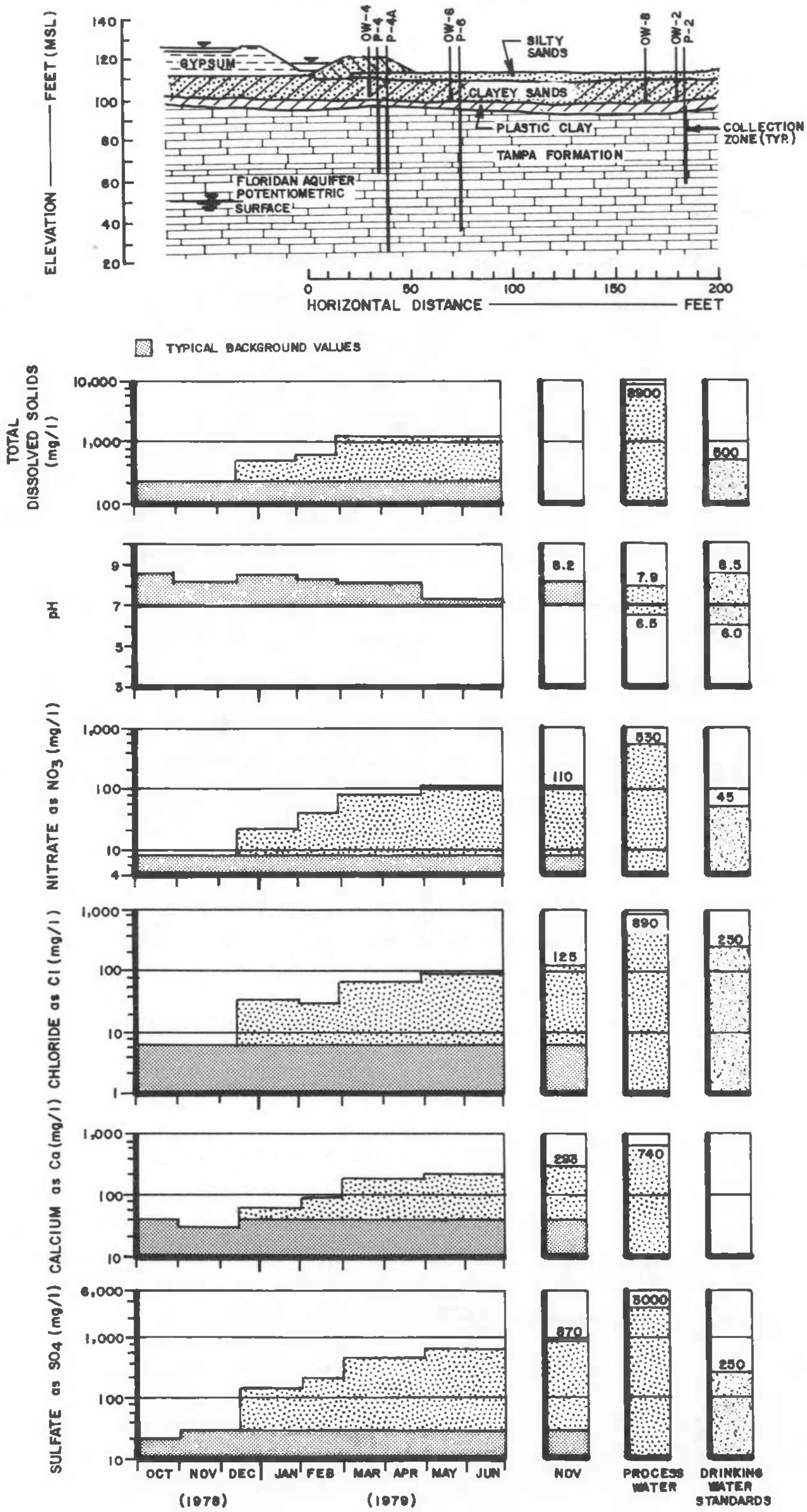


Figure 3-20. Floridan Aquifer Water Quality at Piezometers P-4A And P-6

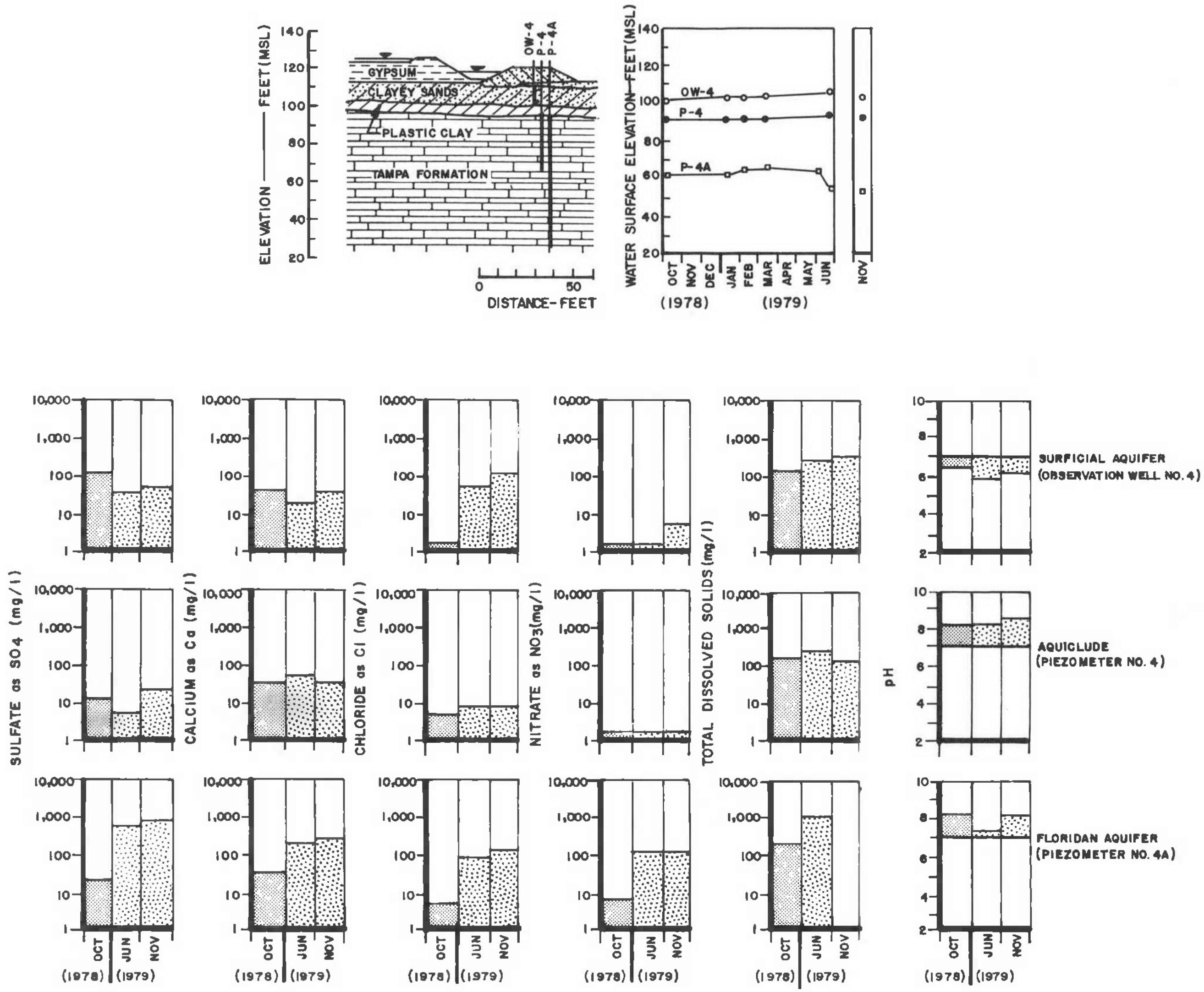


Figure 3-21. Water Quality Versus Depth at Monitoring Station No. 4

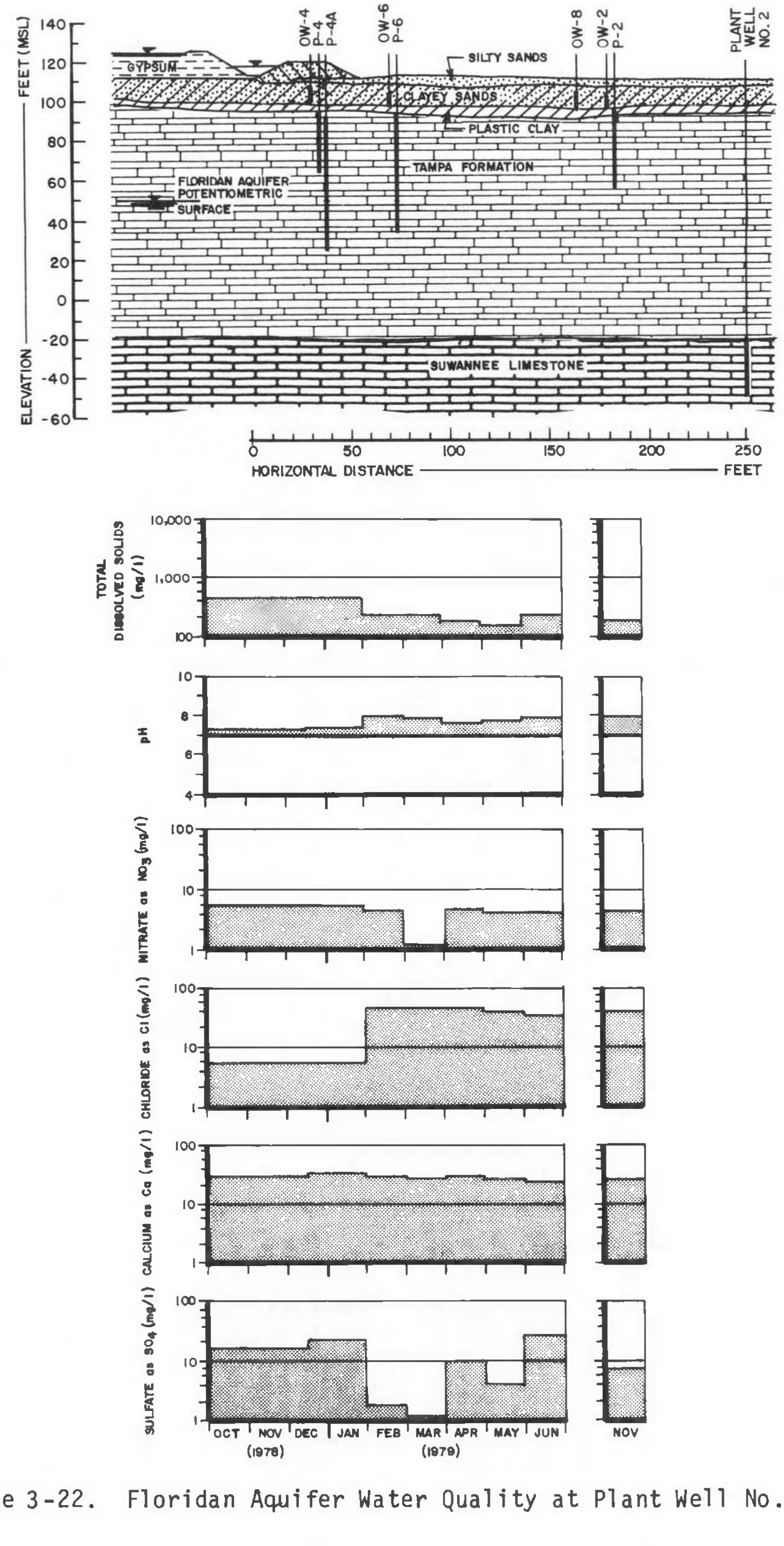


Figure 3-22. Floridan Aquifer Water Quality at Plant Well No. 2

Concentrations for all measured constituents in this well show no increasing trend with time. During operation, Plant Well No. 2 lowers the water surface within the Floridan aquifer approximately 10 to 15 feet (3.1 to 4.6 m) at the well casing. The local direction of groundwater flow within the Floridan aquifer, therefore, is toward the plant well. Since no leachate has been detected at the plant well, the leachate plume appears to be locally concentrated below the gypsum stack within the upper Tampa formation and either not entering the Suwannee limestone or being very effectively diluted by mechanical dispersion prior to reaching the plant well.

Surficial Aquifer Water Quality. Observation wells OW-6 and OW-2 within the surficial aquifer immediately adjacent to the stack indicate increasing concentrations of all measured constituents with time. Figure 3-23 summarizes water quality versus time at OW-6 and OW-2. Water quality data from observation well OW-8, which indicated no change in groundwater quality due to leachate contamination, are also included for comparison.

As shown, the levels of sulfate, chloride, nitrate, and total dissolved solids in OW-2 and OW-6 increased to 5 to 20 times above background levels and are generally above acceptable drinking water standards. Observation well OW-8, approximately the same distance from the gypsum stack as OW-2, indicates no change in groundwater quality. Leachate from the gypsum stack within the surficial aquifer, therefore, appears to be flowing in a southeasterly direction away from the stack. Water level readings from observation wells OW-8, OW-6, OW-4, and OW-2 also generally confirm the direction of surficial groundwater flow to be in a southeasterly direction.

Observation well OW-4 installed on the existing settling pond embankment immediately adjacent to the gypsum stack generally indicates no change in groundwater quality. This result is surprising, since leachate is locally entering the surficial aquifer as shown by OW-6 and OW-2. The absence of contamination within the surficial aquifer at OW-4 and OW-8 indicates leachate is seeping within the surficial aquifer within a relatively small area from the wall of the starter dike along a path from OW-6 towards OW-4.

Observation wells OW-3 and OW-7 indicated some local groundwater contamination of the surficial aquifer from the CT-101 FGD gypsum and dual alkali sludge stored in the existing settling pond. These wells, therefore, should not be considered

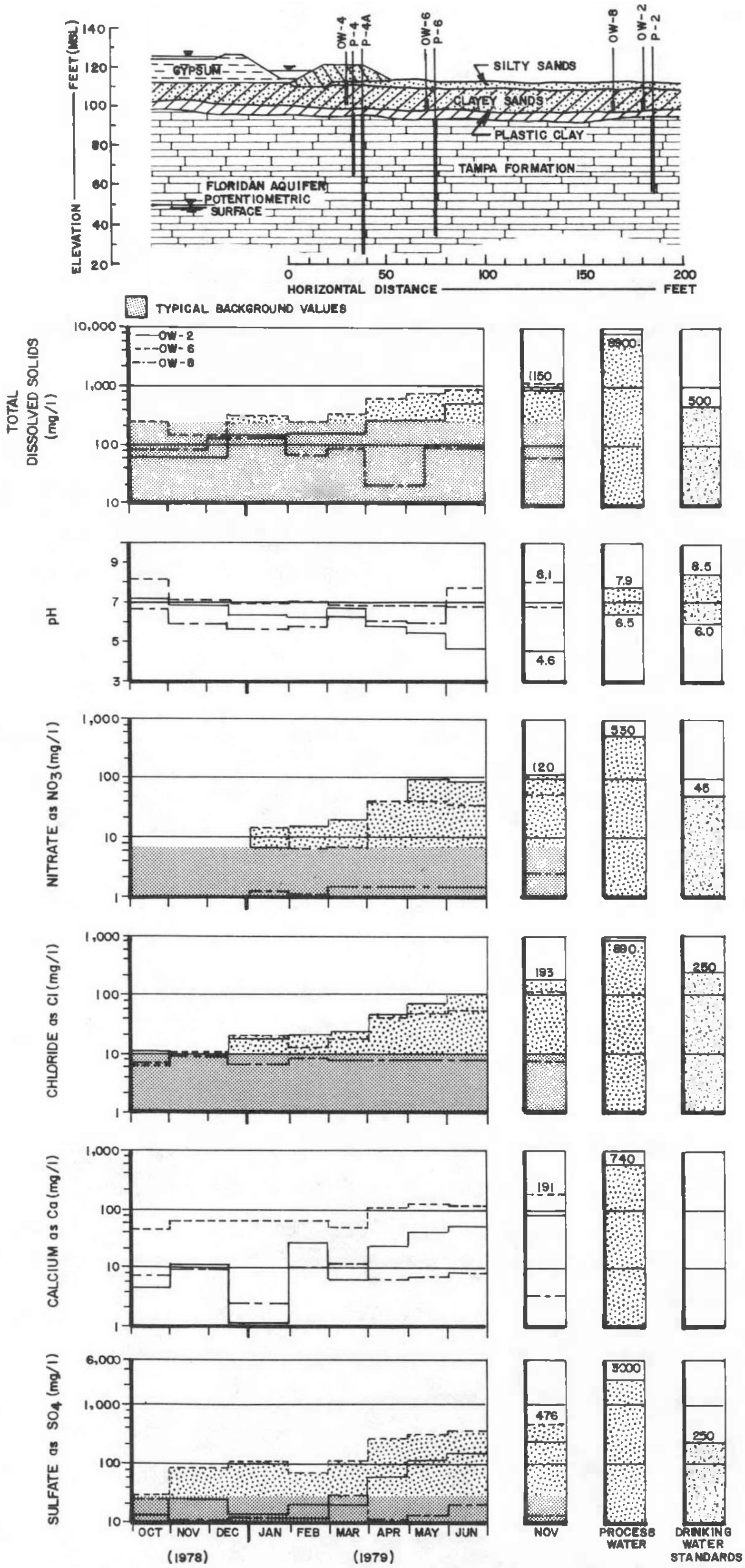


Figure 3-23. Surficial Aquifer Water Quality at Observation Wells OW-2, OW-6 & OW-8

when evaluating changes in groundwater quality due to construction of the gypsum stack, since their local concentration levels were already above the normal background levels in the aquifers underlying the stack.

Aquiclude Water Quality. Water quality within the aquiclude separating the surficial and Floridan aquifers has not changed significantly during the active life of the stack. The absence of contamination within the aquiclude at locations where the surficial or Floridan aquifers are contaminated (i.e., OW-2 and P-4A) indicates leachate is flowing horizontally within the surficial and Floridan aquifers, but not within the aquiclude.

Trace Elements. Trace element determinations by SSMS and ICAPES for the process water, piezometers P-4A and P-6 within the Floridan aquifer, observation well OW-1 within the aquiclude, and observation well OW-2 within the surficial aquifer are shown in Appendix A, Tables A-8 through A-11. Primary drinking water standards of the USPHS and EPA are also included for comparison.

The concentrations of lead, copper, silver, cadmium and zinc within the process water are close or within drinking water standards and pose no groundwater contamination problem. Levels of selenium, arsenic, and chromium within the process waters are 20, 15, and 5 times greater than acceptable drinking water standards, respectively.

Background trace element concentrations were determined on October 4, 1978 prior to placement of gypsum or process water within the stacking area. The process water trace element concentrations represent the average of several determinations on samples obtained from May 12 through May 15.

Figure 3-24 presents measurements of trace element concentrations within the Floridan aquifer for the elements of major pollution concern: arsenic, chromium, and selenium. The measurements of nickel are also presented since the concentrations of nickel is one of the highest in the trace elements. Although the concentrations of major species within the Floridan aquifer have increased with time, the trace elements show no consistent increasing trend.

Table A-11 presents trace element determinations for samples obtained on November 29 from all observation wells and piezometers. These data indicate:

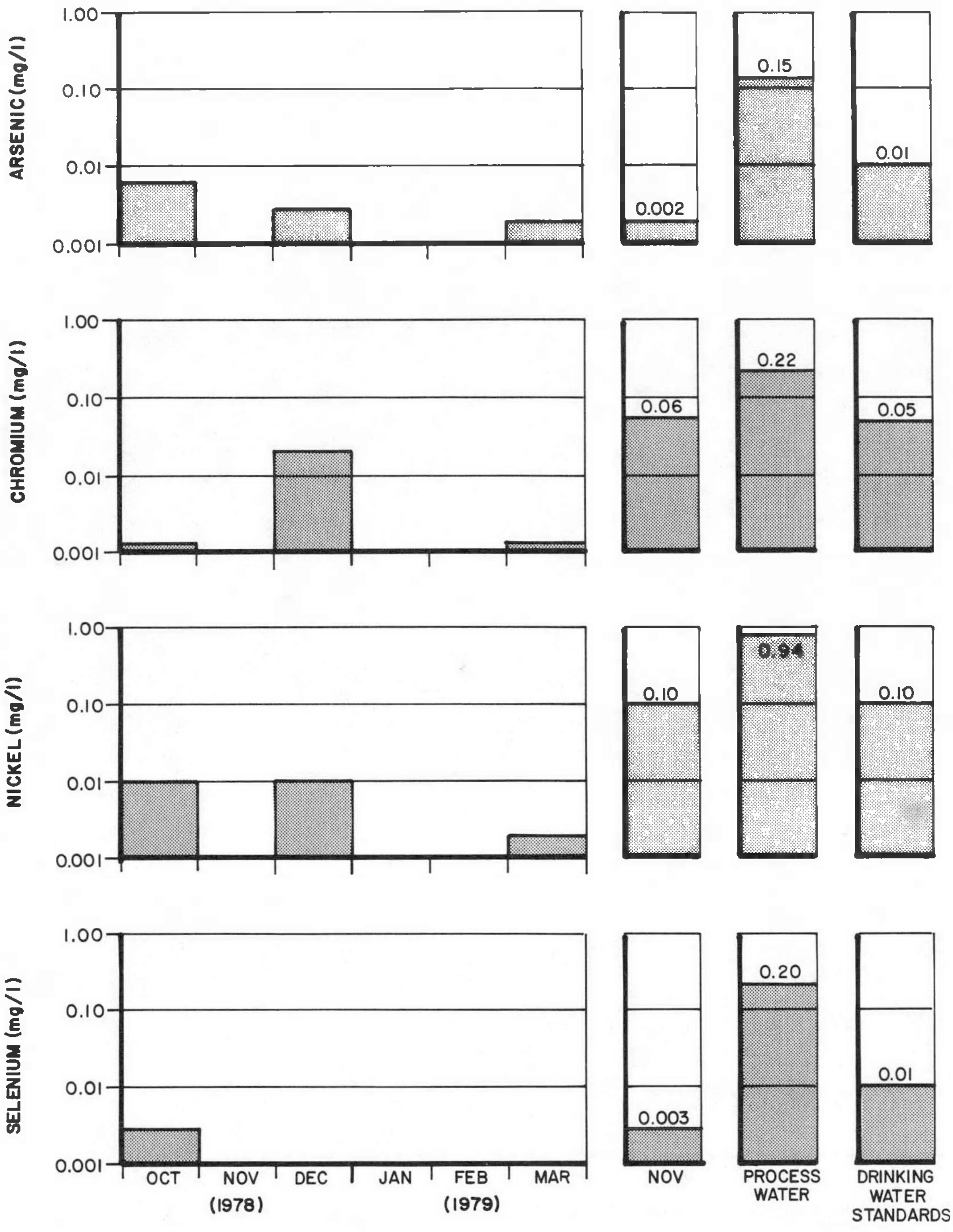


Figure 3-24. Trace Elements in Floridan Aquifer at Piezometers P-4A And P-6

- Concentrations of silver, barium, copper, zinc, beryllium, antimony, and lead are within safe drinking water standards.

- Concentrations of arsenic and selenium, which exceed acceptable drinking water standards in the process water, are within safe drinking water standards in the groundwater.

- Concentrations of chromium, which exceed acceptable drinking standards in the process water, are within safe drinking water standards at all monitoring locations except OW-6 and P-4A (neglecting OW-7 because of existing groundwater contamination). At these two locations the concentrations of chromium exceed drinking water standards by 40 and 20 percent, respectively.

- Cadmium, iron, and manganese concentrations occasionally exceed drinking water standards but were either not detected in the process water or the process water concentration was less than the groundwater concentration.

- Nickel and vanadium concentrations exhibit some increasing trend with time with the November 1979 concentrations 5 to 20 times higher than the October 1978 concentrations. Although no USPHS or EPA drinking water standards exist for nickel, the measured concentrations are generally within the 0.1 mg/l recommendation of Chapter 17-3 of the Florida Administrative Code.

As with phosphate gypsum stacks, groundwater contamination from the CT-121 FGD scrubber process waters is a concern. The CT-121 process waters contain concentrations of sulfate, calcium, chloride, nitrate, magnesium, and sodium that are several orders of magnitude greater than drinking water standards as well as natural background levels within the aquifers at Plant Scholz. Trace elements such as arsenic, chromium, and selenium are also present within the process water above drinking water standard and may pose a contamination problem. For the stacking of CT-121 FGD gypsum to be environmentally acceptable over the long-term operation of a full-scale stack, therefore, the seepage of leachate must be controlled or prevented. Surface and groundwater surrounding these stacks must also be monitored to indicate the effectiveness of the selected seepage control measures and to provide sufficient warning if remedial seepage control measures become necessary.

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Section 4

DESIGN AND MANAGEMENT OF GYPSUM STACKS

INTRODUCTION

Gypsum stacking has been successfully utilized by the phosphate industry for disposal of waste by-product gypsum for more than 20 years. Although the specific crystal geometry, particle size, and engineering properties of phosphate gypsum vary considerably between phosphate fertilizer plants, the overall settling, dewatering, and structural characteristics of waste gypsum always have been favorable for stacking methods of waste disposal. Some basic concepts concerning the design and management of gypsum stacks in the phosphate industry, which may be adopted by the utility industry, are briefly discussed in this section to illustrate the stacking method of waste disposal.

Gypsum stacks in the phosphate industry typically are 50 to 300 acres ($2.0x10^5$ to $1.2x10^6$ m^2) in area and reach heights of 100 to 150 feet (30.5 to 45.7 m). The selected area and height of the stack are normally governed by gypsum production rates, land availability, foundation conditions, operations costs, and perhaps aesthetic considerations. Gypsum stack areas and production rates at several phosphate fertilizer plants in Florida are presented in Table 4-1. As shown, typical plants produce on the order of 1,000,000 to 2,000,000 tons ($9.1x10^8$ to $1.8x10^9$ kg) of gypsum per year and use stack areas of approximately 100 acres ($4.0x10^5$ m^2). Several individual stacks are normally constructed over the life of a plant. The gypsum stack shown in Figure 1-1, for example, is approximately 100 acres ($4.0x10^5$ m^2) and varies from 50 to 100 feet (15.2 to 30.5 m) in height.

UPSTREAM METHOD OF CONSTRUCTION

Stacking waste gypsum normally utilizes the upstream method of construction. In this method, illustrated in Figure 4-1, an earthen starter dike is first constructed to form a sedimentation pond and stacking area. Gypsum is then pumped to the sedimentation pond in slurry form, usually at 10 to 20 percent solids, and allowed to settle and drain. Process water is decanted from the pond and returned to the plant. Once sufficient gypsum is deposited within the pond, gyp-

Table 4-1

TYPICAL GYPSUM STACK AREAS AND PRODUCTION RATES AT PHOSPHORIC ACID PLANTS

Company and Location	Gypsum Stack (Acres)	Annual Production (Tons Per Year)
Agrico Chemical Company South Pierce, Florida	250	1,000,000
Borden Chemical Company Piney Point, Florida	100	900,000
Gardinier, Inc. East Tampa, Florida	260	5,500,000
Central Phosphates Zephyrhills, Florida	100	1,000,000
C. F. Chemicals, Inc. Bartow, Florida	200	2,500,000
Farmland Industries, Inc. Green Bay, Florida	60	2,300,000
W. R. Grace & Company Bartow, Florida	75	1,600,000
Occidental Chemical Company White Springs, Florida	100	1,000,000
U.S.S. Agri-Chemicals		
Bartow, Florida	80	1,500,000
Fort Meade, Florida	80	600,000

Source: Florida Department of Natural Resources, Special Publications No. 18, 1972, p.3.

Note: 1.0 Acre = 4047 m^2; 1.0 ton/year = 907 kg/year

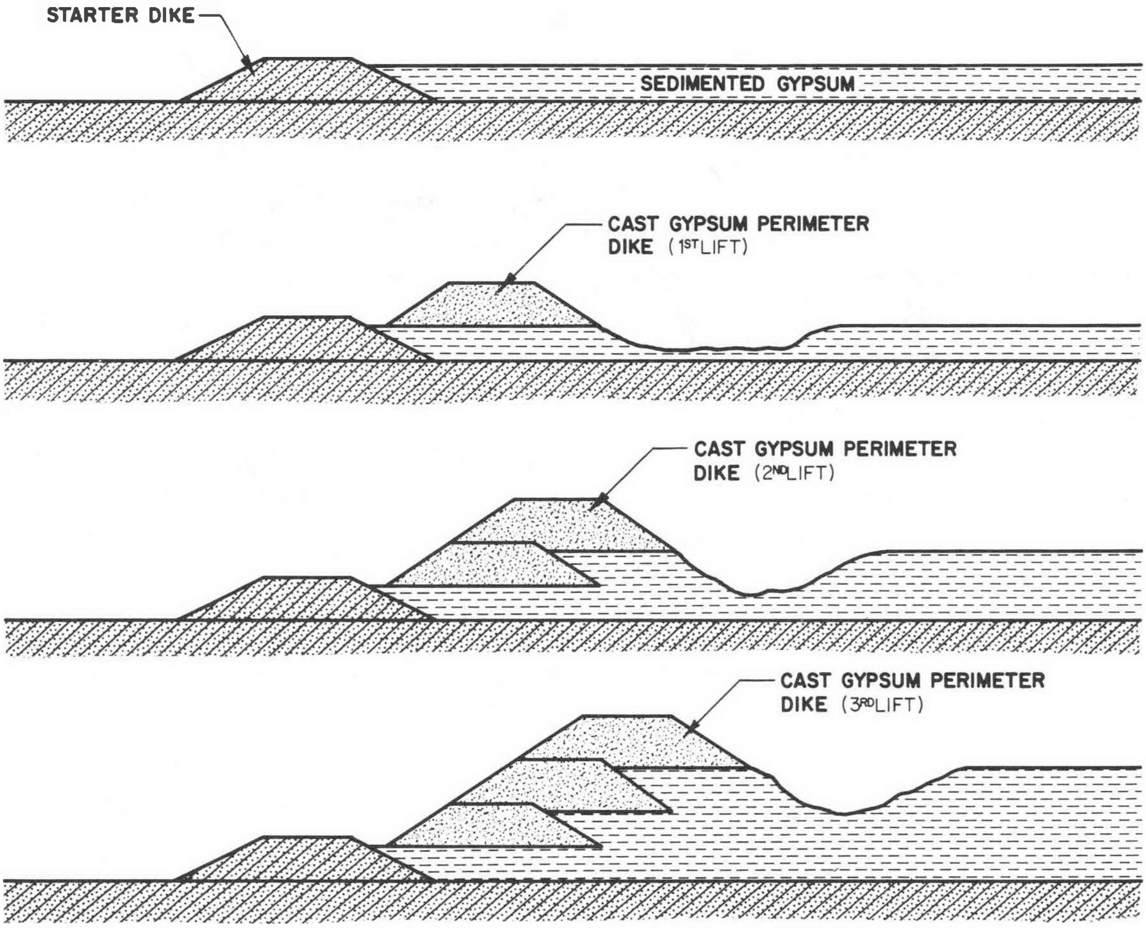


Figure 4-1. Upstream Method of Gypsum Stack Construction

sum is excavated with a dragline to raise the perimeter dikes of the stack. The draglines typically have a working reach of 60 feet (18 m) and a 2 to 3 cubic yard (1.5 to 2.3 m^3) bucket. The process of sedimentation, excavation, and raising of the perimeter dikes continues on a regular basis during the active life of the stack.

Using the upstream method of construction, gypsum stacks have reached heights exceeding 100 feet (30.5 m) with slopes of 1.5 Horizontal to 1.0 Vertical, which is approximately the angle of repose of some gypsums. These steep slopes result from casting the gypsum with a dragline and allowing some gypsum to roll down the outside of the stack to eliminate shaping. Therefore, the gypsum perimeter dikes of some stacks have a factor of safety very close to unity and from a conventional geotechnical engineering point of view, failures of gypsum stacks sometimes occur.

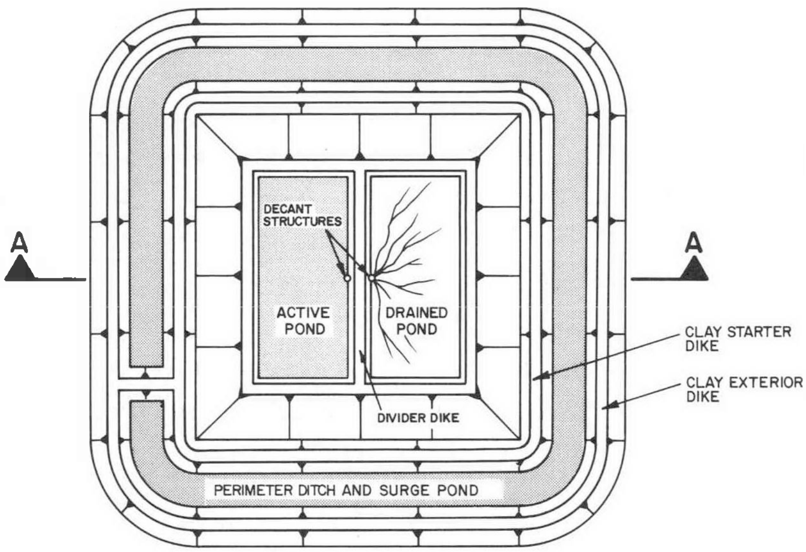
Fortunately, gypsum is a very forgiving material and, unlike most mine tailings, gypsum does not readily flow. Therefore, the consequence of these failures are usually not dramatic. The most serious consequence of a failure is the loss of process water stored on the gypsum stack. If process water escapes the plant property, liabilities from pollution and environmental damage may also result.

LAYOUT OF DISPOSAL AREAS

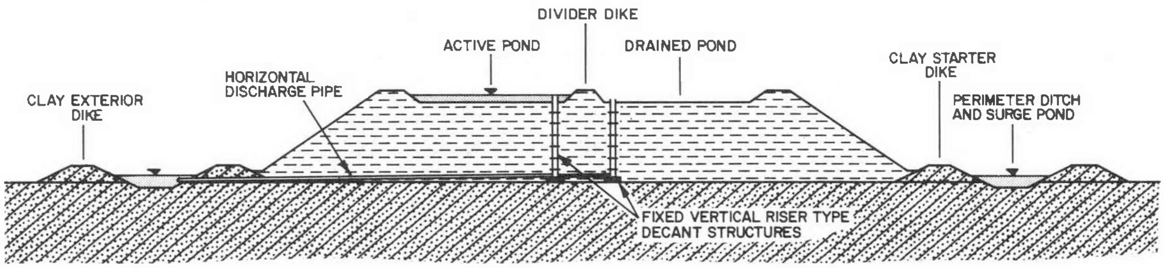
The experience gained from the operation and performance of phosphate gypsum stacks may be used in planning FGD gypsum stacks. An illustration of a typical stack design is shown in Figure 4-2. The specific features included in this stack are discussed below.

In plan, the gypsum stack should be a square or a rectangle with a two to one length to width ratio. Ideally, a circular shape would give the minimum length of perimeter dike enclosing a given area. When a divider dike is included to separate the stack into two ponds, however, the difference in length of perimeter dike between a square or rectangular stack with a two to one length to width ratio and a circular stack is only 7 percent.

The required area of the gypsum stack should be selected to allow raising the perimeter dikes approximately 5 to 8 feet per year (1.5 to 2.4 m/year). For a typical central Florida phosphate fertilizer plant where the production rate of



GYPSUM STACK SITE PLAN



SECTION A-A GYPSUM STACK CROSS SECTION

Figure 4-2. Typical Gypsum Stack Design

gypsum is 2,700 to 5,500 tons per day ($2.4x10^6$ to $5.0x10^6$ kg/day), gypsum stacks have been proportioned for 11 to 170 tons per day per acre (2.5 to 38.1 kg/day/m^2) with an average from eleven plants of 55 tons per day per acre (12.3 kg/day/m^2). For a 2000 megawatt power plant burning 2 percent sulfur coal and assuming the rough rule of thumb from the CT-121 prototype FGD scrubber of one ton of waste gypsum per day per megawatt, approximately 2000 tons ($1.8x10^6$ kg) of gypsum would be produced per day. For this production, a stacking area of approximately 85 acres ($3.4x10^5$ m^2) would be required if the stack were raised 5 feet (1.5 m) per year. A 100-foot (30.5 m) high gypsum stack, therefore, could be utilized for approximately 20 years of operation.

The gypsum stack is divided into at least two ponds. This allows one pond to drain while the other pond is in use. The dragline can then excavate gypsum from the drained pond for raising of the perimeter dike. The divider dike runs parallel to one side of the stack and divides the stack into ponds of approximately equal size.

The depth of water within the active pond should be kept to a minimum for safety reasons in the event of accidental spillage. Sufficient water must be kept in the pond, however, to allow sedimentation of the gypsum to occur and to allow the process water to clarify as much as possible before decanting. A depth of 1 to 3 feet (0.3 to 0.9 m) is typical for many phosphate gypsum stacks.

The process water surge pond is placed completely around the perimeter of the gypsum stack. The exterior dike forming the surge pond has sufficient freeboard to contain water stored on top of the gypsum stack in the event of accidental spillage. The surge capacity of the pond is typically designed to contain the normal fluctuations in operating levels depending on the water balance and 1.5 times a 25 year, 24 hour storm on the watershed of the pond with no storage on the gypsum stack. Freeboard clearance above the maximum fluid level in the pond can vary from 3 to 5 feet (0.9 to 1.5 m) and is normally governed by local regulations. For certain site conditions, a scheme of surrounding the stack with the surge pond has advantages with respect to controlling groundwater contamination and groundwater seepage.

A clay starter dike is shown in the illustration and is preferred if suitable clay material is available. Sand dikes are commonly used in Florida, but must be protected against piping, erosion, and seepage. The starter dike should be constructed to a crest width of 20 feet (6.1 m) to allow easy operation of construction equipment and should not be covered with gypsum when the stack is raised. The starter dike should be high enough to allow sufficient gypsum to sediment within the stacking area for excavation and raising of the first lift of the perimeter dike. A minimum starter dike height of 8 feet (2.4 m) allowing sedimentation of 5 feet (1.5 m) of gypsum and 3 feet (0.9 m) of freeboard is usually sufficient.

Fixed vertical riser type decant structures are shown in the center of the stack near the divider dike so that finer gypsum settles at the center of the stack and coarser gypsum around the perimeter of the stack. This is not an essential feature; however, it does eliminate the problems of trying to use soft, fine, and wet gypsum in construction of the perimeter dikes. The hydraulic capacity of the decant structure must be sufficient to discharge the normal process flow and selected rainfall event. For a 2000 megawatt power plant burning 2 percent sulfur coal and assuming the rough rule of thumb from the CT-121 prototype FGD scrubber of one ton (907 kg) of waste gypsum per day per megawatt, approximately 2000 tons ($1.8x10^6$ kg) of gypsum would be produced per day. Pumping a gypsum slurry to the stack at 10 percent solids would require a normal process flow of about 3000 gallons per minute (0.19 m^3/sec).

DESIGN CONSIDERATIONS

Planning Aspects

The planning of a gypsum stack and process water return system typically involves the consideration of several environmental, construction, and operational factors. Environmental factors normally considered include: (1) the environmental sensitivity of adjacent land and water, (2) prevalent wind directions, (3) evaporation and rainfall, and (4) freeze-thaw effects. For given land availability,the location of the gypsum stack should obviously be selected to minimize adverse environmental impacts on adjacent land and water. Prevalent wind directions should be considered when locating the stack to minimize, if possible, the amount of wind blowing across the stack toward the plant or other developed areas. Evaporation and rainfall affect the water balance of the process and the required storage capacity of the surge pond. If the plant is located in climates where severe cold winters occur, the effects of freezing on the design of the stack and process water return system, as well as the effect on limiting the construction season, must be considered.

Operational considerations typically include an estimate of gypsum production, the planned life of the plant and stack, in-flow and out-flow process water quantities, pumping costs, and dragline operations and maintenance. An estimate of gypsum production and plant life are necessary for sizing the disposal area. Similarily, process water quantities must be known for sizing the process water return system and sizing the stack for sufficient retention time to properly clarify the process water. The location and height of the stack may sometimes be controlled by pumping considerations, although pumping is usually not a major problem except for very high stacks. The scheduling of dragline operations depends on the size of the stack, quantity of gypsum production, and limitations on construction due to adverse weather.

Constuction factors requiring consideration include the availability of suitable borrow materials for construction of the initial starter dikes and surge pond dikes. If feasible, materials for constructing the initial starter dike and surge pond dike can be borrowed from within the stacking area. If clay liners or internal drainage systems are used, the availability of suitable materials for their construction must also be considered.

Stability

Gypsum stack slopes are normally constructed with factors of safety close to unity since the perimeter dikes are essentially formed at the angle of repose by casting the gypsum with a dragline and allowing some gypsum to roll down the outside of the stack to eliminate shaping. Because of the low safety factors, the depth of ponded water within the stack is kept to a minimum. In addition, the area within the stack is normally divided into at least two ponds so that if a slope failure occurs in one pond the incoming slurry can be diverted into an inactive pond. The gypsum stack shown in Figure 1-1, for example, is divided into five separate ponds.

At least two modes of failure are normally considered in evaluating the stability of gypsum stacks:

- The deep seated bearing capacity type failure is primarily controlled by the strength of the underlying foundation soils. This is illustrated in Figure 4-3 where the circular failure surface penetrates the foundation soils. Alternatively, the sliding wedge mode of failure along the interface of the gypsum stack and underlying foundation soils may prove more critical.

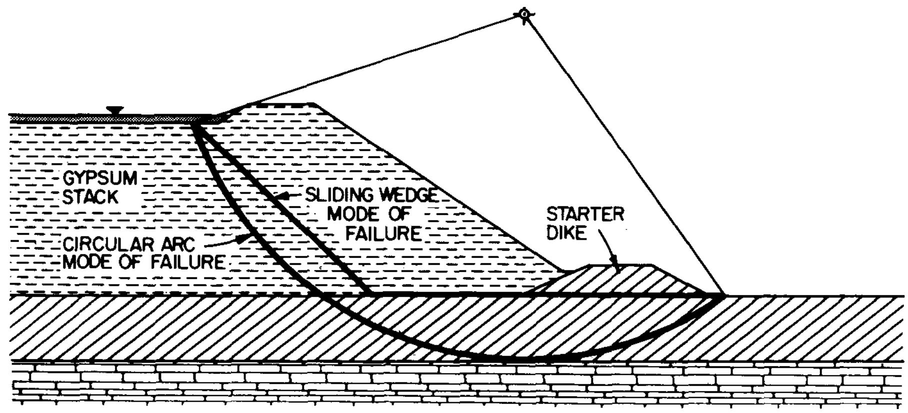


Figure 4-3. Bearing Capacity Type Foundation Failure

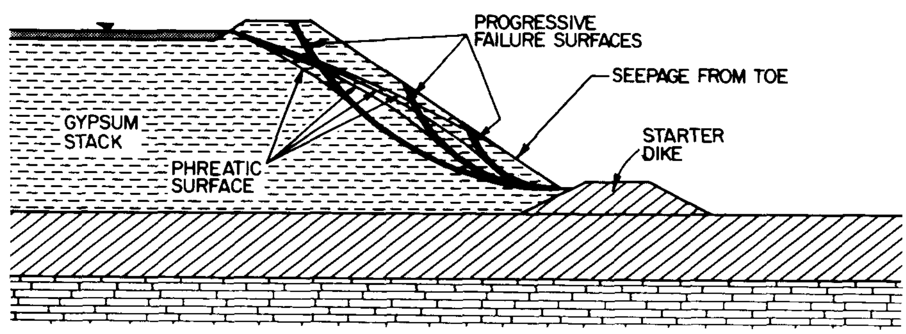


Figure 4-4. Progressive Type Slope Failure

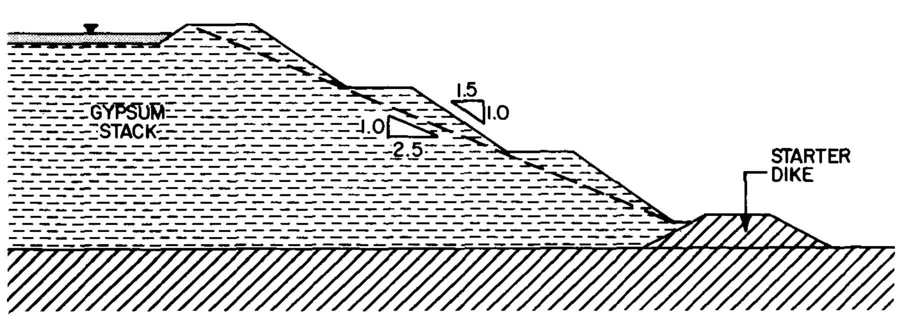


Figure 4-5. Flattening Gypsum Stack Slopes By Benching

In both analyses, the primary controlling factor is the strength of the foundation soils and not the strength of the gypsum. The most probable failure surface and critical mode of failure are found by trial and error procedures and represent conditions that yield the minimum factor of safety. In stability analyses, the factor of safety is defined as the summation of the shear strengths along the failure surface divided by the summation of the shear stresses along the same surface. Flattening the outside slope of the gypsum stack and the use of berms increases the stability of the foundation and allows construction of a higher gypsum stack. For a given stacking area and height, however, these measures reduce the available storage capacity.

- Seepage instability and progressive failure of the gypsum stack slopes is controlled by the strength properties of the gypsum and the seepage pattern through the gypsum stack. A progressive failure (Figure 4-4) may start by local instability at the toe of the slope below the springline where seepage is exiting the face of the stack. The failure starts by a small slide or slough, followed by a working back as progressive sloughing removes more of the support at the toe of slope. Where progressive failure from seepage instability is a potential problem, flatter slopes (i.e., on the order of 3.0 Horizontal to 1.0 Vertical or flatter) must be used below the springline.

A small amount of cohesion from cementation of the gypsum has considerable influence on the factor of safety of the gypsum stack slopes, particularly with regard to seepage instability below the springline. Phosphate gypsum stacks in Florida have been constructed up to 100 feet (30.5 m) high with slopes on the order of 1.5 Horizontal to 1.0 Vertical. These stacks, however, develop cohesion from cementation.

Gypsum stacks within the phosphate fertilizer industry are generally built as steep as possible so the retention and storage capacity of the stack is maximized. The steep slopes result because each time the perimeter dike is raised, the cast gypsum dike is essentially contructed at the angle of repose of the gypsum. If an average slope flatter than the angle of repose is required for stability, the perimeter dikes are generally offset from the outer perimeter as shown in Figure 4-5 to form benches in the slope. This eliminates the need for shaping the perimeter dike slopes which are simply cast and allowed to develop slopes corresponding to the angle of repose of gypsum.

Seepage

In evaluating the stability of gypsum stacks, it must be assumed that sufficient water is available on top of the gypsum stack to develop the full seepage pattern.

While this water should be kept to a minimum for safety reasons, it cannot be completely eliminated, because gypsum is continuously deposited hydraulically on top of the stack. Rain water can also keep the gypsum stack saturated.

Figure 4-6 shows a flow net constructed for a gypsum stack on a pervious foundation. Under these conditions, the flow is vertically downwards through the gypsum stack and, consequently, no seepage exits on the surface of the slope. From a stability point of view, this increases the factor of safety of the slope considerably with respect to potential sloughing and piping. However, because of cracking and solution cavities, concentrated downward seepage could develop through the stack causing the foundation sand to pipe at the toe because of high gradients in the sand which acts as a drain below the stack. Further, this downward flow could cause groundwater contamination. Under these conditions, the starter dike is not subjected to seepage and, therefore, could conceivably be constructed of any material with sufficient strength without consideration of piping.

Figure 4-7 illustrates flow through a gypsum stack on an impervious foundation. Under these conditions, the starter dike and gypsum stack slope below the springline are subjected to seepage. If the starter dike is not constructed of suitable material, problems associated with piping will result. Sloughing of the outside slope of the gypsum stack will also result unless the gypsum develops some cementation or relatively flat slopes are used.

Figure 4-8 illustrates the effect of an internal drain in eliminating the problems occurring with seepage through the gyspum stack slope and starter dike. In this case, seepage is collected in the drain and neither the starter dike nor the outside slope of the gypsum stack is subjected to seepage. While the use of an internal drain is a satisfactory solution to many stability problems, it may be relatively expensive at some sites.

GROUNDWATER CONTAMINATION

The process liquor from FGD scrubbers is either an acidic, neutral, or basic gypsum-saturated water and,therefore,can contain high concentrations of calcium and sulfate ions. Depending on the process, the liquor may also contain high concentrations of materials such as chloride and magnesium. The concentrations of these ions can be sufficiently high to pose a groundwater contamination problem. Trace elements such as selenium, arsenic, chromium, lead, copper, zinc, and silver may also be present in the process water.

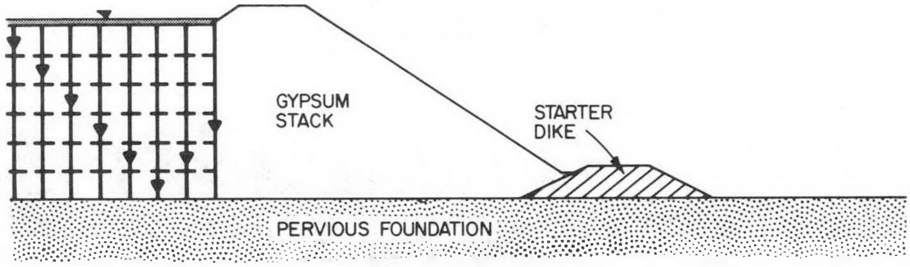


Figure 4-6. Seepage Pattern Through a Gypsum Stack on a Pervious Foundation

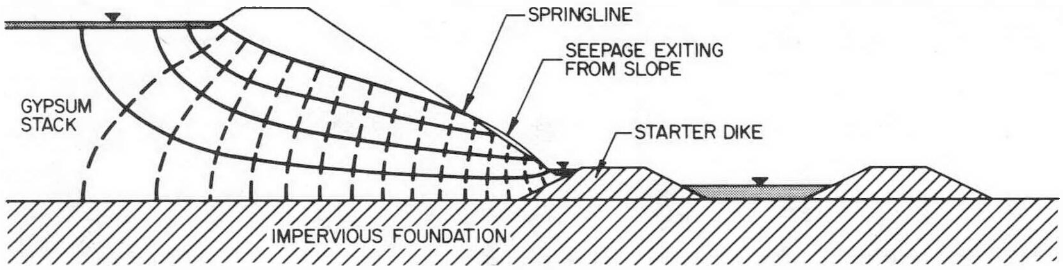


Figure 4-7. Seepage Pattern Through a Gypsum Stack on an Impervious Foundation

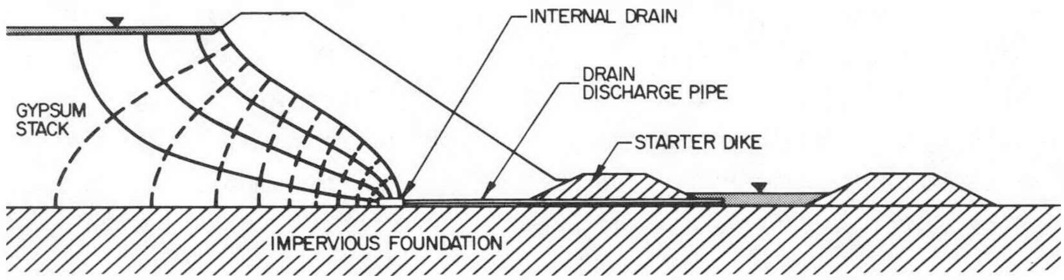


Figure 4-8. Effect of Internal Drain on Seepage Pattern Through a Gypsum Stack on an Impervious Foundation

At sites where the foundation consists of clay strata of low permeability, the quantity of seepage is usually small and contamination of a water supply source underlying the clay strata would most likely be insignificant. Further, highly plastic clays have large specific surface areas and consequently, up to the sorption capacity of the soil, are often effective in purifying the water that ultimately enters the underlying aquifers.

Frequently, gypsum stacks have been constructed directly on a relatively pervious sand stratum overlying relatively impervious clays. This has resulted in contamination of the shallow water table aquifer in the immediate vicinity of the gypsum stack. This seepage can usually be controlled by using impervious clay cutoffs or can be collected by seepage ditches or drains. Where possible, a cutoff is preferred because with a seepage collection ditch or drain, not only is process water seepage being collected, but also uncontaminated groundwater seepage and surface runoff. This can result in an unfavorable positive water balance requiring treatment of excess contaminated water.

The following examples are illustrations of methods that could be used to effectively control contamination from gypsum stacks.

Seepage Collection Ditches

The illustrations in Figures 4-9 and 4-10 show how a seepage collection ditch around the perimeter of a gypsum stack can be effective in containing groundwater contamination. When the pervious foundation is relatively thick, the ditch is fully effective only if the water level in the ditch is kept below the level of the surrounding groundwater table (Figure 4-9). If the pervious layer is relatively shallow, the ditch need only be excavated to the underlying impervious stratum. The water level in the ditch needs to be kept at or slightly below the surface of the impervious stratum (Figure 4-10).

A disadvantage of seepage collection ditches is that they add additional water to the system which must be stored and evaporated or treated before being released. However, this is not a major disadvantage for FGD systems, since make-up water requirements of the system may be at least partially, if not completely, satisfied by the addition of water from seepage. On the other hand, where feasible, a seepage collection system is frequently the least expensive means of containing seepage.

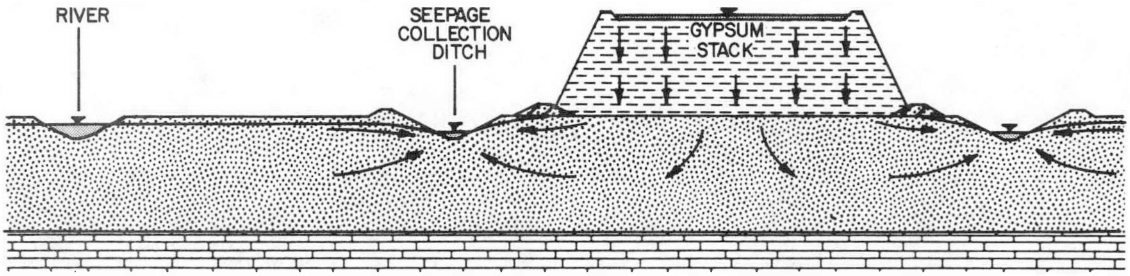


Figure 4-9. Perimeter Seepage Collection Ditch For Gypsum Stack on a Deep Sand Deposit Overlying an Impervious Foundation

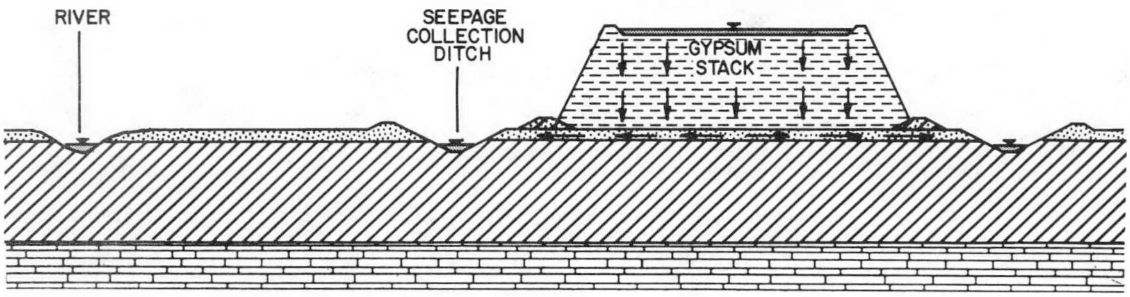


Figure 4-10. Perimeter Seepage Collection Ditch For Gypsum Stack on a Shallow Sand Foundation Overlying a Thick Clay Deposit

Impervious Cutoffs

Where the pervious foundation is relatively shallow and a trench can be excavated to the underlying impervious stratum without major dewatering problems, a cutoff trench backfilled with low permeability soil can be effective in containing contamination from a gypsum stack (Figure 3-11). Impervious cutoffs are relatively expensive when compared with seepage collection ditches, but the initial construction cost may be more than offset by the cost of treating excess water that can result when seepage collection ditches are used.

Soil Sorption Capacity

At some sites the subsurface soils may be effective in reducing the concentrations of some species within leachate from gypsum stacks by soil sorption. An analysis of the textural, chemical, and mineralogical compositions of the foundation soils, supplemented by laboratory tests on the reactivity of the soils with the process water can help determine the purification potential at a given site. In Florida, for example, where the primary aquifer is a cavernous limestone formation, the confining bed, which is composed of calcareous clays and limestones often protects the aquifer from contamination by leachate from phosphate gypsum stacks.

Impervious Liners

Where gypsum stacks must be placed on deep deposits of pervious sands adjacent to rivers or other bodies of fresh water which could become contaminated despite the groundwater controls described above, a liner can be used under the stack (Figure 4-12). Where a good quality naturally occurring clay is locally available, it can be used to form the seepage barrier. In such cases,an extensive study is required to determine the suitability of the clay as a liner. The effectiveness of a clay liner can be substantially increased by using a pervious sand/gravel layer above the clay liner. By properly designing the sand layer, any seepage flowing through the gypsum would be collected by the sand layer and drained through a grid of perforated pipes. With a fully effective sand drain, the underlying clay blanket would be subjected to a relatively low hydraulic gradient and essentially all head loss would occur through the gypsum.

Another alternative is to use a reinforced synthetic liner to replace the clay as the seepage barrier. Again, the use of a sand/gravel layer above the liner would give additional protection.

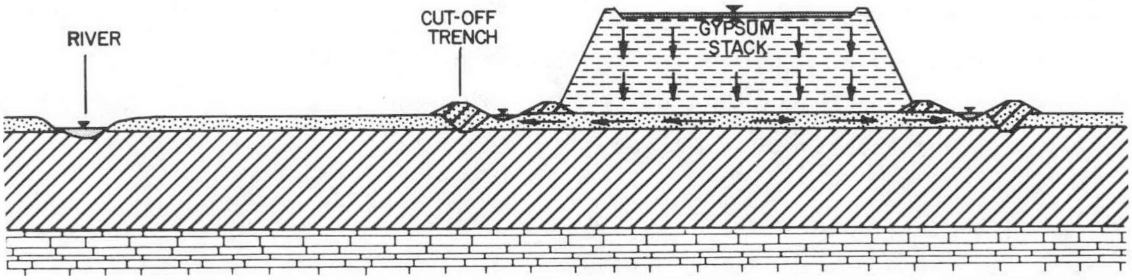


Figure 4-11. Use of a Cut-Off Trench to Control Seepage From a Gypsum Stack

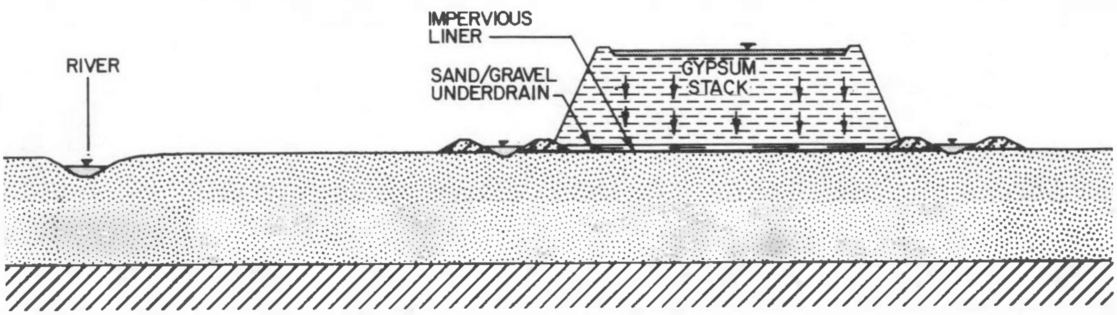


Figure 4-12. Use of an Impervious Liner and Underdrain to Control Seepage From a Gypsum Stack

Monitoring Programs

The effectiveness of any selected seepage control system should be determined with a monitoring program of surface water and groundwater adjacent to the disposal area. Minimum water quality monitoring programs are normally specified by state Departments of Environmental Regulation or the U. S. Environmental Protection Agency. At Plant Scholz, for example, the Florida Department of Environmental Regulation required monthly groundwater sampling for sulfate, calcium, sodium, pH, and conductivity.

PROCESS WATER RETURN SYSTEM

Process water pumped to the stacking area is decanted from the waste gypsum and returned to the plant for reuse. The type and location of the decant system used to return process water from the waste gypsum to the plant influences the quality and performance of the gypsum stack.

The location of the intake of the decant structure in relation to the point that waste slurry is discharged into the pond influences the length of the flow path and retention time of the pond. The longer the flow path the longer the retention time, with all other factors being the same and, therefore, the clearer the decanted water. The coarser fraction of gypsum settles close to the point of discharge and the finest fraction accumulates around the intake of the decant system. From seepage and stability considerations, it is desirable to have the coarse gypsum deposit along the perimeter of the stack and to have the finer gypsum settle in the center of the stack. Coarse gypsum typically has a higher friction angle and higher coefficient of permeability than the finer gypsum, providing a more stable perimeter dike and allowing faster drainage during excavation and casting of the gypsum while raising the perimeter dike.

From solely geotechnical considerations,having the intake of the decant system located away from the edges and preferably in the center of the pond is most desirable although it introduces several operational and maintenance problems. First, special provisions are necessary for access to the decant system for general maintenance. Access is also needed for the fixed vertical riser type decant system where spillway boards or collars must be added to the riser as the surface of the gypsum rises. Further, the cost of the decant system increases as the spillway is located farther in from the edge because of the increased length of horizontal discharge pipe.

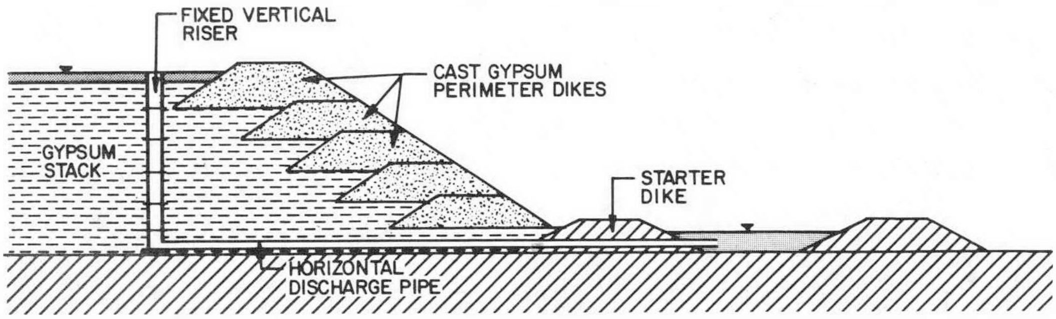


Figure 4-13. Fixed Vertical Riser Decant System

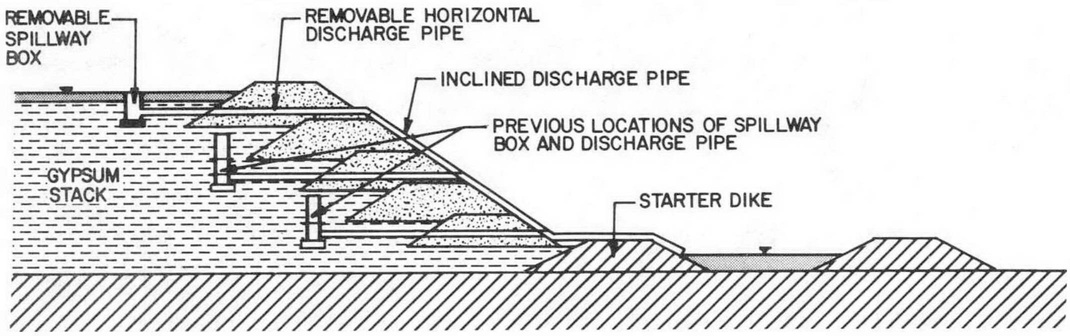


Figure 4-14. Stage Decant System

The fixed vertical riser type decant structure shown in Figure 4-13 is the most commonly employed system, requires the least maintenance, but must be continuously raised as the surface of the gypsum rises. Another disadvantage is that the horizontal discharge pipe is located at the bottom of the gypsum stack and,therefore, cannot be easily repaired or replaced and is subjected to increasing pressure as the surface of the pond rises. Piping of the starter dike soil around the discharge pipe may also occur if precautions and good construction procedures are not used.

To avoid some of the disadvantages of the fixed vertical riser type decant system, a stage decant system can be used as illustrated in Figure 4-14. In this system, the intake spillway box and the horizontal section of the discharge pipe are removed and raised each time the spillway needs raising and an extention is added to the inclined section of the discharge pipe running down the gypsum stack slope. This system is feasible only when the intake spillway box is located close to the edge of the gypsum stack.

GYPSUM DEPOSITION AND DISTRIBUTION

The most important considerations in the operation of gypsum stacks are typically: (1) the retention of fine-grained gypsum within the stack, (2) the characteristics of the gypsum deposited around the periphery of the stack, and (3) the raising of the cast perimeter dikes. The proper design and management of gypsum stacks with regard to these considerations can influence the overall quality and performance of the stack and economies of the disposal method.

Retention Time

The location of the intake of the decant structure should be selected to be as far as possible from the point of the slurry discharge into the stack. Generally, the further the distance between the point of discharge and the decant structure the clearer the decanted water. If sufficient retention time is not provided within the ponded area on top of the stack, complete clarification will not occur and the finer particles of gypsum will discharge through the spillway and sediment within the surge pond. This problem has occurred at several phosphate gypsum stacks and required the dredging of fine-grained gypsum from the surge pond.

The required retention time of a pond to allow complete removal of gypsum particles from suspension can be roughly approximated using Stokes law. For the

0.007 mm minimum particle size of CT-121 FGD gypsum (e.g., see Figure 2-3), the settling velocity is 0.25 cm/sec. For a ponded water depth of 3 feet (0.9 m) atop a stack, approximately six hours of retention time would be required to completely clarify the process water.

Decanting Process Water

The depth of process water within the stack should be kept to a minimum for safety reasons in the event of accidental spillage. To allow sedimentation of the gypsum to occur and to allow clarification of the process water prior to decanting, a working depth of 1 to 3 feet (0.3 to 0.9 m) is typically used.

In cold climates where freezing occurs, the top of ponded water within the stack often freezes. Sedimentation of gypsum and clarification of process water is then obtained within the ponded water beneath the ice layer. Since the initial temperature of process water normally exceeds 40°C, freezing is not a major problem at the point of discharge into the pond. The most difficult aspect to decanting process water in cold climates, therefore, is to maintain sufficient water depth to allow a zone of water flow below the ice layer. There are several phosphate fertilizer plants with gypsum stacks in northern states and Canada which have utilized this technique with success.

Gypsum Deposition Along Stack Perimeter

Although finer-grained gypsum can often be cast to raise the perimeter dikes, the lower permeability of this material does not allow drainage to occur as quickly as with coarser-grained gypsum. Consequently, it is more difficult and time-consuming to use the finer material to raise the stack. For this reason, it is desirable to deposit the coarser material around the periphery of the stack.

It is possible to operate a gypsum stack so that the coarser material is always deposited around the perimeter of the stack while simultaneously providing sufficient retention time for the finer particles to settle within the interior of the stack. This is accomplished by using an elevated ditch to carry the gypsum around the periphery of the stack and to create a ponded area within the interior of the stack. This concept is shown schematically in Figure 4-15. Note the decant structure is located within the interior ponded area and the elevated ditch passes over the discharge pipe. The direction of flow within the elevated ditch can be alternated such that coarse gypsum is deposited along all four walls of the stack.

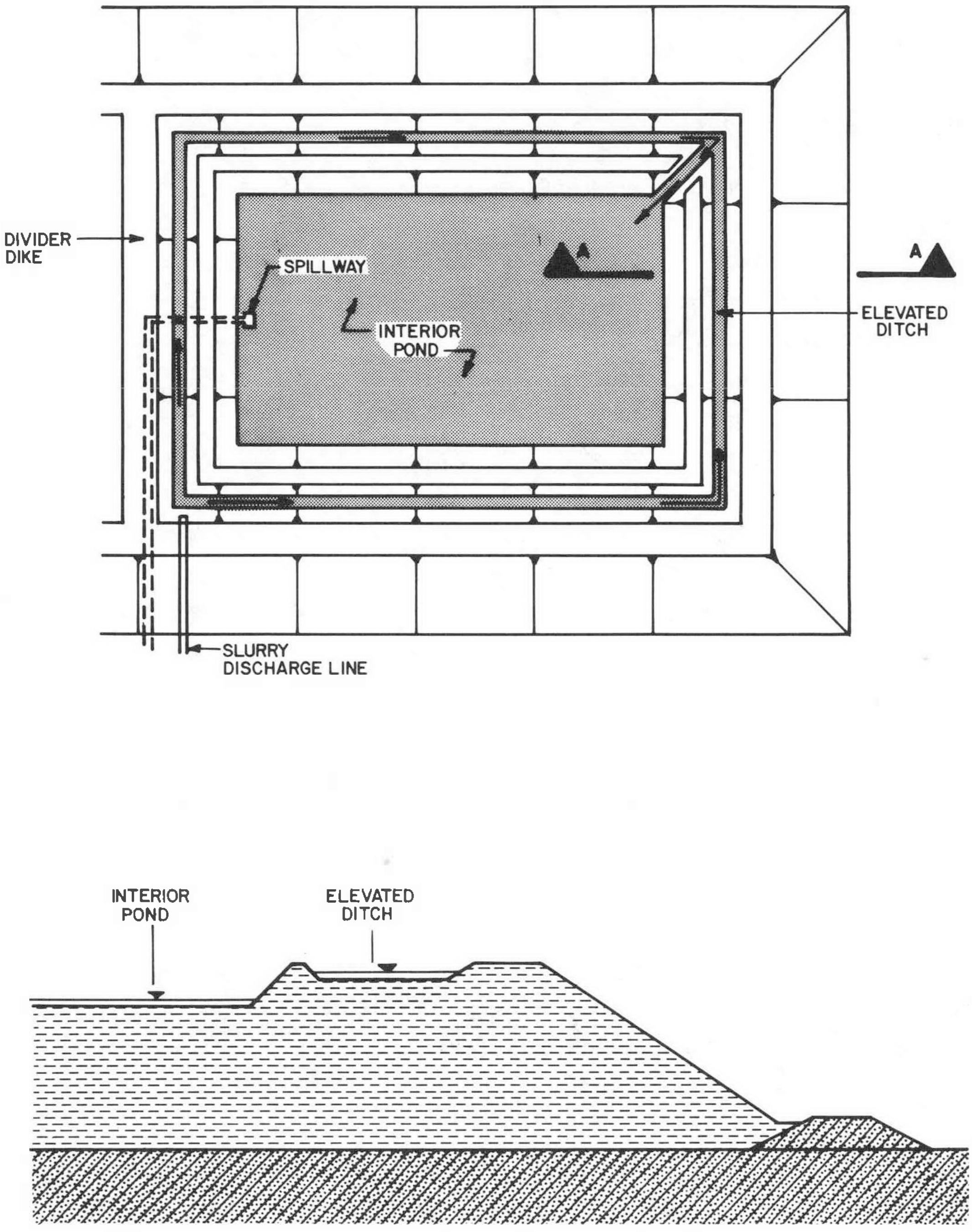


Figure 4-15. Use of Elevated Ditch to Sediment Coarse Gypsum Around Stack Perimeter

In addition, the gypsum in the elevated ditch can drain prior to raising the perimeter dikes while the interior of the stack remains ponded.

RAISING PERIMETER DIKES

Gypsum is generally cast to raise the perimeter dike using a dragline. The cast gypsum is then shaped to form a road on the crest of the dike using a bulldozer. In some cases, a bulldozer has been used to both raise and shape the perimeter dikes. It is desirable to allow the gypsum to drain prior to raising the stack, although it is often possible using the dragline, but more time consuming, to raise the stack without draining the gypsum.

The draglines used to raise gypsum stacks typically have a working reach of 60 feet (18.3 m) and 2 to 3 cubic yard (1.5 to 2.3 m^3) buckets. If the process waters are acidic, the dragline bucket may need to be coated with a layer of stainless steel.

The cast gypsum dikes should have a minimum crest width of 20 to 25 feet (6.1 to 7.6 m) and should be raised approximately 5 to 8 feet (1.5 to 2.4 m) per year. Depending on the size and efficiency of the dragline, approximately 100 to 200 feet (30.5 to 61.0 m) of cast dike 5 feet (1.5 m) high with a 20-foot (6.1-meter) crest width can be constructed in one day.

The slopes of the cast gypsum dikes are allowed to develop at the angle of repose of gypsum. If an overall average stack slope that is flatter than the angle of repose is required for stability, the perimeter dikes are generally offset from the outer perimeter to form benches in the slope (i.e., See Figure 4-5). This eliminates the need for shaping the perimeter dike slopes which are simply cast and allowed to develop slopes corresponding to the angle of repose of gypsum.

In cold climates where freezing occurs,the perimeter dikes are not raised in winter months. Instead, sufficient capacity is provided within the stack to store all gypsum produced during the winter months without raising the perimeter dikes.

ENVIRONMENTAL CONSIDERATIONS

Erosion protection is not normally provided on the outside slope of a gypsum stack. Experience has shown that there is essentially no erosion of gypsum slopes from rainfall. Dusting has also not been a significant problem.

Gypsum stacks in northern climates will be subject to freeze-thaw cycles. A number of phosphate fertilizer plants with gypsum stacks are located throughout the northern states and in Canada. Experience at these northern locations, where temperatures can drop below -40°C, indicates no deleterious effects on the gypsum slopes from the freeze-thaw cycles. Earthen starter dikes, however, must be designed with due consideration for freeze-thaw effects. Depending on the soils used to construct the starter dikes, cyclic freezing and thawing can result in a significant reduction in the shear strength of the soils due to increased moisture content and altered soil structure. These problems result if the freezing soil has access to free water and movement of water occurs through the voids of the soil toward the surface, where ice crystals and ice lenses can form within the soil. The detrimental effects of freeze-thaw cycles can be reduced by providing surface or subsurface drainage to remove free water and reduce the degree of saturation of the surface soils. Alternately, if drainage is not possible, the starter dike can be designed using a shear strength reduced to account for freeze-thaw effects.

If long-term maintenance and reclamation require the slopes be grassed, it may be expedient to flatten the slopes to 2.5 Horizontal to 1.0 Vertical or flatter as the stack is raised. These flatter slopes will generally hold topsoil cover and can be maintained using conventional equipment. Several grassing experiments with and without a topsoil dressing have been performed on retired phosphate gypsum stacks. The results of these experiments are not completed at this time, but initial results appear favorable even for relatively steep slopes (approximately 1.5 Horizontal to 1.0 Vertical).

To our knowledge, no regulations presently exist for the retirement or reclamation of gypsum stacks. Gypsum stacks that have been retired have generally not been reclaimed. Probable future regulations (i.e., Resources Conservation and Recovery Act (RCRA) of 1976) may require: the regrading of the stacks to enhance runoff and minimize leachate, the placement of a relatively impervious soil cover above the gypsum to minimize leachate, and reclamation with an indigenous vegetation (2, 3).

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2. A. E. Z. Wissa and N. F. Fuleihan. "Critique of Proposed Phosphate Industry Waste Storage Regulations." In Proceedings of the 1980 Environmental Symposium of the Fertilizer Institute, April 1980, New Orleans, Louisiana.

3. W. A. Duval, Jr. "Solid-Waste Disposal: Landfilling." Chemical Engineering, July 1979, pp. 77-86.

Section 5

CONCLUSIONS AND RECOMMENDATIONS

The feasibility of stacking CT-121 FGD gypsum has been evaluated using geotechnical laboratory testing to determine the engineering properties of the material relevant to stacking, and by observation of a prototype stack operated at Plant Scholz. Geotechnical laboratory testing of pilot plant and Plant Scholz CT-121 FGD gypsum, and comparisons of CT-121 FGD and phosphate gypsum engineering properties indicate the following conclusions:

- CT-121 FGD gypsum has settling, dewatering, and structural characteristics similar to, and in some instances, more favorable than phosphate gypsum, making stacking methods of waste disposal a feasible alternative. Results from geotechnical laboratory testing presented in Section 2 indicate CT-121 FGD gypsum: (1) sediments to an initial dry density greater than typical phosphate gypsums, (2) is more permeable than phosphate gypsum at equal dry densities, and (3) exhibits stress-strain-strength behavior similar to many phosphate gypsums. The pore fluid pH also has negligible effect on the engineering behavior of CT-121 FGD gypsum.

The nine-month operation of a prototype FGD gypsum stack at Plant Scholz further confirmed the feasibility of utilizing stacking for disposal of CT-121 FGD gypsum. The completed stack, approximately one-half acre (2023 m^2) and 12 feet (3.7 m) high, was generally constructed and operated as normally accomplished in the phosphate industry. Successful completion of the stack provided the following observations:

- CT-121 FGD gypsum can be stacked with a dragline using the upstream method of construction as accomplished in the phosphate industry. Based on this study, it appears the basic design and operations concepts utilized by the phosphate industry may largely be adopted without modification by the utility industry for stacking FGD gypsum.

- As with phosphate gypsum stacks, the cast CT-121 FGD gypsum dikes and slopes developed a thin drying crust which was relatively resistant to erosion from rainfall and prevented excessive dusting.

- The only significant stacking characteristic not observed in CT-121 FGD gypsum was the gradual development of some cohesion in the stack slopes from cementation. Although the self-cementation process is desirable for stacking, the absence of cementation does not preclude the use of stacking. Without cementation, however, some structural precautions are necessary to prevent sloughing below the springline such as relatively flat slopes or an internal drain.

- As with phosphate gypsum stacks,groundwater contamination from FGD scrubber process waters is a concern. The process waters can contain concentrations of sulfate, calcium, chloride, and magnesium several orders of magnitude greater than natural background levels and drinking water standards. Trace elements such as arsenic, chromium, or selenium may also be present within the process water at levels above drinking water standards and could pose a contamination problem. Seepage from FGD gypsum stacks, therefore, must be controlled or prevented, and the surface and groundwater surrounding the stack monitored.

The effect of fly ash addition on the stacking characteristics of CT-121 FGD gypsum was briefly investigated since the potential exists for simultaneous disposal of fly ash and gypsum. This evaluation was not included in the original research program for RP536-3, but was performed as interest developed in the topic. The results of laboratory testing on the effect of fly ash addition on the permeability, sedimentation-consolidation, and shear strength characteristics of CT-121 FGD gypsum all indicated reductions in the favorable stacking characteristics of CT-121 FGD gypsum. Additional research, however, is required to assess the stackability of fly ash-gypsum mixtures and to investigate potential methods for simultaneous disposal of fly ash and gypsum.

Based upon the results obtained during this investigation, several areas for additional research are recommended:

- Laboratory testing of FGD gypsums from various scrubbers for comparison to CT-121 FGD gypsum to further substantiate the feasibility of utilizing stacking methods of waste disposal for other FGD gypsums.

- If stacking is selected for disposal of FGD gypsum, several of the initial full-scale stacks should be thoroughly monitored during operation. Particularly, the long-term effects of aging and gradual development of cementation, which could not be accomplished at Plant Scholz, should be carefully monitored.

- Research is necessary to determine if feasible alternatives exist for simultaneous disposal of fly ash and FGD gypsum.

Appendix A

WATER QUALITY DATA

This Appendix includes a detailed tabulation of water quality data obtained from monitoring wells surrounding the CT-121 FGD prototype gypsum stack at Plant Scholz. The locations of the wells are shown in Figure 3-17.

All chemical analyses presented in this Appendix were performed by Radian Corporation for RP536-4. The approximately monthly sampling during the active life of the stack included chemical analyses for calcium, magnesium, sodium, chloride, nitrate, sulfate, total dissolved solids, pH, and conductivity. Results from the monthly sampling are shown in Tables A-1 through A-7.

Trace element determinations are summarized in Tables A-8 through A-11. The trace elements were determined by spark source mass spectroscopy for the 10/4/78, 1/18/79, and 3/13/79 samples, and inductively coupled argon plasma emission spectroscopy for the 11/29/79 samples.

Table A-1

WATER QUALITY AT OBSERVATION WELL OW-1 AND PIEZOMETER P-1

OBSERVATION WELL OW-1

Date	T°C	pH	Concentration (mg/l)								Conductivity
			Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	(mhos/cm^2)
10-04-78	-	8.1	99	32	88	25	-	510	-	855	-
11-17-78	23	8.0	70	24	96	22	-	282	200	-	-
01-18-79	15	8.6	53	28	32	14	<0.6	115	255	-	-
02-14-79	20	8.4	6.0	26	15	10	<0.6	75	-	402	-
03-13-79	21	8.5	53	26	18	14	<0.6	74	245	-	4.59×10^{-4}
04-12-79					No Sample						
05-18-79					No Sample						
06-26-79	24	7.8	74	29	9.7	11	1.3	100	-	410	5.3×10^{-4}
11-29-79	-	8.5	53	25	10	9.9	<0.6	47	-	218	4.6×10^{-4}

PIEZOMETER P-1

Date	T°C	pH	Concentration (mg/l)								Conductivity
			Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	(mhos/cm^2)
10-04-78					No Sample						
11-17-78	23	7.7	36	12	12	6.7	-	44	168	-	-
01-18-79	16	7.9	36	20	19	5.0	1.2	13	74	136	-
02-14-79					No Sample*						
03-13-79					No Sample						
04-12-79					No Sample						
05-18-79					No Sample						
06-26-79					No Sample						
11-29-79					No Sample						

* Piezometer P-1 damaged after January sampling - no further sampling possible.

Table A-2

WATER QUALITY AT OBSERVATION WELL OW-2 AND PIEZOMETER P-2

OBSERVATION WELL OW-2

Date	T°C	pH	Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity ($mhos/cm^2$)
			Concentration (mg/l)								
10-04-78	-	7.2	4.7	1.5	22	11	-	13	-	61	-
11-17-78	22	6.9	11.3	2.8	12	10	-	24	25	-	-
01-18-79	16	6.4	1.2	1.5	14	19	6.8	13	34	146	-
02-14-79	20	6.3	26	11	0.2	21	16	21	-	156	2.11×10^{-4}
03-13-79	18	6.7	6.8	4.4	18	24	21	21	26	155	1.78×10^{-4}
04-12-79	23	5.8	25	14	34	49	-	68	380	272	1.4×10^{-4}
05-18-79	23	5.5	44	32	35	79	100	114	-	280	1.9×10^{-4}
06-16-79	24	4.7	52	45	35	106	96	149	-	570	7.85×10^{-4}
11-29-79	16.7	4.6	94	63	40	193	120	270	-	933	1.4×10^{-3}

PIEZOMETER P-2

Date	T°C	pH	Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity ($mhos/cm^2$)
			Concentration (mg/l)								
10-04-79	-	8.0	26	12	3.5	4.1	-	10	-	187	-
11-17-78	22	7.8	34	11	8.4	5.3	-	48	115	-	-
01-18-79	18	8.3	22	11	10	4.6	2.5	5.8	136	192	-
02-14-79	20	8.0	22.2	11.7	< 0.23	3.9	2.5	2.9	-	140	1.90×10^{-4}
03-13-79	20	7.8	26.8	10.9	6.5	4.6	2.5	7.7	120	136	1.68×10^{-4}
04-12-79	22	7.9	27	11	7.0	5.5	2.8	9.0	120	130	8.0×10^{-5}
05-18-79	23	7.7	36	11	6.9	7.1	2.9	34	-	184	6.5×10^{-5}
06-26-79	24	8.3	27	12	4.0	5.4	2.9	8.2	-	160	2.16×10^{-4}
11-29-79	18.3	7.9	28	12	4.0	5.7	2.5	7.7	-	140	2.20×10^{-4}

Table A-3

WATER QUALITY AT OBSERVATION WELL OW-4 AND PIEZOMETERS P-4 AND P-4A

OBSERVATION WELL OW-4

Date	T°C	pH	Concentration (mg/l) Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity (mhos/cm^2)
10-04-78					No Sample						
11-17-78	23	6.45	45	8	36	< 1	-	118	125	-	-
01-18-79	16	6.8	20	5.8	8	4.6	< 0.6	13	133	160	-
02-14-79	20	8.1	29.6	18.0	7.1	7.4	< 0.6	17.3	-	244	3.24×10^{-4}
03-13-79	21	6.8	10.4	4.1	5.5	9.6	< 0.6	13.4	63	90	1.38×10^{-4}
04-12-79	21	6.45	2.4	7.0	-	25	10	30	48	174	2.35×10^{-4}
05-18-79	22	6.65	33	8.8	10	33	2.2	63	-	210	1.05×10^{-4}
06-26-79	24	5.9	20	9.4	10	41	1.0	39	-	240	2.9×10^{-4}
11-29-79	14.4	6.0	35	114	20	95	4.3	46	-	300	3.70×10^{-4}

PIEZOMETER P-4

Date	T°C	pH	Concentration (mg/l) Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity (mhos/cm^2)
10-04-78	-	8.2	34	18	15	6.1	-	13	-	211	-
11-17-78	22	8.0	36	4.7	5.0	4.6	-	11	180	-	-
01-18-79	18	8.0	37	19	18	5.7	1.2	13	194	274	-
02-14-79	20	7.0	5.2	2.7	6.4	7.4	< 0.6	8.6	-	-	-
03-13-79	22	8.0	37.6	34.3	14.5	5.3	< 0.6	13.4	180	198	2.88×10^{-4}
04-12-79	24	8.2	40	18	4.8	5.2	< 0.6	17	90	182	2.95×10^{-4}
05-18-79	22.5	8.2	55	18	8.2	7.3	< 0.6	65	-	262	2.55×10^{-4}
06-26-79	24	8.2	52	19	4.3	7.0	0.9	5.8	-	280	3.80×10^{-4}
11-29-79	16.7	8.4	42	20	47	9.2	< 0.6	30	-	190	3.40×10^{-4}

PIEZOMETER P-4A

Date	T°C	pH	Concentration (mg/l) Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity (mhos/cm^2)
10-04-78	-	8.3	38	17	15	5.5	-	22	-	232	-
11-17-78	21	8.0	35	3.5	6.3	5.7	-	14	150	-	-
01-18-79	17.5	8.1	64	34	33	36	20	168	157	548	-
02-14-79	20	8.3	88	51	4.1	32.6	33.5	196	-	600	6.91×10^{-4}
03-13-79	22	8.1	176	94	36.8	69.0	79.4	490	157	1200	1.23×10^{-3}
04-12-79					No Sample						
05-18-79					No Sample						
06-08-79	-	-	200	97	12	76	104	584	-	980	-
06-26-79	24	7.3	241	126	13	104	110	700	-	1630	1.72×10^{-3}
11-29-79	11.7	8.2	293	165	17	125	110	870	-	-	1.30×10^{-3}

Table A-4

WATER QUALITY AT OBSERVATION WELL OW-6 AND PIEZOMETER P-6

OBSERVATION WELL OW-6

Date	T°C	pH	Concentration (mg/l) Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity ($mhos/cm^2$)
10-04-78	-	8.1	45	11	4.5	5.9	-	29	-	235	-
11-17-78	24	7.05	54	14	8.8	11	-	82	-	150	-
01-18-79	14	6.9	54	20	7.1	21	15	103	144	320	-
02-14-79	19	7.0	54.8	18.2	5.3	12.4	6.2	74.9	-	250	3.62×10^{-4}
03-13-79	18	6.8	49.6	17.3	6.2	18.1	6.8	101.8	126	343	4.17×10^{-4}
04-12-79	22	6.8	113	46	15	44	42	271	144	672	1.57×10^{-4}
05-18-79	23.5	6.8	131	55	16	48	41	345	-	828	2.55×10^{-4}
06-26-79	24	7.8	126	70	16	57	37	375	-	920	1.02×10^{-3}
11-29-79	18.9	8.1	191	86	21	708	57	476	-	1150	1.30×10^{-3}

PIEZOMETER P-6

Date	T°C	pH	Concentration (mg/l) Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity ($mhos/cm^2$)
10-04-78	-	8.6	29	10	3.8	6.7	-	11	-	158	-
11-17-78	22.5	8.2	34	11	17	6.7	-	33	120	-	-
01-18-79	17	8.5	27	13	46	6.0	6.8	11	170	258	-
02-14-79	20	8.2	95.2	59.0	5.9	33.6	39.7	228	-	642	7.66×10^{-4}
03-13-79	21	8.1	78.8	47.6	20.0	32.9	34.1	188	151	533	5.00×10^{-4}
04-12-79					No Sample						
05-18-79					No Sample						
06-08-79	-	-	192	124	13	104	120	538	-	1120	-
06-26-79	24	7.4	157	95	12	90	75	440	-	1160	1.28×10^{-3}
11-29-79					No Sample						

Table A-5

WATER QUALITY AT OBSERVATION WELLS OW-3 AND OW-5

OBSERVATION WELL OW-3

Date	T°C	pH	Concentration (mg/l) Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity (mhos/cm^2)
10-04-78	-	7.0	170	24	15	19	-	200	-	757	-
11-17-78	23	6.5	266	35	27	37	-	492	640	-	-
01-18-79	16	7.1	154	28	22	28	<0.6	154	485	802	-
02-14-79	20	7.7	68	35	7.4	18	14	105	-	500	5.56×10^{-4}
03-13-79	20	6.3	106	23	16	19	1.9	85	480	453	6.87×10^{-4}
04-18-79	22	6.5	127	21	34	16	1.6	172	360	586	7.4×10^{-4}
05-18-79	23	6.6	82	21	16	17	1.7	126	-	446	9.4×10^{-5}
06-26-79	24	6.3	74	26	13	21	1.7	106	-	500	5.7×10^{-4}
11-29-79	18.3	6.6	110	32	40	24	<0.6	300	-	600	9.1×10^{-4}

OBSERVATION WELL OW-5

Date	T°C	pH	Concentration (mg/l) Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity (mhos/cm^2)
10-04-78	-	8.4	34	13	9.5	3.0	-	11	-	232	-
11-17-78	22.5	7.95	29	13	15	2.8	-	16	175	-	-
01-18-79	14	8.0	37	14	12	3.2	0.6	40	190	264	-
02-14-79	19	8.15	23.2	13.9	9.2	2.8	1.24	19.2	-	204	2.6×10^{-4}
03-13-79	20	8.0	24.4	10.7	7.6	3.5	3.1	22.1	142	187	2.49×10^{-4}
04-12-79	22	7.9	106	13	24	3.3	3.7	193	156	420	4.76×10^{-4}
05-18-79	23.5	8.0	32	12	18	4.9	4.3	52	-	194	6.22×10^{-5}
06-26-79	24	8.0	23	12	4.6	2.0	4.2	10.0	-	180	2.16×10^{-4}
11-29-79	17.8	8.1	21	12	9.0	3.2	4.3	7.7	-	140	2.10×10^{-4}

Table A-6

WATER QUALITY AT OBSERVATION WELLS OW-7 AND OW-8

OBSERVATION WELL OW-7

Date	T°C	pH	Concentration (mg/l)								Conductivity ($mhos/cm^2$)
			Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	
10-04-78	-	4.85	100	26	1230	210	-	2700	-	3780	-
11-17-78	23	4.7	166	21	1000	230	-	2900	100	-	-
01-18-79	18	4.5	110	5.1	1075	230	<.6	2975	44	4410	-
02-14-79	20	4.35	90.0	0.5	653.2	29.4	<.6	2400	-	4120	4.66×10^{-3}
03-13-79	21	4.1	71.2	1.9	938.4	3.2	<.6	2410	58	4134	4.40×10^{-3}
04-12-79	-	4.5	196	22	1100	269	3.6	2570	30	4340	-
05-18-79	22 5	4.7	130	20	965	215	-	2290	-	3920	1.35×10^{-3}
06-26-79	24	4.3	92	21	896	197	-	2210	-	3870	4.35×10^{-3}
11-29-79	-	4.3	86	26	880	180	<.6	2050	-	3330	4.10×10^{-3}

OBSERVATION WELL OW-8

Date	T°C	pH	Concentration (mg/l)								Conductivity ($mhos/cm^2$)
			Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	
10-04-78	-	6.7	7.1	2.9	20	7.7	-	25	-	83	-
11-17-78	24	5.9	9.0	1.9	15	9.9	-	7	35	-	-
01-18-79	15	5.7	2.4	3.9	7.4	7.4	1.2	13	74	136	-
02-14-79	19	5.8	10.0	2.7	6.0	8.5	0.62	12.5	-	70	0.91×10^{-4}
03-13-79	18	6.3	10.8	2.4	6.2	8.1	1.24	31.7	18	97	1.11×10^{-4}
04-12-79	22	6.1	6.2	1.9	6.8	7.8	1.2	11	24	20	1.94×10^{-5}
05-18-79	23.4	6.0	7.5	2.2	8.3	8.3	1.5	14	-	-	4.75×10^{-5}
06-26-79	24	6.8	8.3	2.0	6.7	8.1	1.5	19	-	100	9.89×10^{-5}
11-29-79	20	6.9	3.7	2.1	8.0	8.2	2.5	13	-	61	1.10×10^{-4}

Table A-7

WATER QUALITY AT PLANT WELL NO. 2

PLANT WELL NO. 2

Date	T°C	pH	Concentration (mg/l) Ca	Mg	Na	Cl	NO_3	SO_4	CO_3	TDS	Conductivity (mhos/cm^2)
10-04-78					No Sample						
11-17-78	21.5	7.3	32	14	3.4	6.4	-	17	140	-	-
01-18-79	17	7.4	33	16	15	6.4	5.6	23	167	482	-
02-14-79	21	8.0	31.2	14.8	15.2	45.0	4.3	1.9	-	226	3.16×10^{-4}
03-13-79	21	7.85	26.8	13.4	20.7	44.9	<0.6	<1.0	136	226	3.34×10^{-4}
04-12-79	-	7.7	32	14	28	45	4.7	10	120	182	-
05-18-79	22	7.75	28	13	25	42	4.2	4.2	-	158	5.26×10^{-5}
06-26-79	24	7.9	27	14	20	34	4.0	28	-	230	-
11-29-79	-	8.0	27	14	24	50	4.3	7.7	-	190	4.0×10^{-4}

Table A-8

FLORIDAN AQUIFER TRACE ELEMENTS AT PIEZOMETERS P-4A AND P-6

Element	Concentration (mg/l)									
	Process Water	Drinking Water Stds. USPHS	Drinking Water Stds. EPA	Piezometer P-6 10/4/78	Piezometer P-6 1/18/79	Piezometer P-6 3/13/79	Piezometer P-4A 10/4/78	Piezometer P-4A 1/18/79	Piezometer P-4A 3/13/79	Piezometer P-4A 11/29/79
Aluminum				0.10	0.02	0.08	0.02	0.01	0.01	0.76
Arsenic	0.15	0.05	0.05	0.006	<0.003	0.002	0.006	<0.002	0.002	<0.002
Barium		1.0	1.0	0.06	0.04	0.04	0.03	0.08	0.5	0.26
Boron				0.001	0.007	0.002	0.001	0.1	0.09	<0.01
Bromine				0.03	0.06	0.05	0.03	0.3	0.04	
Calcium				MC	MC	MC	MC	MC	MC	
Cerium				0.001					0.001	
Chlorine				0.3	0.70	0.20	0.3	0.5	0.1	
Chromium	0.22	0.05	0.05	0.001	0.02	<0.001	0.001	0.01	<0.001	0.06
Cobalt				<0.002	<0.002	<0.001	<0.002	0.007	<0.001	
Copper	0.005	1.0	1.0	0.007	0.02	0.005	0.006	0.02	0.003	0.17
Fluorine				0.4	0.2	0.007	0.3	0.5	0.001	
Gallium				<0.001	<0.002	<0.001	0.004		<0.001	
Germanium				<0.001					<0.001	
Iodine				0.002	<0.003	0.004		<0.007	0.004	
Iron		0.3	0.3	0.1	0.09	0.08	0.06	0.09	5	0.07
Lanthanum				0.003					0.002	
Lead	<0.002	0.05	0.05	<0.005	0.01	<0.003		<0.01	<0.003	<0.001
Lithium				<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Magnesium	650			5.0	MC	MC	7	MC	MC	
Manganese		0.05	0.05	0.005	0.02	0.004	0.006	0.04	0.002	0.13
Molybdenum				0.02	<0.005	0.04*	0.006	0.02	0.005	
Nickel	0.94			0.005	0.007	0.001	0.01	0.01	0.001	0.10
Phosphorus				0.05	0.10	0.06	0.04	0.3	0.04	
Potassium				4.0	7.0	1.0	0.7	5	4	
Rubidium				0.002	0.003	<0.001	<0.001	0.001	<0.001	
Scandium				<0.001	<0.001	<0.001	<0.001	<0.004	<0.001	
Selenium	0.20	0.01	0.01	<0.003						0.003
Silicon				2.0	2.0	3.0	1.0	MC*	1	
Silver	0.07	0.05	0.05	0.05			0.02			<0.002
Sodium				>3	>4	>2	>3	>9	>2	
Strontium				0.05	0.06	0.05	0.02	0.04	0.03*	
Sulfur	900			>7	3	>5	0.7	MC	6	
Titanium	0.065			0.06	0.20	0.02*	0.01	0.9	0.03	
Vanadium	1.1			0.002	0.003	<0.001	0.002	0.003	<0.001	0.008
Zinc	0.67	5.0	5.0	0.05	0.10	0.01	0.04	0.09	0.03*	0.45
Zirconium				0.002		0.002	0.002		0.006	

* : Heterogeneous

MC: > 10 mg/l

Table A-9

SURFICIAL AQUIFER TRACE ELEMENTS AT OBSERVATION WELL OW-2

Element	Concentration (mg/l)						
	Process Water	Drinking Water Stds. USPHS	Drinking Water Stds. EPA	10/4/78	1/18/79	3/13/79	11/29/79
Aluminum				0.03	0.05	0.02	7.0
Arsenic	0.15	0.05	0.05	0.001	<0.004		<0.002
Barium		1.0	1.0	0.02	0.09	0.07	0.26
Boron				<0.001	0.003	<0.001	<0.01
Bromine				0.01	0.1	0.06	
Calcium				5	5	MC	
Cerium						0.002	
Chlorine				0.5	0.5	0.09	
Chromium	0.22	0.05	0.05	<0.02	0.004	0.001	<0.007
Cobalt				<0.001	<0.003	<0.002	
Copper	0.005	1.0	1.0	0.003	0.01	0.002	0.040
Fluorine				0.3	0.09	0.006	
Gallium				<0.005			
Germanium				<0.001			
Iodine							
Iron		0.3	0.3	1	0.4*	0.04	0.08
Lanthanum						0.004	
Lead	<0.002	0.05	0.05		0.02	<0.006	0.017
Lithium				<0.001	0.001	<0.001	
Magnesium	650			4	0.8	3	
Manganese		0.05	0.05	0.02	0.04	0.04	0.94
Molybdenum				0.02	0.02	0.04	
Nickel	0.94			0.003	0.006	0.003	0.07
Phosphorus				0.03	0.07	0.07	
Potassium				MC	2	2	
Rubidium				<0.001		<0.001	
Scandium				<0.001	<0.001	<0.002	
Selenium	0.20	0.01	0.01			0.004	0.002
Silicon				0.9	1	6	
Silver	0.07	0.05	0.05				<0.002
Sodium				>2	MC	>4	
Strontium				0.01	0.03	0.03	
Sulfur	900			>5	1	3	
Titanium	0.065			0.02	0.05	0.02	
Vanadium	1.1			<0.001	0.001	0.001	0.02
Zinc	0.67	5.0	5.0	0.01	0.1	0.005	0.39
Zirconium					<0.006	0.008	

* : Heterogeneous
MC: > 10 mg/l

Table A-10

AQUICLUDE TRACE ELEMENTS AT OBSERVATION WELL OW-1

Element	Process Water	Drinking Water Stds. USPHS	Drinking Water Stds. EPA	10/4/78	1/18/79	3/13/79	11/29/79
	Concentration (mg/l)						
Aluminum				0.03	0.1	0.01	0.23
Arsenic	0.15	0.05	0.05	0.002	<0.008	0.006	0.003
Barium		1.0	1.0	0.06	0.1	0.02	0.17
Boron				0.001	0.01*	<0.001	<0.01
Bromine				0.02	0.08	0.01	
Calcium				MC	MC	MC	
Cerium				<0.001			
Chlorine				0.09	0.5	0.04	
Chromium	0.22	0.05	0.05	<0.01	0.005	<0.001	<0.007
Cobalt				0.008	<0.01	<0.001	
Copper	<0.005	1.0	1.0	0.007	0.03	0.009	0.02
Fluorine				0.5	1	0.002	
Gallium				0.002		<0.001	
Germanium				0.001			
Iodine				0.001	<0.02	0.002	
Iron		0.3	0.3	0.03	0.1	0.4	0.05
Lanthanum							
Lead	<0.002	0.05	0.05		<0.04	<0.002	<0.001
Lithium				<0.001	0.003		
Magnesium	650			MC	10	MC	
Manganese		0.05	0.05	0.3	0.2	0.03	0.01
Molybdenum				<0.001	0.08	0.06	
Nickel	0.94			0.002	0.09	0.007	0.10
Phosphorus				0.04	0.7	0.2	
Potassium				>6	1	2	
Rubidium				<0.001	0.002	<0.001	
Scandium				<0.001	<0.004	<0.001	
Selenium	0.20	0.01	0.01	0.003			0.002
Silicon				0.8	3	6	
Silver	0.07	0.05	0.05				<0.002
Sodium				>1	MC	>2	
Strontium				0.9	0.4	0.3	
Sulfur	900			>3	7	4	
Titanium	0.065			0.05*	0.4	0.008	
Vanadium	1.1			<0.001	0.003	0.002	0.01
Zinc	0.67	5.0	5.0	0.04	1	0.1	0.24
Zirconium				0.002	<0.03	0.003	

* : Heterogeneous

MC: > 10 mg/l

Table A-11

TRACE ELEMENTS FROM NOVEMBER, 1979 SAMPLES

Sample	Concentrations (mg/l)																
	Aluminum	Silver	Boron	Barium	Cadmium	Chromium	Copper	Iron	Manganese	Nickel	Vanadium	Zinc	Beryllium	Arsenic	Selenium	Antimony	Lead
	Al	Ag	B	Ba	Cd	Cr	Cu	Fe	Mn	Ni	V	Zn	Be	As	Se	Sb	Pb
OW-1	.23	<.002	<.01	.17	.01	<.007	.020	.050	.01	.10	.01	.24	<.001	.003	.002	<.006	<.001
OW-2	7.0	<.002	<.01	.26	.02	<.007	.040	.08	.94	.07	.02	.39	<.001	<.002	.002	<.006	.017
OW-3	.13	<.002	<.01	.22	<.008	<.007	.010	.04	.69	.05	.01	.14	<.001	<.002	<.001	<.006	<.001
OW-3	.31	<.002	<.01	.19	.02	<.007	.004	15.	.89	.07	.01	.16	<.001	<.002	<.001	<.006	<.001
OW-4	< .08	<.002	<.01	.12	<.008	<.007	.020	.07	.15	.06	.02	.22	<.001	<.002	<.001	<.006	<.001
OW-4	.16	<.002	<.01	.20	.02	<.007	.030	4.8	.46	.26	.01	.84	<.001	<.002	<.001	<.006	<.001
OW-5	.18	<.002	<.01	.09	<.008	<.007	.008	.03	.01	.05	.02	.09	<.001	<.002	<.001	<.006	<.001
OW-5	.32	<.002	<.01	.09	.02	.04	.008	.01	.03	.07	.003	.08	<.001	<.002	<.001	<.006	<.001
OW-6	.89	<.002	<.01	.22	.03	.07	.050	.04	.06	.07	.005	.34	<.001	<.002	<.001	<.006	<.001
OW-7	29.	<.002	<.01	.22	.06	.08	.210	21.	1.3	.12	.01	.73	<.001	<.002	<.001	<.006	.05
OW-8	.63	<.002	<.01	.10	.02	.04	.020	.05	.02	.09	.008	.24	<.001	<.002	<.001	<.006	<.001
P-2	.20	<.002	<.01	.10	.01	.05	.030	.04	.02	.17	.01	.82	<.001	<.002	<.001	<.006	<.001
P-4	.29	<.002	<.01	.18	.01	.03	.010	.06	.02	.07	.007	.12	<.001	<.002	<.001	<.006	<.001
P-4	.16	<.002	<.01	.18	.02	<.007	.006	.05	.04	.02	.006	.09	<.001	<.002	<.001	<.006	<.001
P-4A	.76	<.002	<.01	.26	.02	.06	.17	.07	.13	.10	.008	.45	<.001	<.002	.003	<.006	<.001
Plant Well	.38	<.002	<.01	.13	.02	.04	.01	.24	.01	.06	<.005	.14	<.001	<.002	<.001	<.006	.003
Process Waters	-	0.07	-	-	<0.002	0.22	<0.005	-	-	0.94	1.1	0.67	0.021	0.15	0.20	0.011	<0.002
Drinking Water Stds.		0.05		1.0	0.01	0.05	1.0	0.3	0.05			5.0		0.05	0.01	0.01	0.05

Appendix B

MONITORING WELL INSTALLATION AND SAMPLING

Figure B-1 illustrates the two types of monitoring wells that were installed at Plant Scholz to sample for groundwater quality. Observation wells were installed in the surficial soils and consisted of two-inch (5.08 cm) diameter slotted polyvinyl chloride (PVC) pipe. The void surrounding the observation well was backfilled with silica sand followed by a cement-bentonite grout cap at the surface.

A piezometer is an observation well sealed in a given stratum to measure the hydraulic pressure and to sample the water quality in that pacticular stratum. The piezometers consisted of 1-1/4 (3.18 cm) or one-inch (2.54 cm) diameter polyvinyl chloride pipe with a 2 to 5-foot (0.6 to 1.5 m) slotted tip. The void surrounding the piezometer was backfilled with silica sand within the stratum to be sampled, followed by a bentonite clay plug and cement-bentonite grout to the surface to prevent leakage along the sides of the piezometer.

Sampling of the observation wells and piezometers was accomplished by both airlift and bailing methods as illustrated in Figure B-2. The air-lift method uses reagent grade compressed nitrogen gas to force the water sample up to well casing as the gas rises from the bottom of the well. Prior to retrieving water samples for chemical testing, the wells were normally flushed by removing at least one well pipe volume.

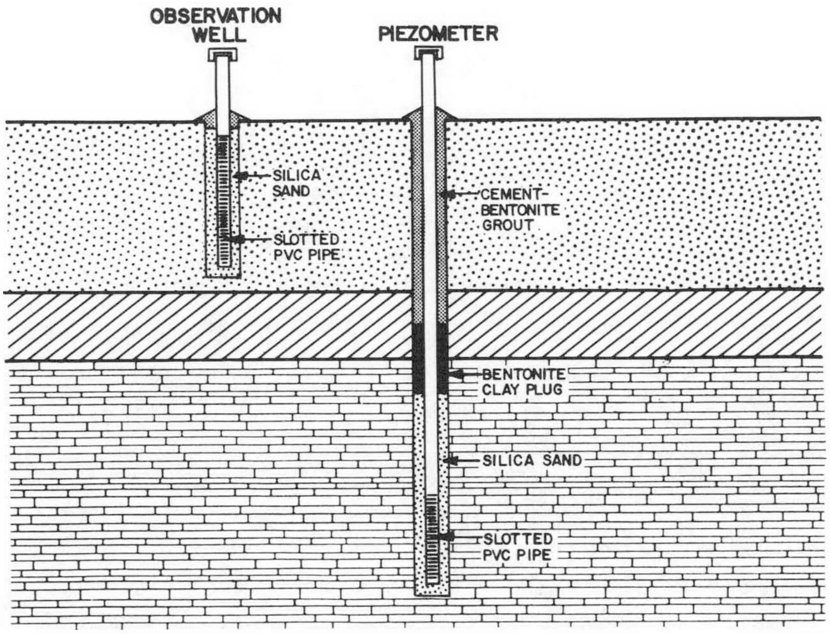

Figure B-1. Types of Monitoring Wells

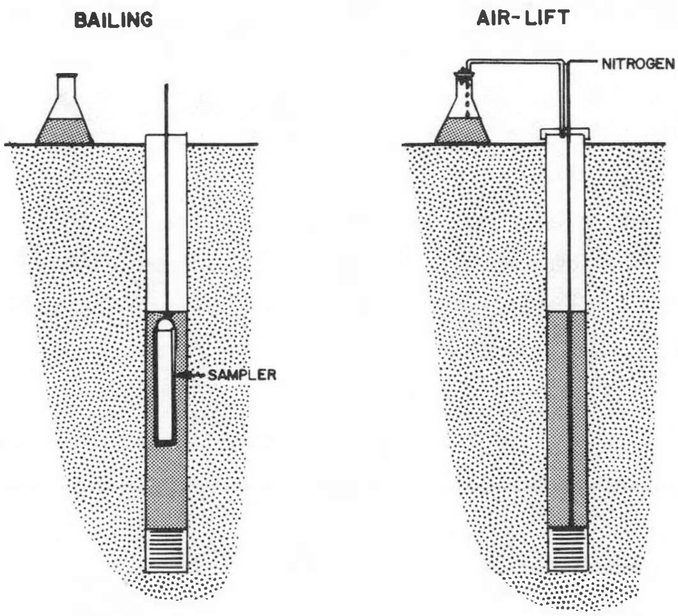

Figure B-2. Methods of Water Quality Sampling

Appendix C

GLOSSARY AND NOMENCLATURE

GLOSSARY

Angle of Repose: The maximum slope angle at which a material can be stacked or dumped and remain stable. The larger the angle of repose, the steeper the stable slope angle.

Aquiclude: A saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients.

Aquifer: A saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients.

Attenuation: A natural geochemical process whereby geologic units remove constituents from leachate by either absorption or adsorption.

Coefficient of Consolidation: The parameter expressing the time rate at which excess pore pressures dissipate and settlement occurs during primary consolidation. The larger the coefficient of consolidation, the quicker primary consolidation occurs. The coefficient of consolidation is typically expressed in units of cm^2/sec or ft^2/day.

Coefficient of Permeability: A parameter expressing the apparent velocity at which a fluid flows through a material. The larger the coefficient of permeability, the greater the velocity of flow through the material. The coefficient of permeability is normally expressed in units of cm/sec or ft/day.

Coefficient of Secondary Compression: A parameter expressing the rate at which secondary compression occurs. The coefficient of secondary compression C_α , is calcualted as the change in vertical strain (ϵ_v) per log cycle of time (t), $C_\alpha = \Delta\epsilon_v/\Delta \log t$.

Cohesion: The shear strength of a material in the absence of any effective stress, or that part of the shear strength in excess of the strength derived from friction. Cohesion is normally expressed in units of lb/ft^2 or kg/cm^2.

Compression Ratio: A parameter expressing the magnitude of one-dimensional consolidation settlement (i.e., vertical, but no lateral deformation) occurring for a given change in applied load. The compression ratio, CR, is calculated from the slope of the stress, σ, (on a log scale) versus vertical strain, ε_v, curve from a consolidation test, $CR = \Delta\varepsilon_v / \Delta \text{Log}\sigma$.

Consolidation: The gradual time dependent process describing the compression (or "densification") of a saturated soil in response to an increased load during the dissipation of excess pore pressure (i.e., explusion of pore water). Primary consolidation (or primary compression) is that compression that occurs while excess pore pressures dissipate. The slow continued consolidation that continues after the excess pore pressures have dissipated is termed secondary compression.

Dry Density: The weight of dry solids per unit volume. The dry density of a soil is normally expressed in lb/ft^3.

Effective Stress: Defined as the total stress at a point (σ) minus the pore water pressure (u) at the point. Effective stress is denoted by a horizontal line over the stress ($\bar{\sigma}$) and is expressed in kg/cm^2.

Fines Content: The percent by dry weight of a material finer than the U.S. No. 200 sieve (0.074 mm mesh size).

Leachate: A fluid derived from the percolation of water through a waste material resulting in the removal by solution of various soluble constituents within the waste material.

Moisture Content (or water content): The ratio of the weight of water to the weight of dry solids.

Penetration Twin: A twin crystal in which the two parts interpenetrate each other.

Percent Solids: The ratio of the weight of dry solids to the total weight.

Phreatic Surface (or water table): The location at which the pore water pressure is atmospheric (i.e., zero gage pressure).

Piezometer: An instrument or specially constructed well used to measure the hydraulic pressure and/or sample the water quality of a particular stratum within a soil or rock mass (see Appendix B).

Piping: The formation of a pipe-shaped discharge channel or tunnel within a soil mass from seepage through the soil causing the removal (by scour or erosion) of soil particles.

Porosity: The ratio of the volume of the voids (volume of air and water) to the total volume.

Shear Strength: The measure of the resistance of a material to shear stresses. The shear strength of a soil is divided into the components of friction and cohesion as modeled by the Mohr-Coulomb failure criteria. The friction component of strength is expressed by the effective friction angle, $\bar{\phi}$. The larger the value of $\bar{\phi}$, the greater the shear strength of the soil. The cohesion component of strength is expressed by the effective cohesion, $\bar{c}$.

Springline: The position at which the phreatic surface exits the face of a slope.

Standard Penetration Test: The standard penetration test is a widely accepted method of in-situ testing of foundation soils (ASTM D-1586). A 2-foot long, 2-inch O.D. split-barrel (or split-spoon) sampler attached to the end of a string of drilling rods is driven 18 inches into the ground by successive blows of a 140-pound hammer freely dropping 30 inches. The number of blows needed for each 6 inches of penetration is recorded. The sum of the blows required for penetration of the second and third 6-inch increments of penetration constitutes the standard penetration test resistance N-value. After the test, the sampler is extracted from the ground and opened to allow visual examination and classification of the retained soil sample (split-spoon sample).

Unconformable: The lack of continuity in deposition between rock strata in contact, corresponding to a period of nondeposition, weathering, or erosion.

Undisturbed Samples: Undisturbed sampling implies the recovery of soil samples in a state as close to their natural condition as possible. Complete preservation of in-situ conditions cannot be realized; however, with careful handling and proper sampling techniques, disturbance during sampling can be minimized for most geotechnical engineering purposes.

Normally, undisturbed samples are obtained by pushing a 2.33-inch I.D., 16-gauge wall, brass tube 24 inches into the soil with a single stroke of a hydraulic ram. The sampler, which is a Shelby tube, is 30 inches long.

Void Ratio: The ratio of the volume of the voids (volume of air and water) to the volume of the dry solids.

NOMENCLATURE

$\bar{c}$	Effective Cohesion
c_v	Coefficient of Consolidation
C_α	Coefficient of Secondary Compression = $\Delta\epsilon_v/\Delta \text{Log } t$
CR	Compression Ratio $=\Delta\epsilon_v/\Delta \text{Log } \bar{\sigma}$
CIDC	Consolidated Drained Triaxial Compression Test
$\overline{\text{CIU}}$C	Consolidated Undrained Triaxial Compression Test with Pore Pressure Measurements
e	Void Ratio
G_s	Specific Gravity of Solids
k	Coefficient of Permeability
LL	Liquid Limit
NM	Natural Moisture Content
PL	Plastic Limit
PI	Plasticity Index
γ_b	Bouyant Unit Weight
γ_d	Dry Density
γ_t	Total Unit Weight
ϵ_v	Vertical Strain
σ	Normal Total Stress
$\bar{\sigma}$	Normal Effective Stress
$\bar{\sigma}_{vc}$	Vertical Effective Consolidation Stress
$\bar{\sigma}_c$	Isotropic Effective Consolidation Stress
$\bar{\phi}$	Effective Friction Angle